The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization
IAEA
International Atomic Energy Agency

2263-38

Beyond the Standard Model: Results with the 7 TeV LHC Collision Data

19 - 23 September 2011

4th Generation Searches in CMS

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Searches for 4th Generation at CMS Experiment

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On behalf of CMS Collaborations

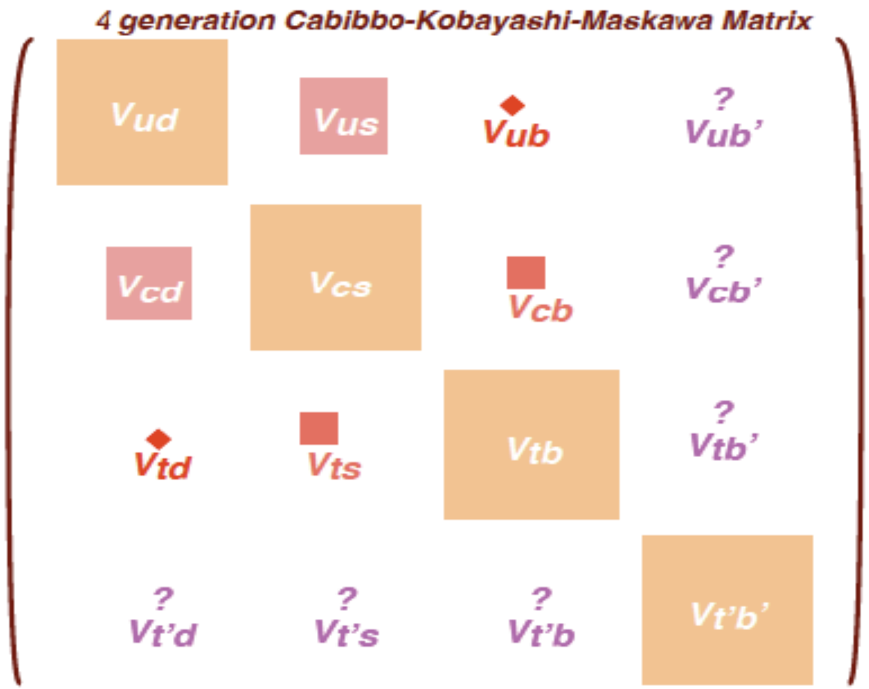
Beyond the Standard Model: results with the 7 TeV LHC Collision Data
The Abdus Salam ICTP, Trieste, Italy
22 Sep, 2011

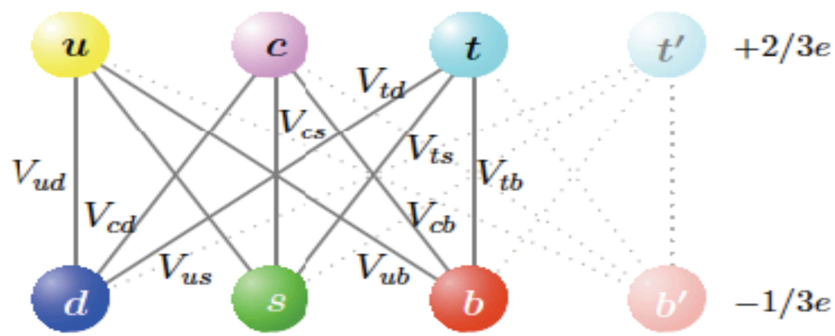
Outline

- Why the fourth generation?
  - Flavor Physics
  - The fourth generation is not excluded by EWK precision data
  - New CP source for Baryogenesis
- Results from other experiments
- Results from CMS
- Summary

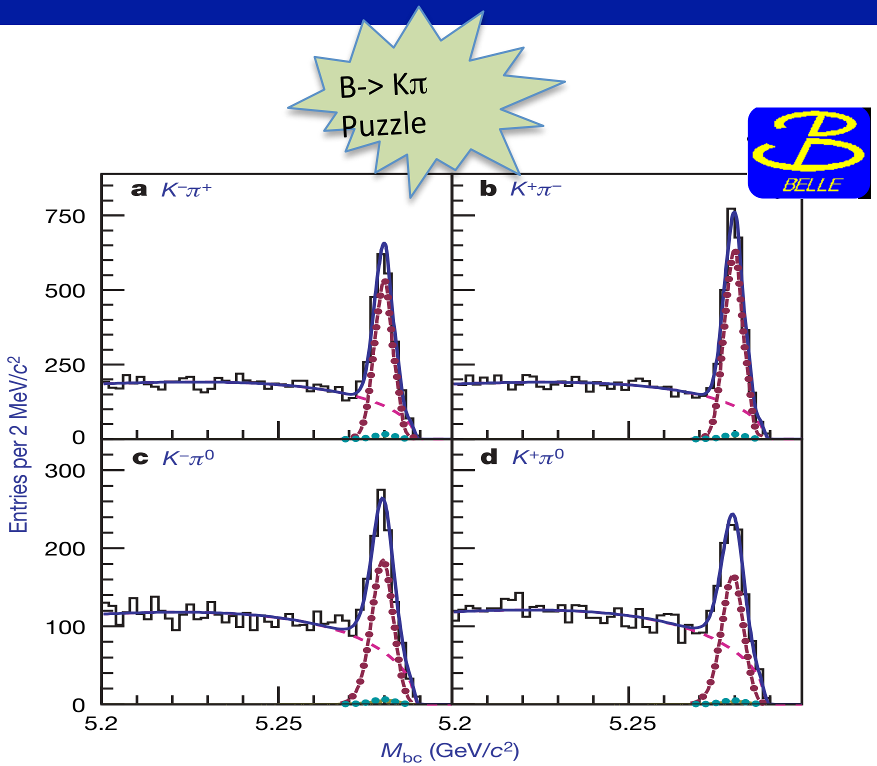
4th Generation (SM4)

- SM4 is a simple extension of SM3 = SU(3)×SU(2) ×U(1)
- It could explain some observed discrepancies



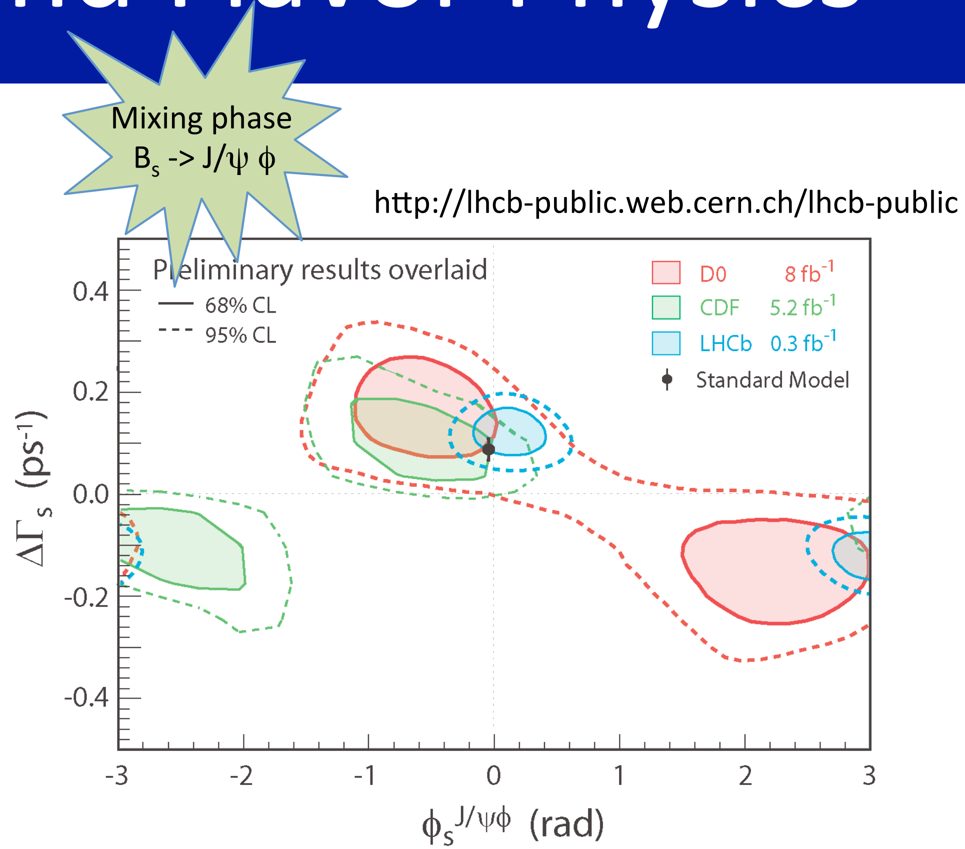


4^{th} Generation and Flavor Physics



Nature 452, 332(2008)

$$\Delta\mathcal{A} \equiv \mathcal{A}_{K^\pm\pi^0} - \mathcal{A}_{K^\pm\pi^\mp} = +0.164 \pm 0.037$$



$\phi_s = 0.03 \pm 0.16 \pm 0.07$

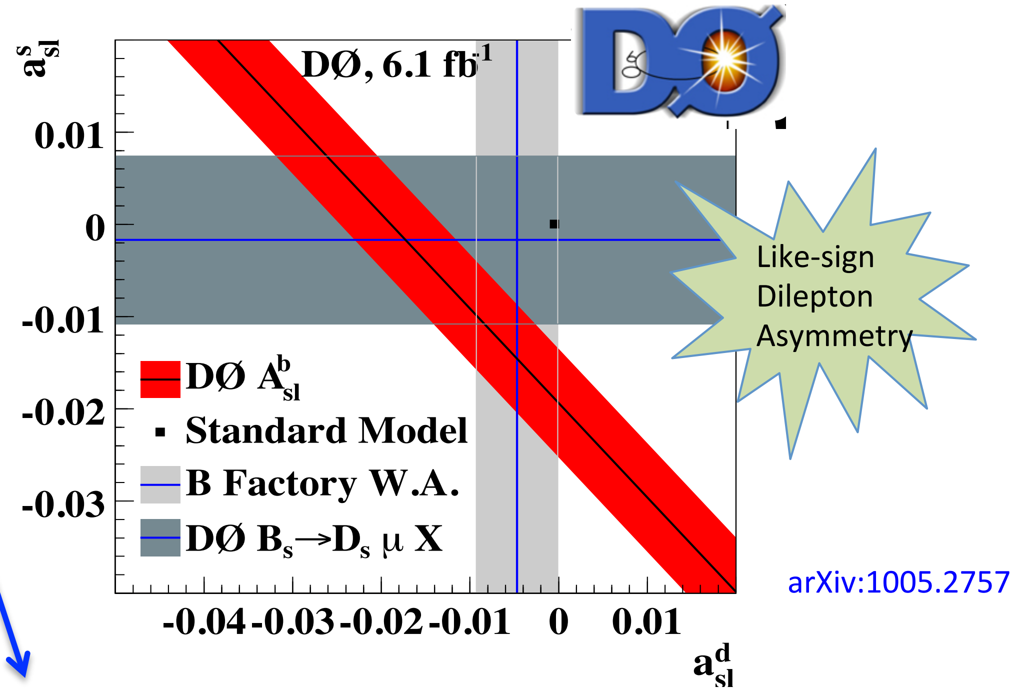
Since t-quark is non-decoupled, introducing t' in bcZ penguin for B^+-> K π^0 and in the box diagram for B mixing brings in new CPV phase via $V^*_{t's}V_{t'b} = r_s e^{i\phi_s}$

