

High p_T Signatures and Resonances

YR BSM chapter sections 5 & 6

arXiv:1812.07831

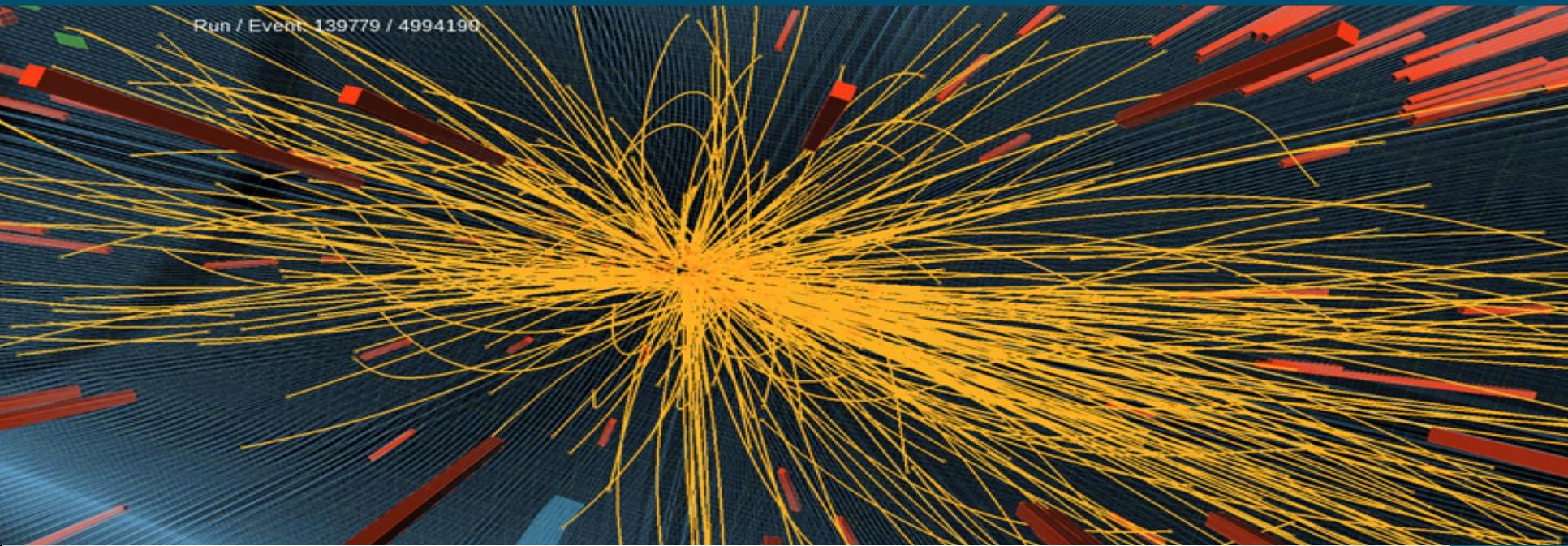
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on behalf of the Yellow Report authors, ATLAS and CMS collaborations

HL/HE – Jamboree CERN

March 1st 2019

Run / Event 139779 / 4994190



This talk

Sec.5: High p_T signatures from flavour

Sec.6: Resonances and other BSM signatures

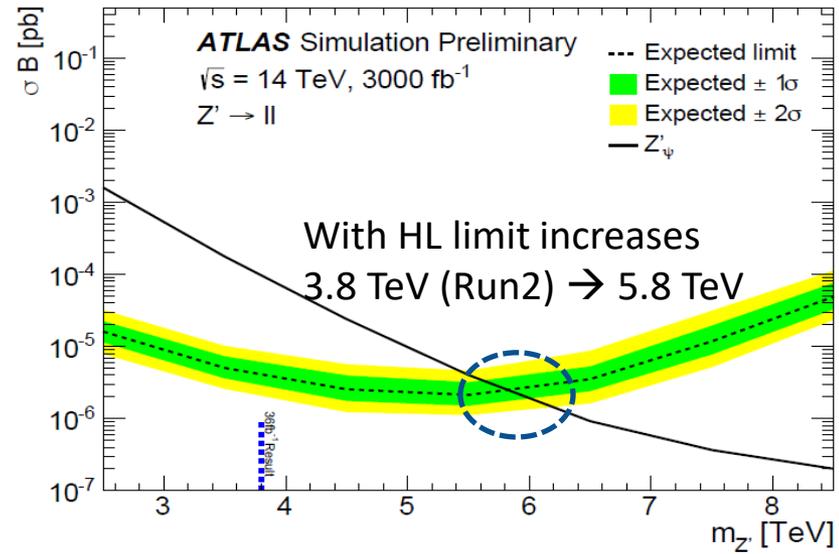
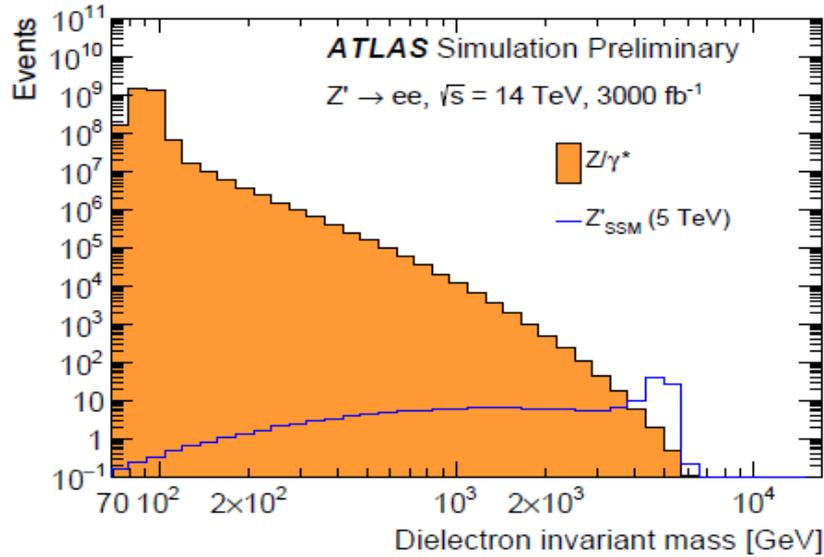
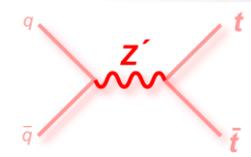
HL: 3/ab @ $\sqrt{s} = 14$ TeV
HE: 15/ab @ $\sqrt{s} = 27$ TeV
(no real HE detector simulation)

36 analyses and projections
→ Can only show a selection

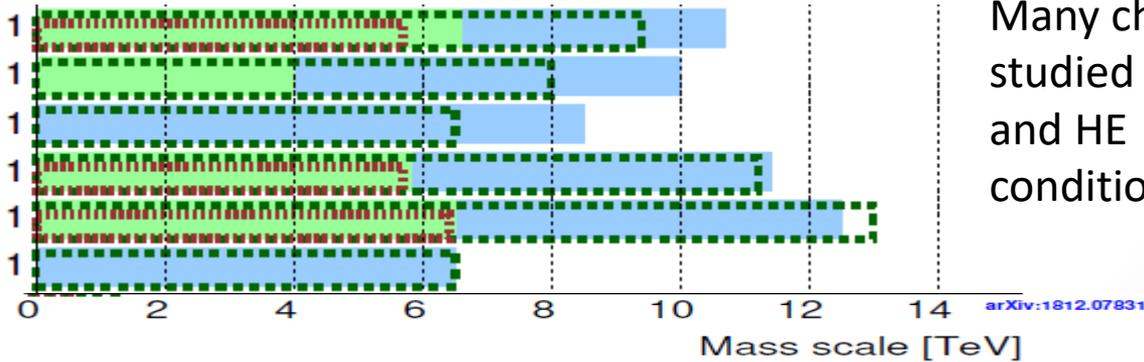
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Dilepton Resonance at HL

Key benchmark BSM searches, e.g. Sequential SM (SSM) model. Leptonic channels ($ee, \mu\mu$) with max sensitivity due to BR, high reconstruction efficiency.



- $G_{RS} \rightarrow t\bar{t}$
- $Z'_{TC2} \rightarrow t\bar{t}$
- $Z'_{SSM} \rightarrow t\bar{t}$
- $Z'_\psi \rightarrow l+l^-$
- $Z'_{SSM} \rightarrow l+l^-$
- $Z'_{SSM} \rightarrow \tau^+\tau^-$

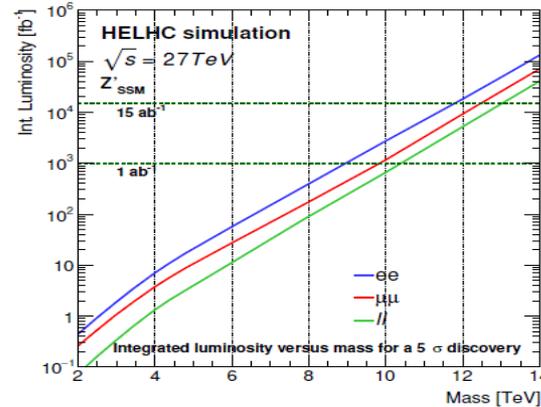
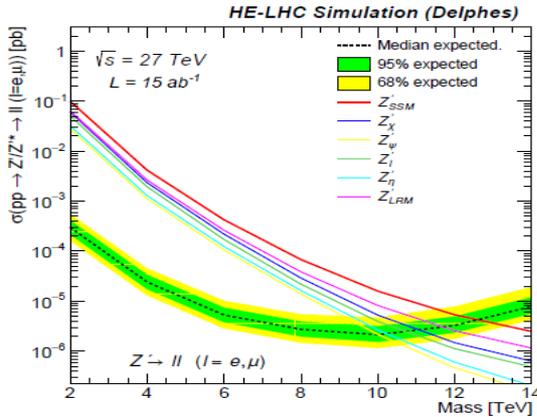


Many channels studied for HL and HE conditions.

Dilepton Resonances at HE

Theory projection

SSM
 $Z'(ee, \mu\mu)$
 Limit ~ 13 TeV

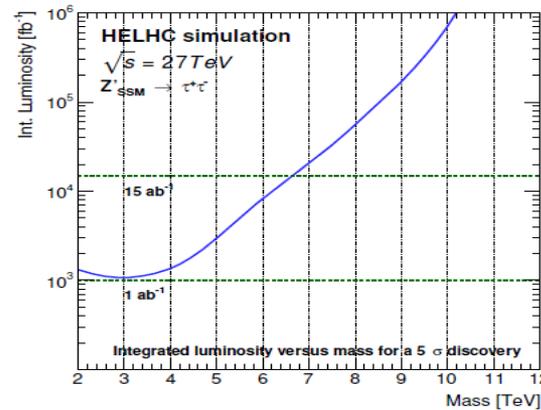
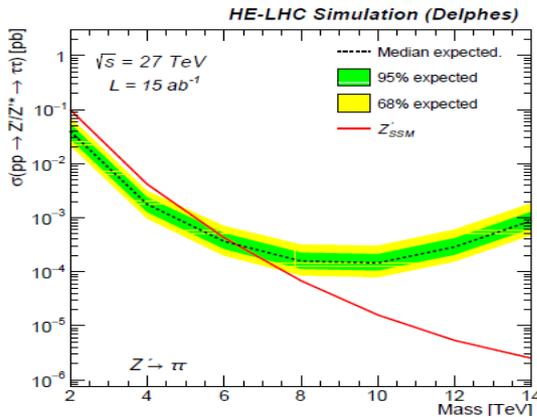


SSM
 $Z'(\tau\tau)$
 Limit ~ 6 TeV

Exclusion reach

Discovery sensitivity

Lower sensitivity due to BR and reco eff.



