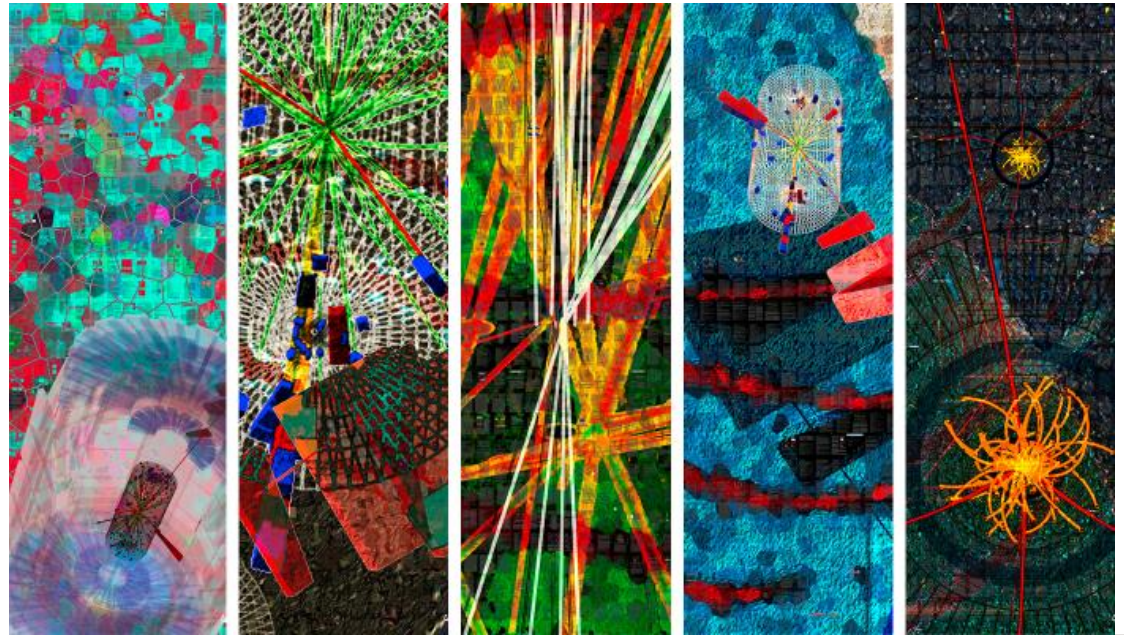


# Plans for HE-LHC Projections

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Brown University

July 17, 2018



# Considerations for Projections

- High energy running scenario specified (27 TeV and  $15 \text{ ab}^{-1}$ )

parameter	unit	LHC	HL-LHC	HE-LHC	FCC-hh
$E_{cm}$	TeV	14	14	27	100
circumference	km	26.7	26.7	26.7	97.8
peak $\mathcal{L} \times 10^{34}$	$\text{cm}^{-2}\text{s}^{-1}$	1	5	25	30
bunch spacing	ns	25	25	25	25
number of bunches		2808	2808	2808	10600
goal $\int \mathcal{L}$	$\text{ab}^{-1}$	0.3	3	10	30
$\sigma_{inel}$	mbarn	85	85	91	108
$\sigma_{tot}$	mbarn	111	111	126	153
BC rate	MHz	31.6	31.6	31.6	32.5
peak pp collision rate	GHz	0.85	4.25	22.8	32.4
peak av. PU events/BC		27	135	721	997

## • Assumptions for Detectors

- performances are not specified
- assume pile-up and detector performance same as for HL-LHC
- perform basic extrapolation (energy and luminosity)
- projections will rely on combined theory and experimental input



# Higgs Couplings

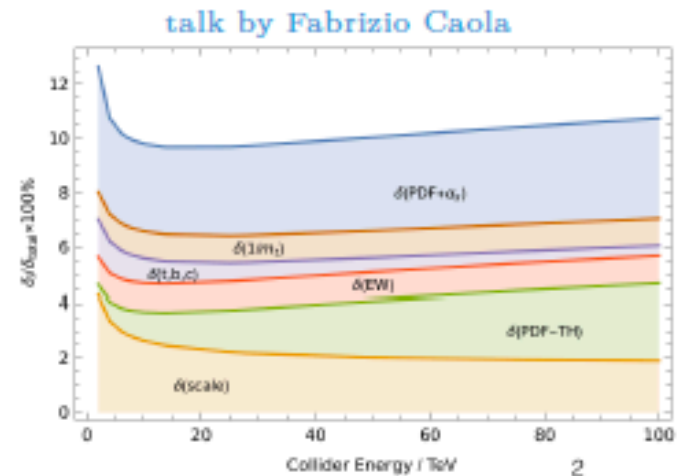
- Focus of Yellow Report:
  - provide a new benchmark that is accurate, not necessarily precise, for the HL-LHC
  - re-appraisal in several channels necessary
  - **provide a rough estimate for HE-LHC coupling measurements**
- Extrapolate from Run 2 analyses when possible
  - increased luminosity
  - Scale cross sections w/ increased center-of-mass energy (14, 27 TeV)
  - reconstruction performance with new different PU conditions (200)
  - different systematic scenarios
  - agreement almost all systematics
  - theory uncertainties centralized by LHC Higgs XS working group
  - common experimental uncertainties proposed by from ATLAS+CMS