4^{th} Generation and Flavor Physics

$$A_{\rm sl}^{b} \equiv \frac{N_b^{++} - N_b^{--}}{N_b^{++} + N_b^{--}},$$

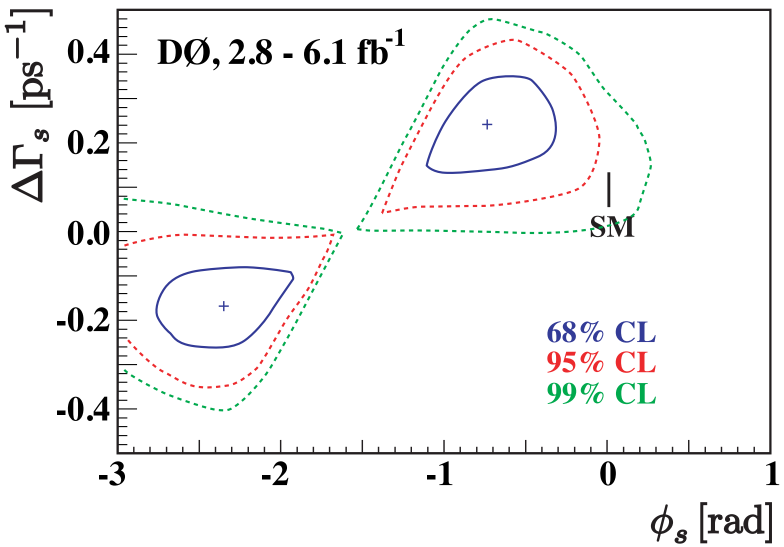
$$A_{\rm sl}^{b}(\mathrm{SM}) = (-2.3^{+0.5}_{-0.6}) \times 10^{-4},$$

which is 3.2 σ away from the observation



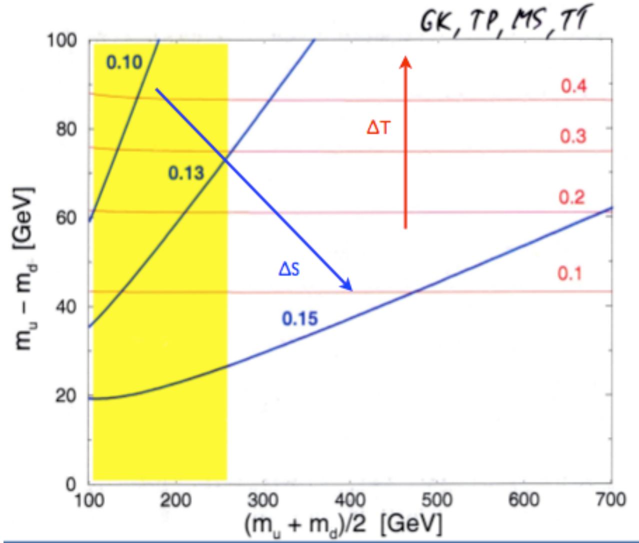
arXiv:1005.2757

$$A_{\rm sl}^{b} = -0.00957 \pm 0.00251\ (\mathrm{stat}) \pm 0.00146\ (\mathrm{syst})$$

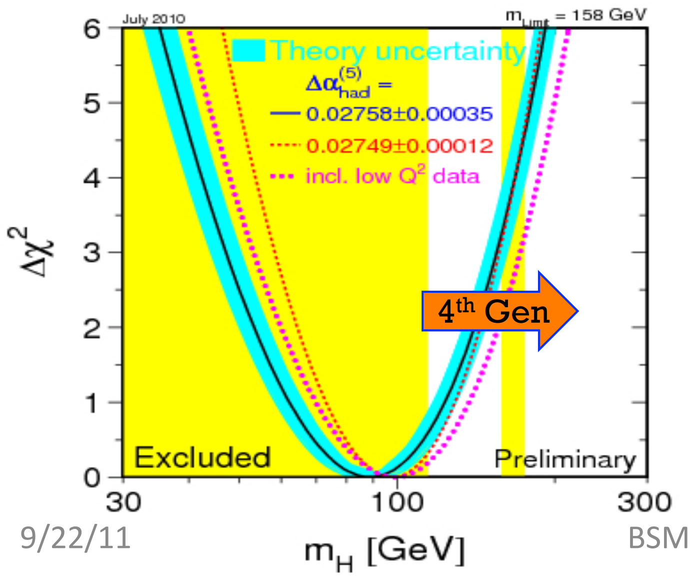


This result can be interpreted in the scope of $\Delta\Gamma_s$ and Φ_s

4th Generation and EWK precision data



G. Kribs, T. Plehn, M. Spannowsky, T. Tait
PRD 76 (2007) 075016



- Constraints from electroweak precision data require small oblique corrections: ΔS, ΔT, ΔU
- If SM4 exists, expects small mass splitting between 4-th generation t' and b' :
  - $|m_{t'} - m_{b'}| < m_W$
- $m_{t'}$ and $m_{b'}$ ~ a few hundreds GeV
- b-quark A_{FB} shows ~ 2.6 σ deviation
- Tension could be resolved by introducing quarks with non-V-A couplings (Vector Like quark).

Baryogenesis with 4 Generations

- SM3 falls short of the needed level of baryogenesis by at least 10 orders of magnitude
- With four generations, one can construct 3 independent CP odd Jarlskog invariant, one of which is proportional to two of the bigger masses

$$J_{234} = 2(m_{t'}^2 - m_t^2)(m_{t'}^2 - m_c^2)(m_t^2 - m_c^2)(m_{b'}^2 - m_b^2)(m_{b'}^2 - m_s^2)(m_b^2 - m_s^2)A_{234}$$

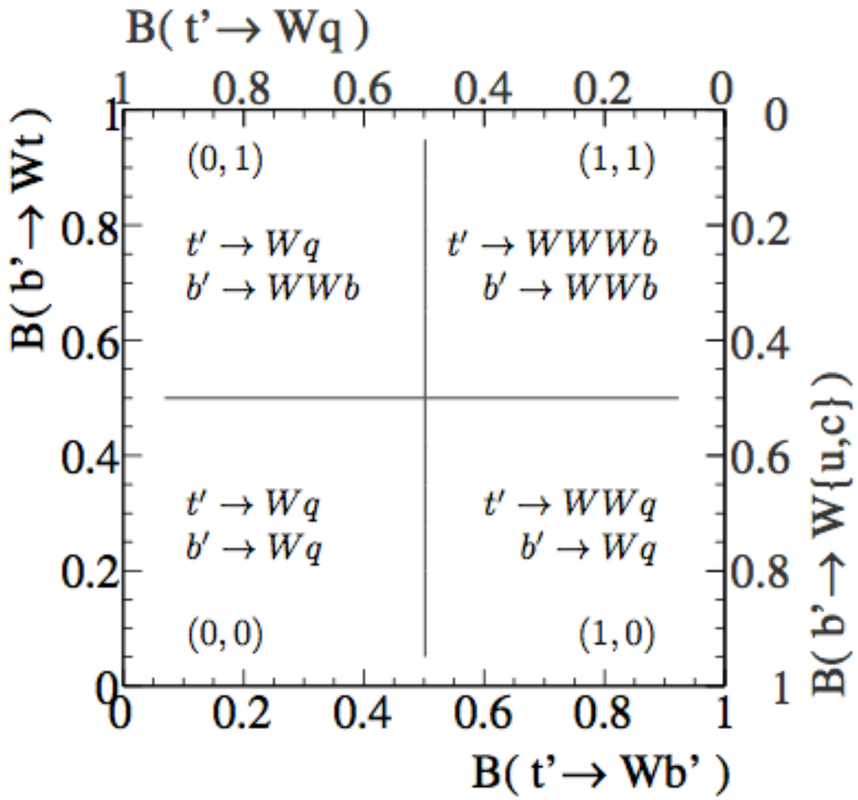
- From the heavy mass dependence ($m_{t'}$, $m_{b'}$ ~ 300 to 600 GeV) , there is a huge gain over the single three generation invariant:

$$\frac{J_{234}}{J} : 10^{15-17}$$

From David Atwood, DPF2011

- Baryogenesis now becomes possible [George W. S. Hou 2008]
- One advantage of this kind of model over CPV from random new physics is that fermion edm's are naturally small.

