
Searches for New Physics in Topologies Containing Beyond-Two-Generations Quarks at CMS

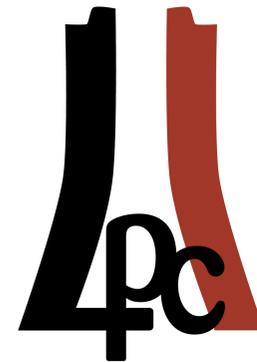
Freya Blekman



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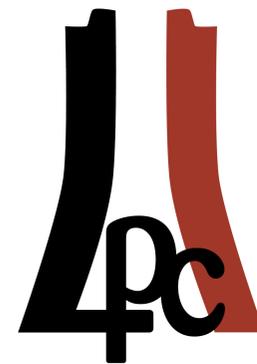
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Searches for Exotic New Physics
in
top-quark (like) final states
at CMS

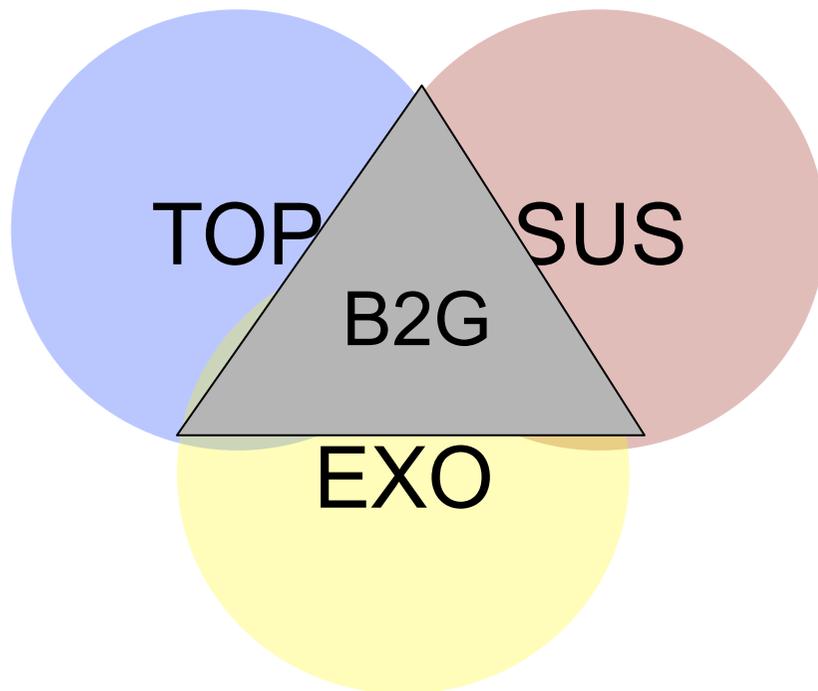
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Beyond two Generations group

CMS:



ATLAS:

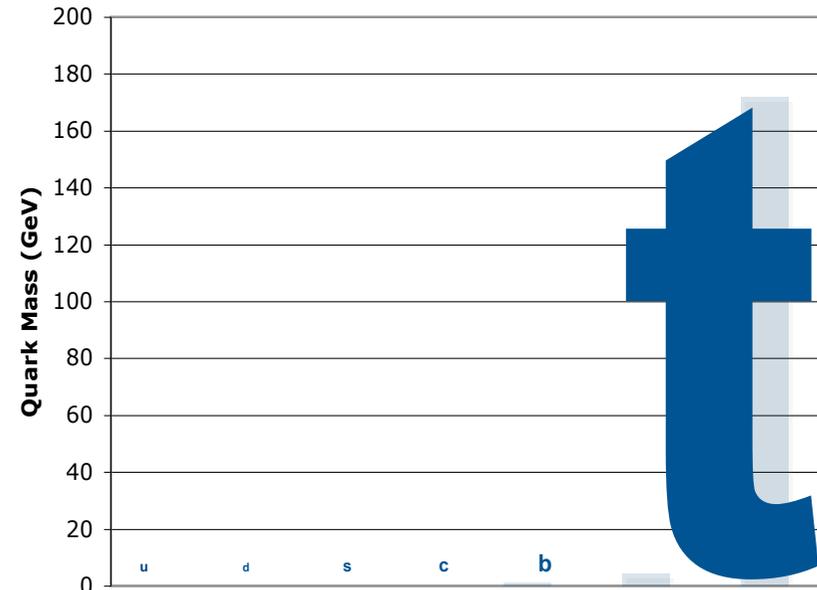
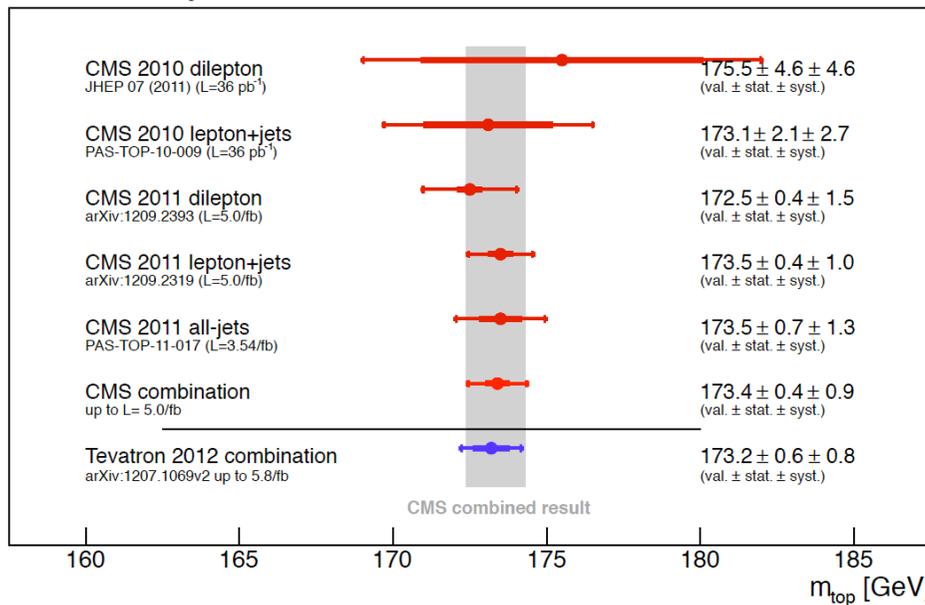


- Gives interesting insight in how collaborations work in practice
- ATLAS has found different solution to same problem

The top quark

- First evidence 1994, CDF
- Discovery by D0 and CDF in 1995
- Heaviest known fundamental particle, $m_t \approx 173 \text{ GeV}/c^2$
- Lifetime $\sim 5 \times 10^{-25} \text{ s} \rightarrow$ no hadronization before decay

CMS Preliminary



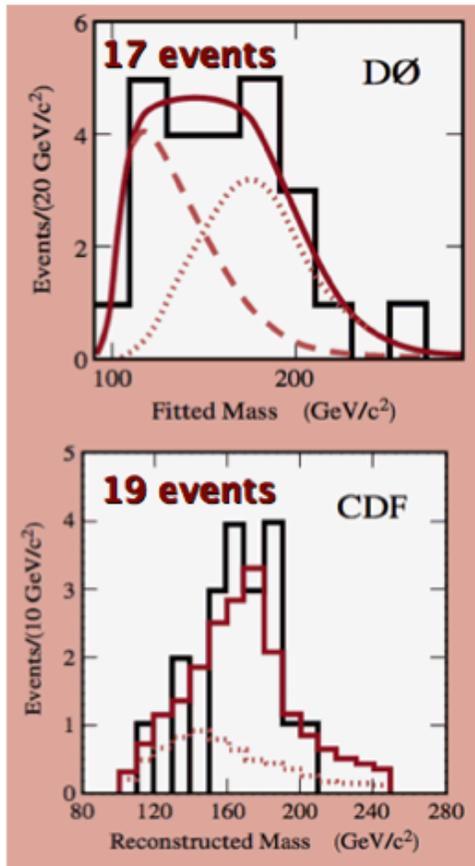
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History of the top quark

discovery

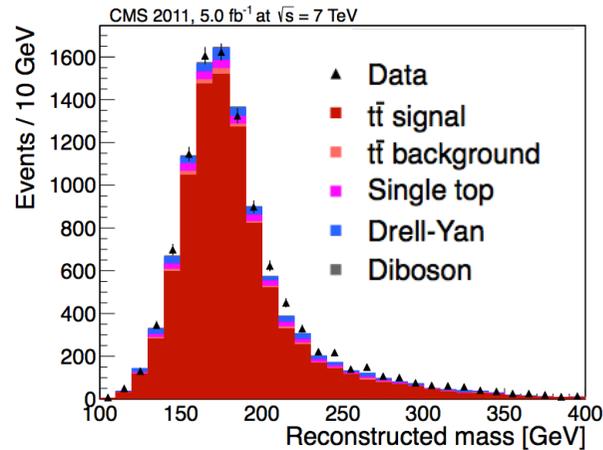
PRL 74, 2632 (1995)
PRL 74, 2626 (1995)



