Resonance and VLQs @ HL-LHC

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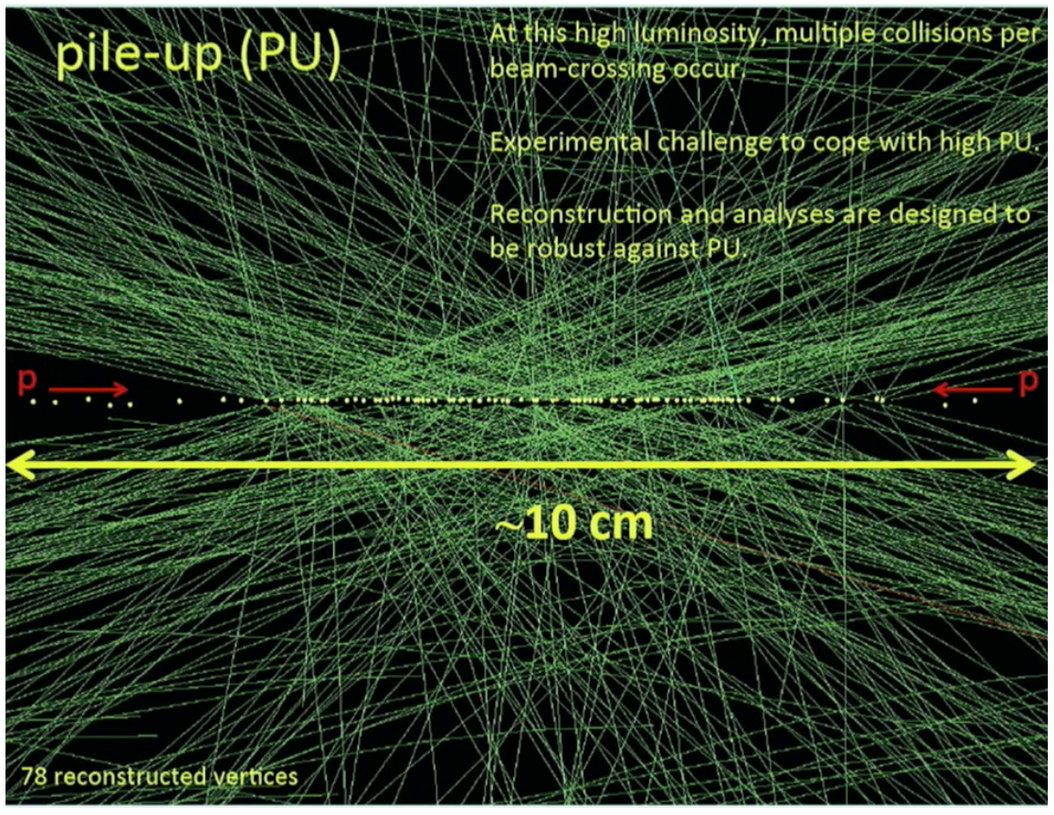
On behalf of CMS Collaboration



HE/HL LHC Workshop, Fermilab, USA; Apr 5, 2018

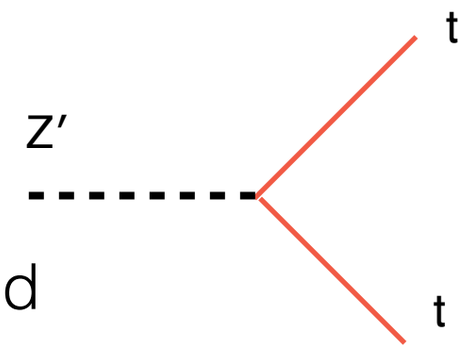
Outlook

- In this talk I will be summarizing the prospects and plans of discovering new physics that could show up as a heavy resonances at the HL-LHC with CMS experiment.
  - Z' → tt
  - W' → tb
  - W' → eν, $\tau\nu$
  - LQ_3 → τ b
  - VBF di-Higgs→ 4b
  - Vector-like quarks: Single T →tH (l+jets)

Also see talk by Kerstin in Flavor BSM model this morning

Z' → tt

- CMS published Z´ → tt searches distinguished by decay of W (from t → Wb) in two channels
  - l+jets (B2G-15-002), all-hadronic (B2G-15-003)
  - Discriminating variable: M(tt) reconstructed from final states, and total of six channels in both analyses are used



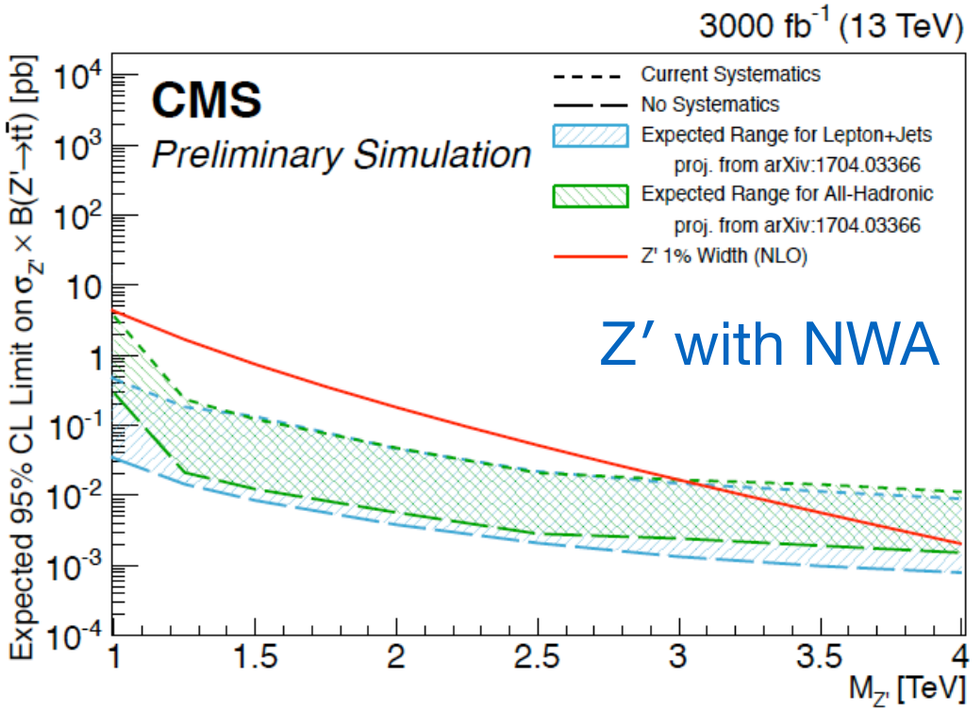
Semileptonic Channel	All-Hadronic Channel
e + 0 b-tag + 0 top-tag	0 subjet b-tag + $\|\Delta y\| < 1.0$
e + 1 b-tag + 0 top-tag	1 subjet b-tag + $\|\Delta y\| < 1.0$
e + 1 top-tag	2 subjet b-tag + $\|\Delta y\| < 1.0$
μ + 0 b-tag + 0 top-tag	0 subjet b-tag + $\|\Delta y\| > 1.0$
μ + 1 b-tag + 0 top-tag	1 subjet b-tag + $\|\Delta y\| > 1.0$
μ + 1 top-tag	2 subjet b-tag + $\|\Delta y\| > 1.0$

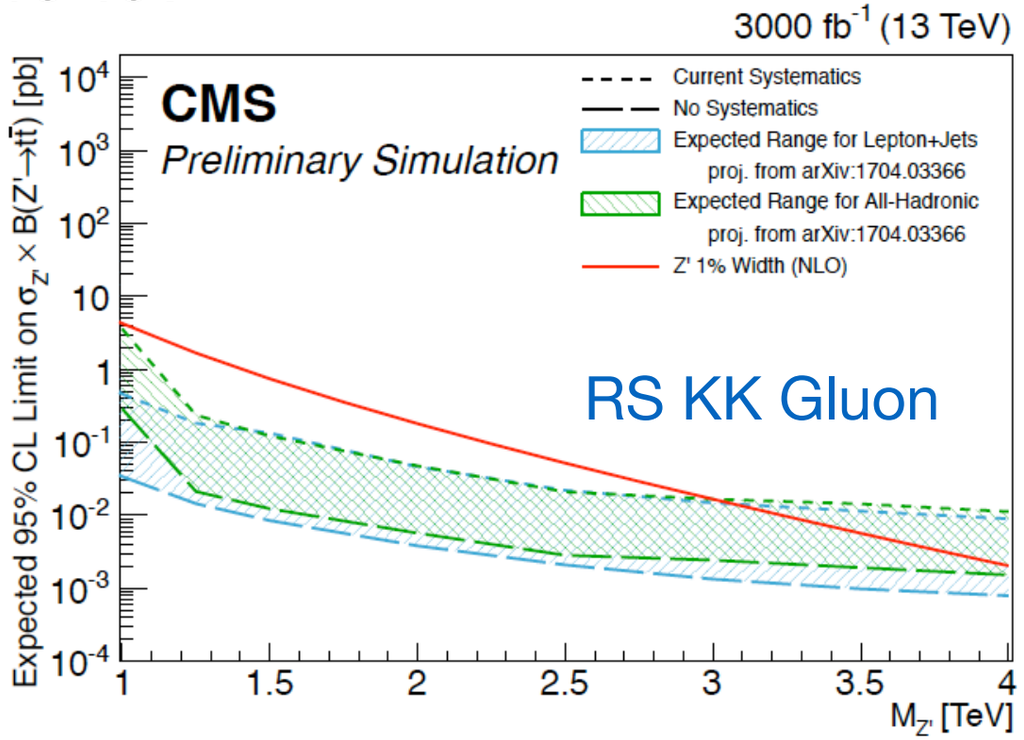
CMS-PAS-FTR-16-005

- Projections for HL-LHC are performed using two scenarios
  - Same systematic uncertainties @13 TeV
  - Remove all systematic uncertainties
- The realistic case should be in between since reduction in systematic uncertainties is expected, e.g; QCD multijet background is derived from data and scales with L, ttbar x-section, jet energy scale and resolution, lepton ID efficiencies