Search for t't': t'->Wq, Wb



- ***Main Decay Modes:***
  - *t'->Wb, Wq*
  - *B'-> tW, Wq*
- ***Search for:***
  - *Q->Wq, Wb, tW=WWb, tZ=WbZ*
  - *Similar to top quark production and decay*
- ***Search Strategy:***
  - *Reconstruct mass of the top (t') quark*
  - *H_T and S_T (in coming slides)*

Constraints by experiments

- Constraints on the pair produced b' mass:
  - $m_{b'} > m_t + m_w$ favored, and limit $m_{b'} > 338$GeV

    CDF 'Search for New Bottomlike Quark Pair Decays QQ → (tW)(tW) in Same-Charge Dilepton Events', Phys. Rev. Lett. 104 (2010) 091801
  - $m_{b'} > 385$GeV direct search: $b'\bar{b}' \to WtW\bar{t} \to WWbWW\bar{b} \to \ell\nu qq'bqq'qq'b$

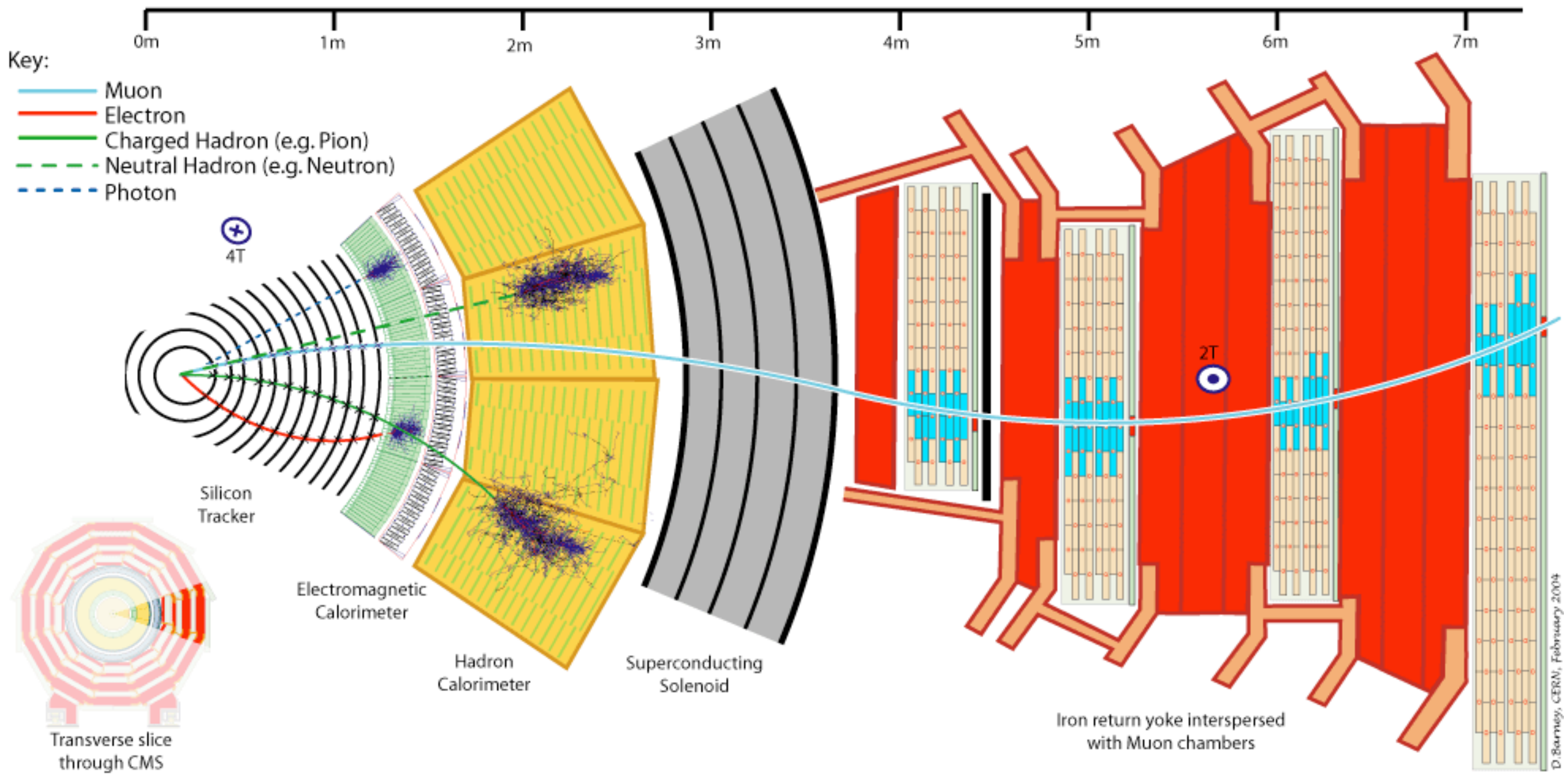
    CDF Phys. Rev. Lett. 106, 141803 (2011)
- Constraints on the pair produced t' mass:
  - $m_{t'} > 358$GeV direct search

    CDF arXiv:1107.3875(submitted to PRL), D0 arXiv:1104.4522)
- $m_{t'} - m_{b'} < 50$GeV from precision electroweak measurements

  Kribs, PRD 76 075016 (2007) Eberhardt, Lenz, Rohrwild, PRD 82 095006 (2010)
- $m_{Q4} > 270$ dilepton + jets ($L=37\ pb^{-1}$)

  ATLAS: ATL-PHYS-SLIDE-2011-223

Searches for 4th generation quark at CMS

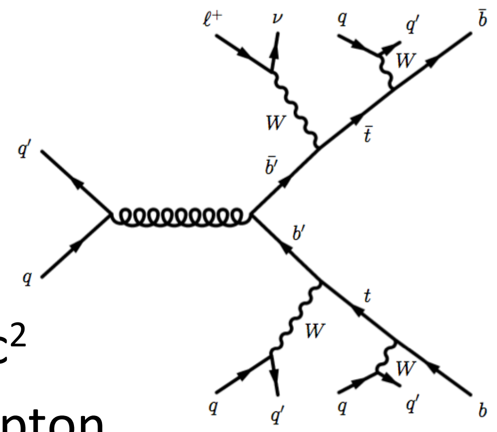


Relevant final states

- $b'\bar{b}'$ → tWtW → bWWbWW
  - 4 or 6 Jets from 1 or 2 W →qq including 2 b-jets
  - Ws decay to two same sign charged leptons or three isolated leptons (i.e. dilepton and trilepton - has small SM background and large B.R.)
- $T'\bar{T}'$ → tZtZ → bbWWZZ
  - ≥ 2 Jets from W →qq, Z →$q\bar{q}$ including 2 b-jets
  - Z → l^+l^- and one W decays to isolated lepton i.e. trilepton decay
- $t'\bar{t}'$ →bbWW:
  - one W decays leptonically, the other hadronically i.e. 4 jets including 2 b jets + 1 visible lepton
  - two W decays leptonically, 2 b jets + 2 visible lepton

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO

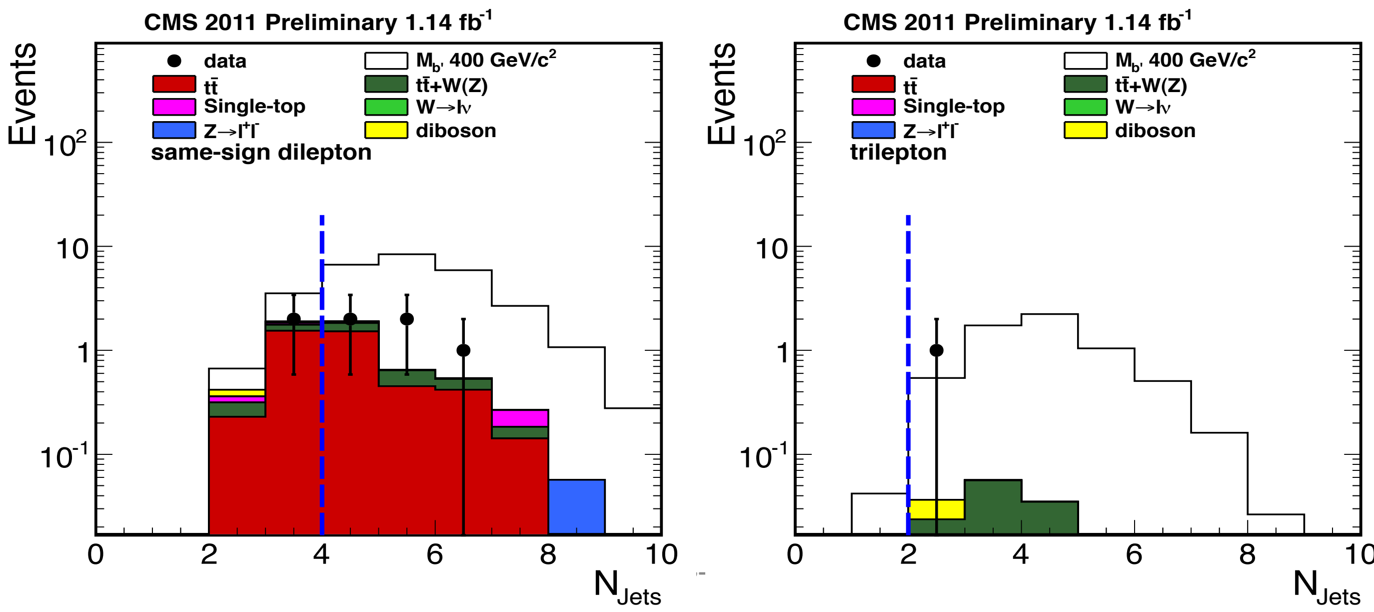
Search for b'b̄' → tWtW→ bWWbWW



Selection

- At least one good interaction vertex
- N(jets)>= 4(6) with p_T> 25, |η|<2.5
- Z events are suppressed by requiring $|M_{ll} - M_Z| < 10$ GeV/c^2
- Events with Njets < 4 (2) are rejected for the same-sign dilepton (trilepton) channel.
- At least one b-jet