# Higgs Couplings

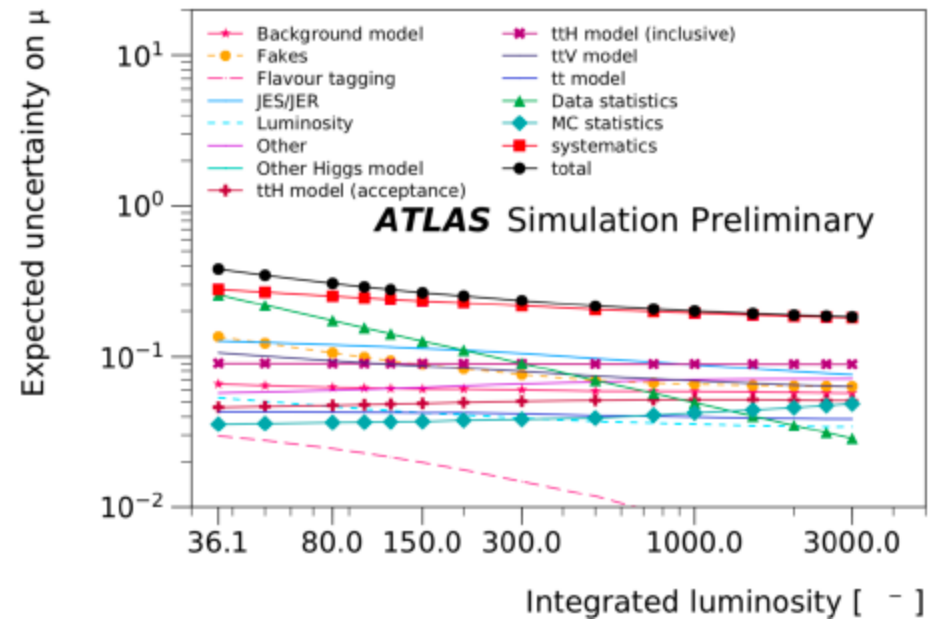
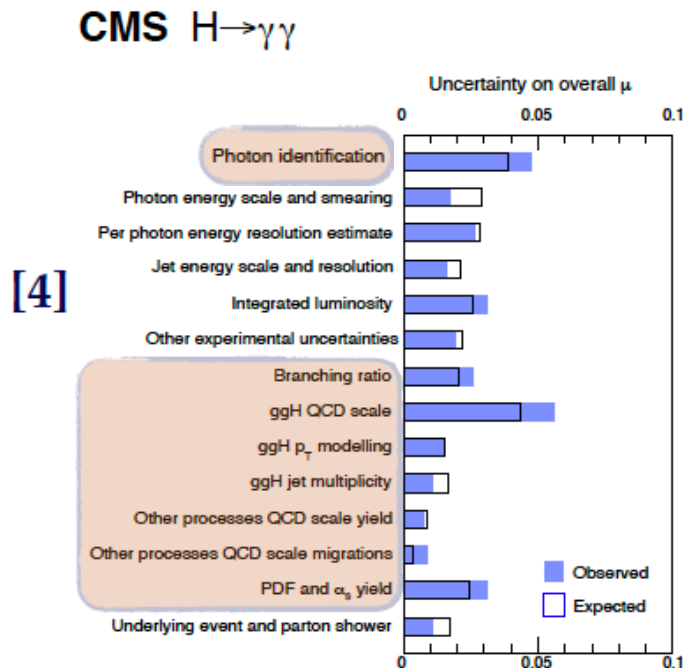
## Theory Cross-sections and Uncertainties

- collaboration with LHC Higgs XS Working Group
- first meeting this week, common meetings to come
- provide cross sections (14 and 27 TeV)
- decide on theory systematic scenarios for HL/HE-LHC
  - similar predictions as [arXiv:1610.07922](https://arxiv.org/abs/1610.07922)
  - consider possible future theory development
  - define scale variation, PDF,  $\alpha_s$ , *etc.* uncertainty
  - one baseline scenario and one optimistic scenario
- essentially done but needs to be written down



# Higgs Couplings

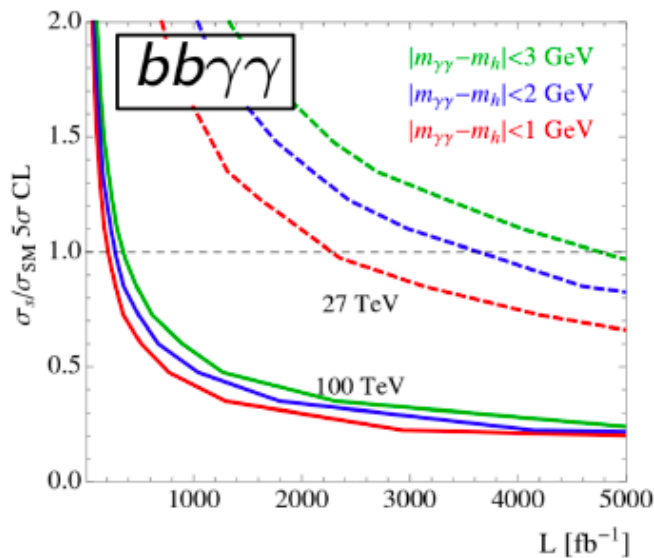
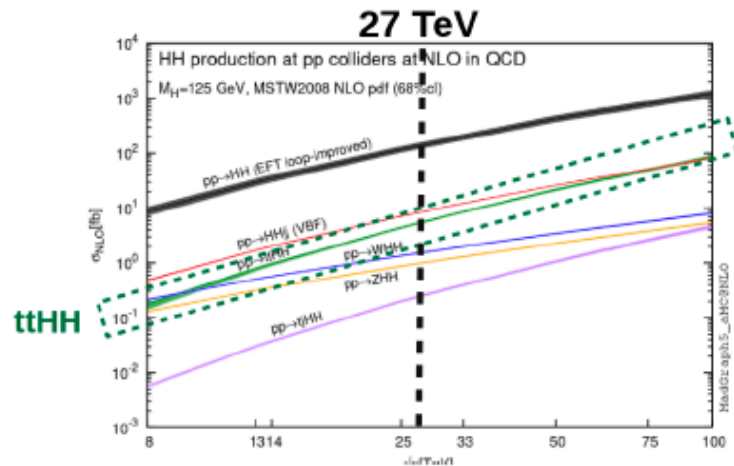
- Extrapolate expected sensitivity from current Run2 results
  - Precision Higgs measurements are becoming systematics-limited
    - both theoretical and experimental nuisances have an impact
    - these will only become more important as we increase integrated luminosity
  - many uncertainties can be constrained by data
  - theory and experimental uncertainties via prescriptions
  - 1% luminosity uncertainty