HE

| Decay | Exclusion [TeV] | Discovery [TeV] |
|----------------------------|-----------------|-----------------|
| $Z'_{SSM} \rightarrow ee$ | 12.8 | 12.8 |
| $Z'_{\psi} \rightarrow ee$ | 11.4 | 11.2 |

ATLAS simulation

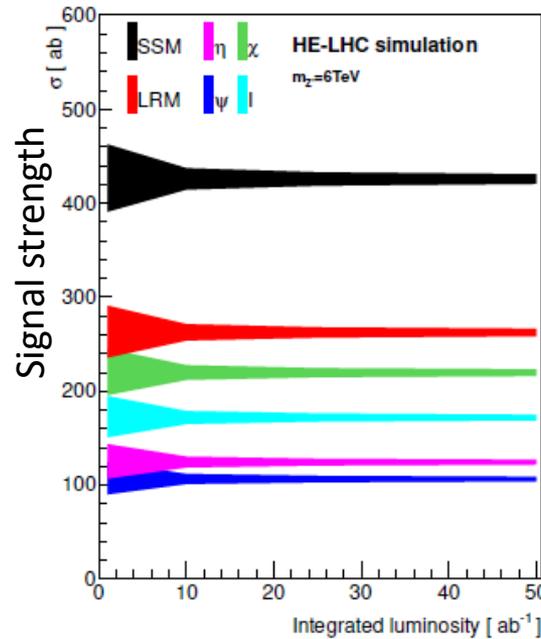
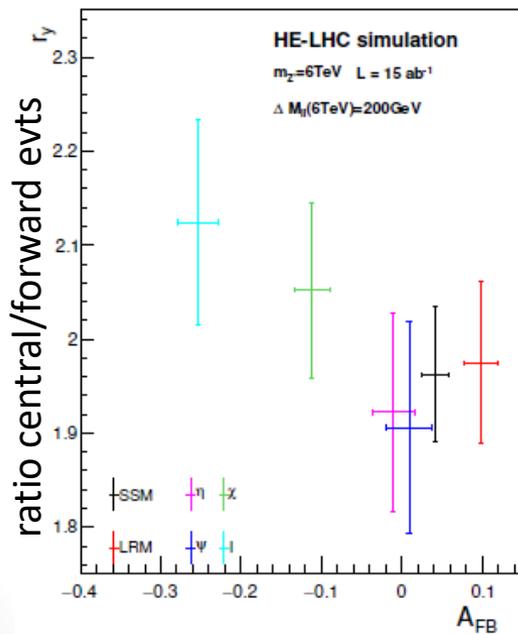
What if we discovered something?



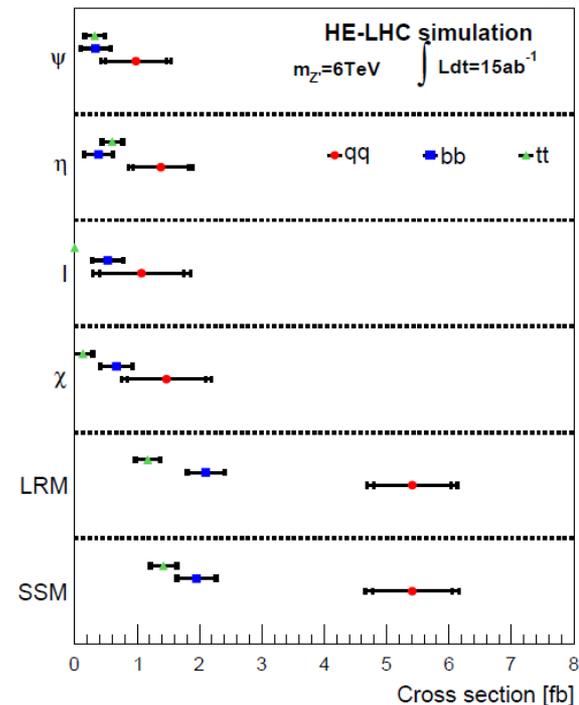
Example of $Z' \rightarrow ee/\mu\mu$. Study discrimination power at HE in case of discovery at HL-phase (Mass ≈ 6 TeV).

With $\sqrt{s}=14 \rightarrow 27$ TeV, σ_{prod} increases by ~ 100 .

Observables: A_{FB} , $r_y = \text{ratio central/forward evts}$



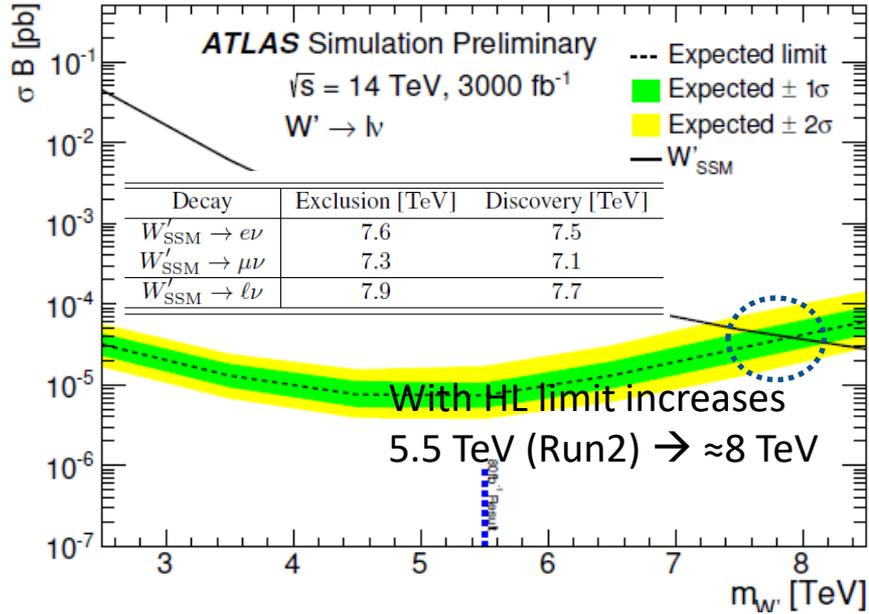
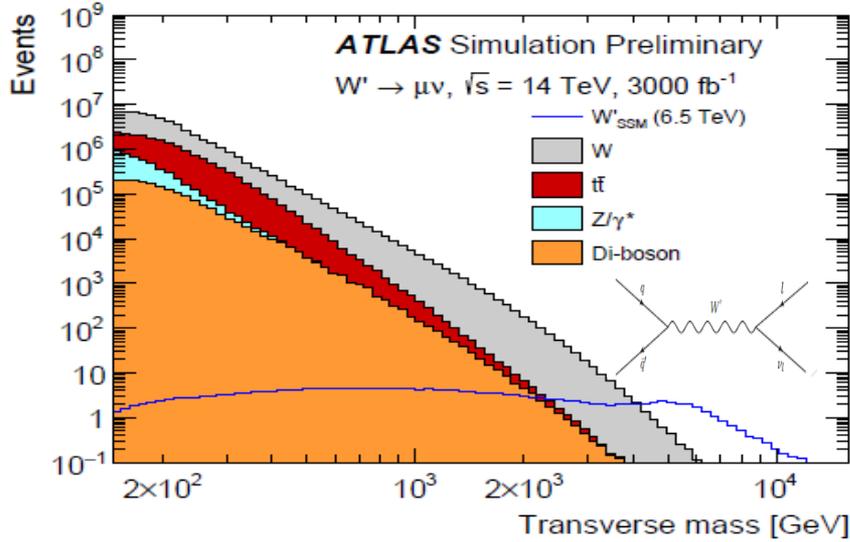
Theory projection



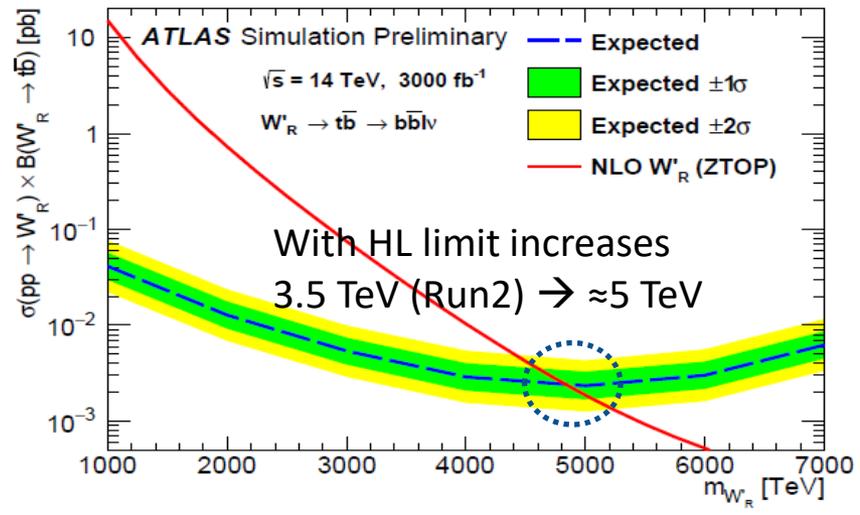
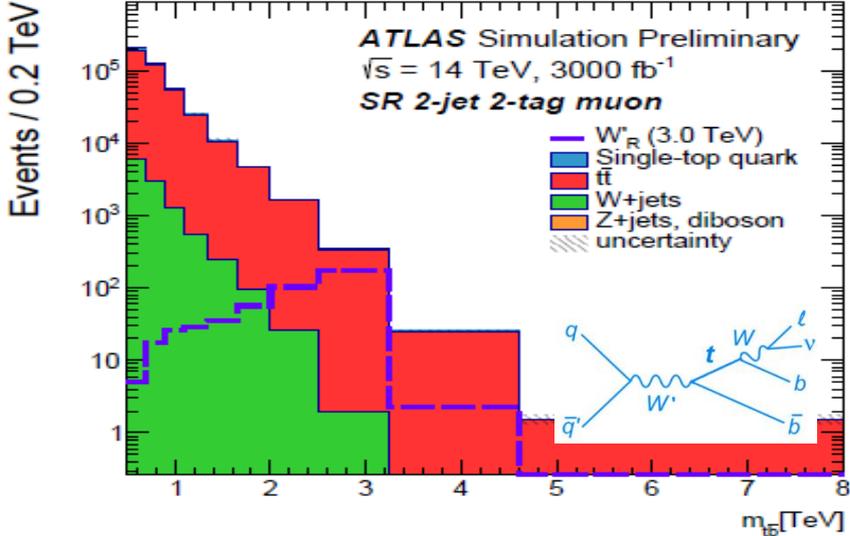
Adding ratio of tt/bb -tagged events w.r.t. jj provides another handle