Z' → tt

Projections of Z′ in *l*+jets and all-had @ 13 TeV





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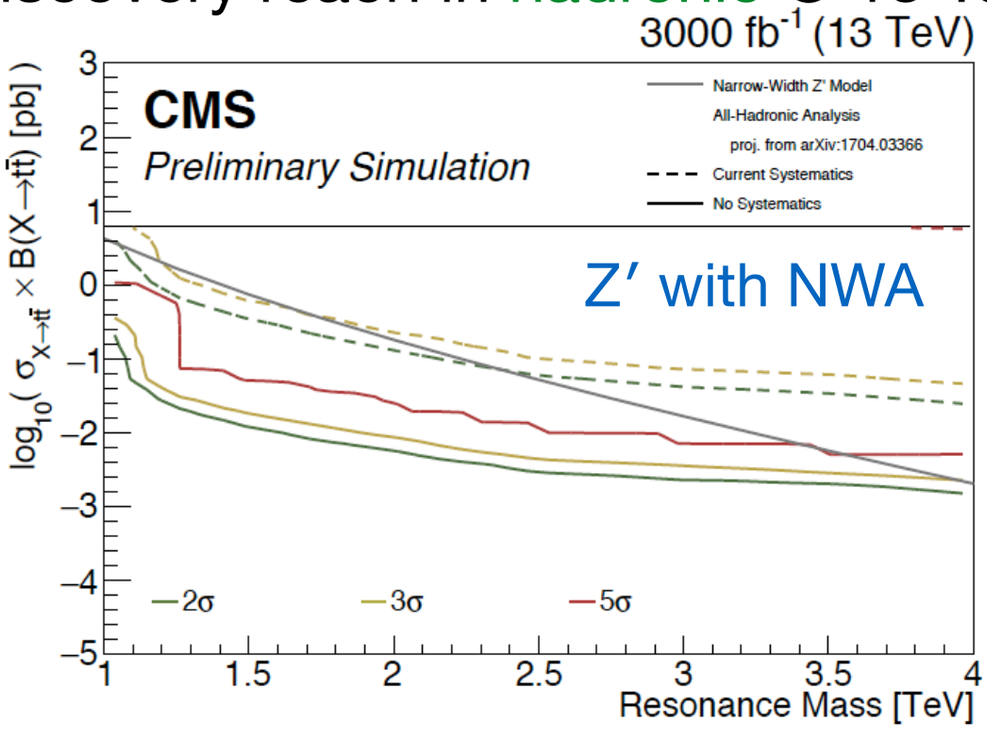
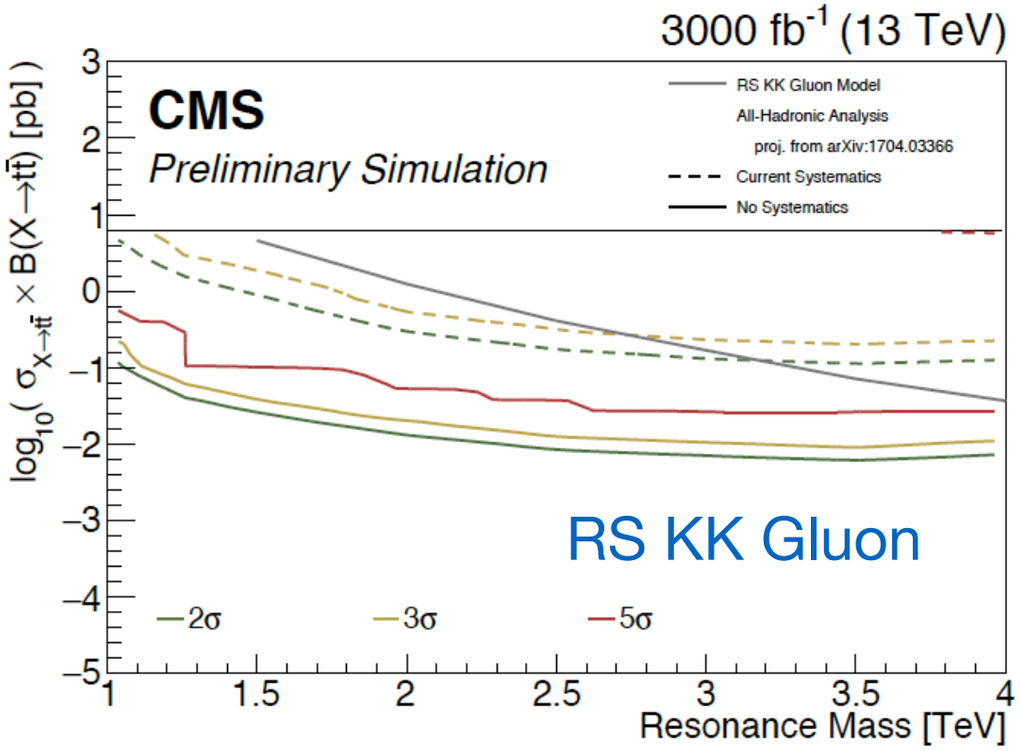
Discovery reach in hadronic @ 13 TeV

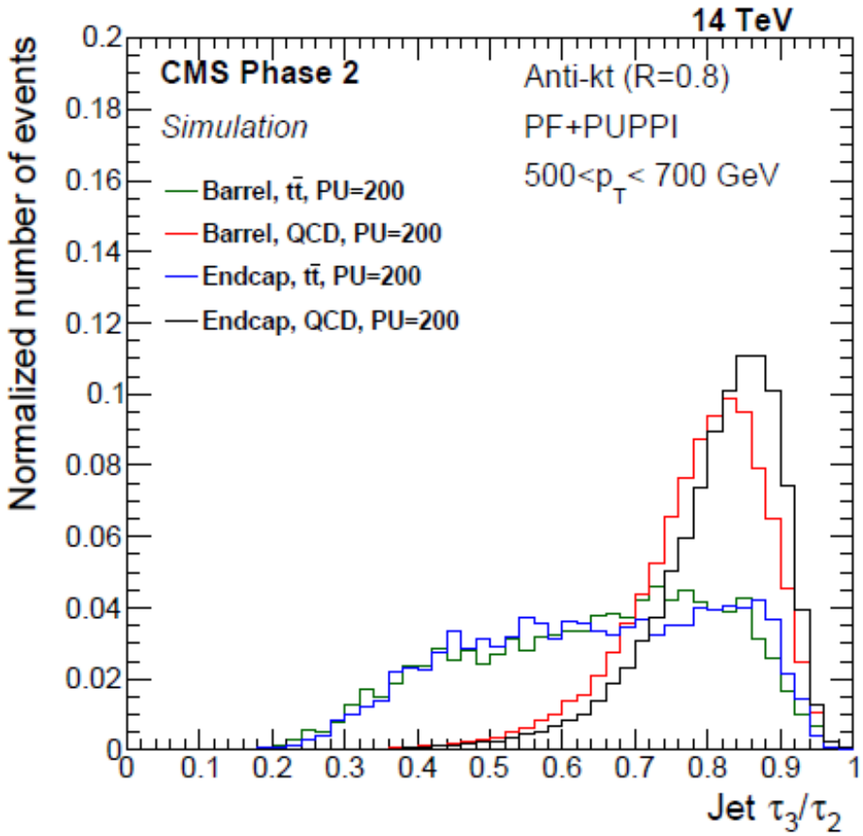


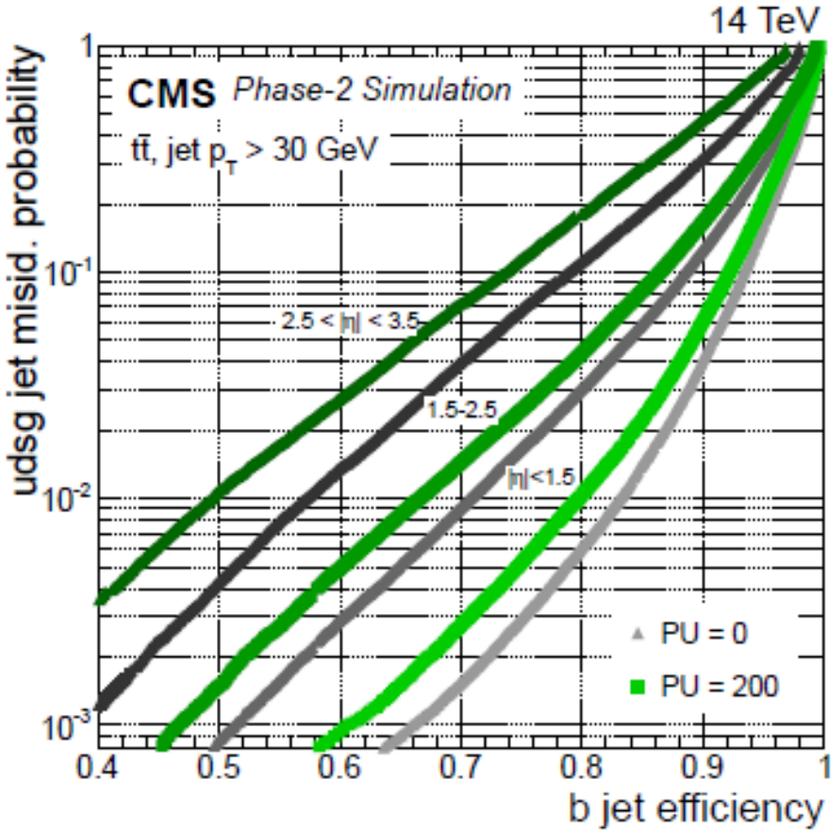


Z' → tt

New Plans

- CMS has plans to perform the study using full simulations with HGCal upgraded detector



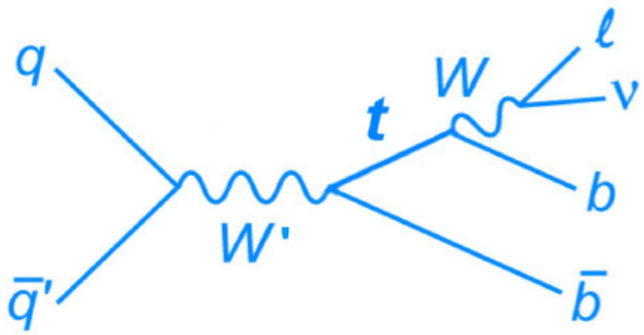


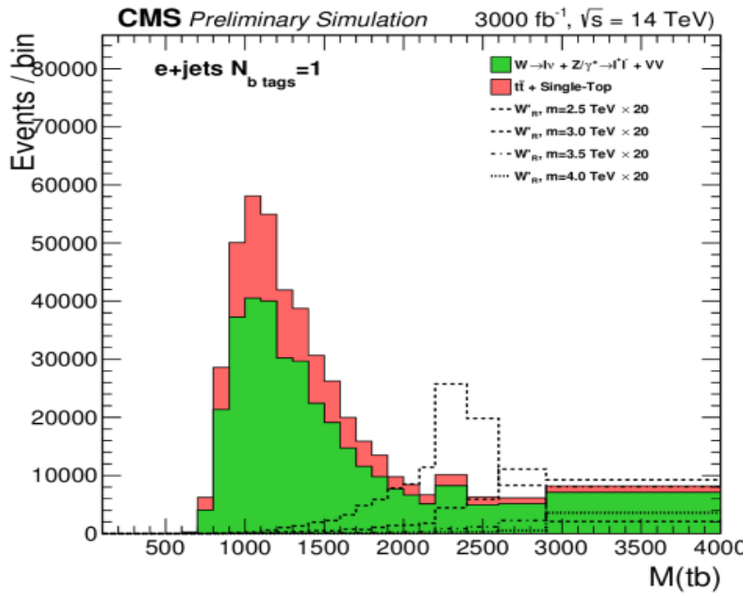
- Combine the l+jets and all-hadronic channels
- Adapt analysis strategy for Z´ masses above 4 TeV where off-shell production becomes important

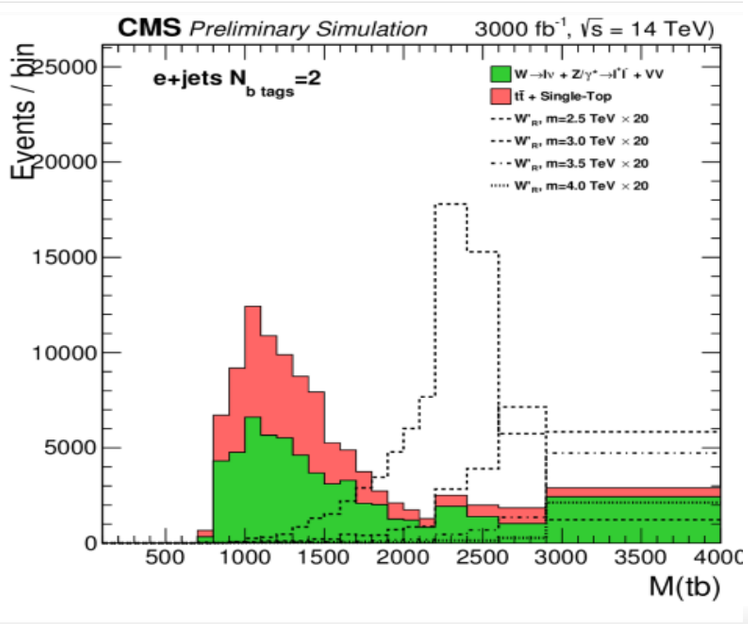
W' → tb

CMS-PAS-FTR-16-005

- A search that probes for W' when $m(\nu_R)>m(W')$, hence forbidding W' → lν decay
- **Projections** using the baseline analysis at $\sqrt{s}$=13 TeV with 12.9 fb^{-1} data that excludes W' up to 2.67 TeV @ 95% CL (B2G-15-004, B2G-16-017)
- Projection techniques
  - Events require high p_T > 180 GeV isolated e/μ with additional lepton veto, and AK4 jets with $|\eta|$ <2.4 with 1 or 2 b-jets
- Discriminating variable: M(tb), such as p_T > (jet1 + jet2) > 350 GeV and p_T (top) > 250 GeV
- Background samples are simulated at 13 TeV and xsec are scaled to 14 TeV
- W'_R signal MC is simulated at 13 TeV with COMPHEP up to 4 TeV mass