PAS EXO-11-036



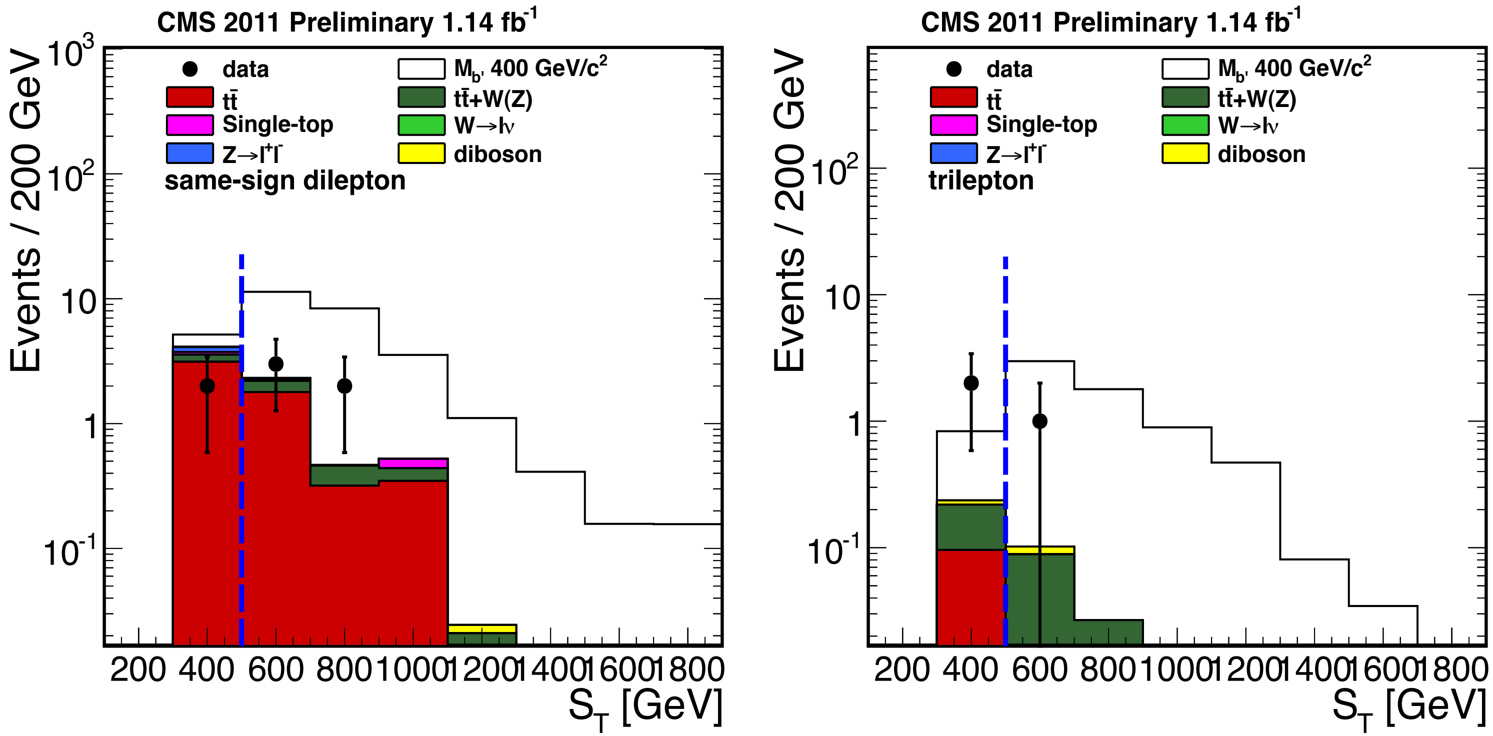
Search for b'b̄' → tWtW

- For each event, the scalar quantity, S_T is determined

$$S_T = \sum p_T(jets) + \sum p_T(leptons) + \not{E}_T$$

PAS EXO-11-036

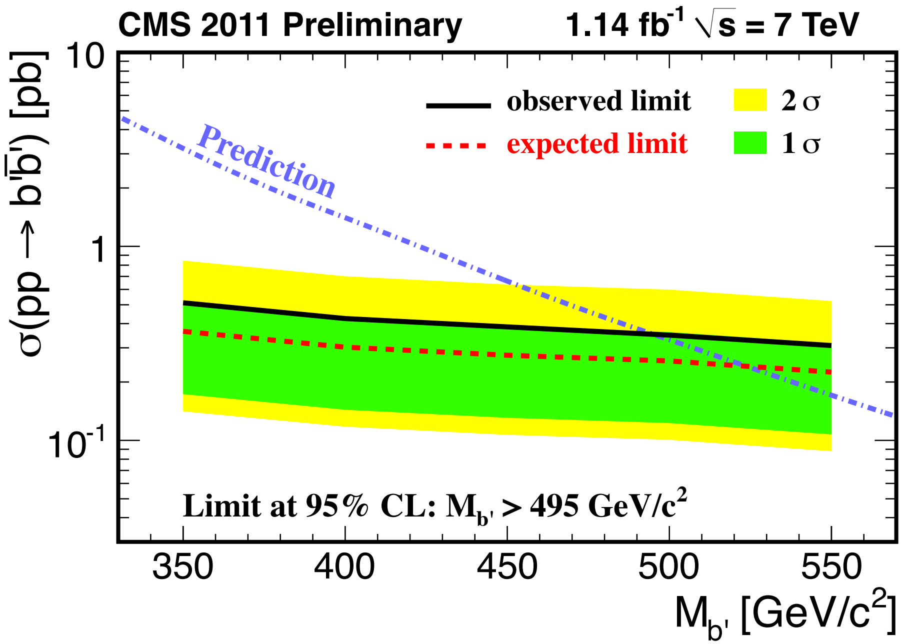
- Require S_T > 500 GeV



Search for b′b̄′ → tWtW

[PAS EXO-11-036]

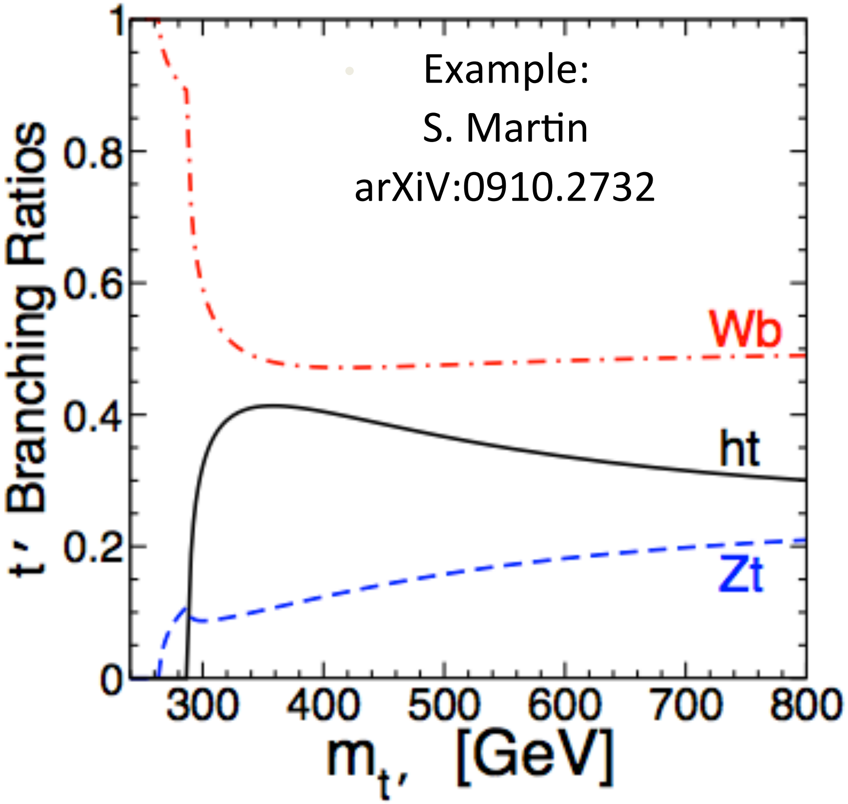
- For each $m_{b'}$ hypothesis, selection efficiencies and associated uncertainties are estimated
- Upper limits on b′b̄′ cross sections at the 95% CL are derived using Bayesian method with a log-normal prior for the integration over the nuisance parameters.

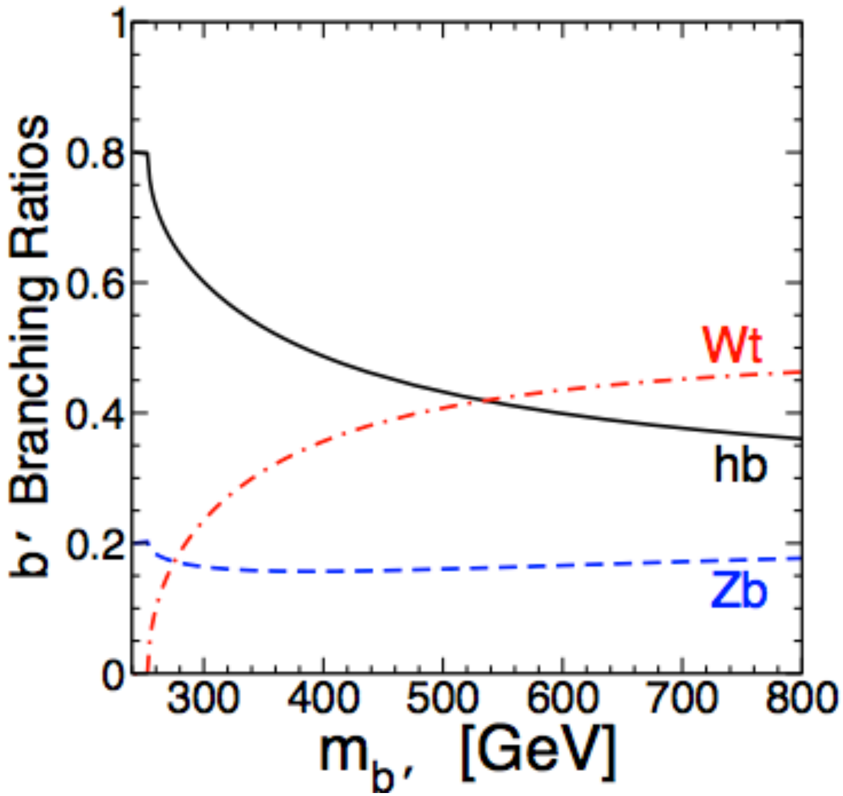


Comparing with NLO production cross sections, $m_{b'} < 495$ GeV/c^2 is excluded.

Vector-like quark T'

- No FCNC-suppression opens new decay modes, e.g. T' ->tH , T' ->tZ
- Can have production cross section enhanced due to different couplings to gauge bosons

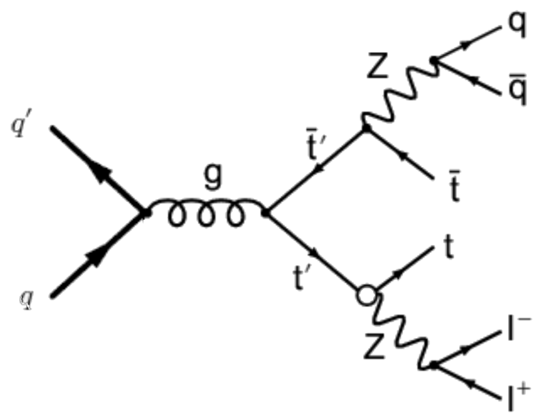


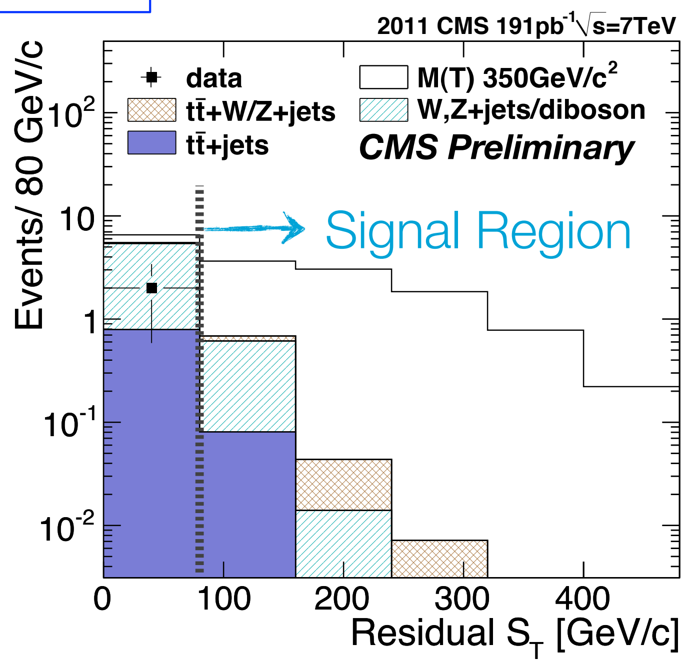


Search for T'T' → tZtZ

See Yeng-Ming Tzeng talk for details

PAS EXO-11-005





Selection and Method

- At least one good interaction vertex
- $p_T(e)>20GeV$, $p_T(\mu)>15GeV$, $\Delta R(e,\mu)>0.1$
- $N_{jets}>= 2$ with $p_T> 25$, $|\eta|<2.4$, $\Delta R(l,jets)>0.4$
- $N(lep) \geq 3$, Z_{ll} (60GeV~120GeV)
- residual $S_T \equiv \sum_{i\neq 1,2} p_T(\mathrm{jet}_i) + \sum_{i \neq 1,2} p_T(\mathrm{lepton}_i)$, $S_T > 80GeV$