$W' \rightarrow e\nu, \mu\nu$ or tb ($t \rightarrow b\nu$)

ATLAS simulation

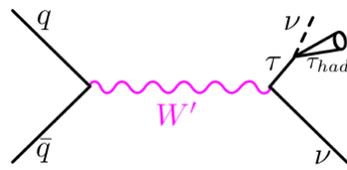


$W' \rightarrow e\nu, \mu\nu$ in SSM with 100% BR, maximum sensitivity

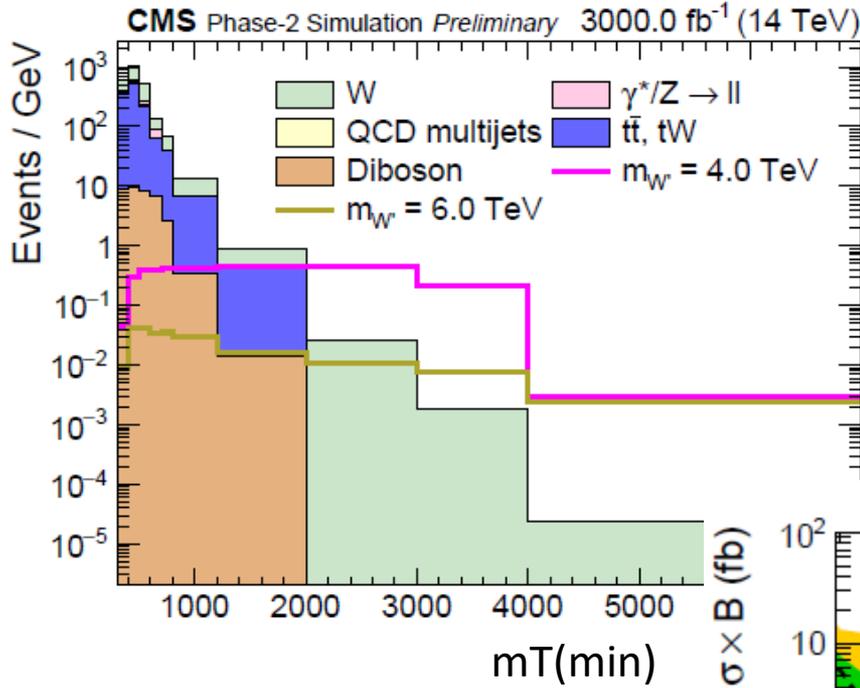


$W' \rightarrow tb$ more complicated decay. BR and reconstruction efficiencies matter.

$$W' \rightarrow \tau \nu$$



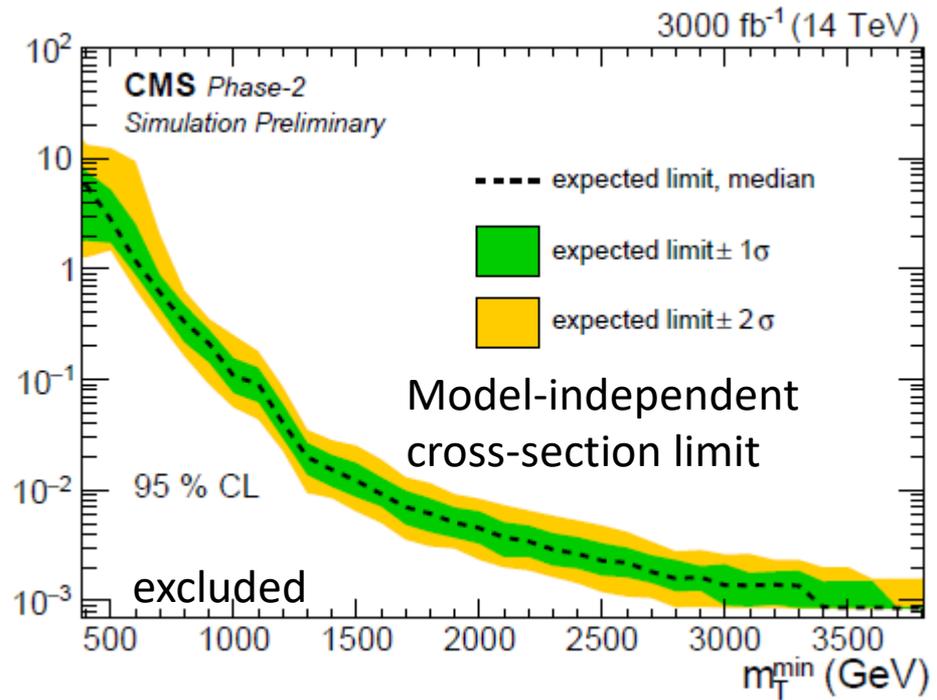
CMS Delphes



SSM W' model with SM-like coupling
 Concentrate (as in Run-2) on hadronically decaying tau (~60% BR).
 Reconstructed as a jet, with tau identification from decay.

SSM $W' \rightarrow \tau \nu$
 Discovery with 3/ab \rightarrow 6.5 TeV (5σ)
 Run-2 (36/fb) exclusion limit \sim 4 TeV

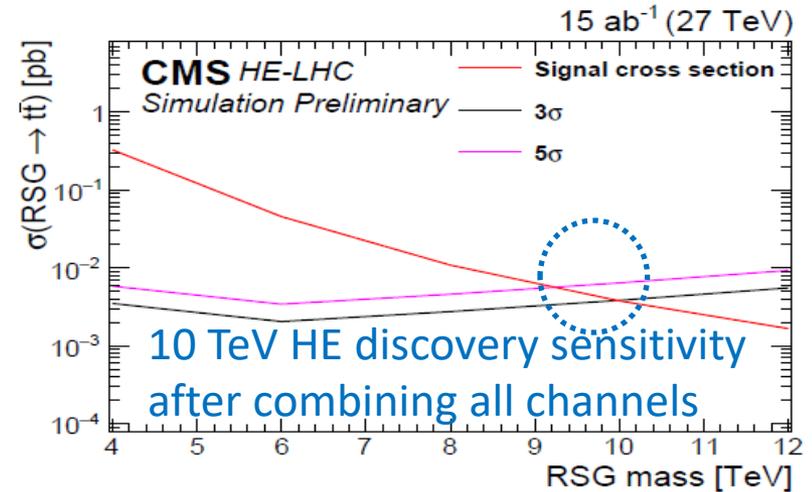
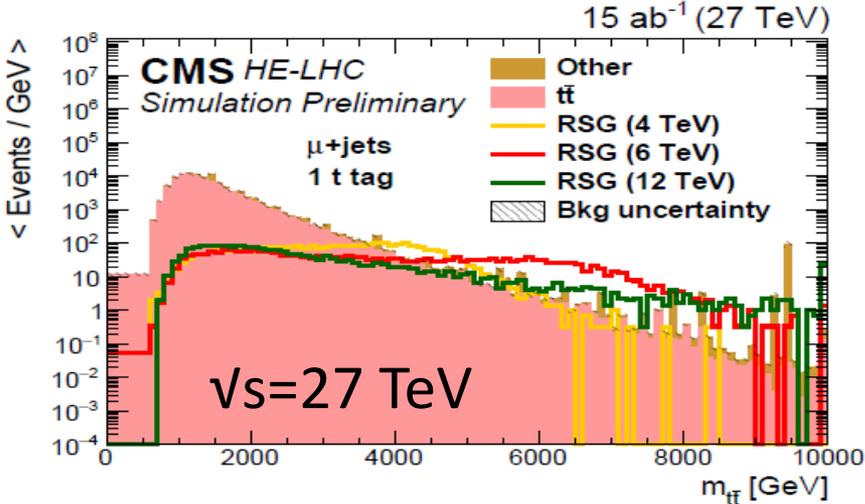
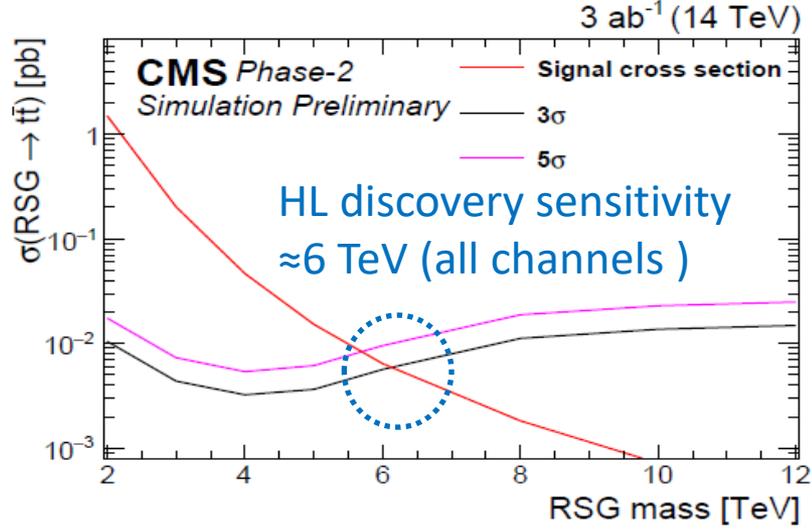
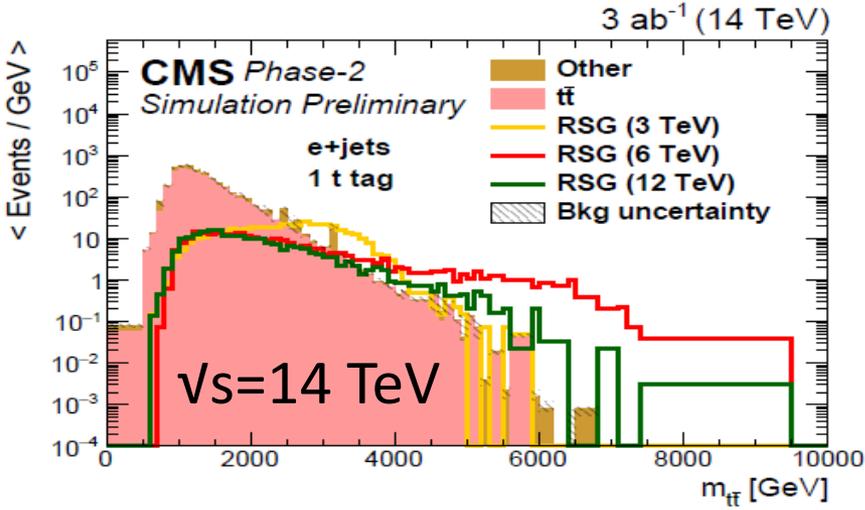
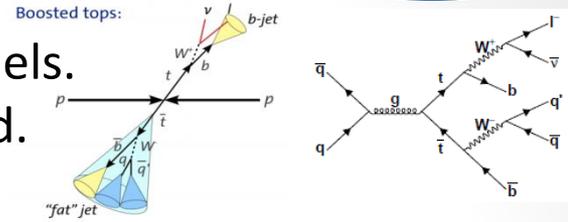
Model-independent xsec limit for interpretations in other models, e.g. explaining flavour observations.