# di-Higgs Production and Higgs Self Coupling

- For HH discovery requires  $2.3\text{ab}^{-1}$  at 27 TeV
- photon and jet mass resolution critical for detector design

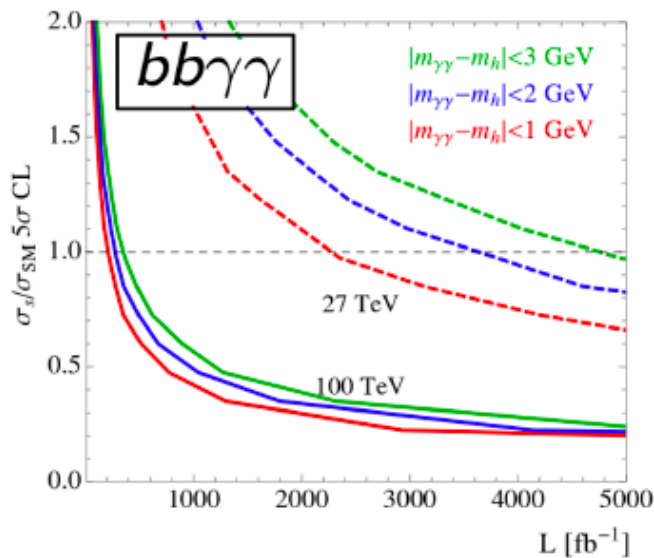
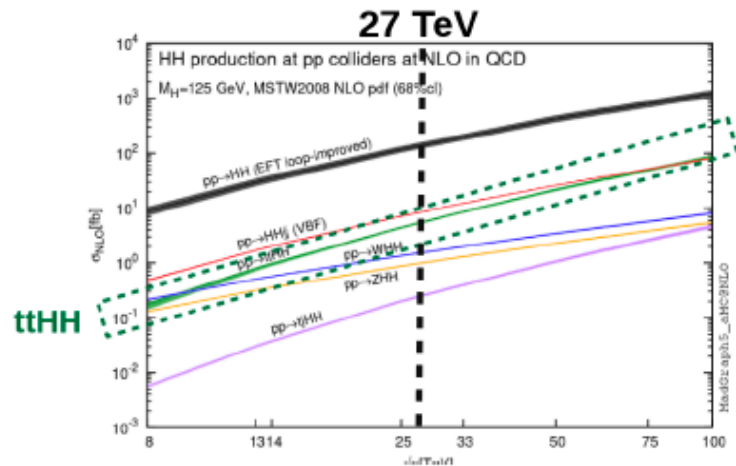


- Significant motivation:  
 $\sigma_{HH}^{SM}(27\text{TeV}) = 127.88$  fb [G.Heinrich]
  - ▶  $\sim 4 \times$  @13TeV
- Recent [pheno studies](#) on prospects at HE collider:  $bb\gamma\gamma$ 
  - ▶ Quote 30% accuracy on  $\lambda_3$  achievable @27TeV
- Potential methods:
  - 1 full 27 TeV Delphes analysis using upgraded detector config [M.Selvaggi+G.Ortona]
  - 2 simply scale cross-section from 14 TeV analysis  $\implies$  projections



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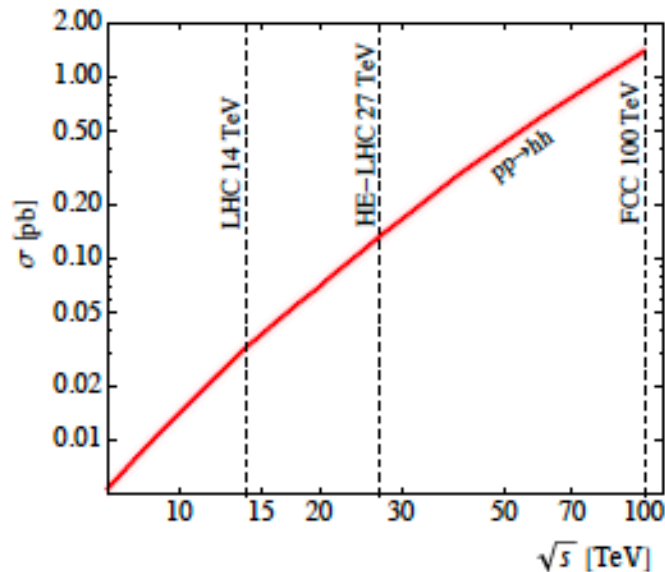


Figure 2. Total cross section for  $pp \rightarrow hh$  production at NLO as a function of the  $pp$  collider energy. The width of the curve reflects the 10% theoretical uncertainty.