T(350GeV)	8.99±1.61
Bkg. (estimated)	0.73±0.31
Data	0

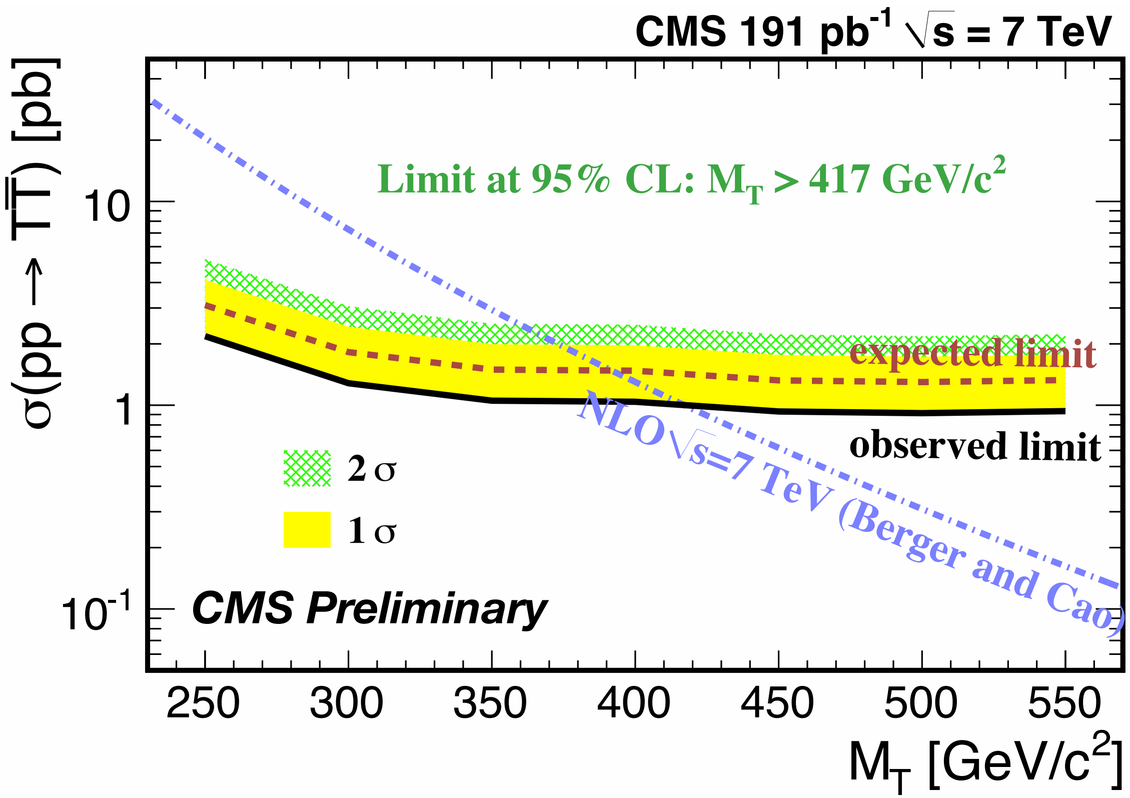
Search for T'T' → tZtZ

See Yeng-Ming Tzeng talk for details

PAS EXO-11-005

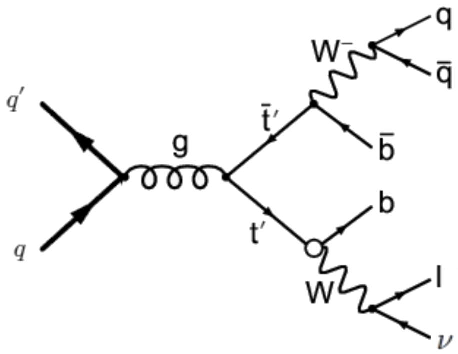
Exclusion limit

- Use Bayesian statistics to compute observed limit at 95% CL and compare it with NLO x-sec



Comparing with NLO production cross sections, $M_T < 417$ GeV/c^2 is excluded.

Search for $t'\bar{t}' \to bWbW \to bl\nu bq\bar{q}$



[PAS EXO-11-051]

Selection

- At least one good interaction vertex
- Electron p_T>30/35/45 GeV to match the trigger threshold, Muon p_T>35 GeV, $|\eta|$<2.1(2.5) for μ(e)
- E_T^{miss}>20 GeV
- At least 4 jets with p_T>120, 90,35,35GeV, $|\eta|$<2.4, $\Delta R(l,jets)$>0.3
- ≥ 1 b jet

Mass Reconstruction

- Known measurements:
  - Lepton p_T
  - Neutrino p_T (E_t^{miss})
  - Jet p_T
- Unknown:
  - Z-component of neutrino
- Constrains
  - $M(l\nu)=m(qq)=M_W$
  - $M(l\nu b) = m(qqb) = M_{t,t'}$
- Possible jet combinations

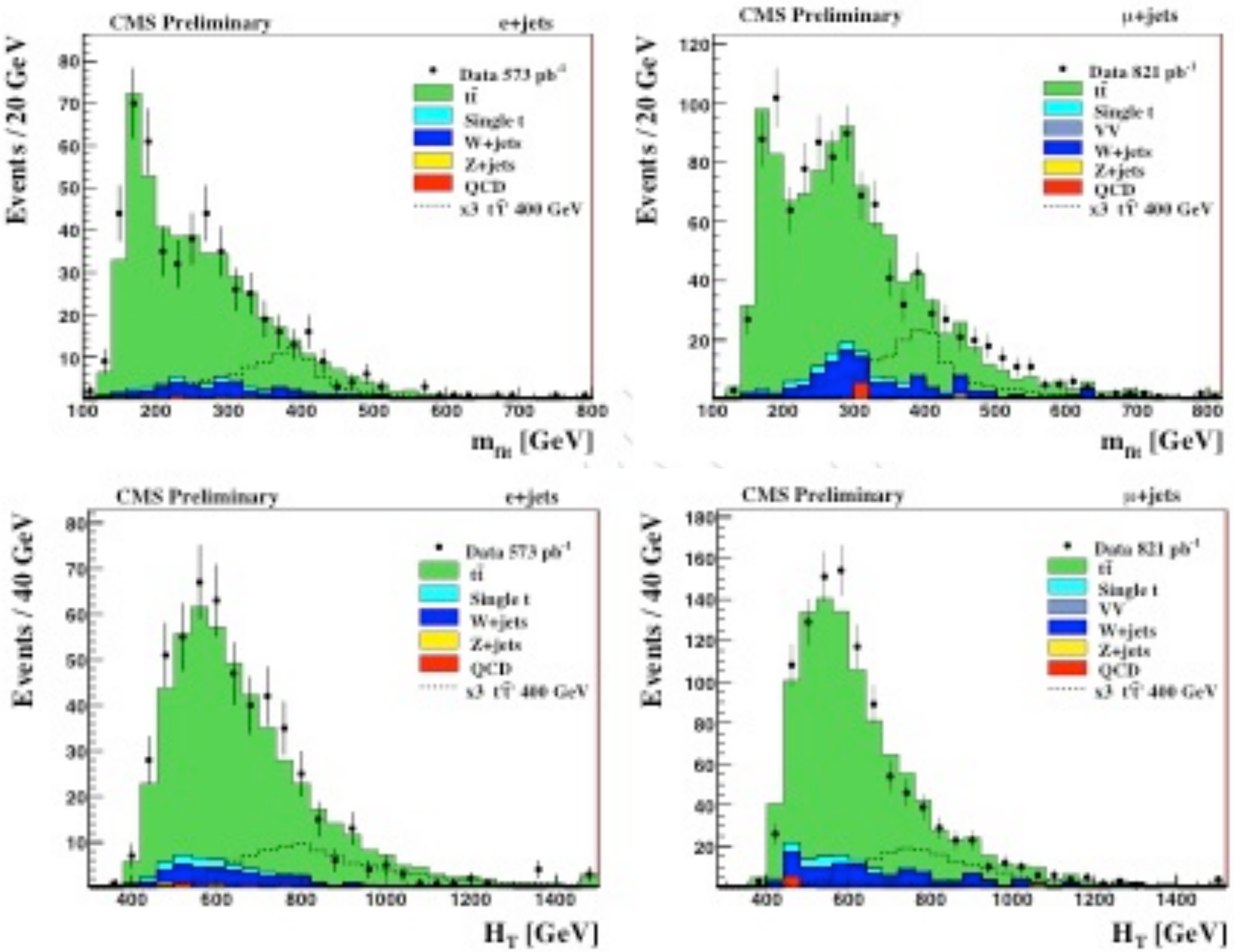
no of jets	combinations
4	12
5	60
6	180

- Minimize the χ^2 for each combination,
  - e + jets: try all 4-jet combs out of the leading 5 jets
  - μ + jets: use 4 leading jets. If 5th jet has highest b-tagging discriminant use it instead of 4th jet
- Using kinematic fit the fitted mass, m_{fit} is reconstructed