Randall-Sundrum Graviton $\rightarrow t\bar{t}$

CMS Delphes

Spin-2 RS graviton predicted by extra dimension models.
 Enhanced couplings to 3rd gen SM particles suggested.
 Substructure technique for boosted jets.



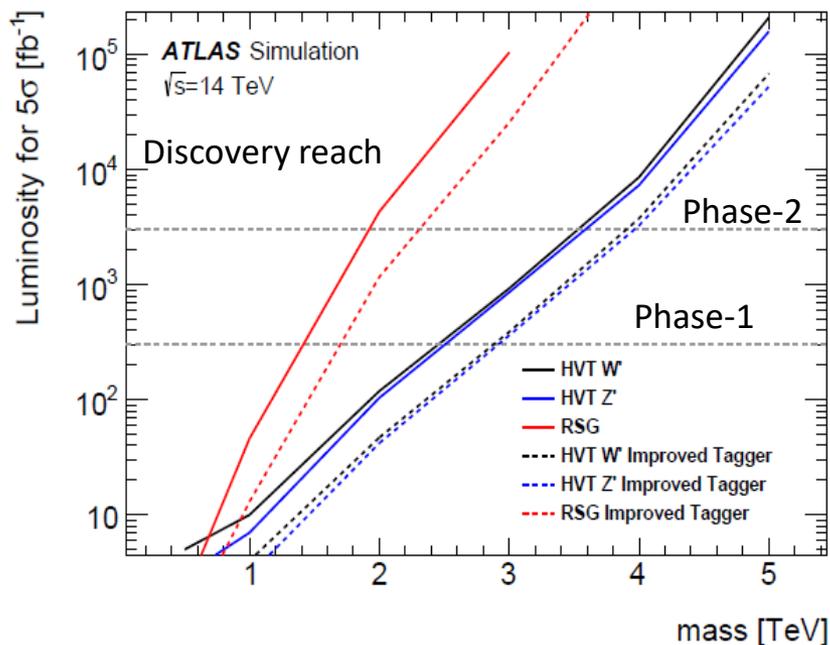
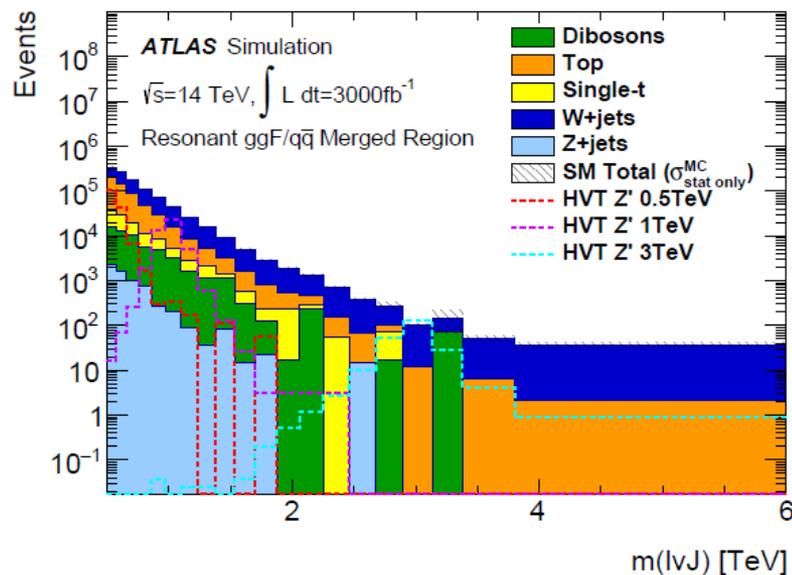
Diboson Resonances at HL/HE

Models: HVT (heavy vector triplet),
RS and narrow scalar resonances

$\Gamma < 6\% \ll$ detector resolution

Resonances $W(l\nu)W/Z(jj)$ using
W/Z tagger and small/large-R jets

ATLAS
simulation



Exclusion limits for HVT-Z' model:

@14 TeV $\rightarrow M_x > 5$ TeV

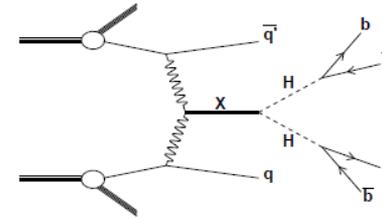
@27 TeV $\rightarrow M_x > 11$ TeV

$X \rightarrow HH \rightarrow 4b$

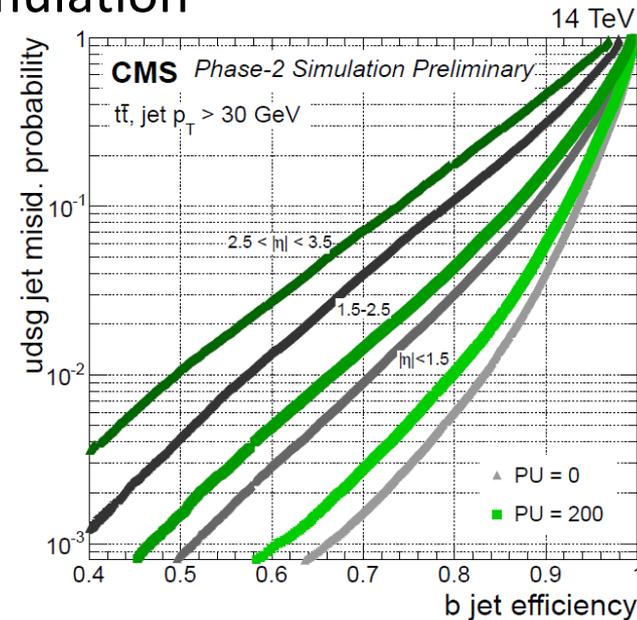
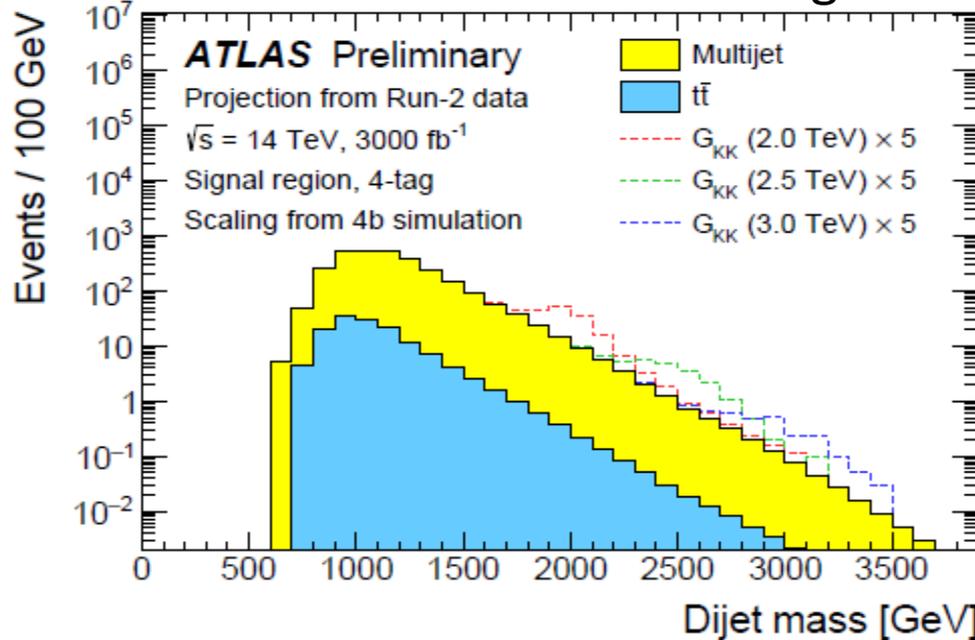
CMS Delphes

ATLAS simulation

Decay of a BSM resonance, e.g. Spin-2 KK graviton to double Higgs and 4b jets



QCD = Main background. Estimated by scaling from Run-2 since HL stats too large for simulation



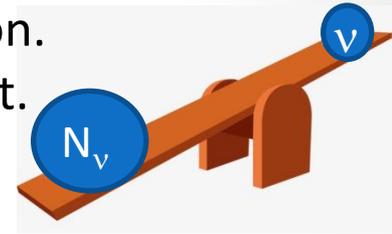
| Model | $\sqrt{s} = 13 \text{ TeV}, 36.1 \text{ fb}^{-1}$ as in Ref. [274] | $\sqrt{s} = 14 \text{ TeV}, 3 \text{ ab}^{-1}$ dijet scaling | $4b$ scaling |
|-----------------------------|---|---|--------------|
| $k/\overline{M}_{PI} = 0.5$ | no limit | 2.15 TeV | 2.00 TeV |
| $k/\overline{M}_{PI} = 1.0$ | 1.36 TeV | 2.95 TeV | 2.75 TeV |

Needs good b-tagging efficiency and low mis-id probability in PU200 \rightarrow Phase-2 high granularity detector helps