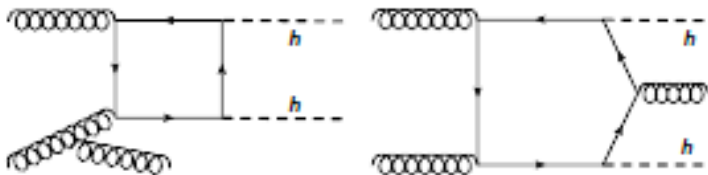


Figure 5. Representative Feynman diagrams contributing to Higgs pair production via gluon fusion including an ISR jet at hadron colliders.

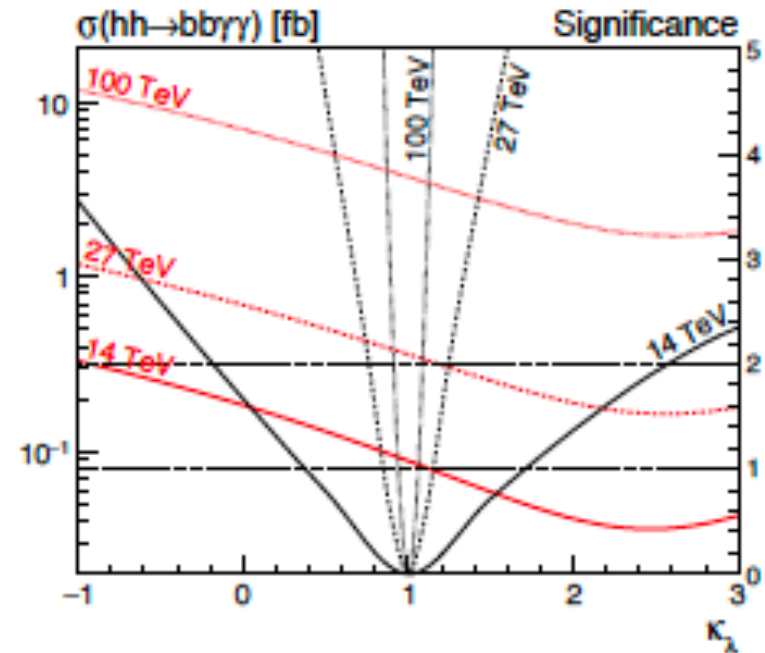


Figure 4. Higgs pair production cross section (red lines with left vertical axis) and maximum significance (black lines with right vertical axis) for discriminating an anomalous self-coupling  $\kappa_\lambda \neq 1$  from the SM, as function of the modified self-coupling. The results are for the HL-LHC, the HE-LHC, and a future 100 TeV collider, respectively. The HL-LHC results are taken from Ref. [17].

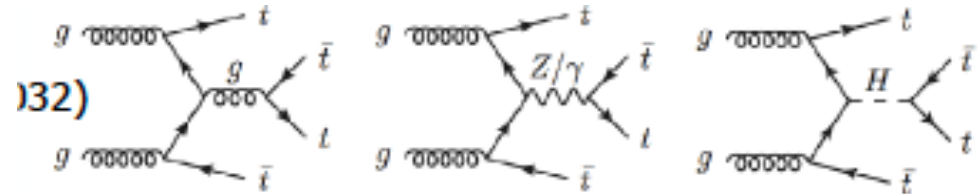
D. Goncalves et al

<https://arxiv.org/pdf/1802.04319.pdf>



# Possible topics in SM

- Four Top Production
- Single Top production (s-channel projection to 27 TeV)
- FCNC (?)  $tqg$ ,  $tZq$ ,  $tHq$



## Four Top Production

- rare process predicted by the Standard Model, not measured yet
- very sensitive to New Physics: color-octet/singlet vectors/scalars, top compositeness, EFT:  $4t$  operator is not constrained elsewhere
- 4 tops as a probe for new physics
  - constraints on the EFT  $qqtt$  4-fermion operator at 14 TeV and 27 TeV (arXiv:1708.05928)
  - constraints on chromo-magnetic and chromo-electric dipole moments at 14 TeV and 27 TeV (arXiv:1804.05598)
  - Higgs width and top quark Yukawa coupling (arXiv:1602.01934)