1995, CDF and DØ experiments, Fermilab

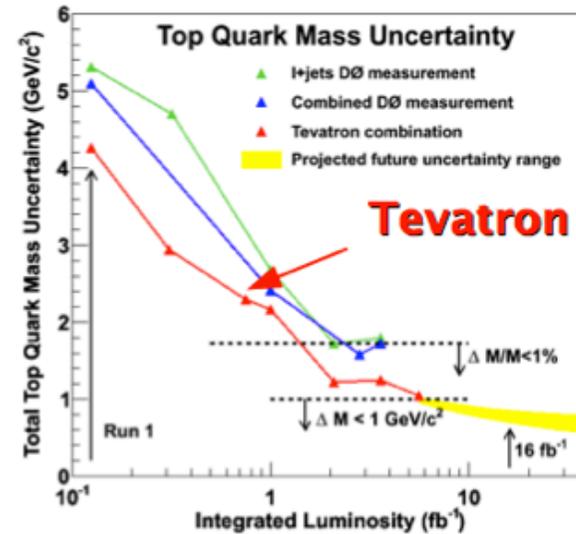
today

10000s of events



**LHC:
top quark
factory**

precision



searches



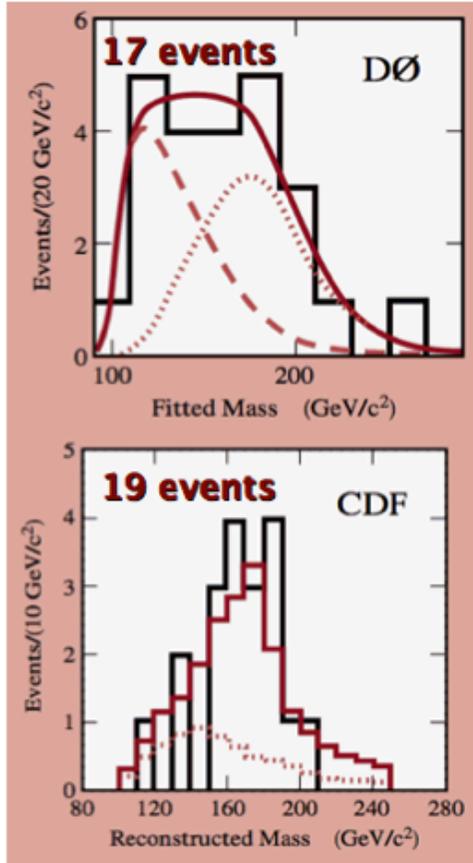
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History of the top quark

discovery

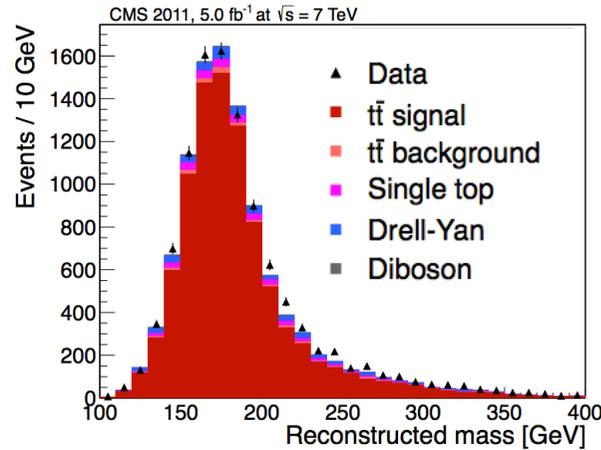
PRL 74, 2632 (1995)
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1995, CDF and DØ experiments, Fermilab

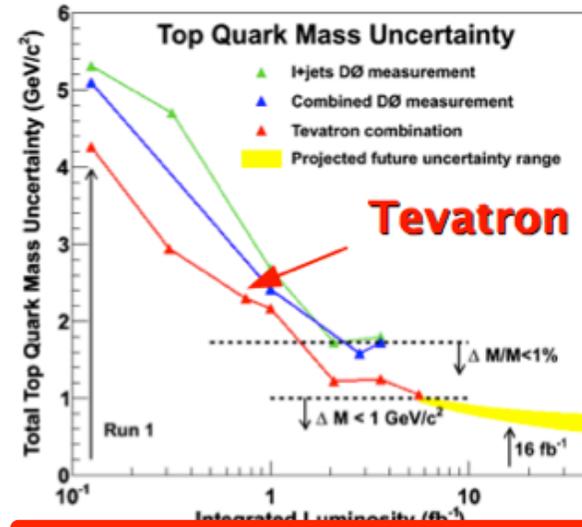
today

10000s of events



LHC: top quark factory

precision



searches

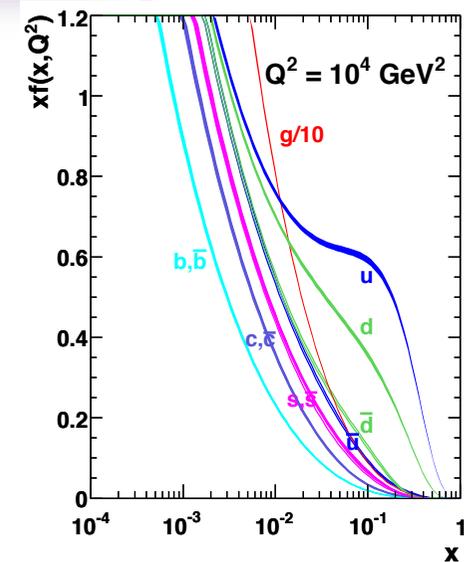
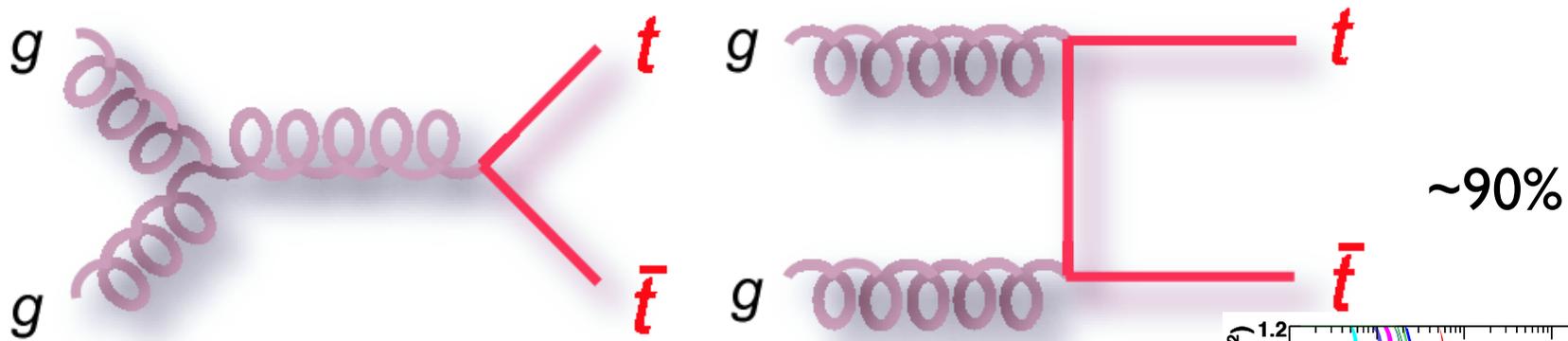