The Neutrino Mass Puzzle

Theory projection

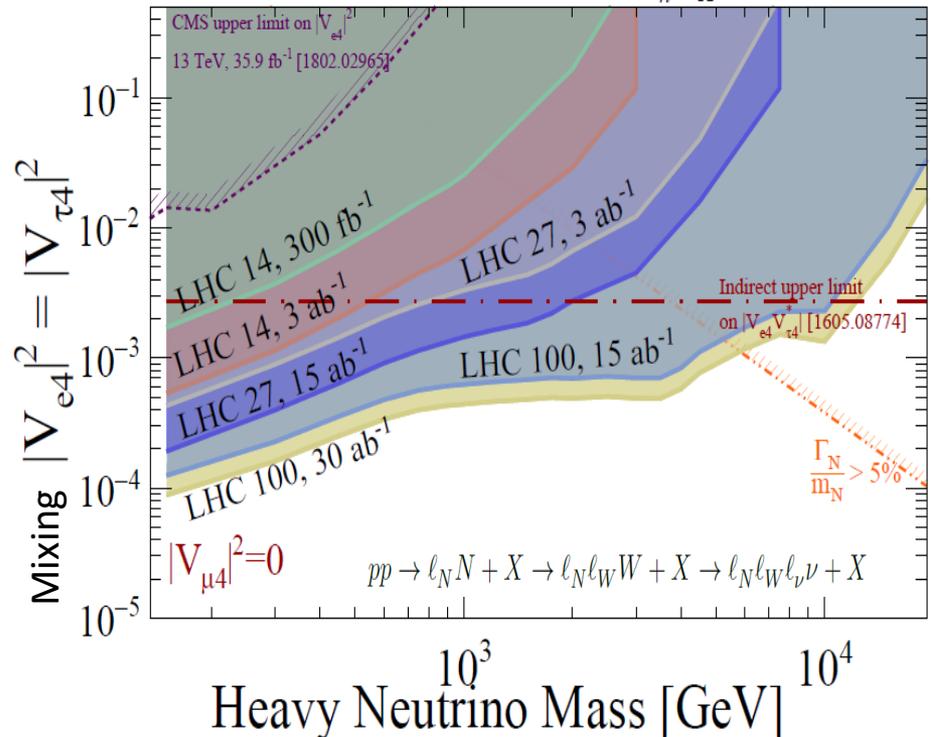
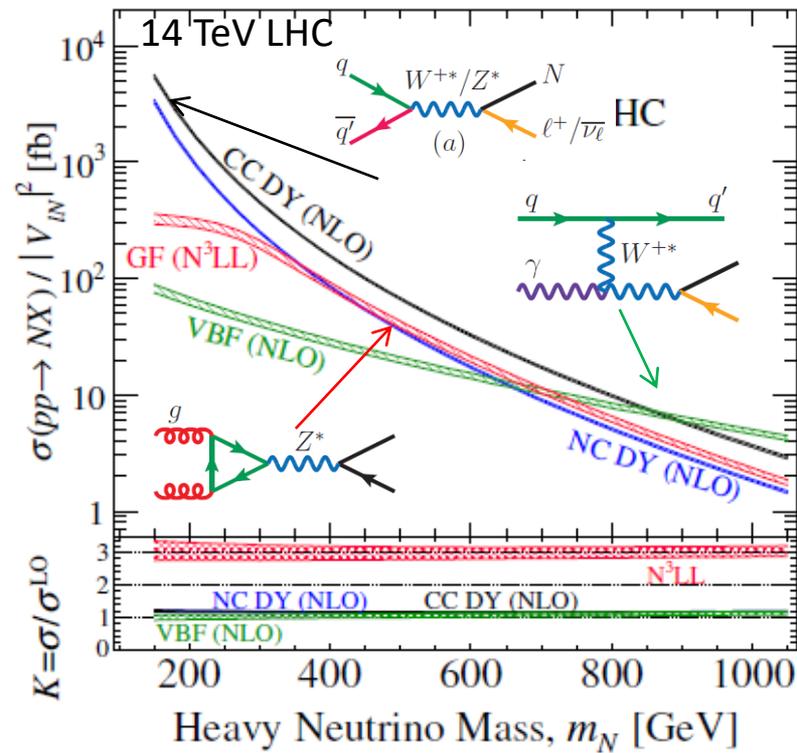
Observed tiny m_ν and large mixing angles still seek explanation. Popular models exploit Majorana nature and see-saw concept. Many possibilities at hadron colliders.



Production via DY, gg-fusion (GF) or VBF covers large mass range

Specific model (low scale see-saw, benchmark mixing) 3 lepton final state

95% Sensitivity - $pp \rightarrow \tau_h e l_X / 3e / 2e\mu$



Heavy Neutrino Mass, m_N [GeV]

$m_N > M_W$ Dirac or Majorana

Not all prod processes shown

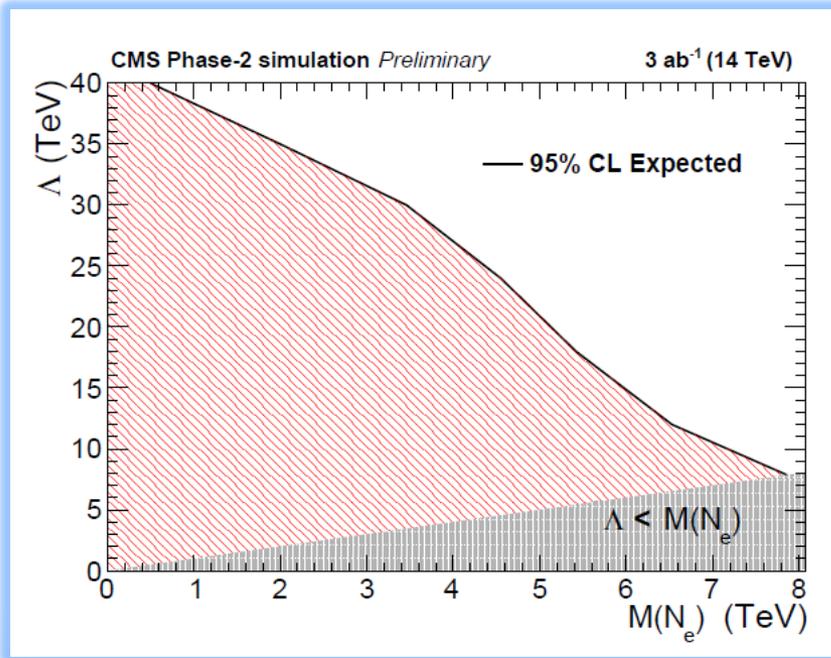
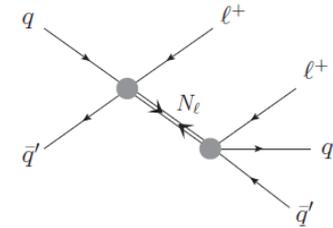
Heavy Composite Majorana Neutrino

Heavy Majorana neutrino N_ℓ using decay modes:

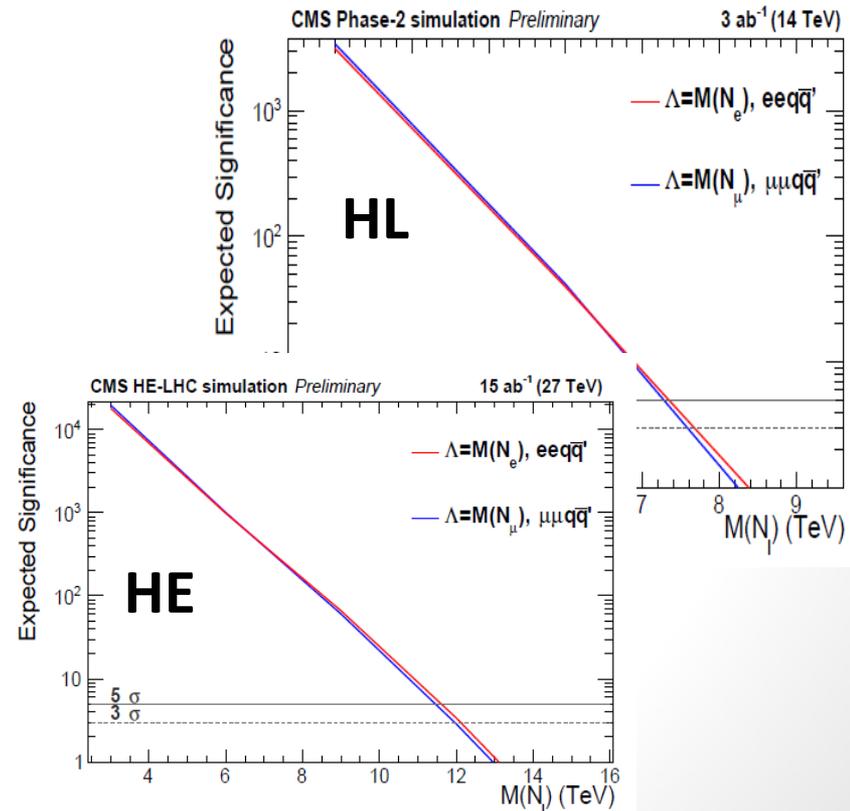
$$qq \rightarrow \ell N_\ell \rightarrow eejj/\mu\mu jj$$

Model parameters $M(N_\ell)$, compositeness scale Λ

- Cut high on lepton p_T and (fat) jet p_T Discovery potential of $M(N_\ell)$ increases to 7.5 TeV (HL) and 11 TeV (HE)



Exclusion for $M(N_\ell) = \Lambda$ improves from 4.6 TeV (Run-2) to 8 TeV (HL)

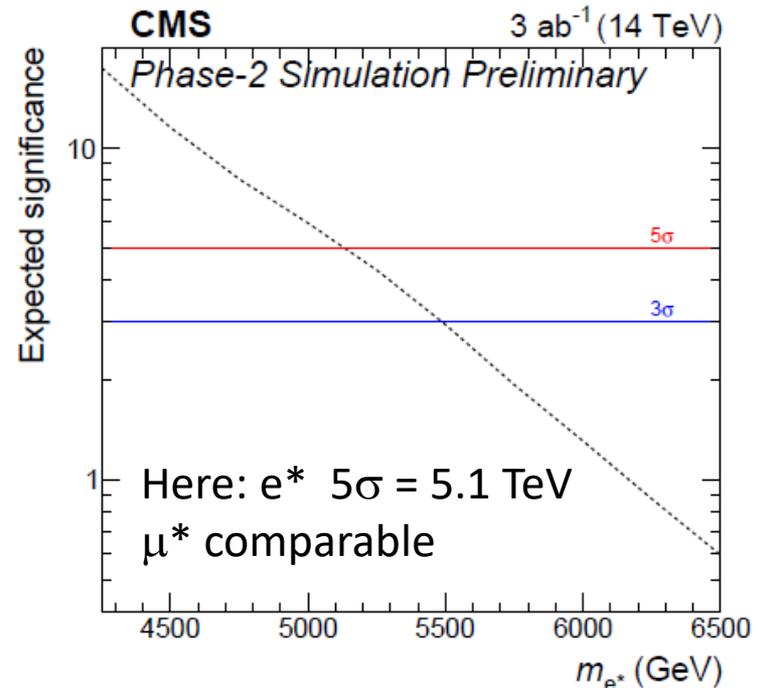
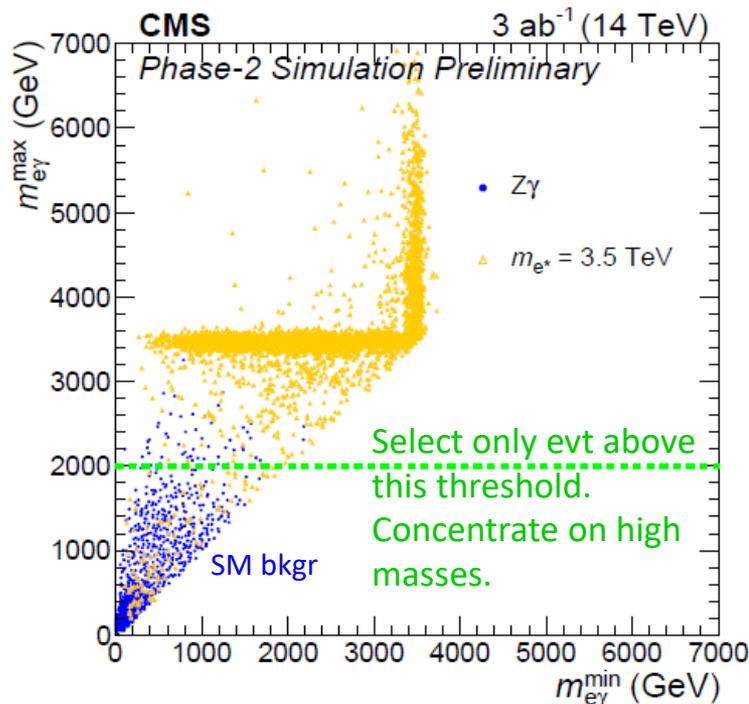
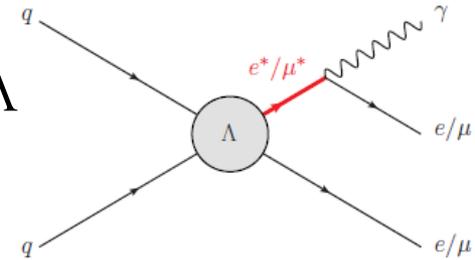


Compositeness

If compositeness \rightarrow excited leptons (or quarks). Several searches in Run-2. Final states $ee\gamma/\mu\mu\gamma$ are classical, also interesting for other models.