W' → tb

- Two scenarios to extrapolate systematic uncertainties from 12.9 fb^{-1} to 3000 fb^{-1}
  1. Leave systematics unchanged ⇒ scale by $\sqrt{L}$
  2. Reduce experimental uncertainties to few percent level, theory uncertainties by factor 2 and top p_T reweighing by 3
  3. No systematic uncertainty

Source	Rate Uncertainty (Flat)	Rate Uncertainty (Scaled)	Shape?
Luminosity	6.2%	1.5%	No
Trigger Efficiency (e/μ)	2%/5%	1%/1%	No
Lepton ID Efficiency (e/μ)	5%/2%	1%/1%	No
Jet Energy Scale	3.8%	1%	Yes
Jet Energy Resolution	1%	0.07%	Yes
b/c-tagging	2.7%	1%	Yes
light quark mis-tagging	1.2%	1.2%	Yes
W+jets Heavy Flavor Fraction	2.3%	1.1%	Yes
Top p_T Reweighting	18%	6%	Yes
Pileup	1.3%	0.09%	Yes
PDF	6.1%	3%	Yes
Matrix element Q^2 scale	18.9%	9.5	Yes
$t\bar{t}$ Parton matching Q^2 scale	1.7	0.9%	Yes
Theoretical top cross section	15%	7.5%	No
Theoretical bosonic cross section	10%	5%	No

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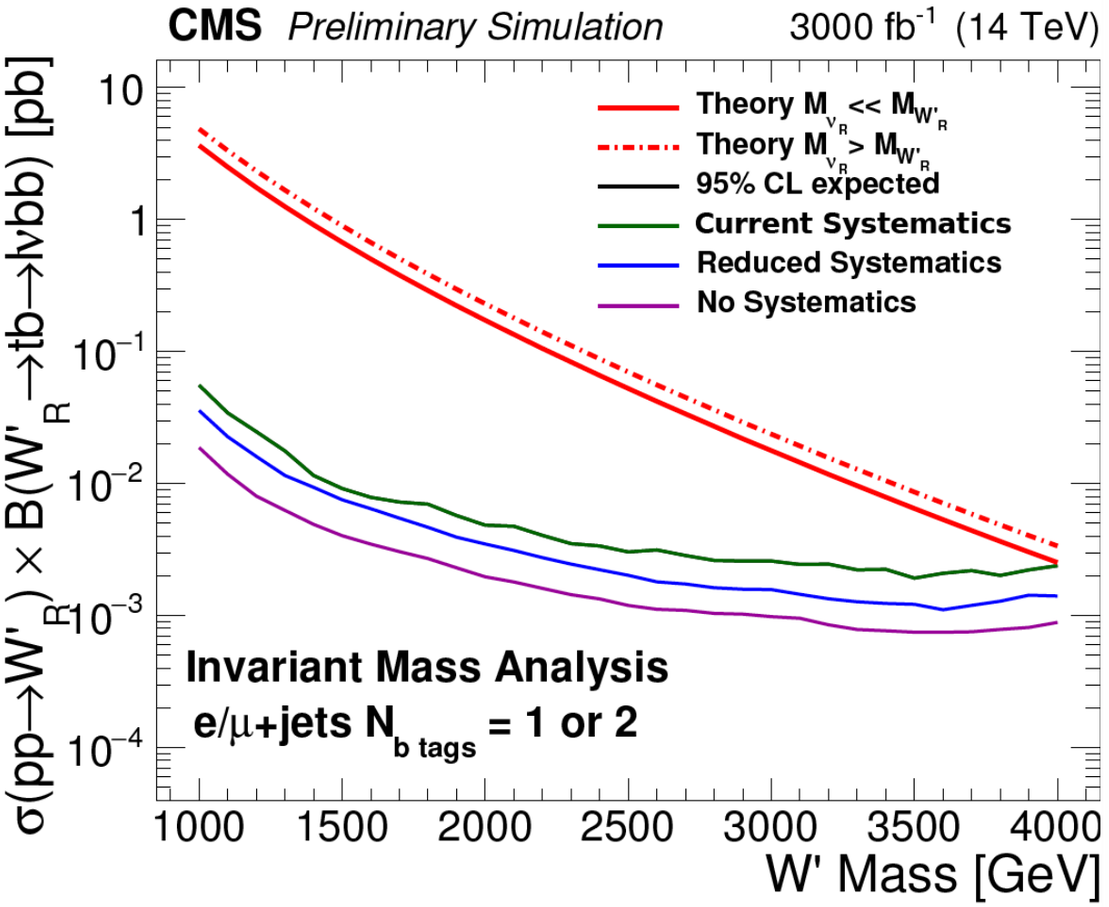
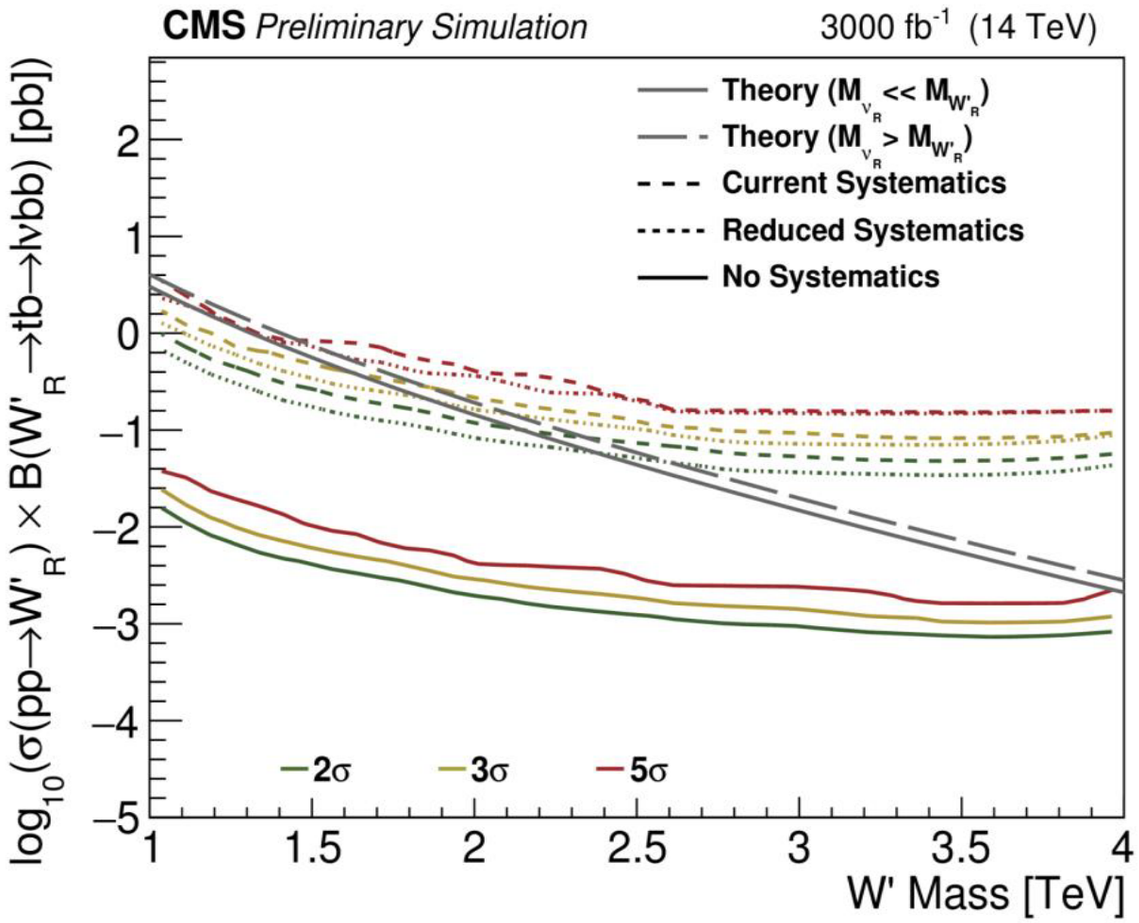
W' → tb

- The two uncertainty scenarios have small impact on projected exclusion limit: 4(4.2) TeV for case 1(2)