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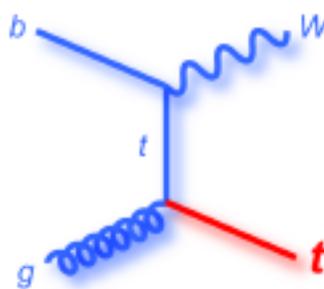
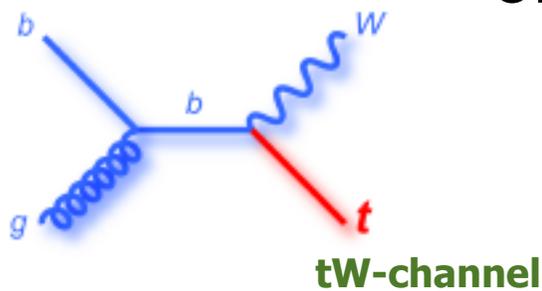
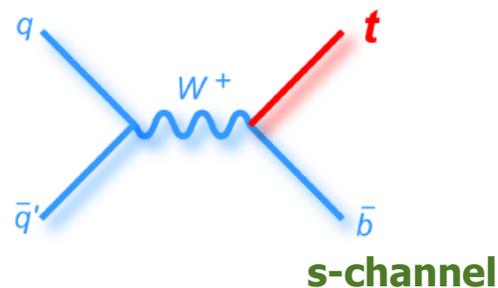
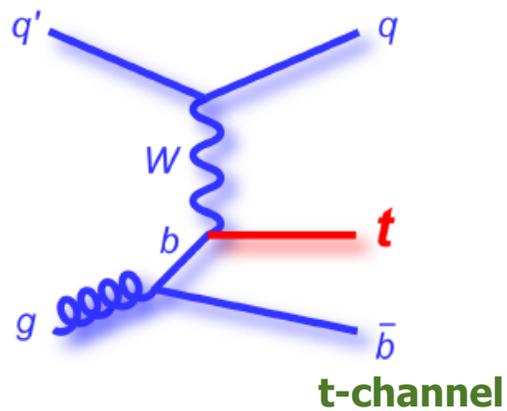
Top pair production at the LHC

- Pair production in 8 TeV pp collisions:



MSTW08: Eur.Phys.J.C63:189-285

Single Top production

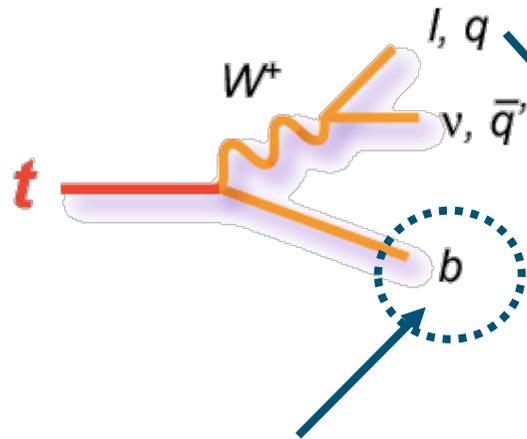


- Electroweak production of top quarks

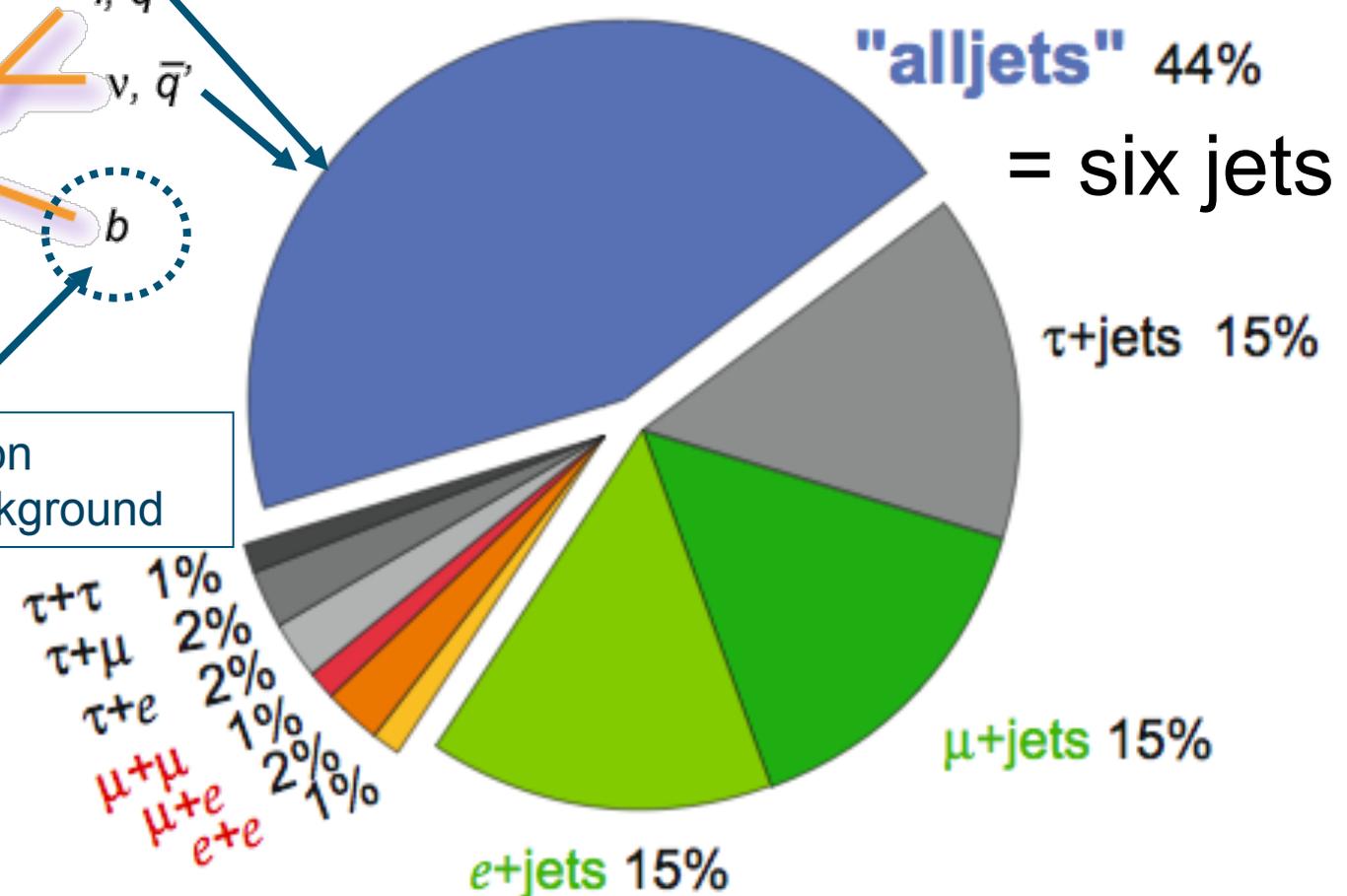
- Dominant channels at LHC @ 8 TeV:

- t-channel: 87 pb
- tW channel: 22 pb
- s-channel: 5.6 pb

Top pair branching fractions



B-quark identification
used to reduce background



"dileptons"

= two jets, two leptons, MET

"lepton+jets"