- Model parameters: Mass $m(\ell^*)$, compositeness scale Λ
- Concentrating on high masses. Xsec scale with Λ
- Signal extracted from 2D of m^{\max} and m^{\min}

CMS Delphes



Run-2 exclusion with 36/fb = 3.8 TeV in $ll\gamma$

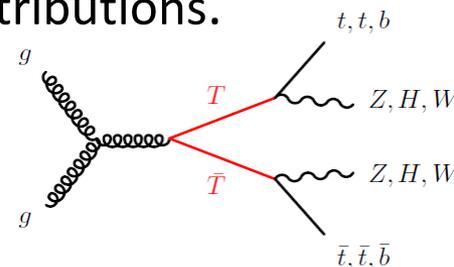
Vector-Like Quarks

Projection

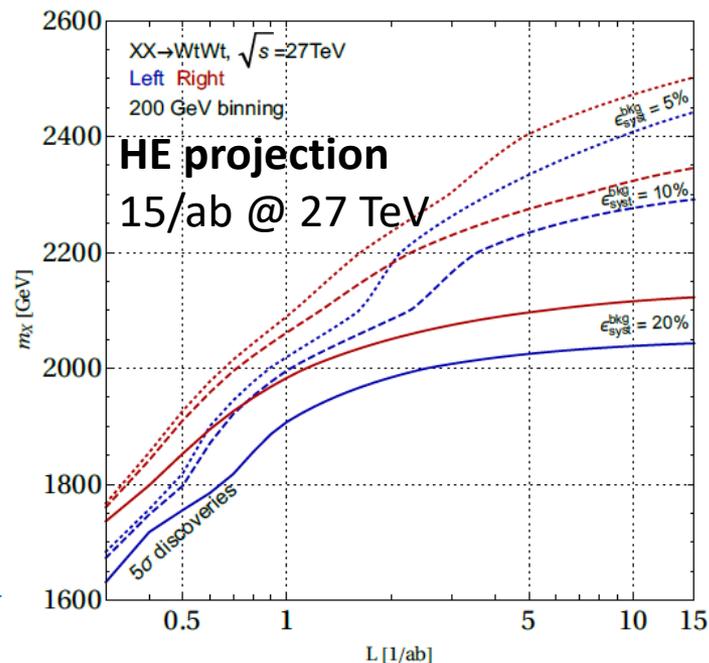
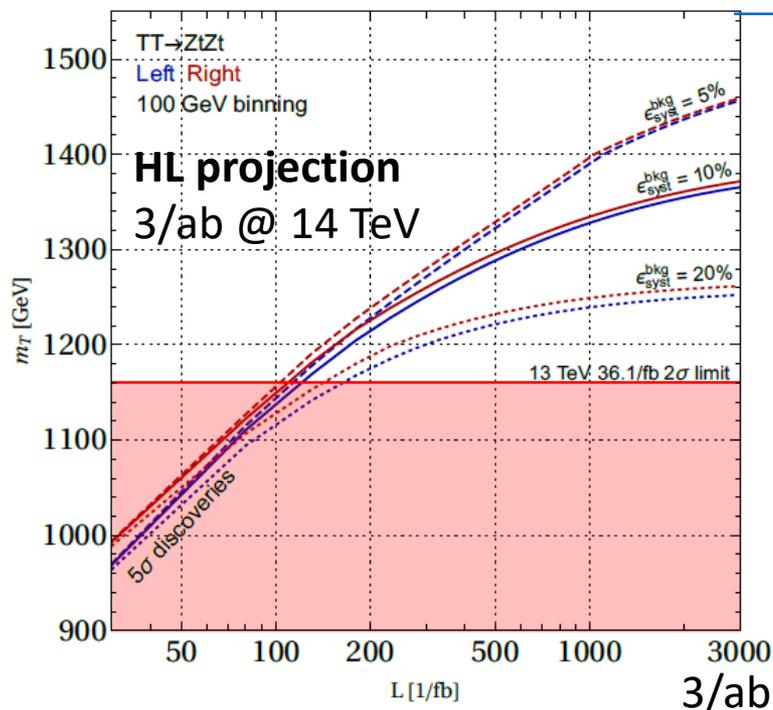
SM extension of 4th generation with SM-like chiral couplings now excluded, would alter Higgs production xsec through their loop contributions.

Spin-1/2 (= vector-like quarks or leptons) still possible.

- **Studying chiral properties** of such states by measuring polarisation of final-state particles to disentangle properties of hypothetical VLQ



Recast of ATLAS Run-2 result in JHEP08(2017)052



Substantial improvement with HE

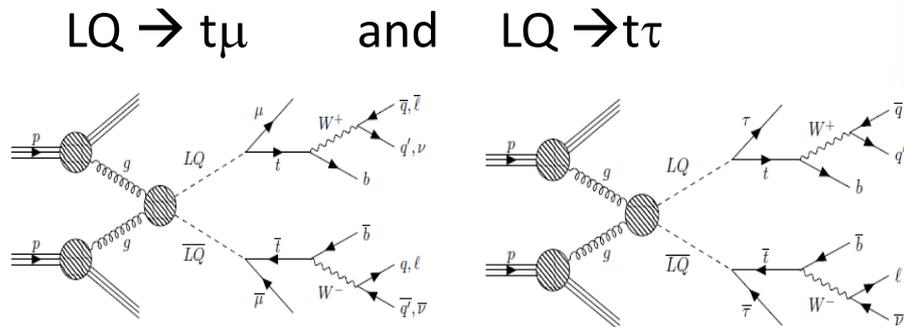
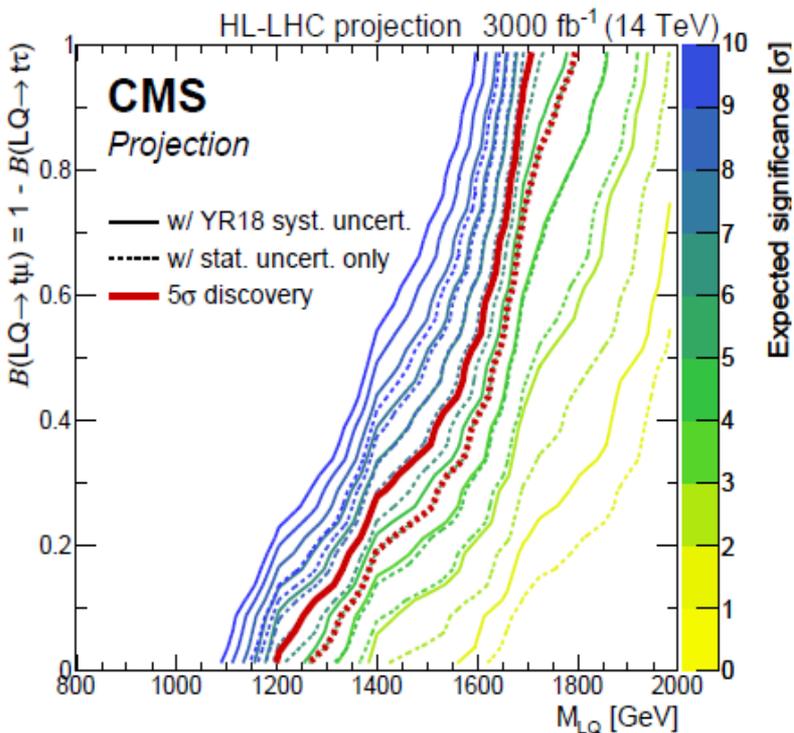
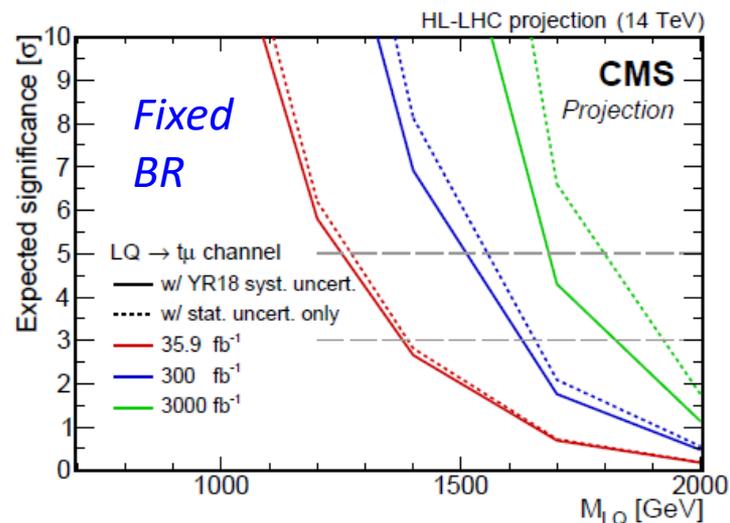
LeptoQuarks $\rightarrow t\tau$ and $t\mu$

CMS Projection

3rd gen. LQ are favoured by models interpreting observed B-anomalies.

Pair-produced LQ. Projection based on Run-2 result. Scaled to HL at 14 TeV.