Discovery Scenario

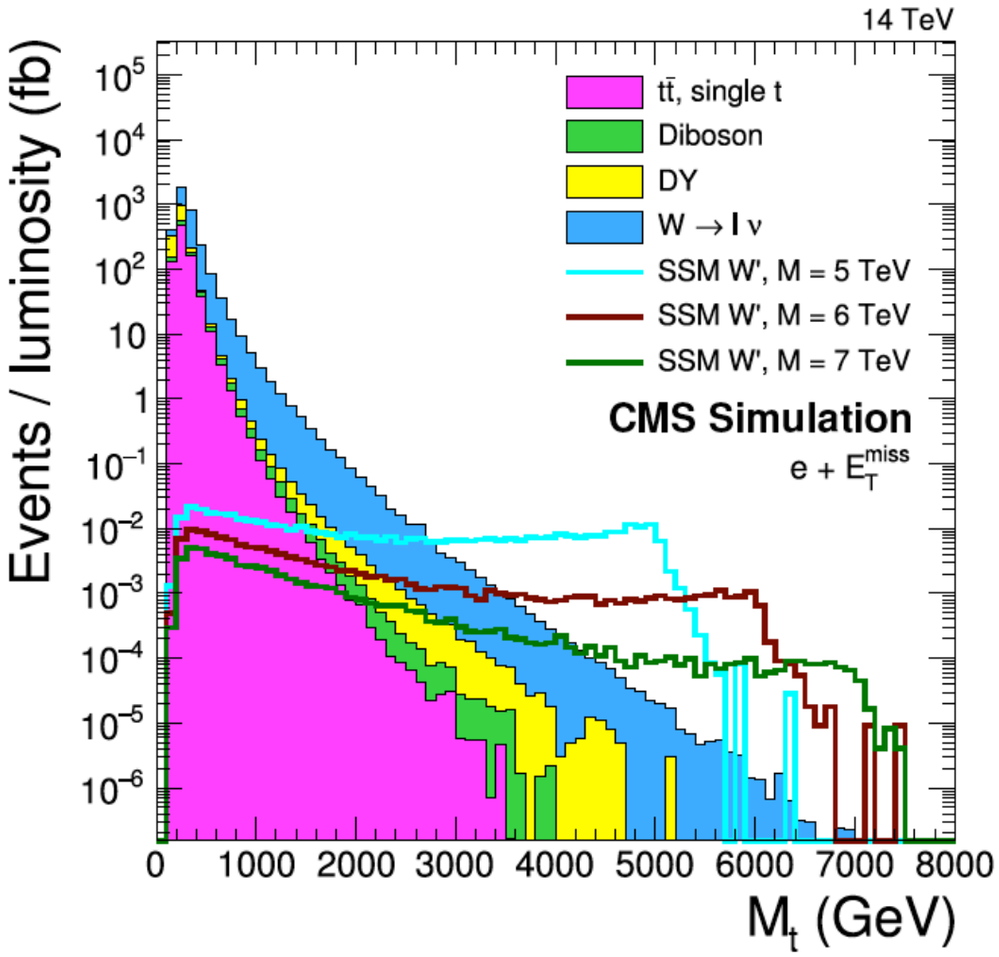


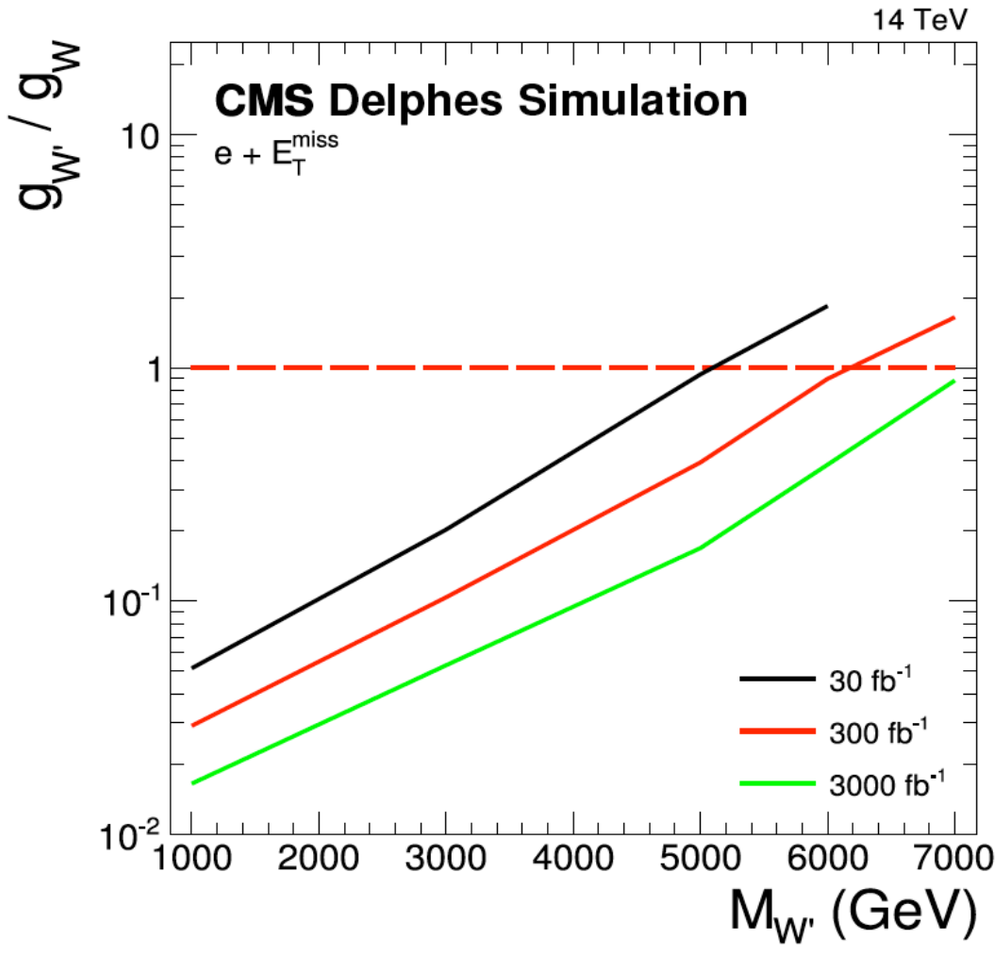
CMS-PAS-FTR-16-005

- For masses beyond 4 TeV, where the off-shell part starts to become important, the selection needs to be re-optimized

W' → eν

- Complementary to W´ → tb, the analysis was performed using Delphes simulations assuming SSM W´
- Final state consists of a high p_T electron and E_T^{miss}
- Discriminator: Transverse mass of W´





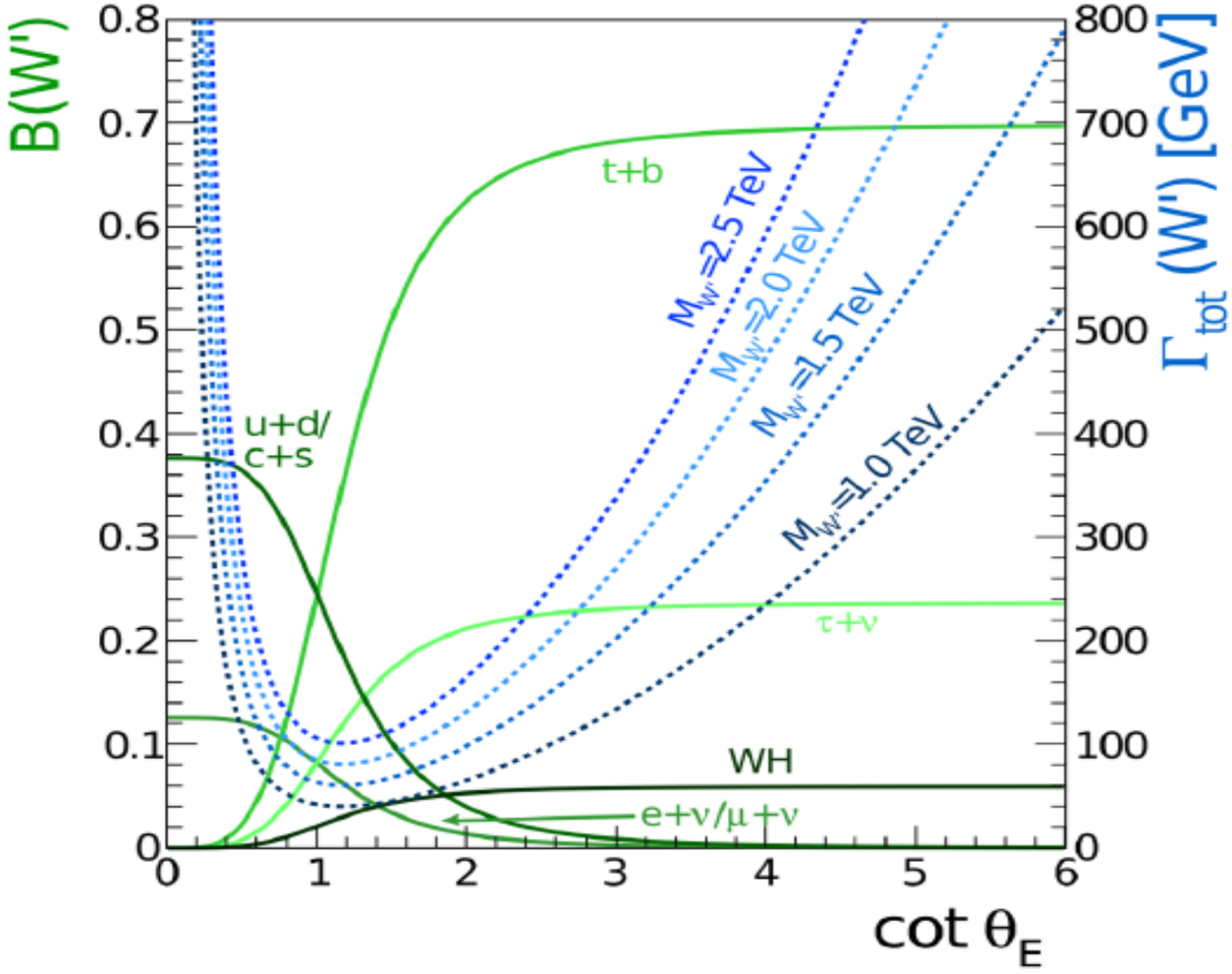
CMS-PAS-EXO-14-007

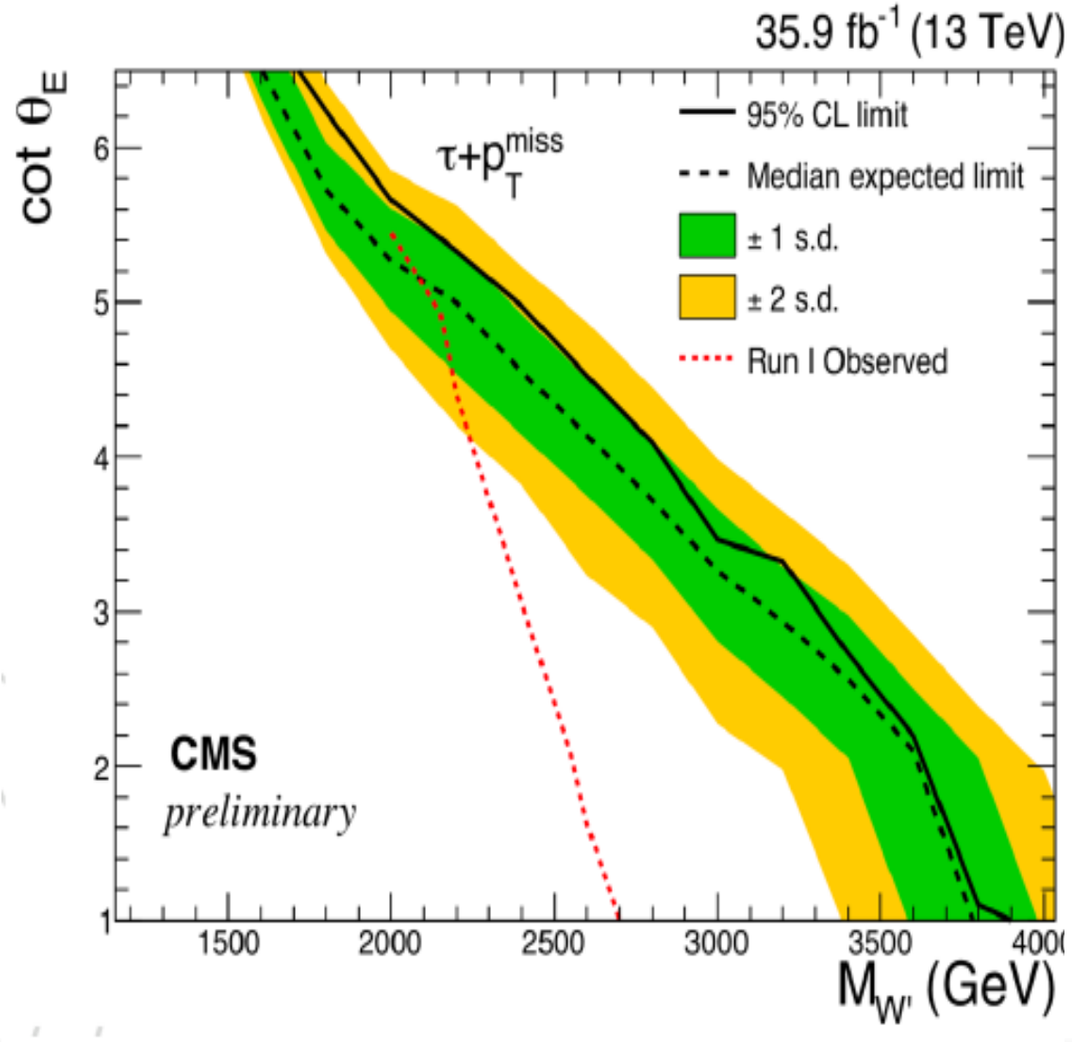
- High luminosities are necessary to reach low couplings of the order 0.1 to 0.01 for a five sigma discovery. Is it worth to repeat with full sim?