= four jets, lepton, MET



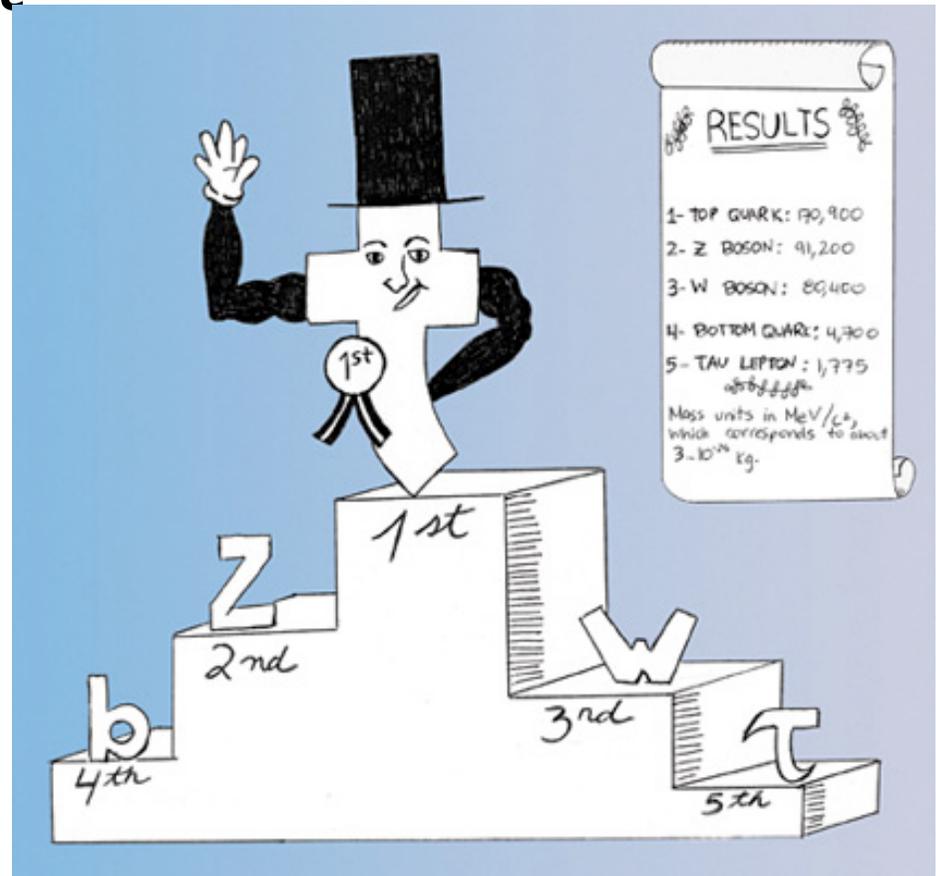
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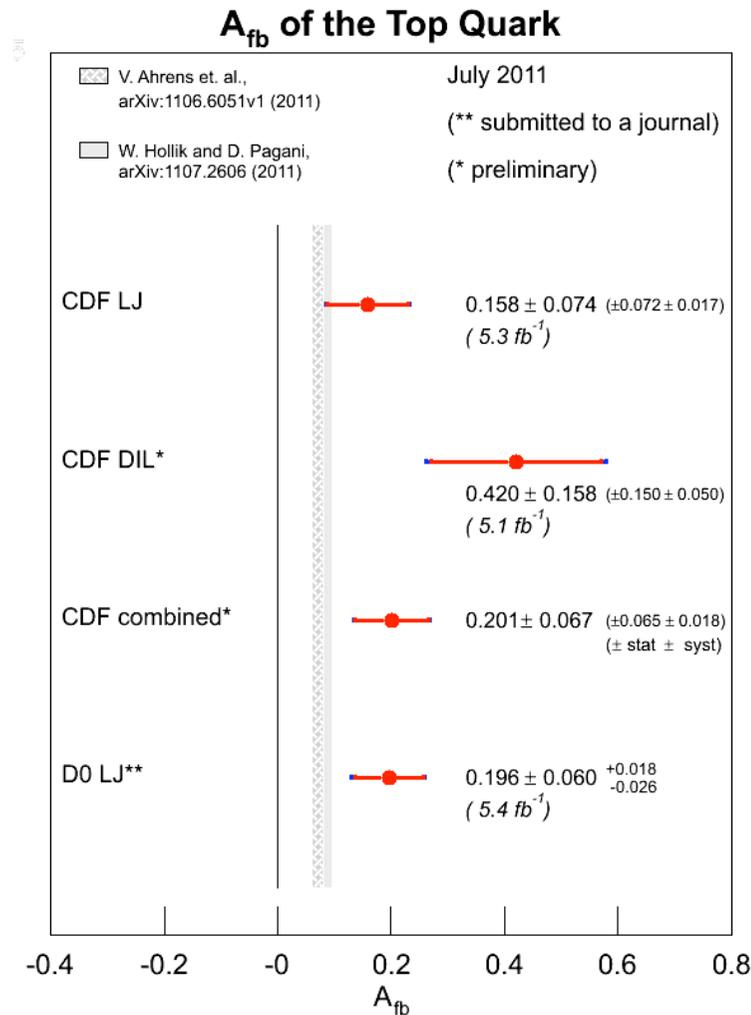
April 19, 2013

Top quark – special?

- Many models predict that top is special in order to explain large mass
- Or top quark has special role because of its large mass



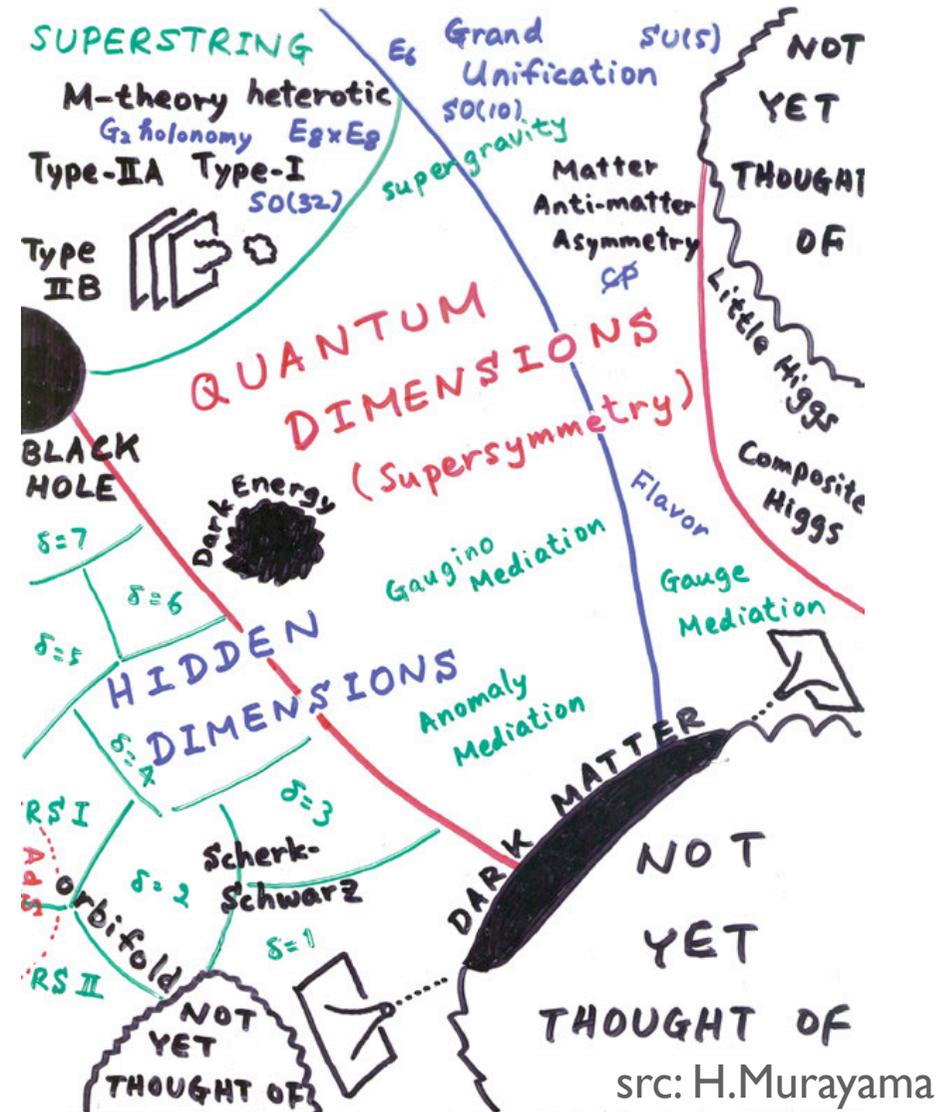
A_{FB} – portal to new physics?