Discovery as function of variable BR

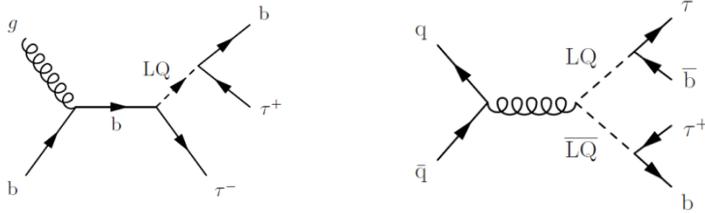


Discovery reach $M_{LQ} \sim 1.7$ TeV ($t\mu$) and 1.2 TeV ($t\tau$) assuming 100% BR for either channel. Exclusion limits are ~ 200 GeV higher. Present limits 1.4 TeV ($t\mu$), 0.9 TeV ($t\tau$)

LQ in $\tau + b$

CMS Delphes

Single LQ ($\tau\tau b$) and Pairproduction ($\tau\tau b b$)

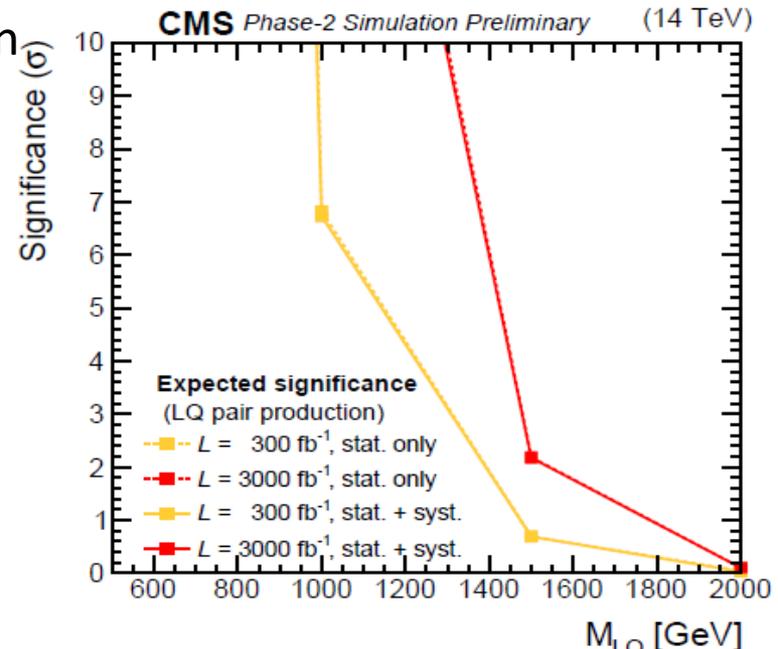
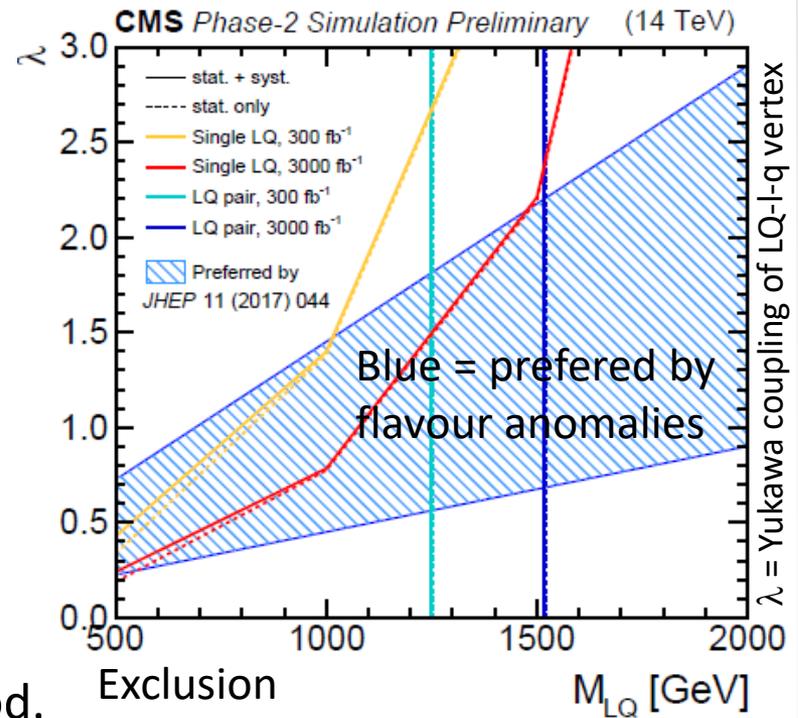


Large fraction of **flavour-preferred region** accessible.

At HL, discovery up to 1.5 TeV with pair prod.

For larger M_{LQ} and large λ single production becomes dominating.

Discovery reach ≈ 1.5 TeV (pair prod.), ≈ 1 TeV (single prod. But xsec scales with λ^2).
 Statistically dominated. No big systematics impact.



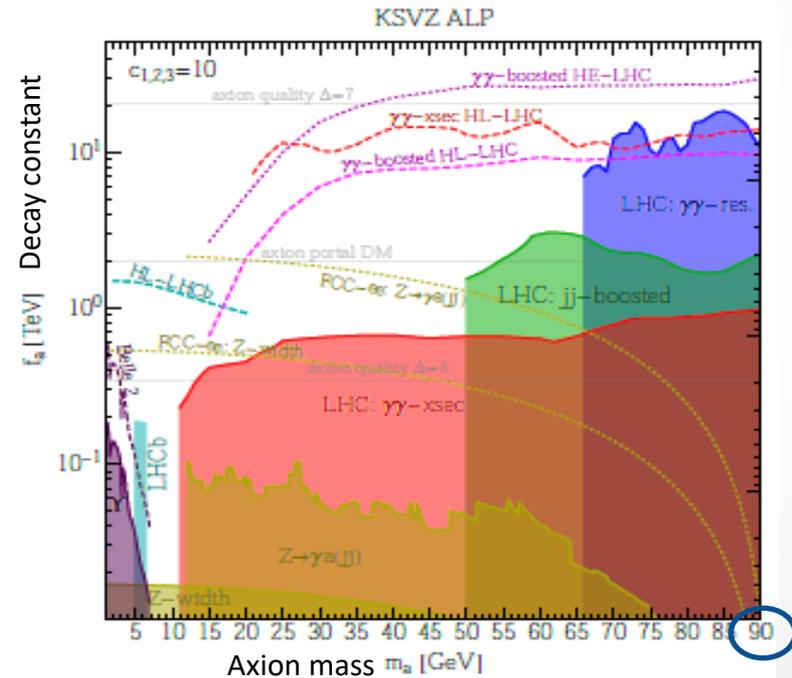
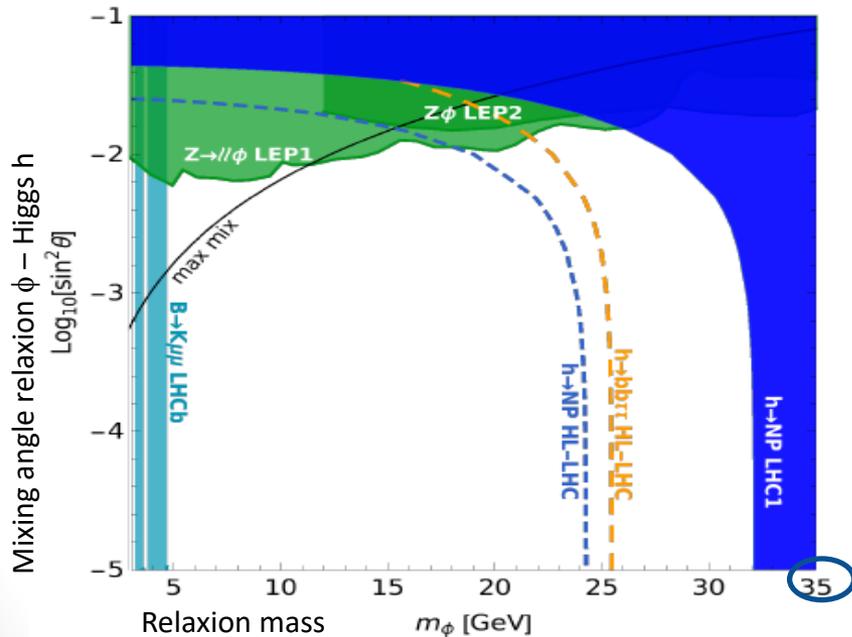
Low-Mass BSM Signatures

Theory projection

Not only high- p_T , also preserve capability for **low mass signals**. Experimentally **challenging** with high PU, e.g. trigger thresholds.

Relaxion mechanism (ϕ) addressing hierarchy problem differently than conventional symmetry-based models.

Axions-like particle (ALP, a).
Interesting mass range 1 – 90 GeV.

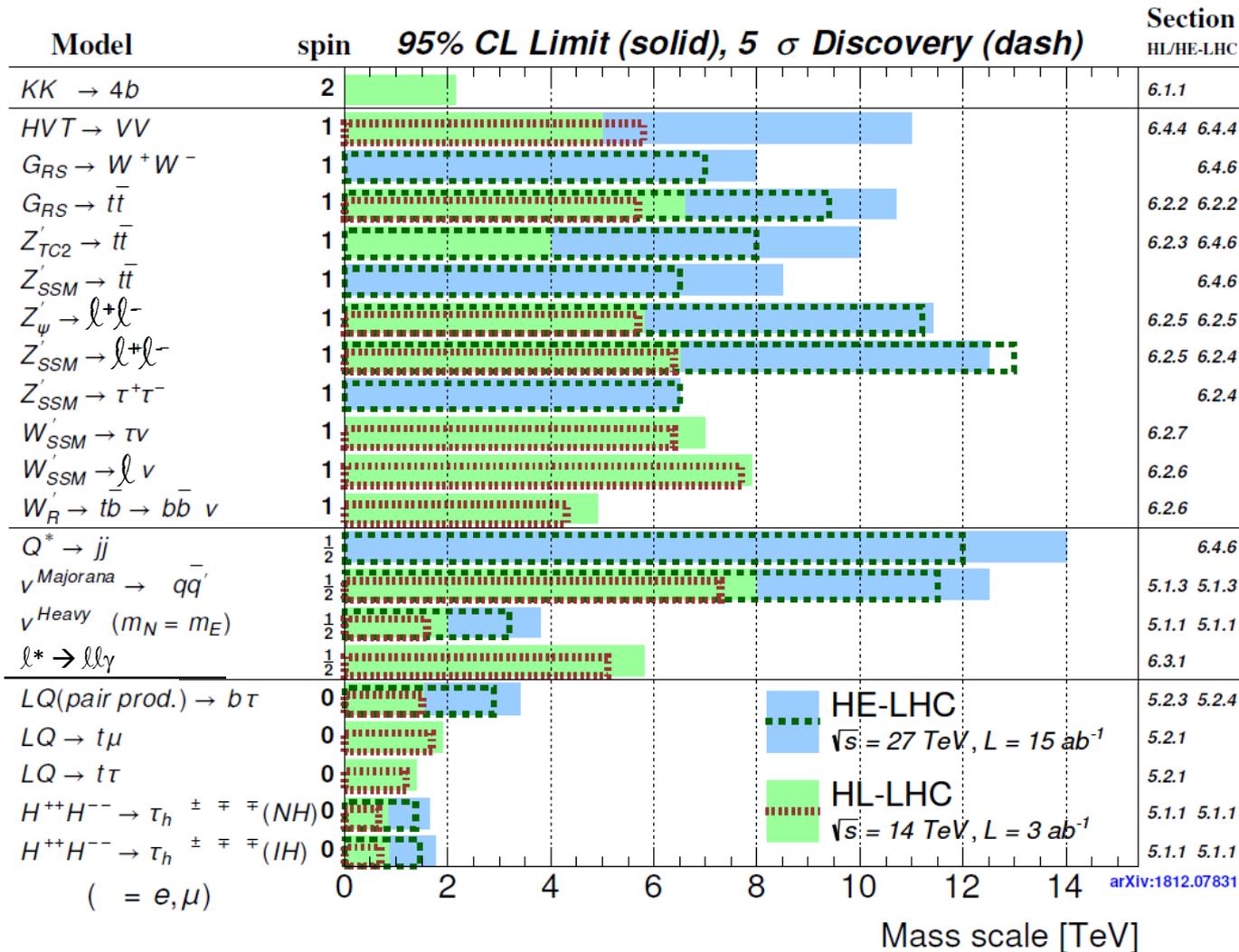


Many interesting channels, $BR = f(m)$.
Best sensitivity for $bb\tau\tau$.