$W' \rightarrow \tau\nu$

New Plans

- Non-universal gauge interaction model (NUGIM) suggest enhance couplings to 3rd generation, where BR depends on the mixing angle $\cot\theta_E$
- $SU(2)_l \otimes SU(2)_h \rightarrow SU(2)_{SM} \otimes SU(2)_{extended}$
- Plan to project the CMS Run2 analysis to HL-LHC

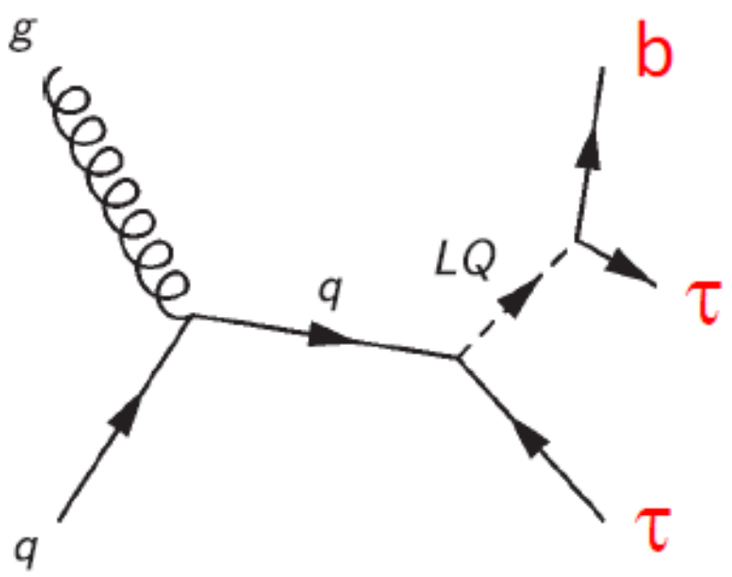




To be based on CMS-PAS-EXO-17-008

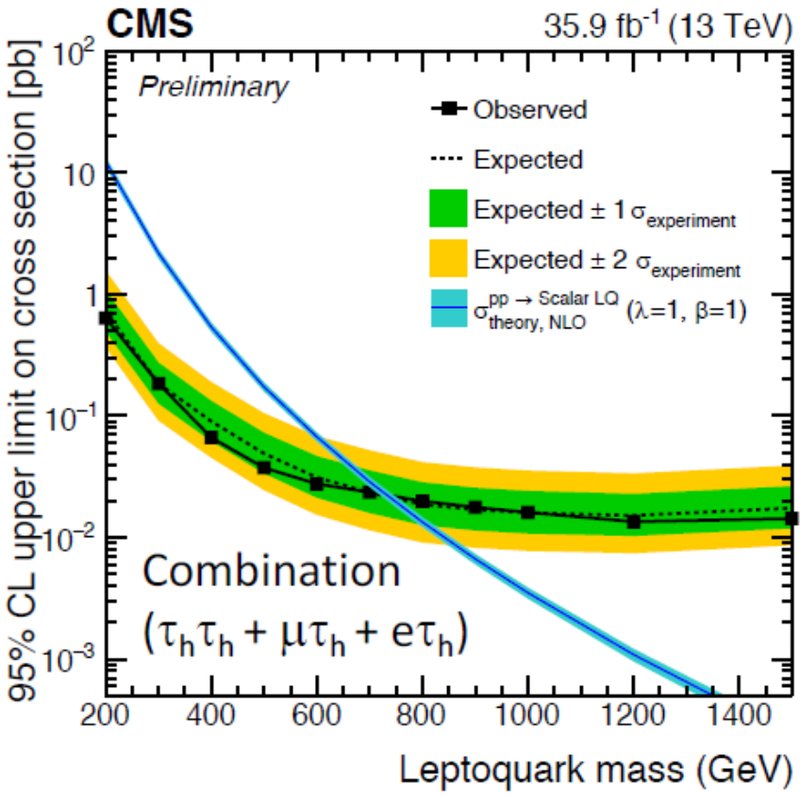
New Plans

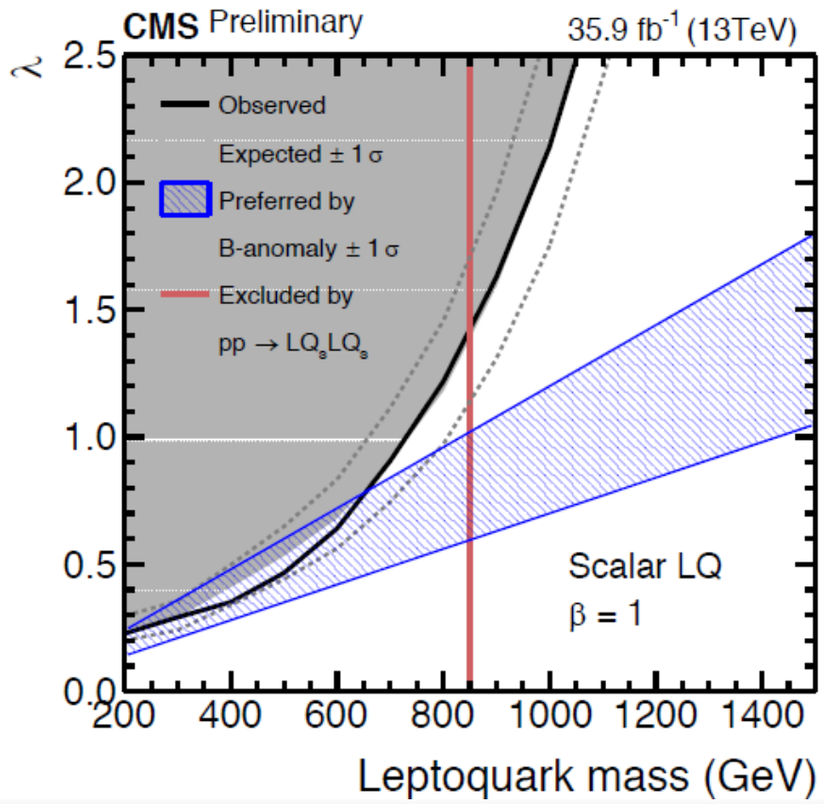
$LQ_3 \rightarrow \tau b$



- LQ always decays into τ + b (β = Br(LQ → τb) = 1)
- Unknown LQ-τ-b coupling λ (LQ-τ-b) = 1
- Model R_2 ~ as described in Phys. Rept. **641** (2016)
- Signal xsec and k-factor from theorist
- Signals simulated in LO with MG
- Sensitive to high-mass/ coupling region

Redo the analysis from existing Run 2 result





To be based on CMS-PAS-EXO-17-029

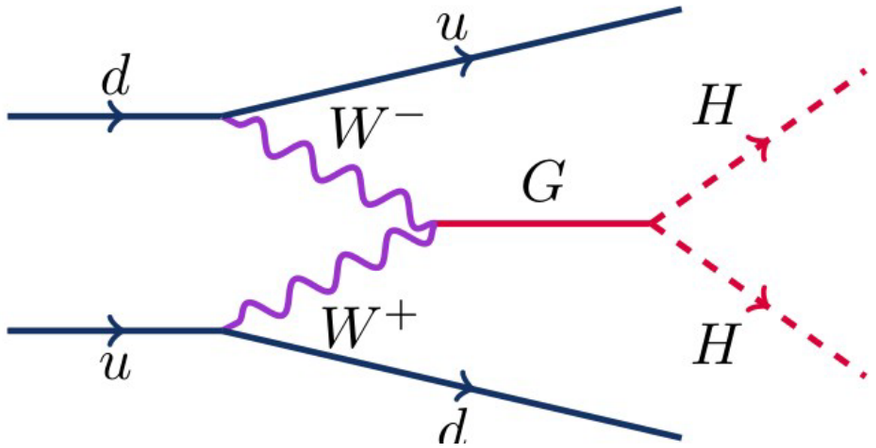
VBF HH→ bbbb

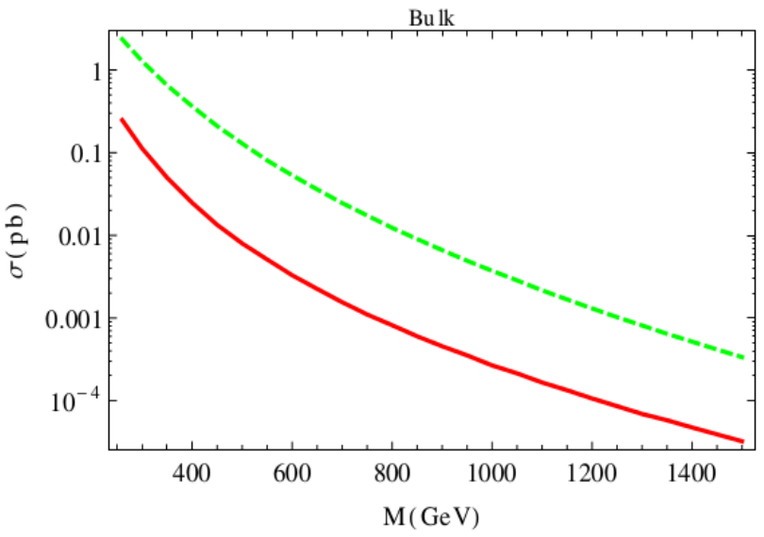
New Plans

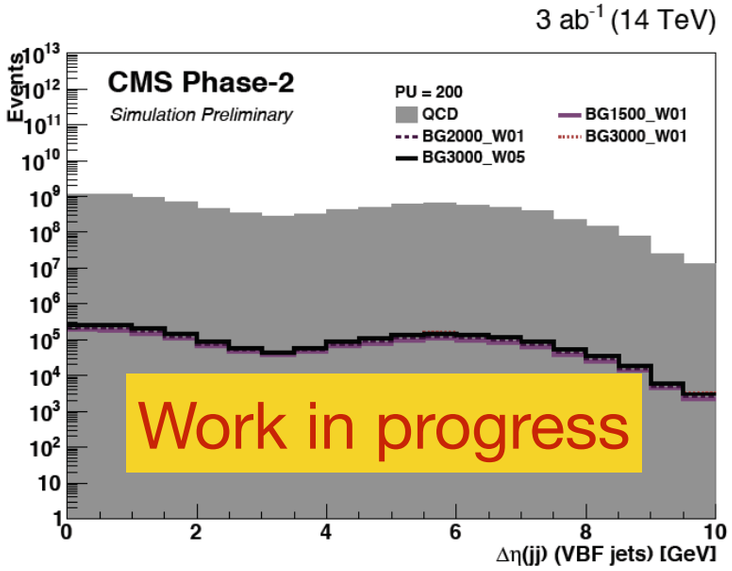
- Search for a massive spin-2 bulk graviton decaying to two Higgs bosons.