Search for t′t̄′ → bWbW → blνbqq̄

- Construct m_T and $H_T = \sum p_T(jets) + \sum p_T(leptons) + \not{E}_T$

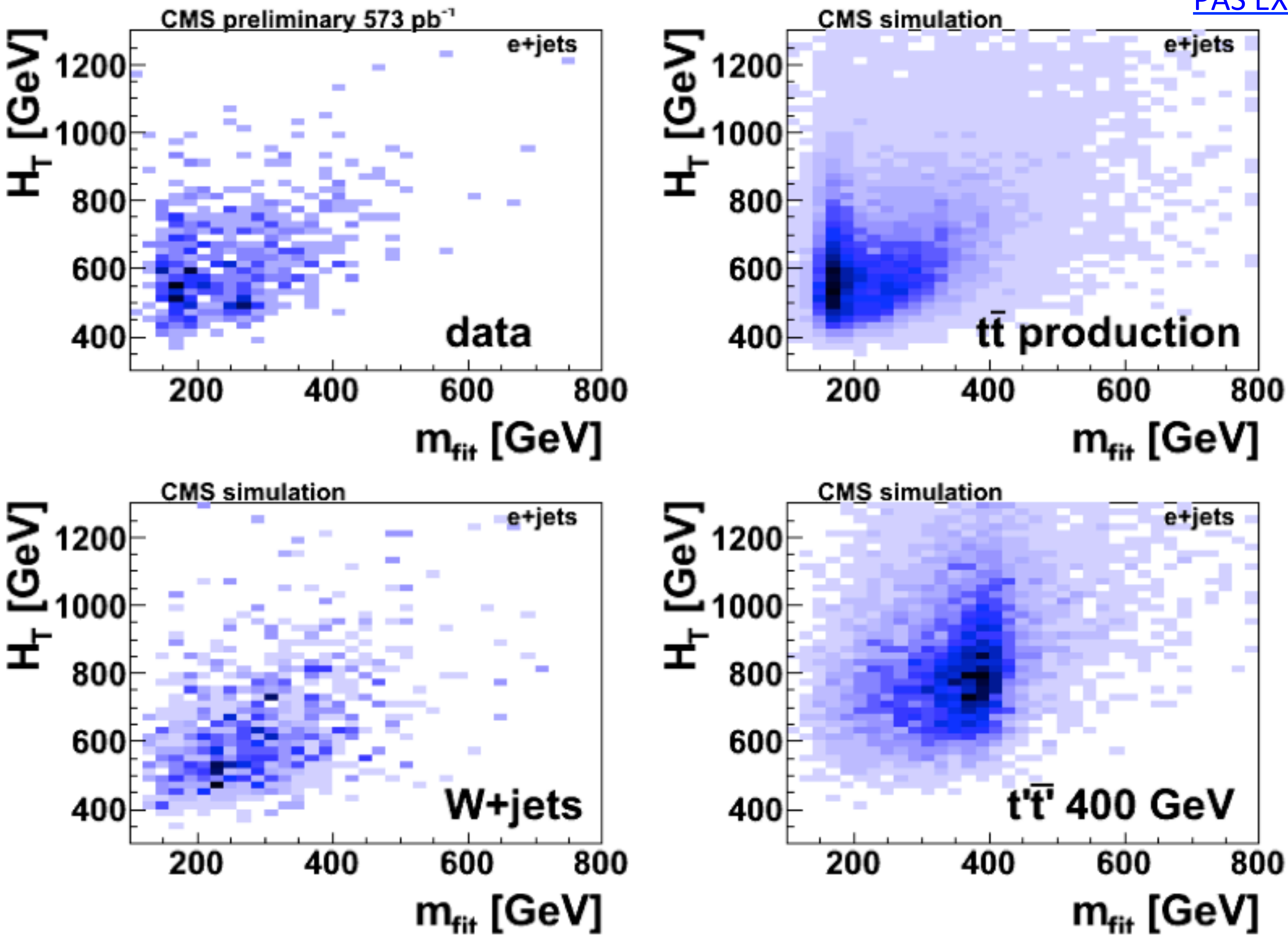
PAS EXO-11-051



Search for $t'\bar{t}' \rightarrow bWbW \rightarrow bl\nu bqq$

- Statistical analysis of the 2D distribution of m_{fit} and H_T, is used to test for the presence of $t'\bar{t}'$ production in the data

PAS EXO-11-051



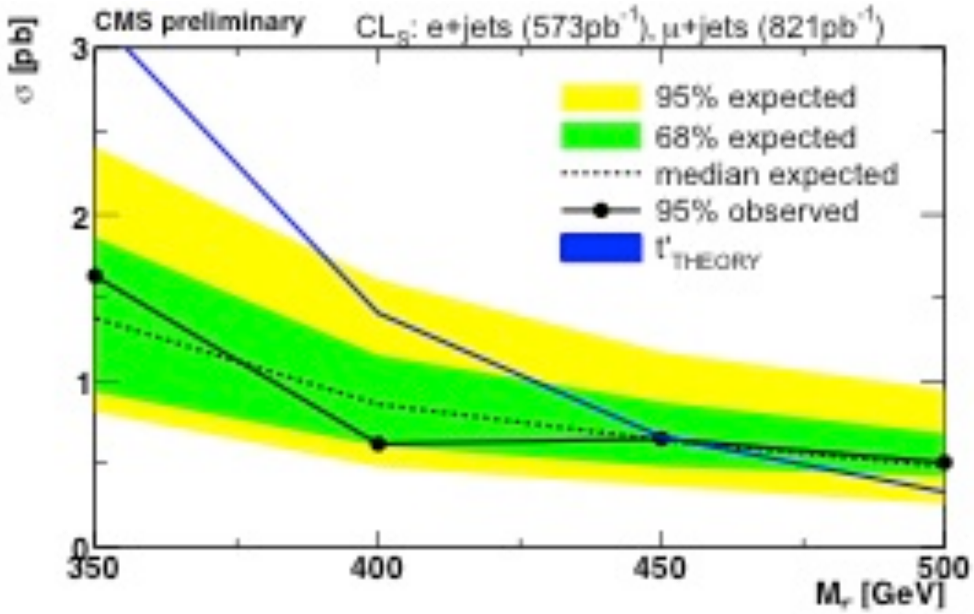
Search for t′t̄′ → bWbW → blνbqq

- In limit calculation, use two hypothesis
  - Background only hypothesis, minimize w.r.t nuisance parameters
  - Signal + background hypothesis, minimize w.r.t signal cross-section
  - Test statistics, $L = L_{s+b}/L_b$
- 95% CL upper limit for the signal cross section is the value of σ for which $C_{LS} = CL_{s+b}/CL_b = 0.05$

PAS EXO-11-051

Exclusion limits on $m_{t'}$ at 95% CL

	expectation	observed
μ+jets	< 435 GeV	< 420 GeV
e+jets	< 425 GeV	<430 GeV
combine		< 450 GeV

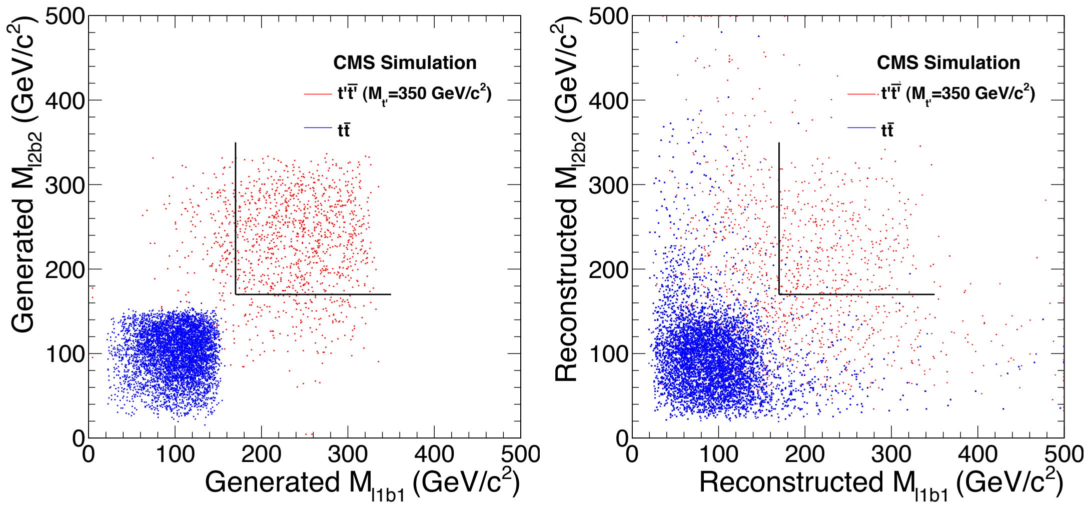


Search for $t'\bar{t}' \rightarrow bWbW \rightarrow bl\nu bl\nu$

- Motivation
  - $m_{t'} < m_{b'}$
  - $m_{t'} > m_{b'}$ with $m_{t'} - m_{b'} < m_W$ favored
- Selection
  - At least one good interaction vertex
  - $p_T(e, \mu)$>20GeV
  - Zveto: Event are removed if 76GeV < M_Z <106 GeV
  - N(jets)>= 2 with p_T> 30, $|\eta|$<2.5
  - 2 b-tag jets
  - E_T^{miss} > 30GeV

- Variables
  - Mass of one pair of leptons and jets:M_{l1b1} and mass of second pair of leptons and jets: M_{l2b2} from t/t' or $\bar{t}/\bar{t}'$ decay

PAS EXO-11-050

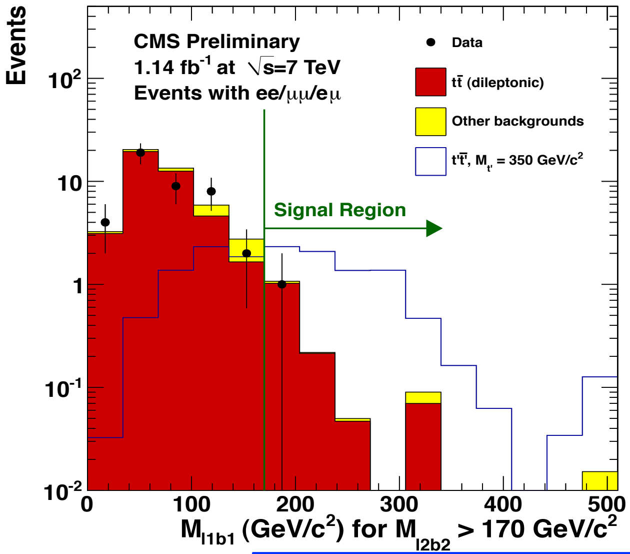


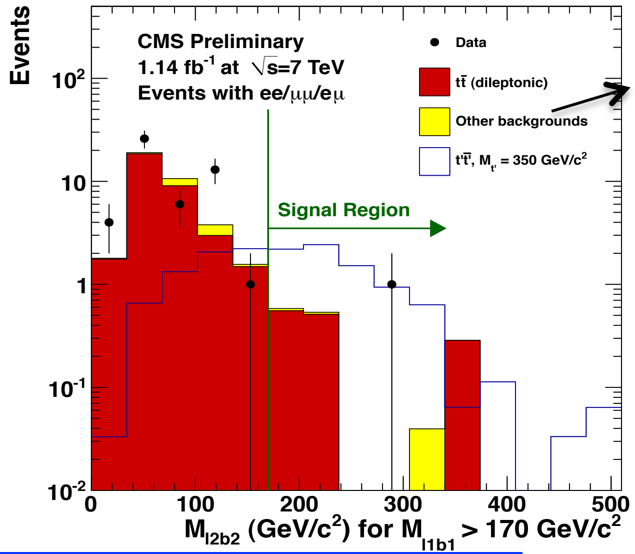
Signal Region = M_{l1b1}, M_{l1b1}> 170 GeV/c^2