Frederix, Pagani, Zaro

14

27

100

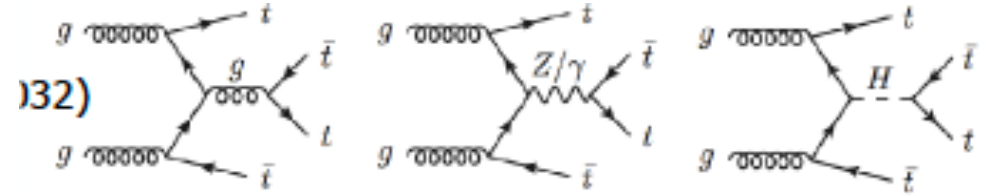
$\sigma$ [fb]	LO <sub>QCD</sub>	LO <sub>QCD</sub> + NLO <sub>QCD</sub>	LO	LO + NLO	$\frac{LO(+NLO)}{LO_{QCD}(+NLO_{QCD})}$
$\mu = H_T/4$	$9.04^{+69\%}_{-38\%}$	$14.72^{+19\%}_{-23\%}$	$10.04^{+63\%}_{-35\%}$	$15.83^{+18\%}_{-21\%}$	1.11 (1.08)
$\sigma$ [fb]	LO <sub>QCD</sub>	LO <sub>QCD</sub> + NLO <sub>QCD</sub>	LO	LO + NLO	$\frac{LO(+NLO)}{LO_{QCD}(+NLO_{QCD})}$
$\mu = H_T/4$	$45.34^{+59\%}_{-35\%}$	$71.31^{+16\%}_{-20\%}$	$48.57^{+54\%}_{-33\%}$	$73.94^{+15\%}_{-18\%}$	1.07(1.04)
$\sigma$ [pb]	LO <sub>QCD</sub>	LO <sub>QCD</sub> + NLO <sub>QCD</sub>	LO	LO + NLO	$\frac{LO(+NLO)}{LO_{QCD}(+NLO_{QCD})}$
$\mu = H_T/4$	$2.37^{+49\%}_{-31\%}$	$3.98^{+18\%}_{-19\%}$	$2.63^{+44\%}_{-28\%}$	$4.18^{+17\%}_{-17\%}$	1.11 (1.05)

Preliminary

x 5

x 56

# Four Top Production



## • Four Top Experimental Status

- inclusive and differential results in the multilepton channel at 14 TeV
- fast simulation analysis (ATLAS) and extrapolation (CMS)
- Description of ATLAS analysis, yields with guessed uncertainties
- Description of CMS extrapolation, yields with guessed uncertainties
- ATLAS and CMS results: estimated cross section uncertainties and examples for differential distributions
- the plan is to have HE-LHC results, not sure time will allow it – Hoping it will pan out
  - CMS Extrapolation of results using rescaling signal and background yields by cross sections.
  - for specific processes where kinematic is expected to differ substantially, check using 27 TeV truth-only simulations

# Possible topics in BSM

- Dark Matter Projections: DM+ttbar, DM+Single top
- Heavy neutrino
- $Z' \rightarrow t\bar{t}$
- For new studies, need to understand the available background samples (which LHE exists in the FCC repository)
  - Any other place we can look at ?
  - Delphes with 800 PU? Or just 200 PU as for HL=LHC?
- Dark Matter Projections:
  - Some studies using Missing ET+jets done at 33 TeV during snowmass studies (see more on next slide)
  - DM+ttbar, DM+Single top
    - Extrapolation of results using rescaling signal and background yields by cross sections.
    - for specific processes where kinematic is expected to differ substantially, check using 27 TeV truth-only simulations

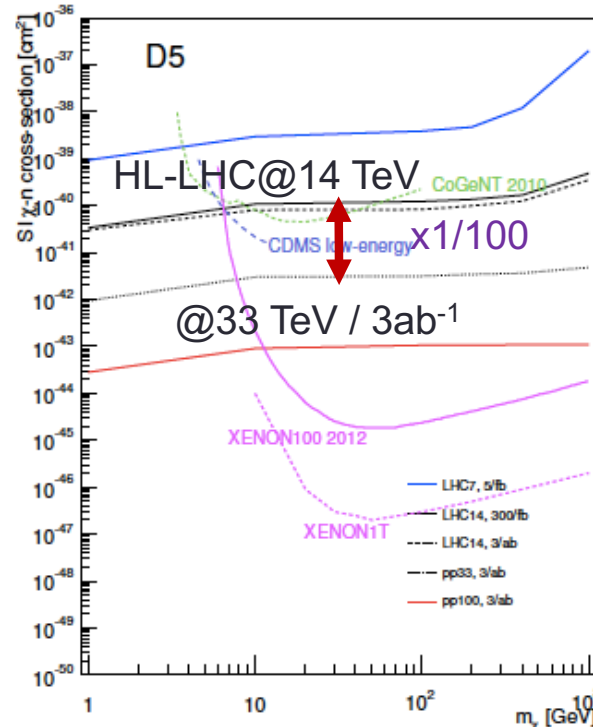
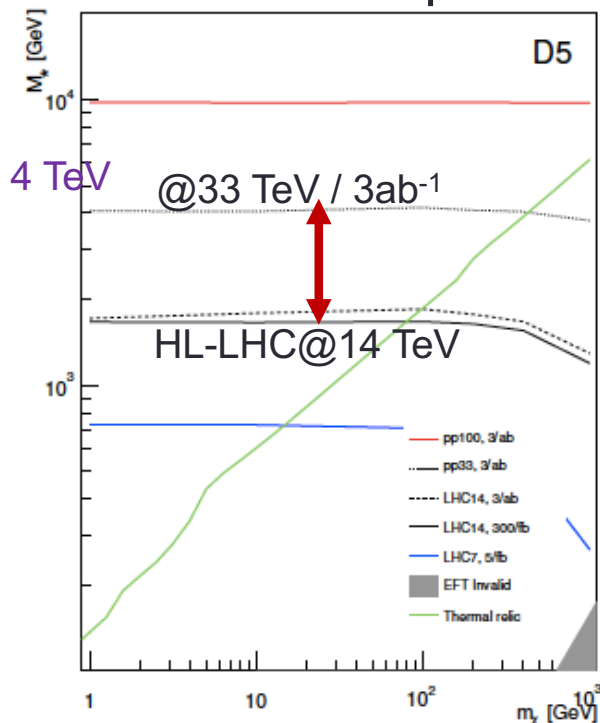