- VBF x-sec is the 2nd largest after gluon fusion production

- A 4-jet signal topology that will profit from the forward HGCal regions and increased coverage in tracker and calorimeter
  - 2 boosted Higgs jets decay
  - 2 light forward VBF-jets with large Δη and di-jet mass







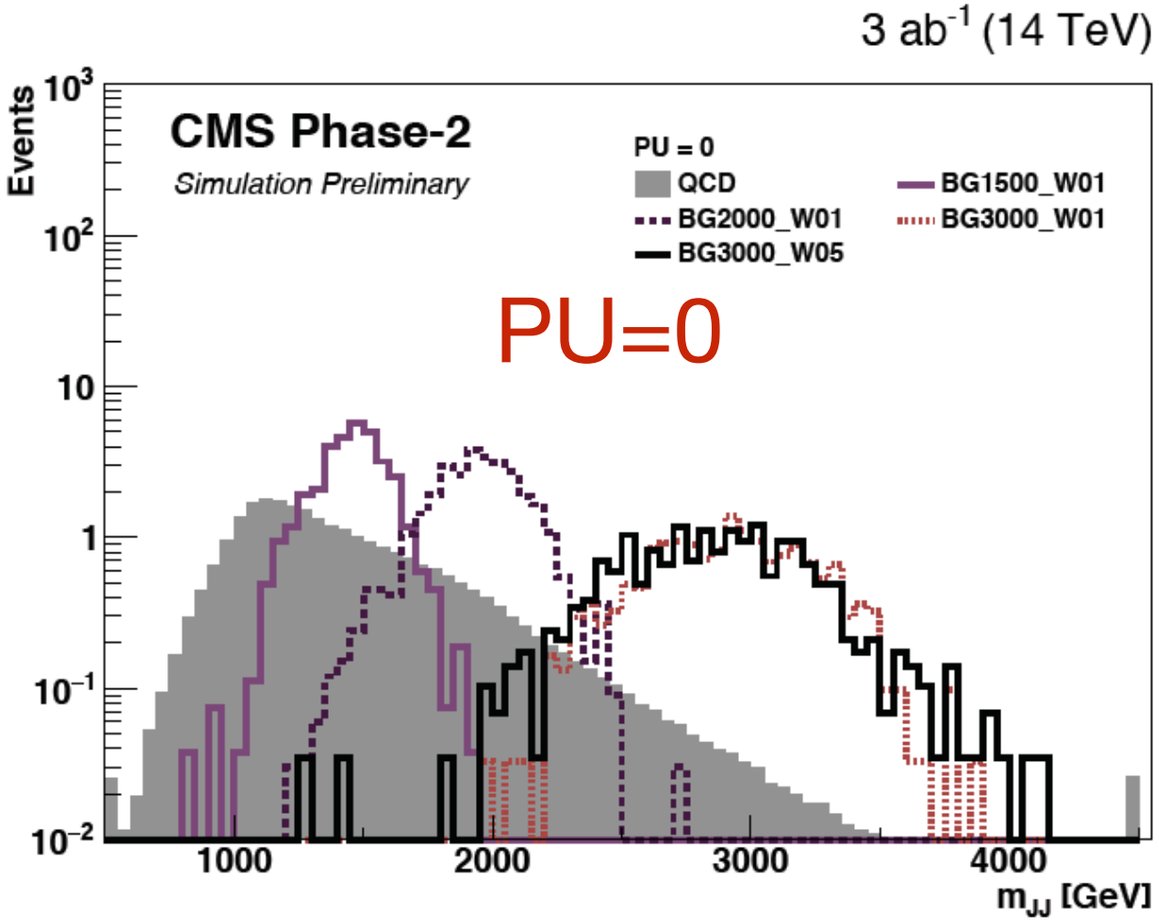
Based on CMS-PAS-B2G-16-026
arXiv:

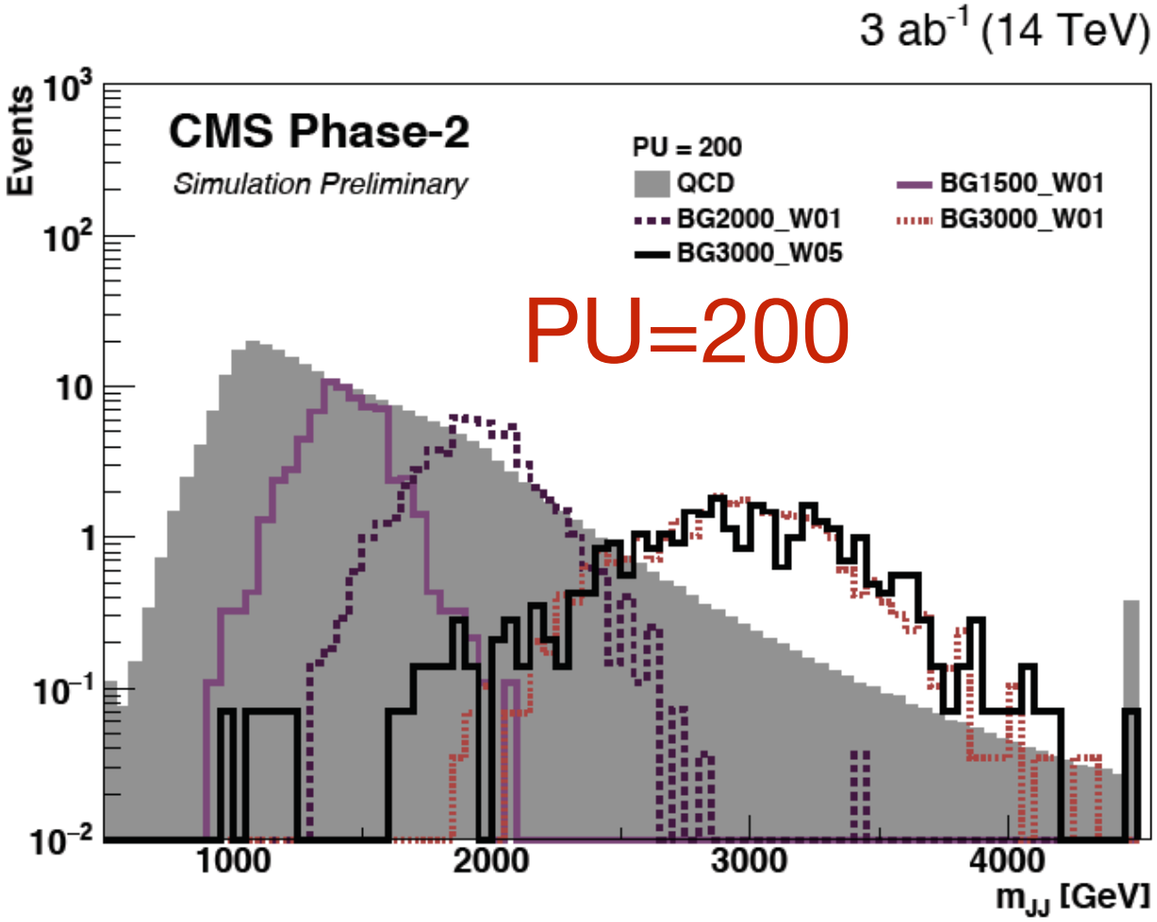
VBF HH→ bbbb

Challenge!

Work in progress

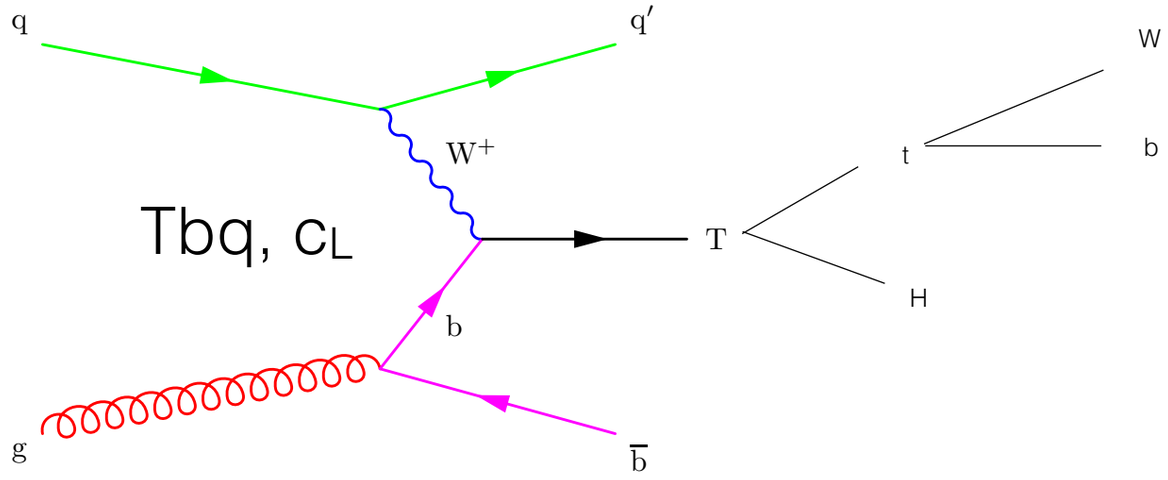
- Large QCD multi-jet background
- Evaluate Higgs mistag rate using an inclusive QCD MC and apply to the events passing the VBF jets selection

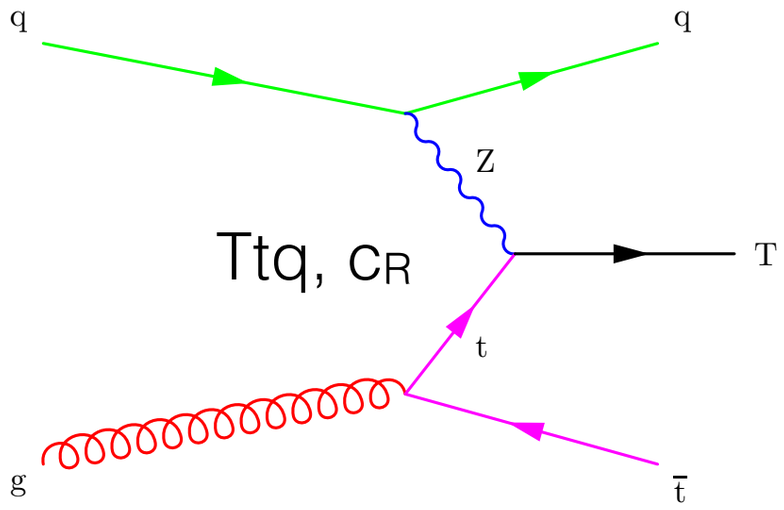




- Signal MC is normalized to 1 fb^{-1} for better visualization

Single VLQ: T → tH (l+jets)





- Models: qg→ Tbq (Ttq) with L (R) EWK couplings, where T → tH
- Signal topology:
  - T → t H → (lvb) (bb) : single lepton + jets + Higgs candidate
- Study sensitivity to the EWK couplings at HL-LHC attributed due to luminosity, tracking in forward region, endcap extension, jet substructure tools, subjet b-tagging
- Signal MC generated using MG+Pythia8 for T masses 1, 1.5, 2, 2.5, and 3 TeV each using NWA (10 GeV)
- Backgrounds: tt+jets, V+jets, single top and dibosons

CMS-PAS-FTR-16-005

Single VLQ: T →tH (l+jets)

Event Selection:

- Exactly one lepton (e/mu) with pt > 30 GeV, |η| < 4.0
- Using PUPPI jet apply 2D isolation:
  - reject event if dR(l,j) > 0.4 and $\Delta p_{T,rel}$> 40 GeV, where $\Delta p_{T,rel}$ is the relative p_T of lepton w.r.t the closest jet
- ≥ 1 forward jet: 2.4 < |η| < 5.0, jet p_T > 30 GeV
- ≥ 3 central jets: |η| < 2.4; leading (sub-leading) jet p_T > 200 (80) GeV
- ≥ 1 b-jet with 70% tagging efficiency
- E_T^{miss} > 20 GeV

Higgs Tagging:

- AK8 jets p_T > 300 GeV, |η| < 2.4
- N subjettiness: τ_{21} < 0.6
- 2 hard softdrop subjets
- ΔR(l, H) > 1.0
- 90 < softdrop mass < 160 GeV
- No subjet b-tagging