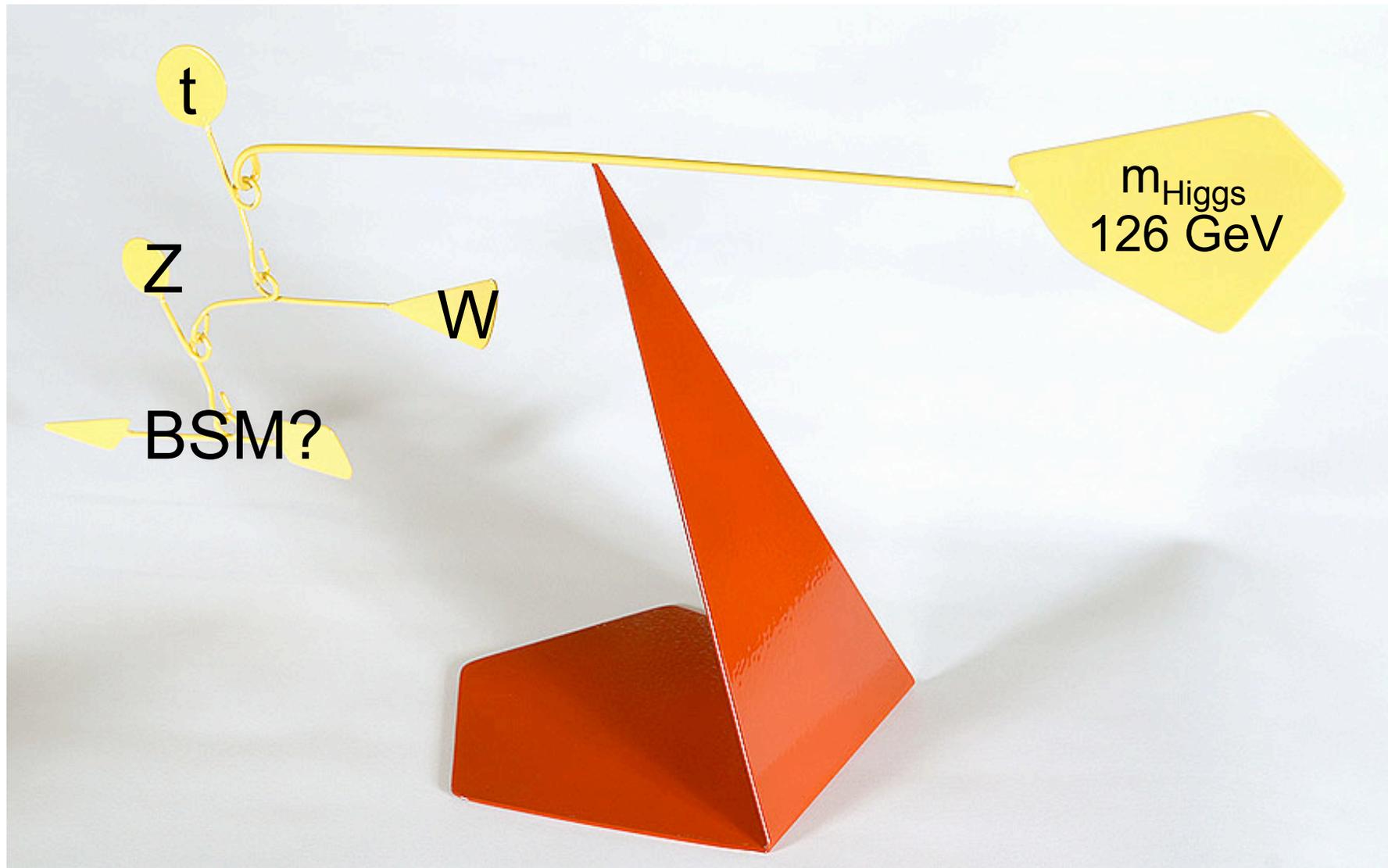
- CDF and D0 measure values not consistent with Standard Model
- In multiple decay channels and across multiple experiments
 - Compelling to explain as new physics

17 SM parameters do not constrain creativity

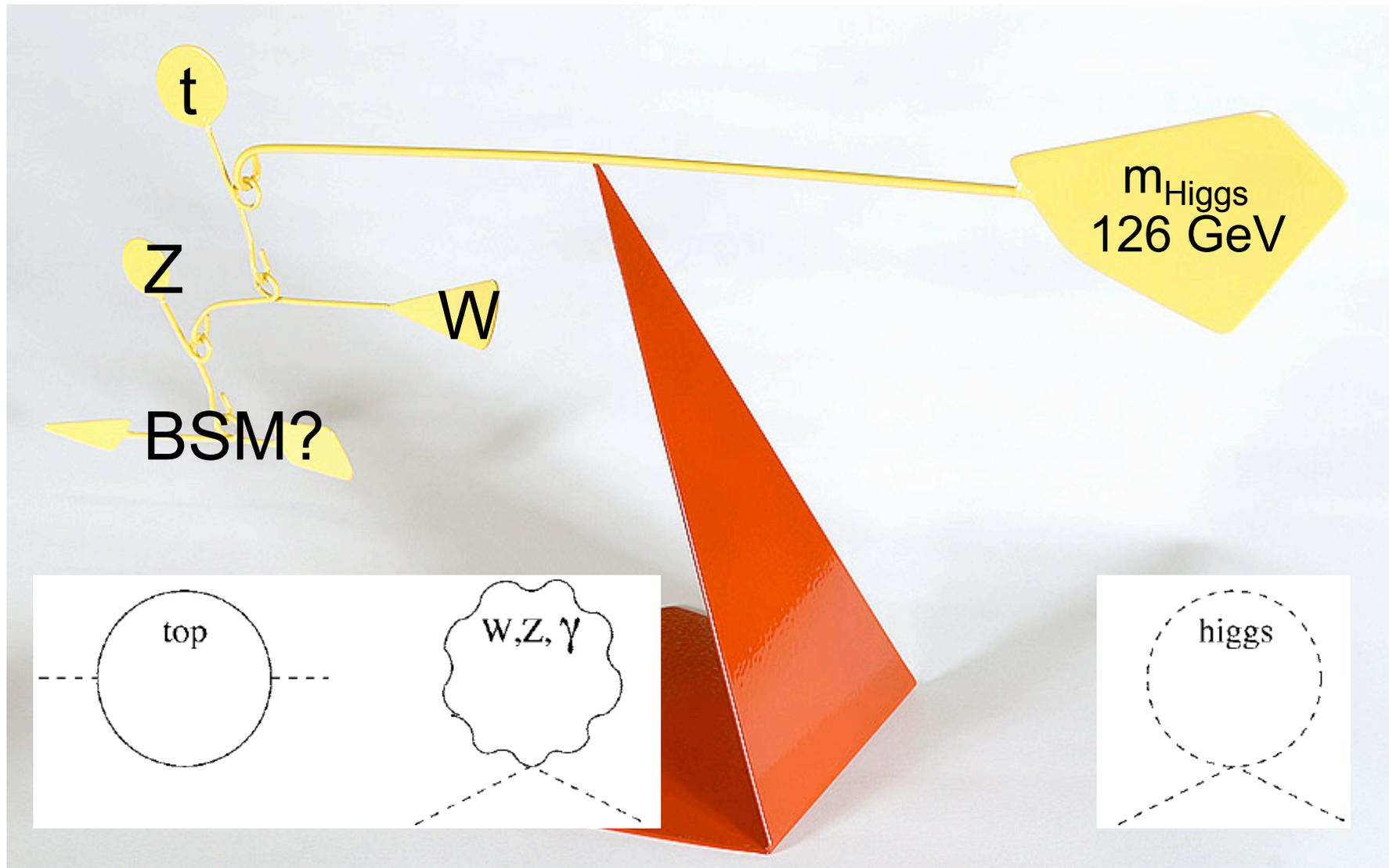
- SUSY in all its variations
 - GMSB
 - MSSM, CMSSM etc
- New strong interactions?
 - Technicolor; excited quarks; compositeness; new “contact” interactions
- Exotica:
 - Weird stuff: leptoquarks?
 - New “forces”?
 - New resonances (W-Z-like)
 - More generations?
 - Fourth generation (b'/t')
 - Gravity descending at the TeV scale?
 - New resonances; missing stuff; black holes; SUSY-like signatures [Universal Extra dimensions]
- SUSY-inspired exotica:
 - Long-lived massive (new) particles?
- Some true inspirations: “hidden valleys”?