# HE-LHC: WIMP search using Missing ET+jets

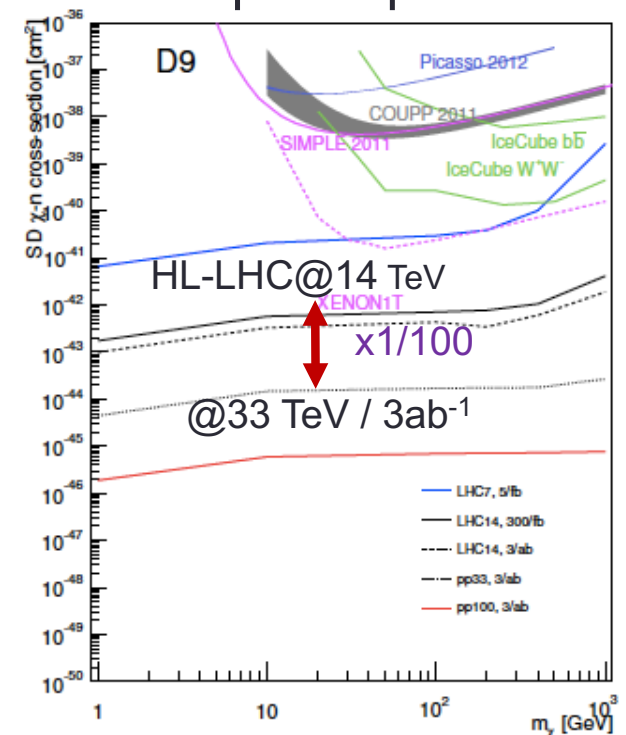
- Significant gains with the HE-LHC:
  - Models tested (circa 2013) – somewhere collider exclusion dominates, others where direct detection dominates.
- Sensitivity to WIMP pair production via effective operators and light mediators

arXiv:1307.5327

Spin independent

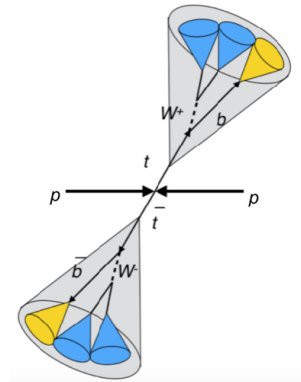
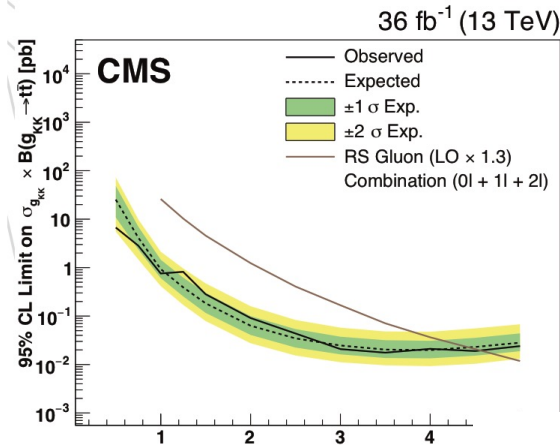
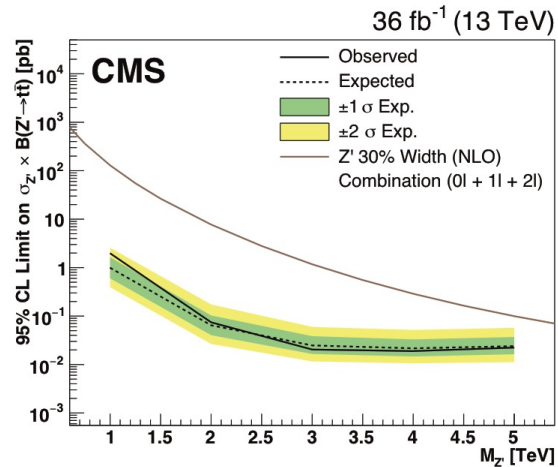


Spin dependent

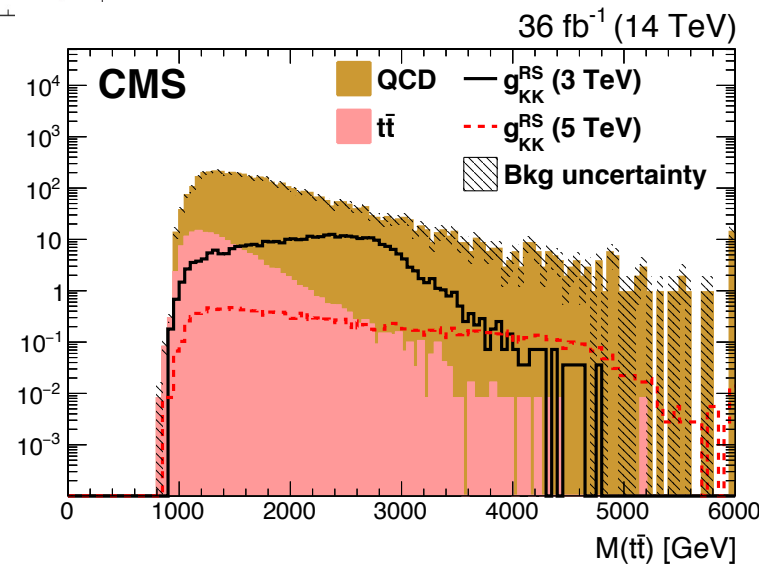


# First look at $Z' \rightarrow t\bar{t}$ events at the HE-LHC

- $Z'$  @ Run 2 (recent result)