Search for t′t̄′ → bWbW → blνblν

Sample	Yield	Prediction source
$t\bar{t} \to \ell^+\ell^-$	1.35 ± 0.67	Data
Fake leptons	$0.0^{+0.4}_{-0.0}$	Data
DY$\to e^+e^-$ or $\mu^+\mu^-$	$0.07^{+0.13}_{-0.07}$	Data
DY$\to \tau^+\tau^-$	0.11 ± 0.11	Simulation
Di-boson	0.02 ± 0.02	Simulation
Single top	0.07 ± 0.04	Simulation
Total prediction	$1.62^{+0.80}_{-0.70}$	
Data	1	

PAS EXO-11-050





Scaled to match estimation from the data control regions

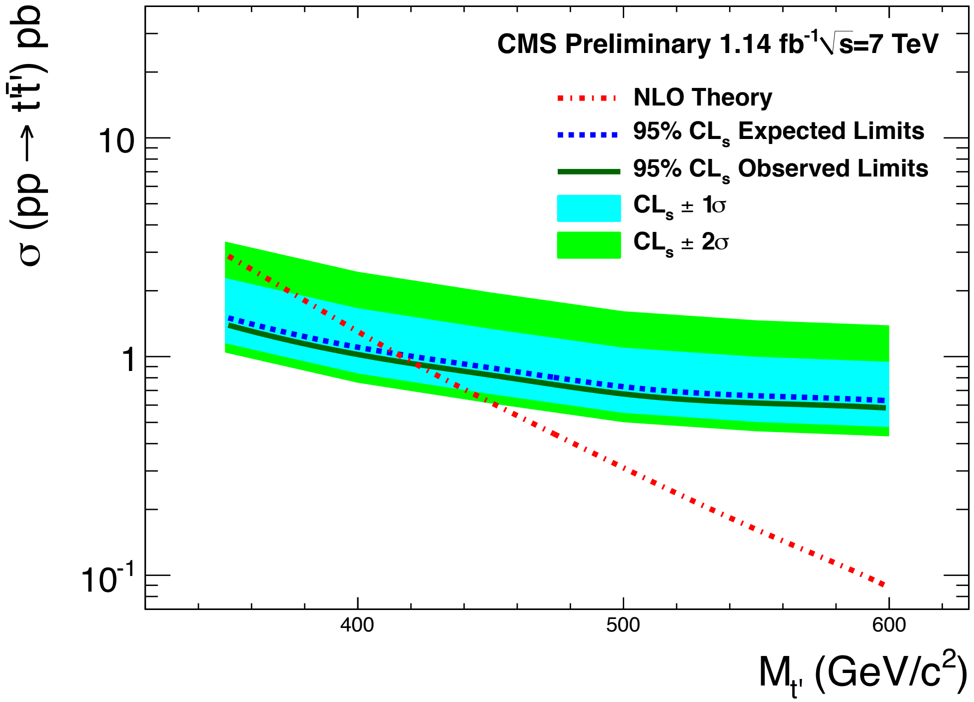
Only one event is observed in signal region

Search for t′t̄′ → bWbW → blνblν

[PAS EXO-11-050]

Exclusion limits on $m_{t'}$ at 95% CL

	expectation	observed
combine	< 425 GeV	< 422 GeV



$M_{t'}$	350 GeV/c^2	400 GeV/c^2	450 GeV/c^2	500 GeV/c^2	550 GeV/c^2	600 GeV/c^2
Theory (pb)	2.940	1.301	0.617	0.310	0.162	0.088
Expected (pb)	1.517	1.103	0.888	0.728	0.662	0.628
Observed (pb)	1.406	1.022	0.823	0.675	0.613	0.582

Summary

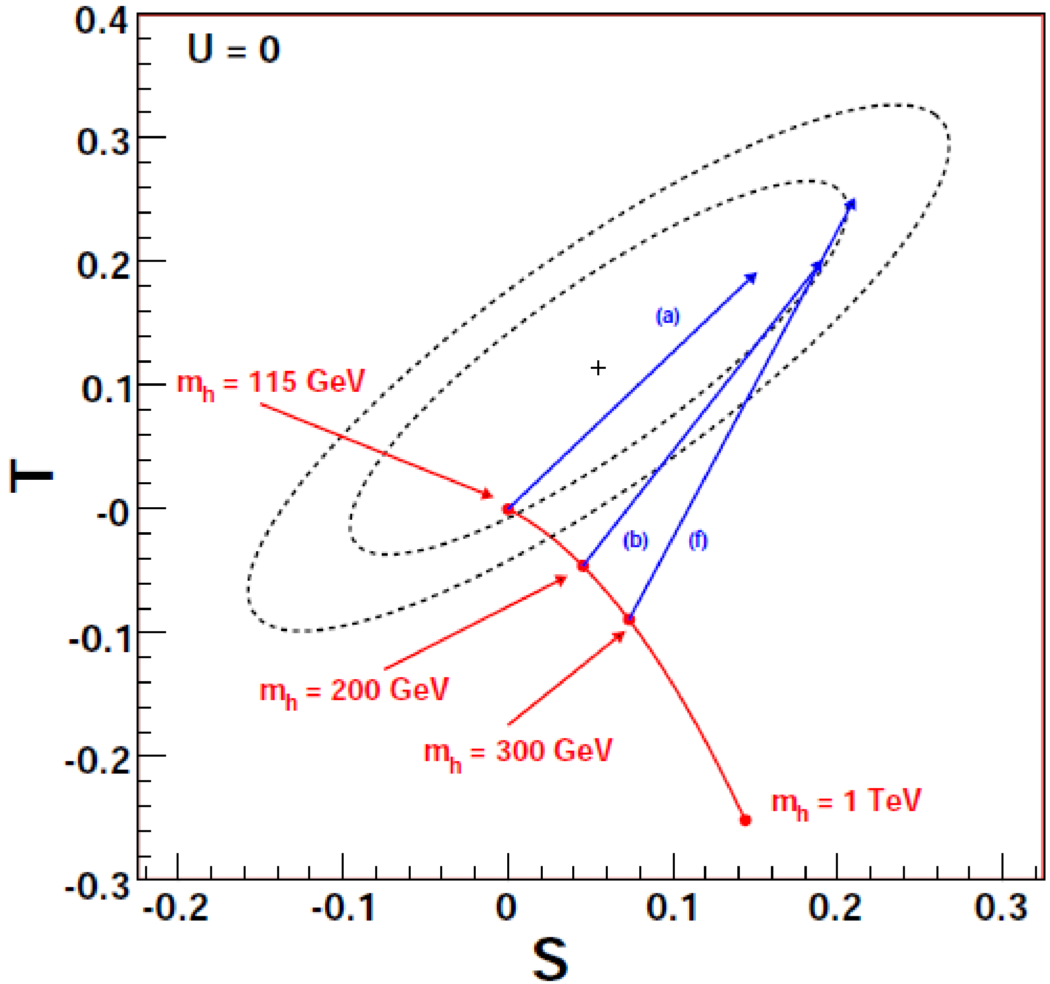
- Presented the results for the 4th Generation quark searches at CMS

Search	Excluded region@95%CL
$b'\bar{b}' \to tWtW \to bWWbWW$	$m_{b'} < 495$GeV
$T'T' \to tZtZ \to bbWWZZ$	$M_T < 417$GeV
$t'\bar{t}' \to bbWW$ (l+jets)	$m_{t'} < 450$GeV
$t'\bar{t}' \to bbWW$ (dilepton + jets)	$m_{t'} < 422$GeV

- Stay tuned!

Backup

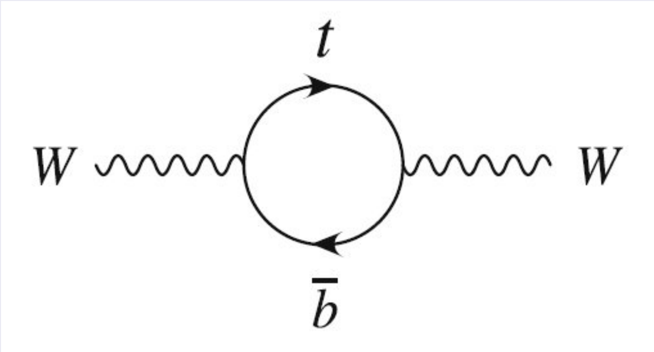
EWK Precision Fit

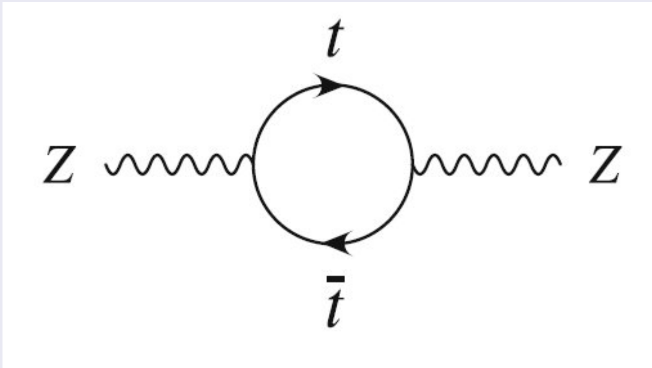


Graham D. Kribs, Tilman Plehn, Michael Spannowsky and Tim M. P. Tait
Four generations and Higgs physics Phys. Rev. D, 76(7):075016, Oct 2007