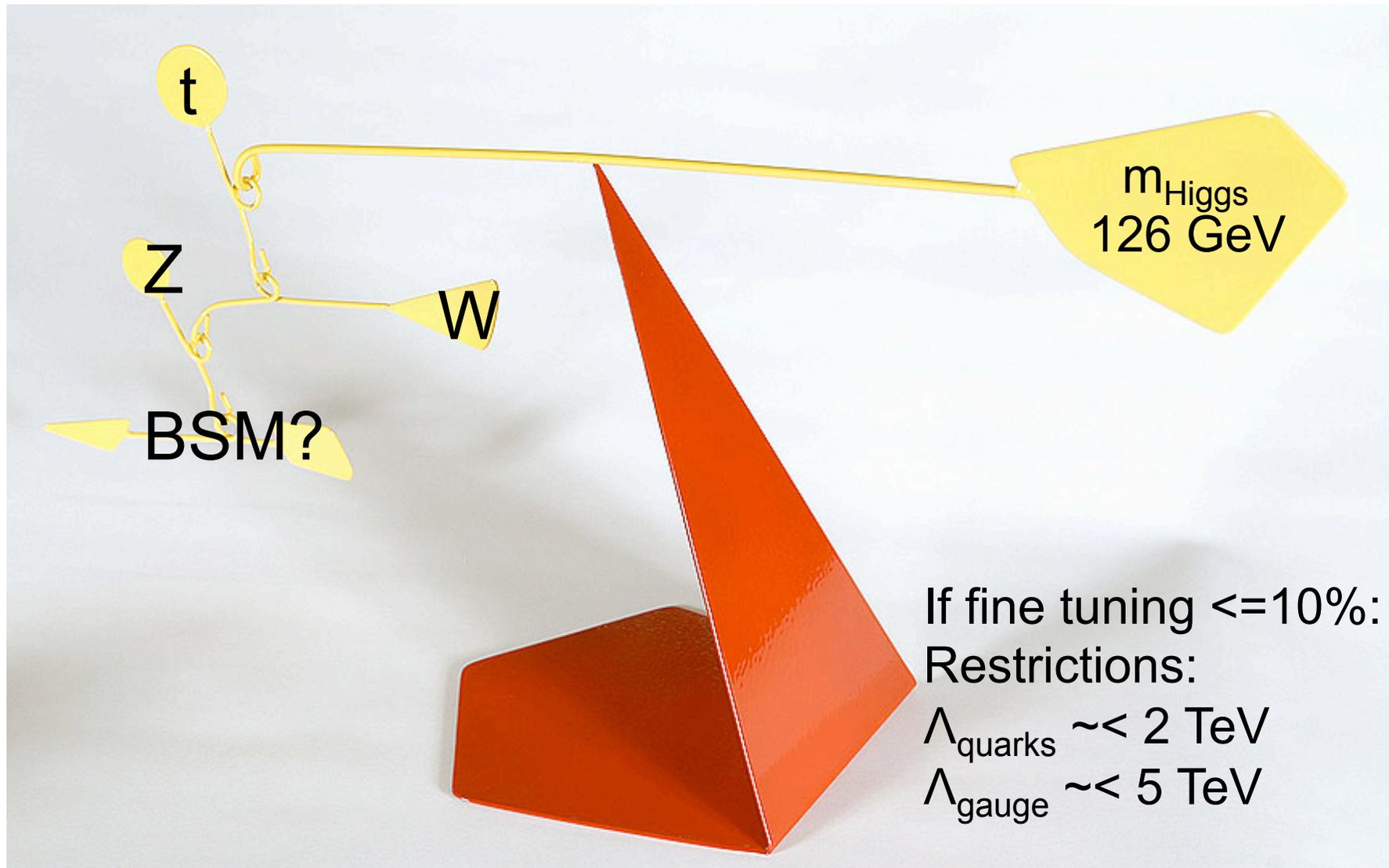
Little Hierarchy problem, Naturalness



Little Hierarchy problem, Naturalness



Little Hierarchy problem, Naturalness



LHC: search engine



“Physics beyond the standard model” -MSSM

Google Search

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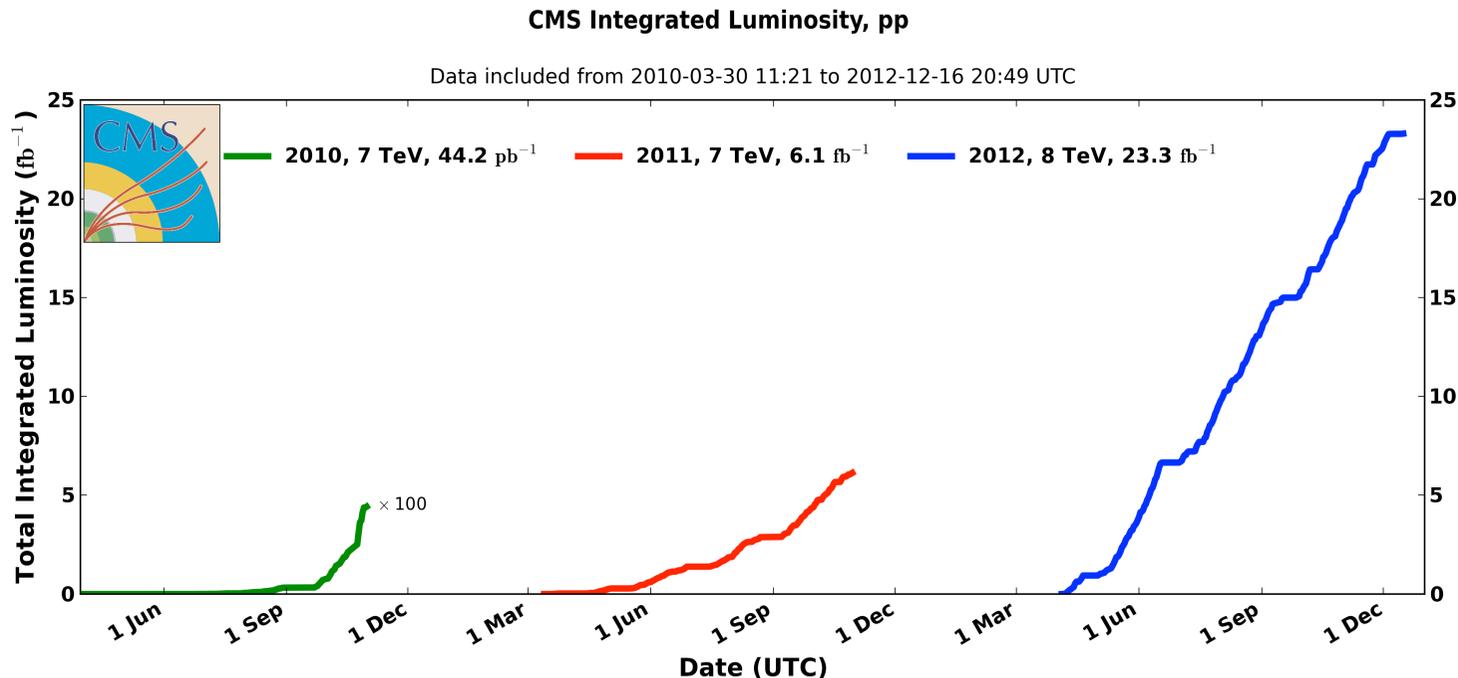


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Freya Blekman, Vrije Universiteit Brussel (Belgium) - BND school, Bonn, Germany

LHC performance



- The LHC and CMS: outstanding performance during LHC Run I
- Detector performance