- hitting the “energy limit”
- Particles w/ mass  $>5\text{TeV}$  & width  $>10\%$  do not show up as resonances, rather as spectrum enhancement
- not “bump hunting”
- energy upgrade essential to reach higher masses

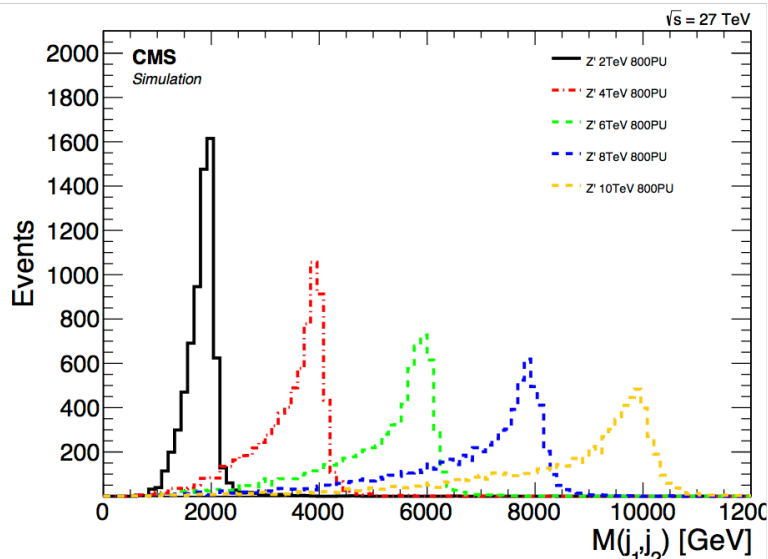




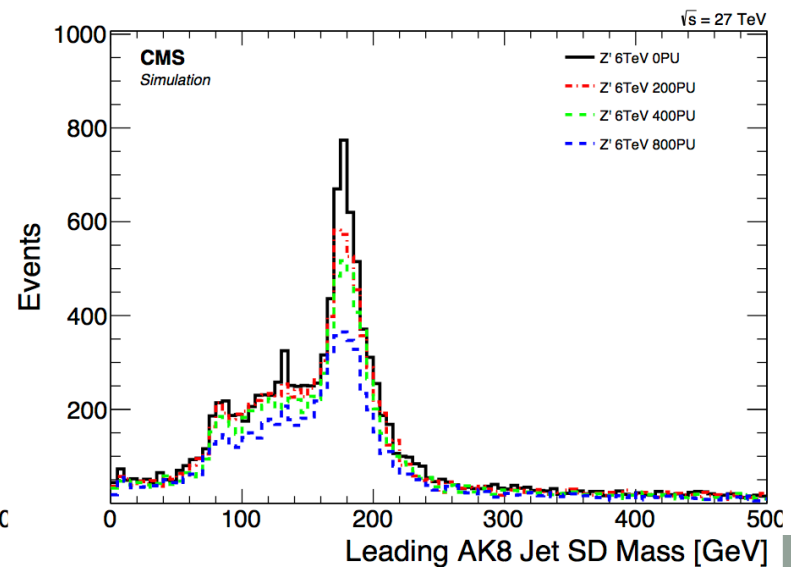
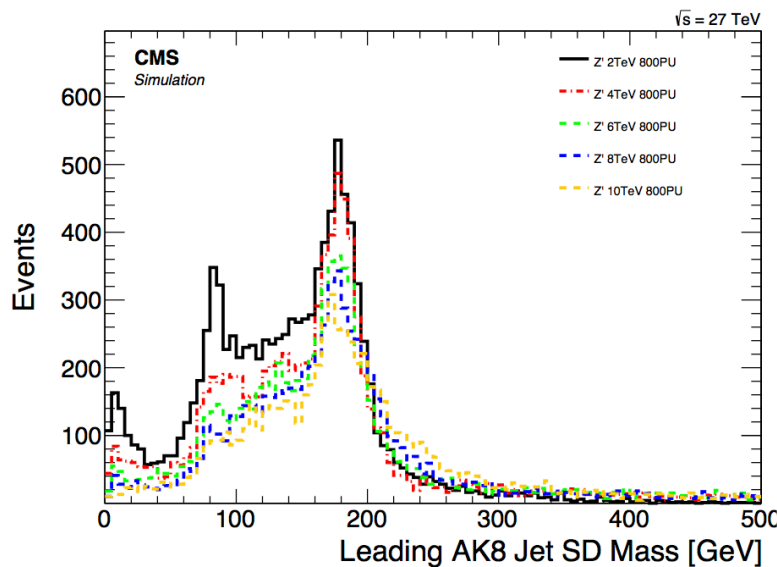
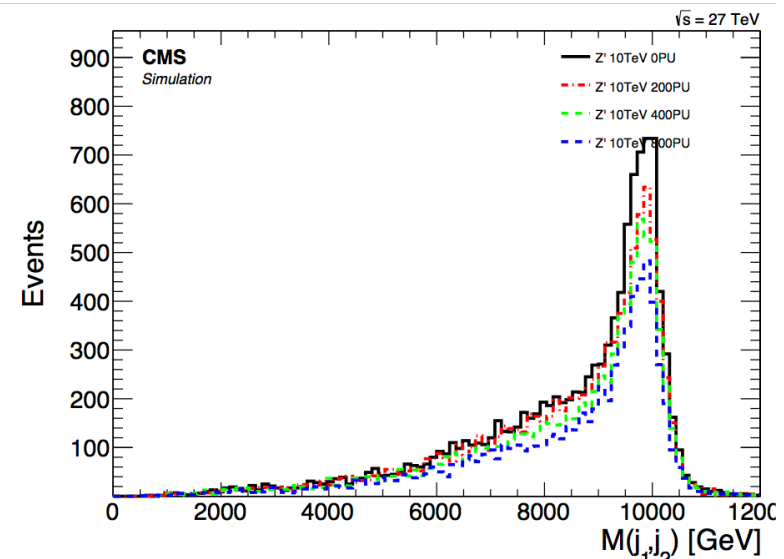
# $Z' \rightarrow t\bar{t}$ @ 27 TeV