STU Formulism

- S: sensitive to chirally coupling fermion $\Longleftrightarrow$ $W^{\pm}, Z$ and H self energy diagrams
- T: sensitive to mass splitting $\Longleftrightarrow$ $W^{\pm}$ and H self energy diagrams



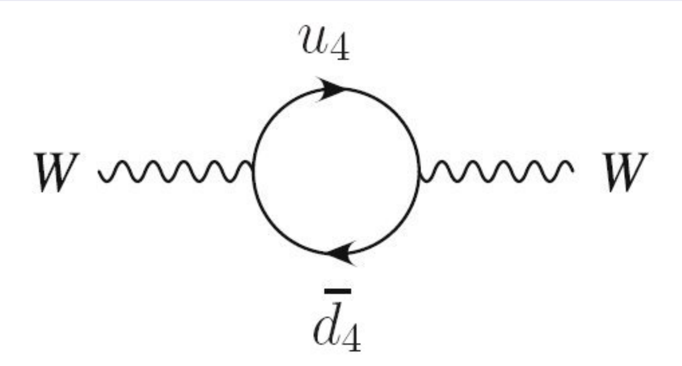


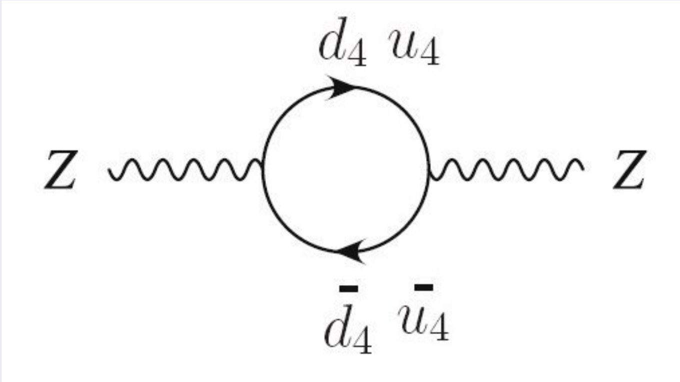
Rocco Mandrysch. PHENO2011

Mass splitting within a 4th Generation

Contributions to S and T:
(Kribs, Plehn, Spannowsky & Tait, Phys.Rev.D76, 075016, 2007)

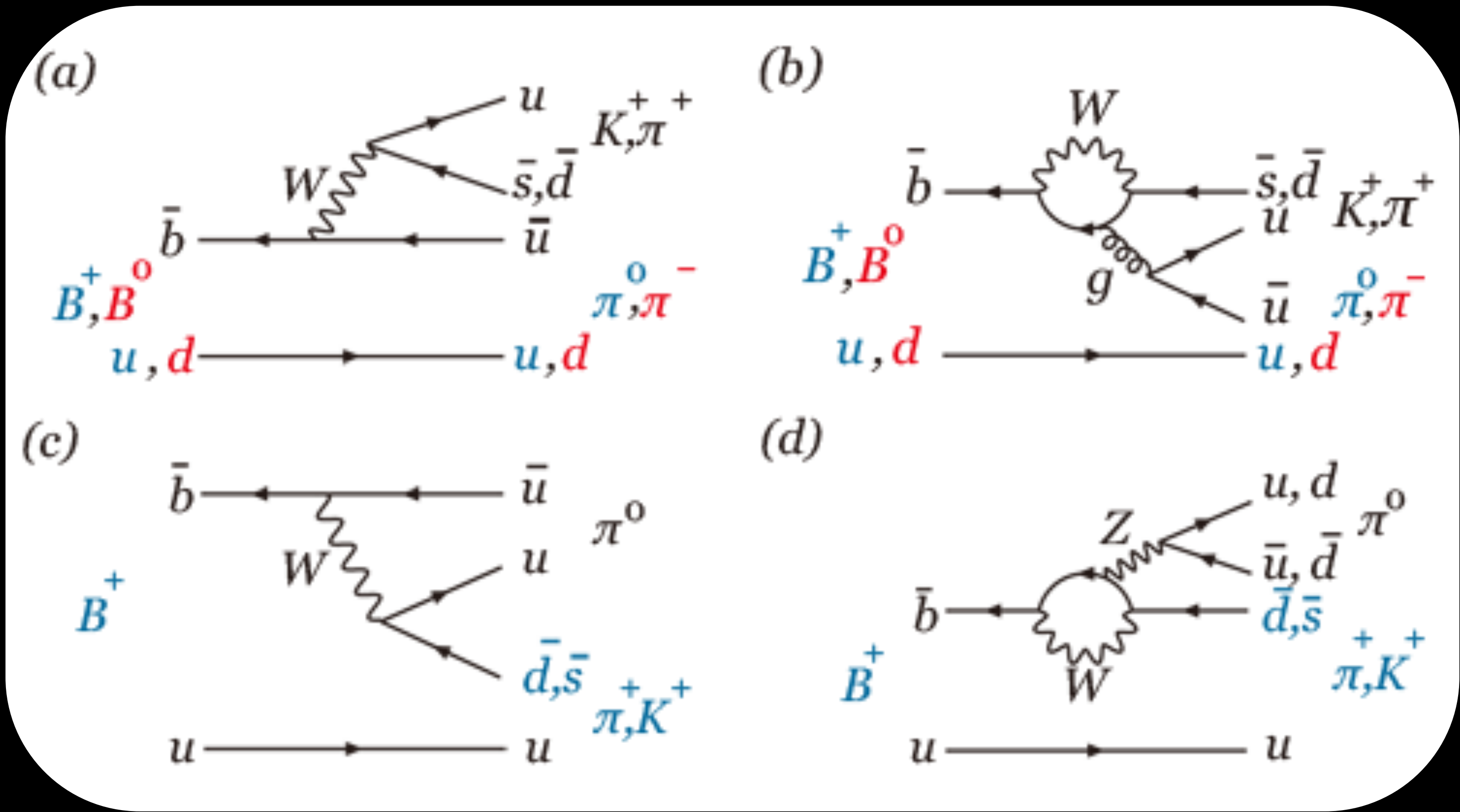
- Additional one loop diagram with 4th gen. particles



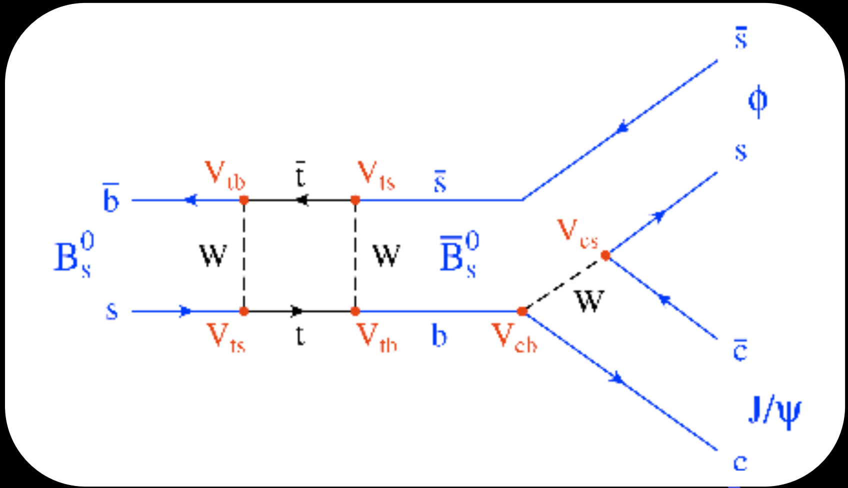


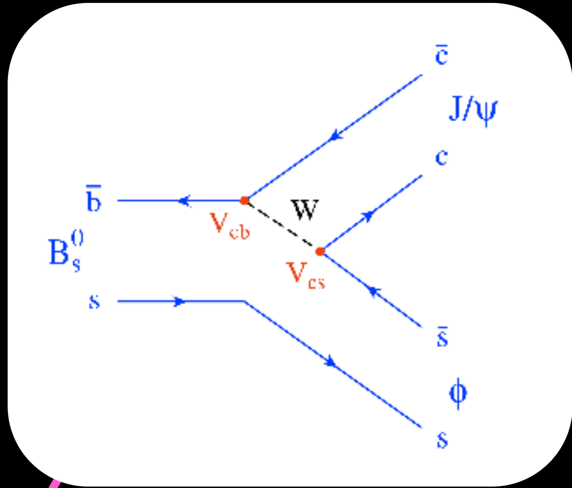
- $\Delta S \propto \left(1 + \ln \frac{m^2_{\ell_4}}{m^2_{\nu_4}}\right) + N_C \left(1 - \frac{1}{3} \ln \frac{m^2_{u_4}}{m^2_{d_4}}\right)$
- $\Delta T \propto \left(N_C |m^2_{u_4} - m^2_{d_4}|^2 + |m^2_{\ell_4} - m^2_{\nu_4}|^2\right)$
- N_C: color factor

$B^0 \rightarrow K^+\pi^-$ vs $B^+ \rightarrow K^+\pi^0$



$B^0_s \rightarrow J/\psi\phi$ - *the golden probe*





Mixing phase sensitive to NP

Tree $b \rightarrow c\bar{c}\bar{s}$ phase ≈ 0

Time-evolution: $2\beta_s = -\arg[(V_{tb}V^*_{ts})^2/(V_{cb}V^*_{cs})^2]$

CKM hierarchy predicts 2βs tiny with ~zero theory error.
Any significant deviation is golden probe for new physics entering the box.

Baryogenesis with 3 Generations

- The CPV needed to drive baryogenesis cannot be provided by the SM3, since masses of the first two generations are small
- In quark sector, CPV is contained in the mass matrices

$$L_q = -M_{ij}^{d}\bar{d}_{Li}d_{Rj} - M_{ij}^{u}\bar{u}_{Li}u_{Rj} + h.c.$$

$$M = \frac{<v>}{\sqrt{2}}\lambda$$

- With 3 generations, a unique CP odd invariant can be constructed from these matrices and is invariant under field redefinitions (Jarlskog 1987):

$$J = \mathrm{Im}\det[M_u M_u^{\dagger} M_d M_d^{\dagger}]$$

$$= 2(m_t^2 - m_u^2)(m_t^2 - m_c^2)(m_c^2 - m_u^2)(m_b^2 - m_d^2)(m_b^2 - m_s^2)(m_s^2 - m_d^2)A$$

Area of unitarity triangle

- Numerically, this quantity is very small:

$$\frac{J}{<v>^{12}} \sim 10^{-20}$$

- SM3 falls short of the needed level of baryogenesis by at least 10 orders of magnitude.