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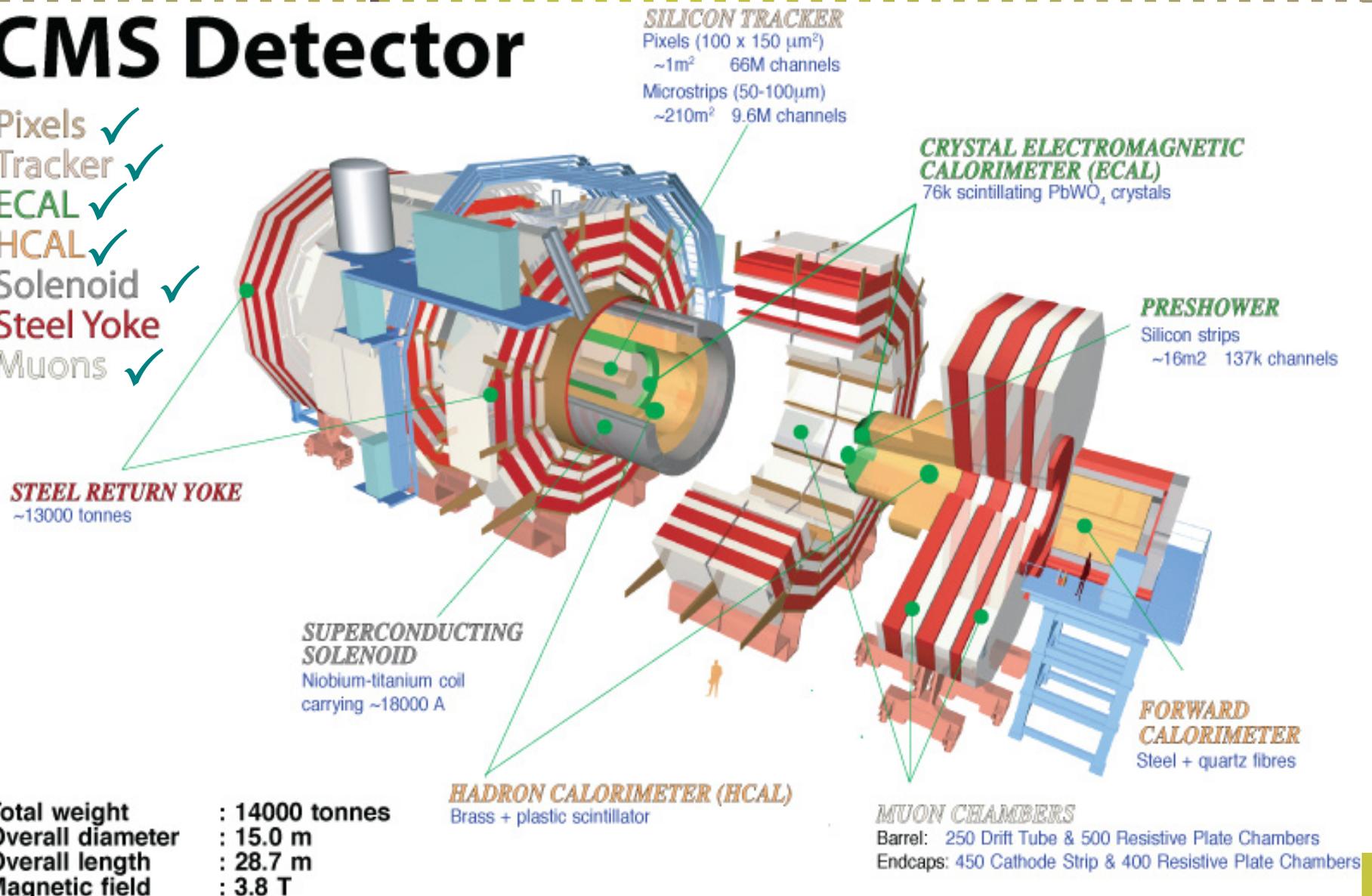


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Compact Muon Solenoid

CMS Detector

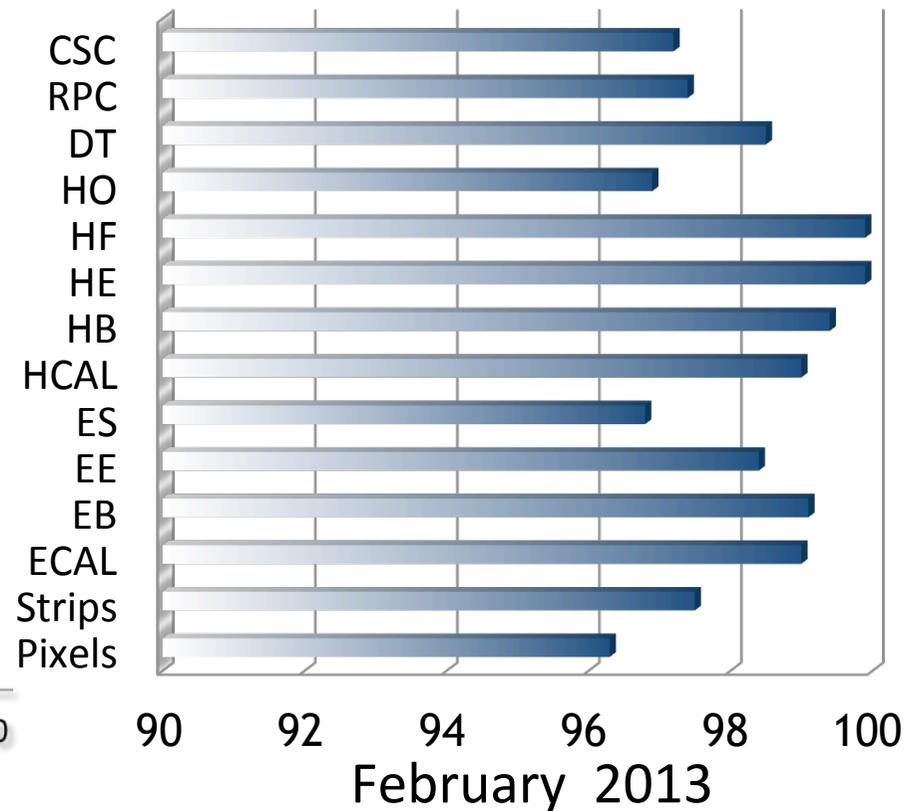
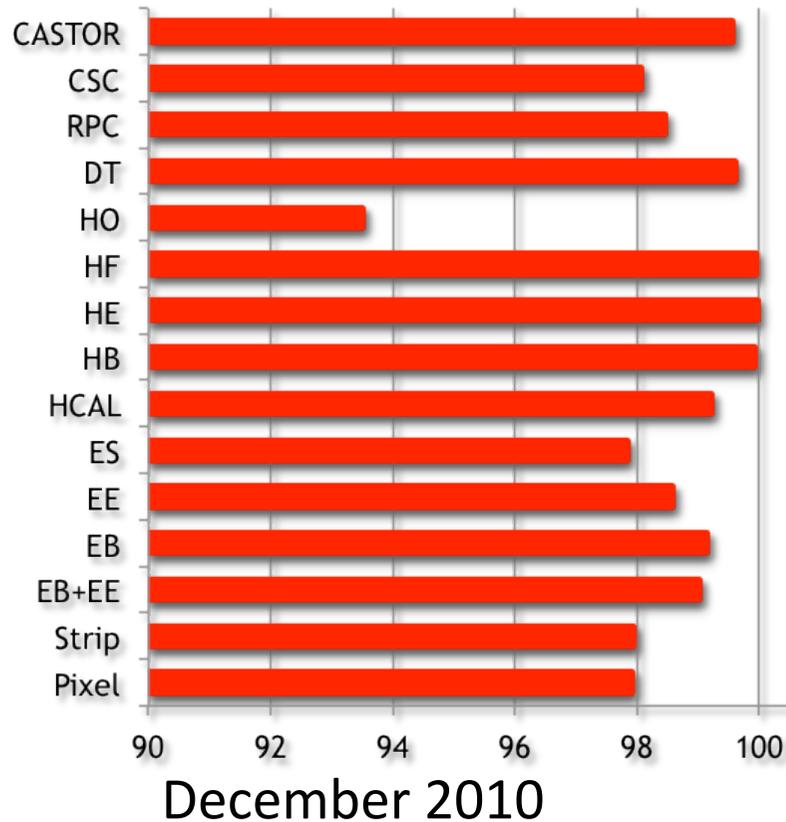
- Pixels ✓
- Tracker ✓
- ECAL ✓
- HCAL ✓
- Solenoid ✓
- Steel Yoke ✓
- Muons ✓