Mass Reconstruction

- Solve for neutrino p_Z
- Permute Higgs candidate with up to two AK4Jets and minimize a χ^2
- Keep the results with ΔR(t,H) > 2

$$\chi^2 = \left(\frac{M_{H,MC} - M_{H,rec}}{\sigma_{M_H,MC}}\right)^2 + \left(\frac{M_{t,MC} - M_{t,rec}}{\sigma_{M_t,MC}}\right)^2 + \left(\frac{dR(t,H)_{MC} - dR(t,H)_{rec}}{\sigma_{dR,MC}}\right)^2$$

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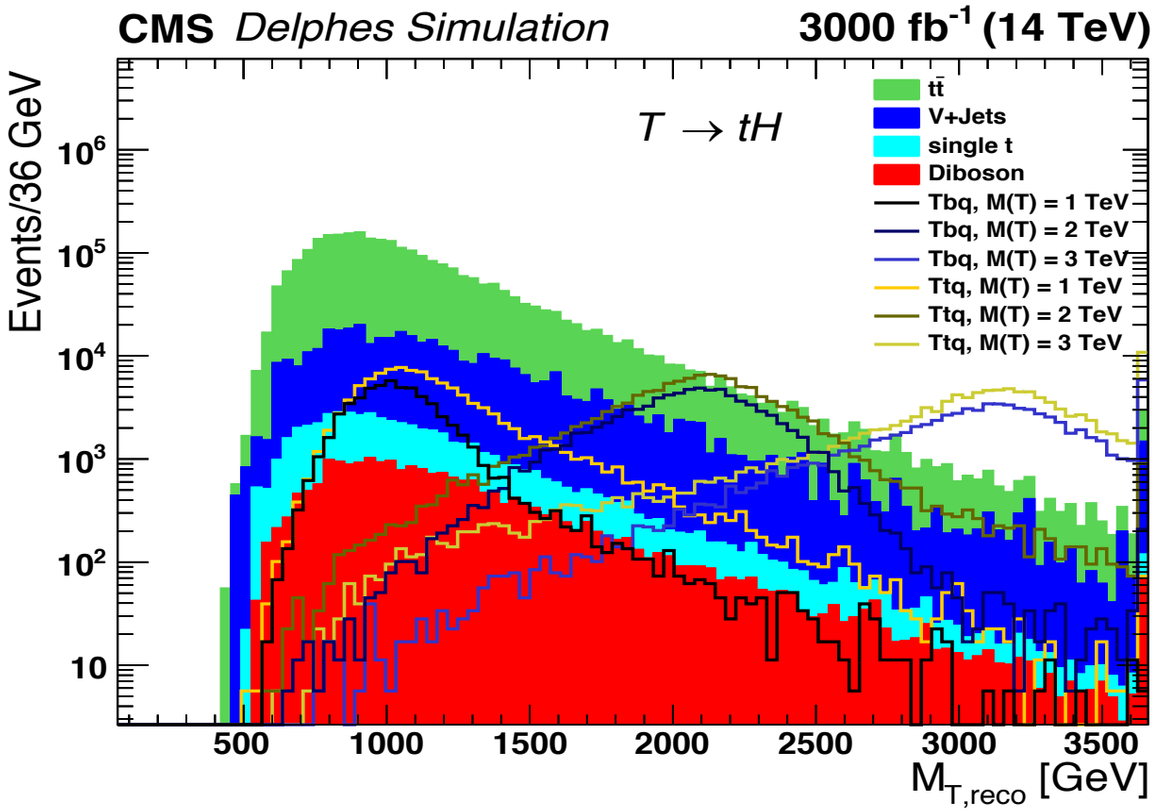
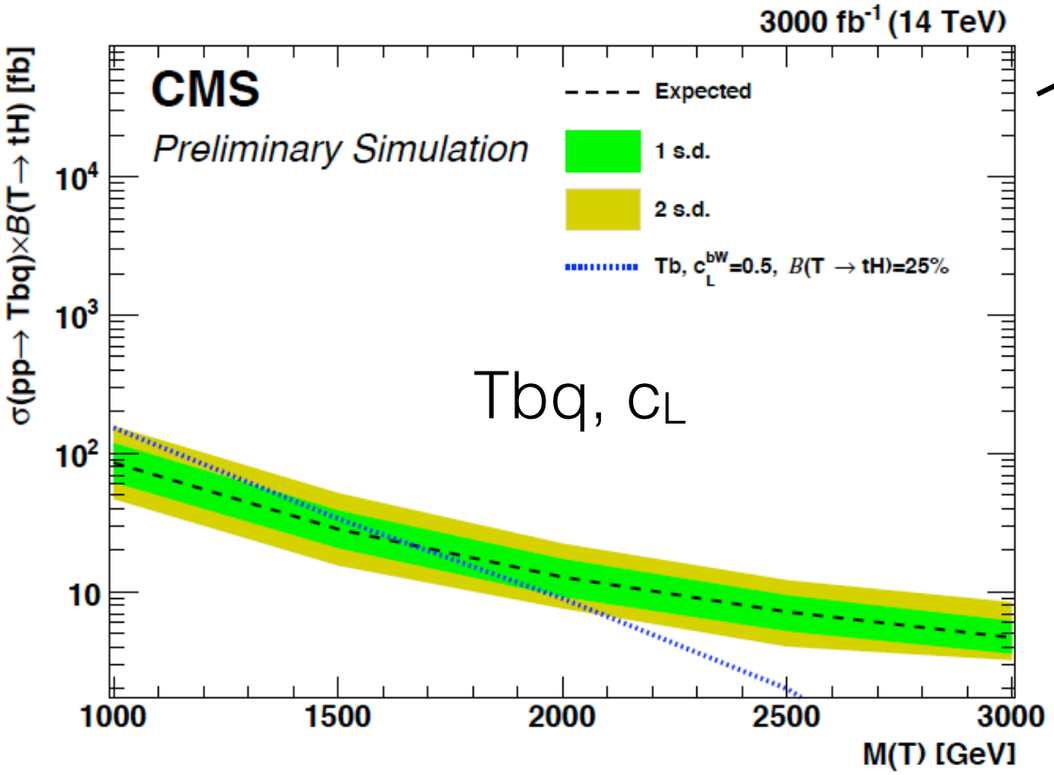
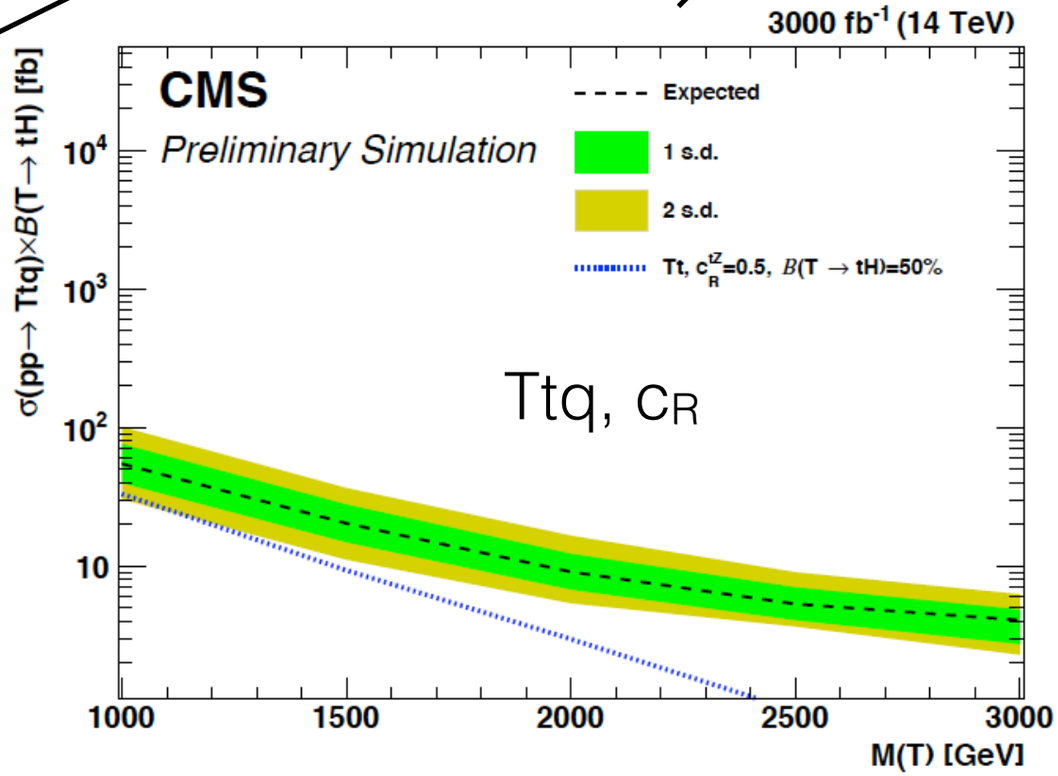
Single VLQ: T →tH (l+jets)



$\mathcal{B}(T \to tH = 0.25)$ $\mathcal{B}(T \to tH = 0.50)$

Mass (GeV)	Expected cross section upper limit (fb)	
	Tbq (LH)	Ttq (RH)
1000	85.9	54.7
1500	28.4	20.3
2000	12.8	9.06
2500	7.20	4.64
3000	4.69	4.69





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Single VLQ: T →tH (l+jets)