Best sensitivity from **boosted $\gamma\gamma$ resonance search** based on monojet trigger projected to HL and HE.

Summary

Could only flash a small selection of analyses and projections.
 Many opportunities for BSM. Looking forward to discovery.
 For heavy particles, HE will \approx double the sensitivity.



Thanks to all contributors!

Backup

Extended Higgs Sector

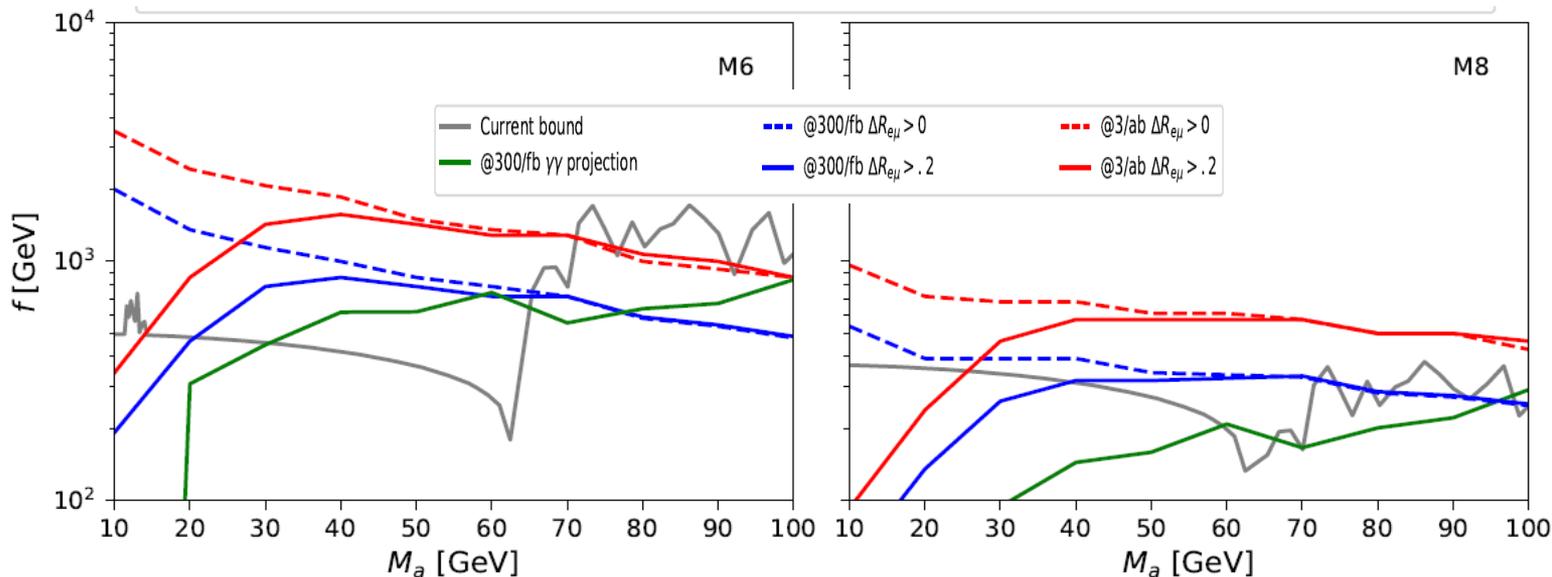
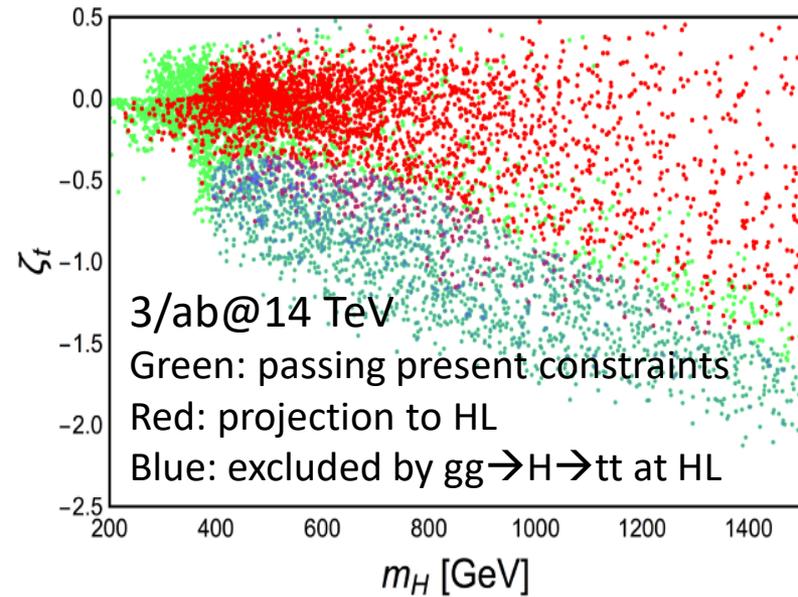
Theory projection

Test compositeness of 2 Higgs-Doublet Models (2HDM)

- Additional Higgs bosons (mass m), mixing of heavy top partner with SM top (ζ_t), scale of compositeness (f), coupling of spin-1

Some composite Higgs models predict **light pseudoscalar singlets** (a, η').

Decay in di-tau provides good sensitivity.



Analysis Techniques for HL Studies

ATLAS

- Generate truth-only 14 TeV event
- Overlay with jets (full sim) from pileup library, $\langle \text{PU} \rangle = 140$ or 200
- Reconstruct particles from truth+overlay
- Smear their energy and p_T using **appropriate smearing functions**, incl. Eff for genuine objects and rates from mis-identified objects.

CMS (two types, projections and full analyses)

Projections from a present analysis

- Existing signal and background samples (simulated at 13 TeV) scaled to higher luminosity and $\sqrt{s}=14$ TeV. Different uncertainty scenarios.
- Analysis steps (cuts) from present analyses.

Full analyses with parametrized detector performance

- DELPHES with up-to-date phase-2 detector performance and $\langle \text{PU} \rangle = 200$
- Dedicated simulation of signal and background samples
- Analysis steps guided by present analysis. Limited optimization for HL.

Analysis Techniques for **HE** Studies

- HE: generated new signal & background, and pileup samples at 27 TeV, using HL-LHC-CMS Delphes simulation.
- Conditions:
 - We assume the same detector of HL
 - PU 200
 - Pileup has been re-simulated at 27 TeV
 - C.O.M. energy = 27 TeV

Example: Systematics for RSG→tt

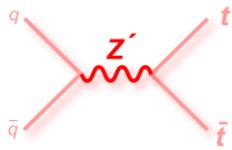
Table 2: Summary of the sources of systematic uncertainties.

| Source | Uncertainty | Single-lepton | Fully hadronic |
|--------------------------------------|-------------|---------------|----------------|
| Integrated luminosity | 1% | ✓ | ✓ |
| Electron identification | 1% | ✓ | |
| Muon identification | 0.5% | ✓ | |
| Jet energy scale | 0.5–4% | ✓ | ✓ |
| Jet energy resolution | 3% | ✓ | ✓ |
| b tagging (subjet) | 1% | | ✓ |
| Light quark mistagging (subjet) | 10% | | ✓ |
| t tagging | 5% | ✓ | ✓ |
| PDF | 2.4% | ✓ | ✓ |
| QCD renorm./fact. scale | 3–4% | ✓ | ✓ |
| t \bar{t} cross section | 3% | ✓ | ✓ |
| Single top quark cross section | 6% | ✓ | |
| W+jets cross section | 3% | ✓ | |
| Z+jets cross section | 6% | ✓ | |
| WW cross section | 6% | ✓ | |
| QCD multijet cross section | 6% | ✓ | |
| QCD multijet modified mass procedure | 2% | | ✓ |
| QCD multijet estimate closure test | 5% | | ✓ |

Spin-1 Vector Resonances

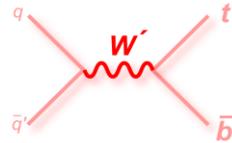
Neutral Z'

$Z' \rightarrow$ di-leptons ($ee, \mu\mu, \tau\tau$)
 $Z' \rightarrow tt, jj$

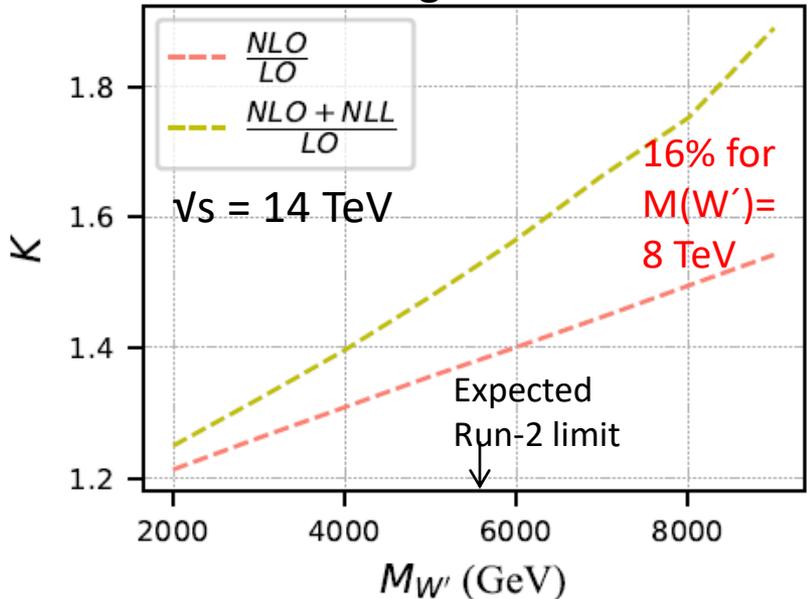


Charged W'

$W' \rightarrow lv, tb$
 $W' \rightarrow \tau\nu$



Higher order corrections important with increasing mass



SSM model: only free parameter = $M(Z')$, $M(W')$

TC (leptophobic top color) model: three additional free parameters = $M(Z')$, $\Gamma(Z')$, f_1 = coupling RH/LH up-type, f_2 = RH/HL down-type

UU (un-unified), NU (non-universal) models: type $SU(2)_1 \times SU(2)_2 \times U(1)$. Parameters: mixing angle, $M(Z')$ or $M(W')$

Impact of final state lepton

Dilepton resonance of $M(Z') = 6$ TeV. Upper = Theory projection