- vary  $Z'$  mass and pileup

vary  $Z'$  mass

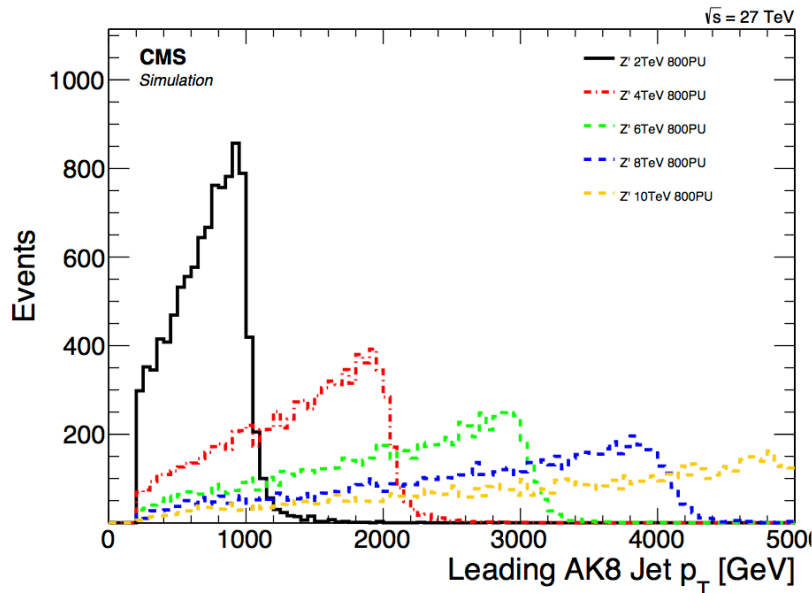


vary pileup

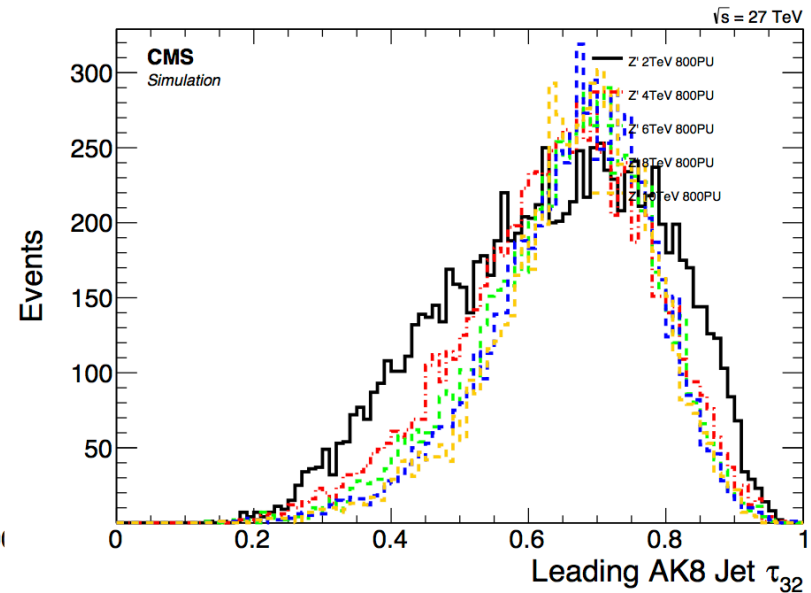


# $Z' \rightarrow t\bar{t}$ @ 27 TeV

pt — vary  $Z'$  mass



tau3/tau2 — vary  $Z'$  mass



- First look at  $Z' \rightarrow t\bar{t}$  events 27 TeV
- masses up to 10 TeV studied: very collimated top jets
- different PU scenarios studied up to 800: PUPPI seems to hold well, must check reliability of the simulation with experts
  - We are probably being too optimistic. Need to investigate if any of the assumptions in Delphes do not hold at 800PU

# Summary

- Given the time constraints choose a few channels which can be projected using the cross section increase and lum
  - needs reinforcement
  - SUSY plans still being developed.
- Planned studies by ATLAS (prelim list)
  - Higgs Coupling projections
  - Di-Higgs ( $HH \rightarrow b\bar{b}\gamma\gamma$ )
  - SM: VBS, 4tops, top s-channel,  $tZq$ , W mass
  - EXO:  $Z' \rightarrow$  di-leptons, VV resonances
  - SUSY (strong production greatly enhanced with  $\sqrt{s}$ )