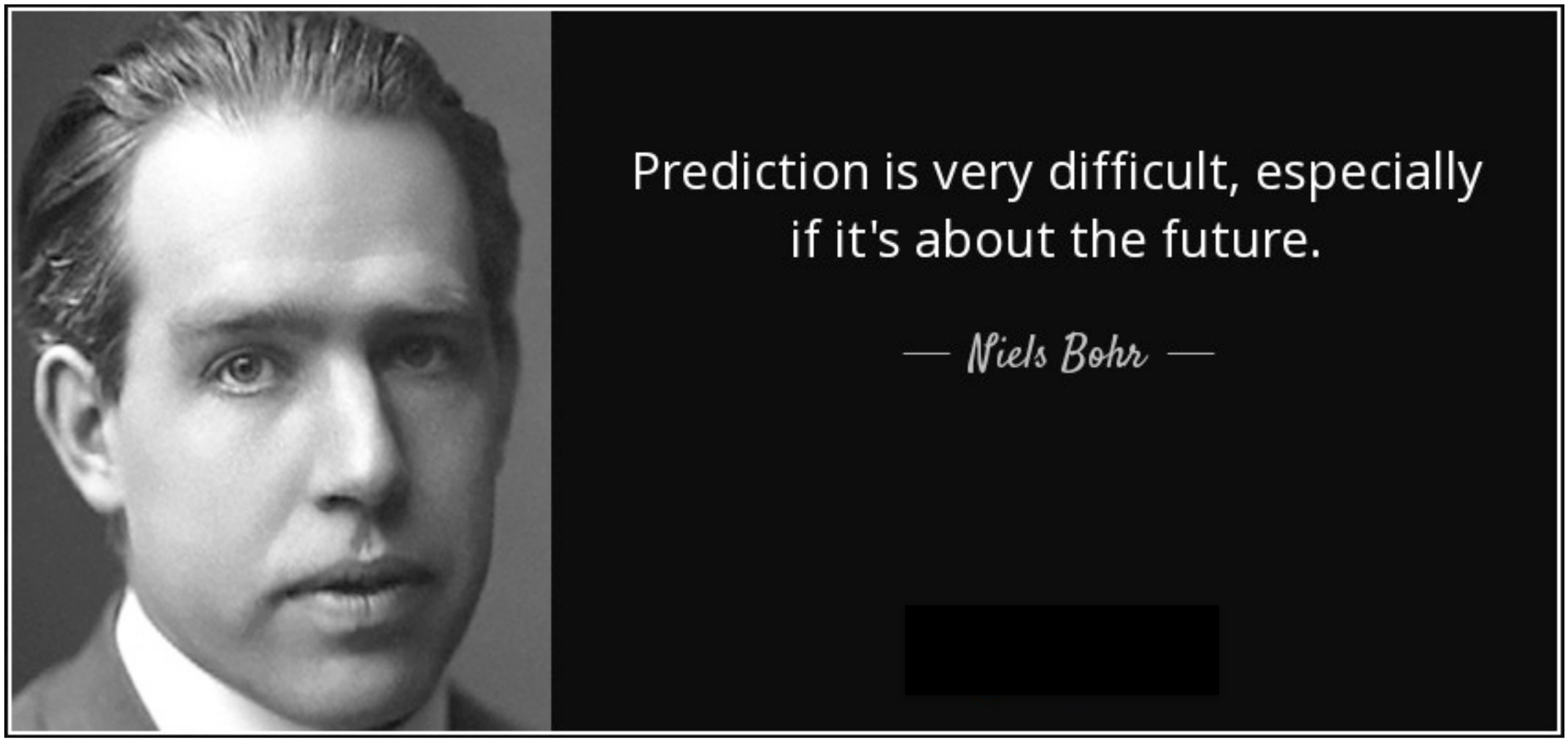
New Plans

- Using full simulation with phase 2 upgrade machine, perform the analysis using for model qg→ Tbq with left EWK couplings
- Signal topology:
  - T → t H → (lvb) (bb) : single lepton + jets + Higgs candidate
- Main change
  - lepton identification using MVA, subjet b-tagging in H-tagging
  - Signal MC generated using MG+Pythia8 for T masses 1, 2 and 3 TeV each for
    - Widths = 10, 20, 30%
  - More realistic systematic uncertainties per CMS recommendations
- Methodology will remain same, i.e, T mass reconstruction

Summary

- Described prospects of discovering many new physics models at LH-LHC that can show up as resonances
  - Z' → tt
  - W' → tb, ev, τv
  - LQ_3 →τ b
  - VBF di-Higgs→ 4b
  - Single VLQ T →tH
- Many of them are currently work in progress either as updates to previous analyses or new analyses, all aiming for LHC Yellow Report

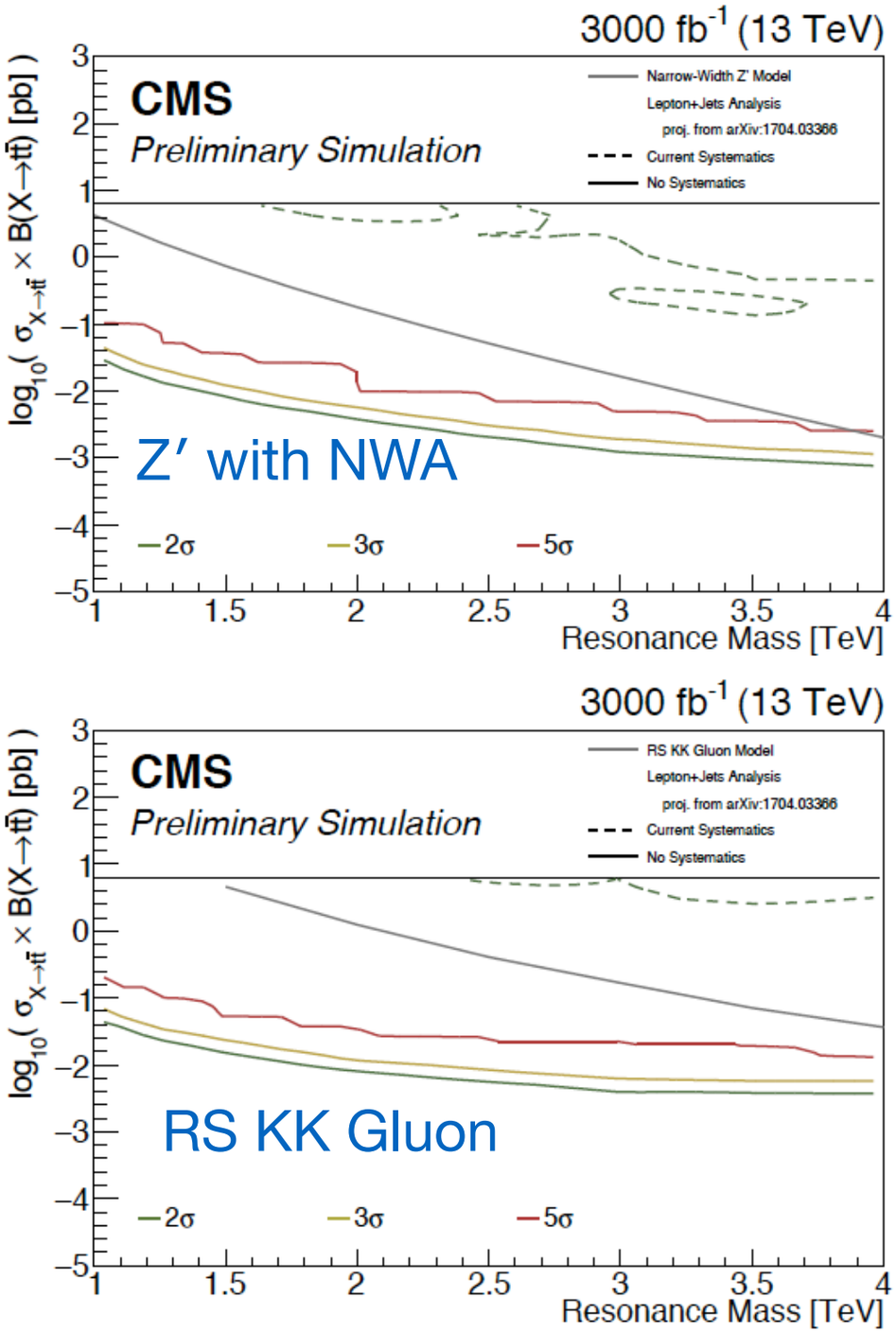
Thank you!


Prediction is very difficult, especially
if it's about the future.
— Niels Bohr —

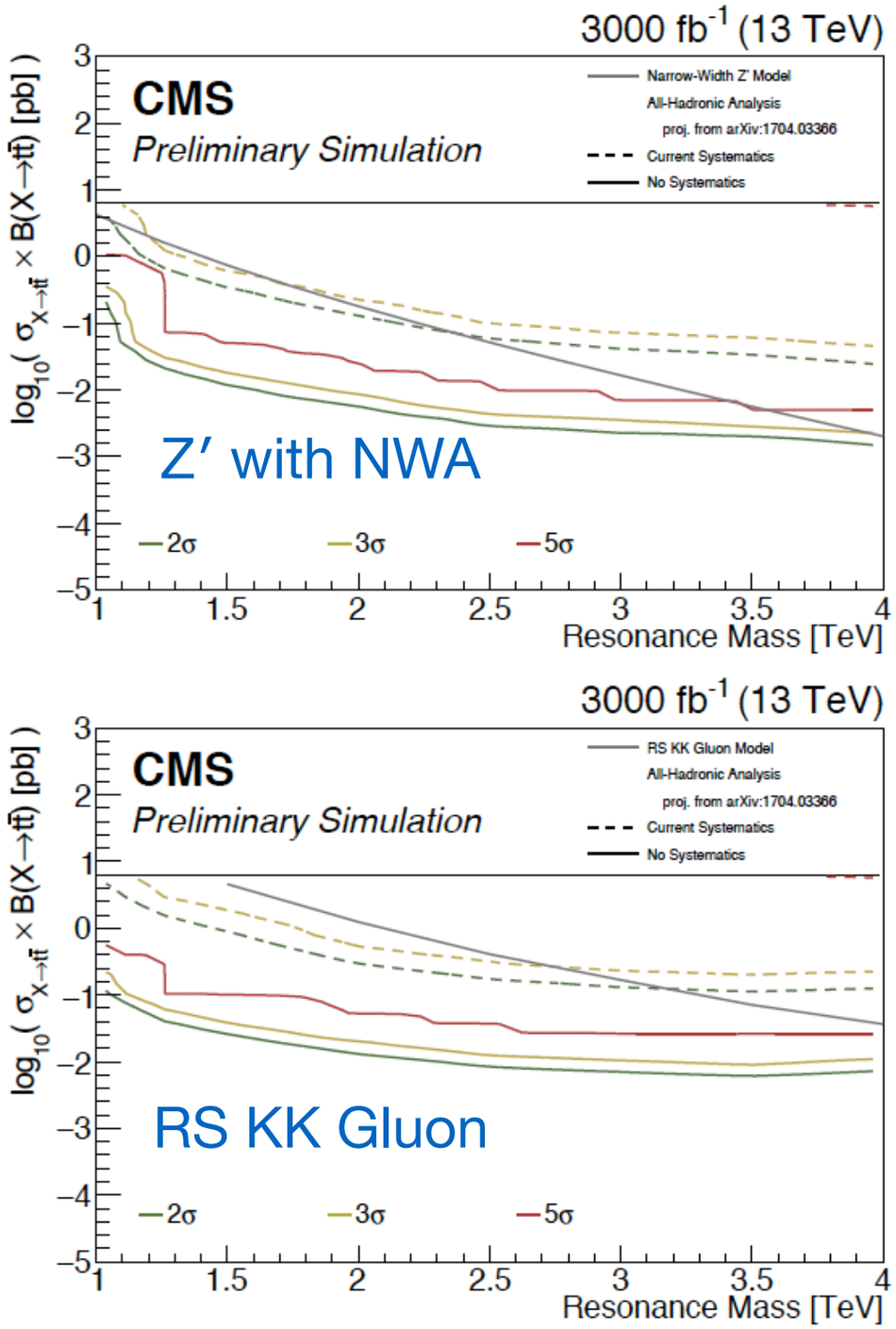
Backup
Ctrl

Z' → tt

Discovery reach in l+jets @ 13 TeV



Discovery reach in hadronic @ 13 TeV



CMS-PAS-FTR-16-005

Single VLQ: T →tH (l+jets)

Systematic Uncertainties

The main SM background in this search are $t\bar{t}$ + jets events, which are normalized to the NNLO cross section. We consider a total of 27% uncertainty on $t\bar{t}$ + jets normalization, which is 1/2 of the total uncertainty on $t\bar{t}$ theory cross section due to PDF and QCD scale, and top quark mass. We keep the same uncertainty on the single top quark background, since for the limit setting procedure, we combine the two samples and treat them as one template. Another large background is V + jets, where V can be a W or a Z boson. This background is combined with the smaller diboson backgrounds and a total of 20% conservative uncertainty is assigned on their normalization.

The largest shape uncertainties comes from b-tagging. To estimate them, we vary the nominal b-tagging SF at medium efficiency working point by scaling it up and down by 1% for b jets, 2% for c jets, and 5% for the light jet, and use the resultant shape template in our statistical analysis. For the jet energy scale an estimated flat uncertainty of 3.8% is applied. In Run-2 for Higgs-tagging, the measured uncertainty on jet mass and N-subjettiness selection scale factors are found to be 1.03 ± 0.13, and we expect the uncertainty to improve with new tagging tools and hence do not apply any uncertainty due to these sources. Other uncertainties include 1% on jet energy resolution, 1.5% on luminosity, 1% on presumed trigger scale factor, 1% on lepton reconstruction and identification.