Total weight : 14000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T



CMS detector performance



CMS Subsystem	CSC	RPC	DT	HCAL Outer	HCAL forw.	HCAL end.	HCAL barrel	HCAL	Presho wer	ECAL end.	ECAL barrel	ECAL	Strips	Pixels
% operational Feb 2013	97.2	97.4	98.5	96.9	99.9	99.9	99.4	99	96.8	98.4	99.1	99	97.5	96.3

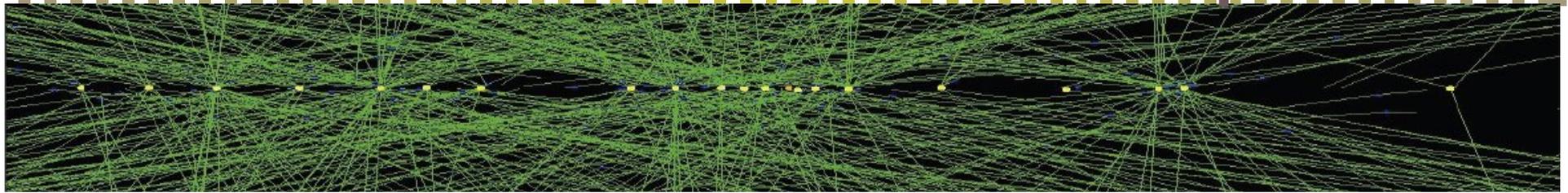


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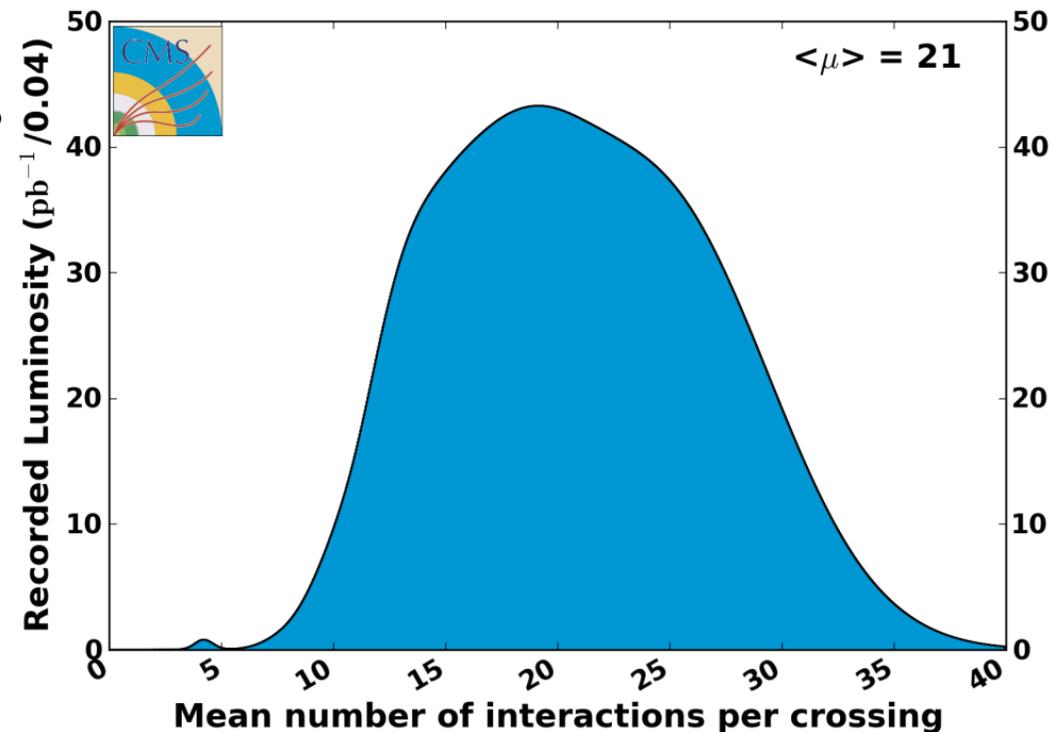
April 19, 2013

LHC 2012 run: Pile-Up

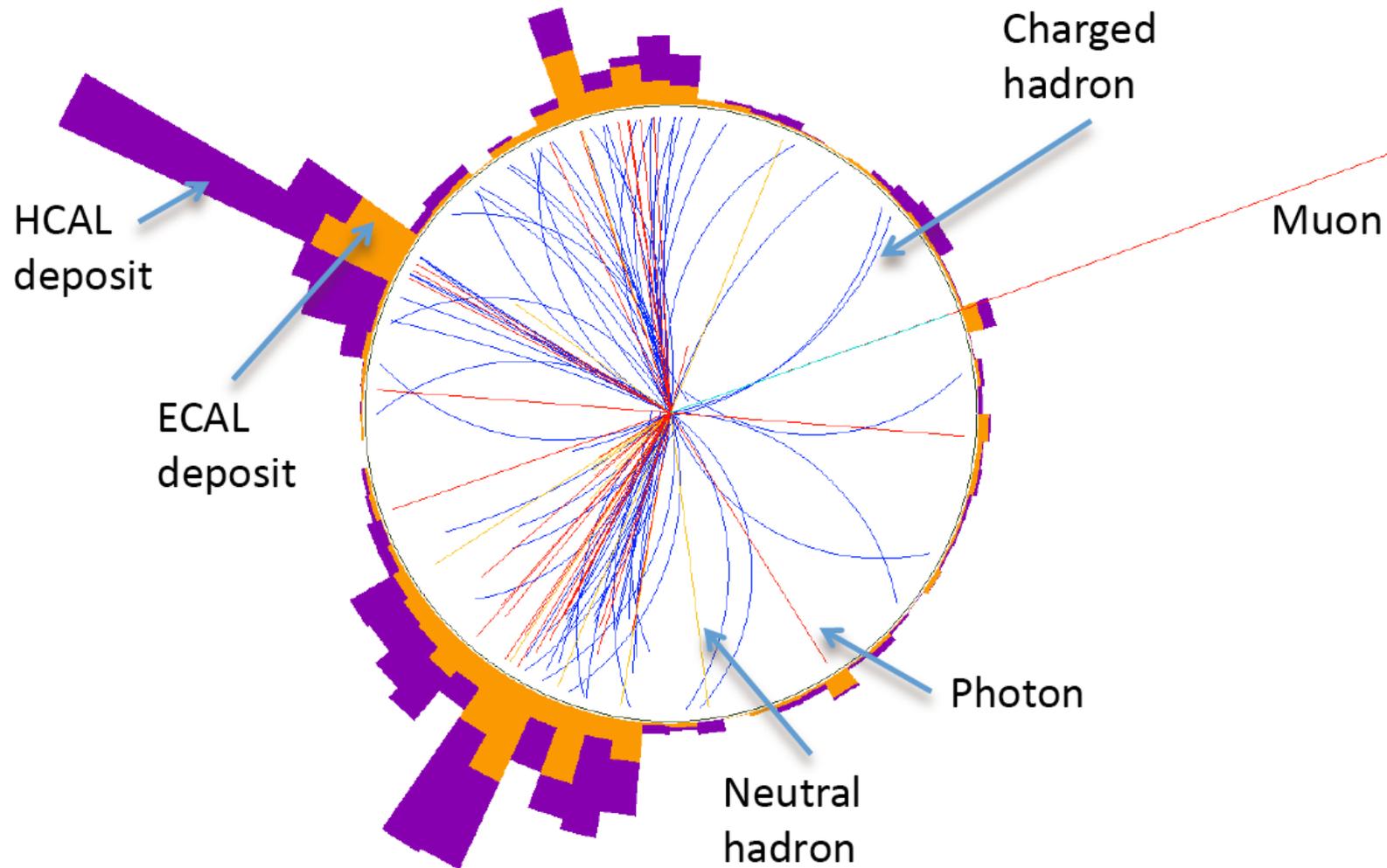


- Outstanding LHC performance comes at a price:
- 2011:
 - Run A: 5 PU
 - Run B: 8 PU
- 2012:
 - Average: 21 PU

CMS Average Pileup, pp, 2012, $\sqrt{s} = 8$ TeV

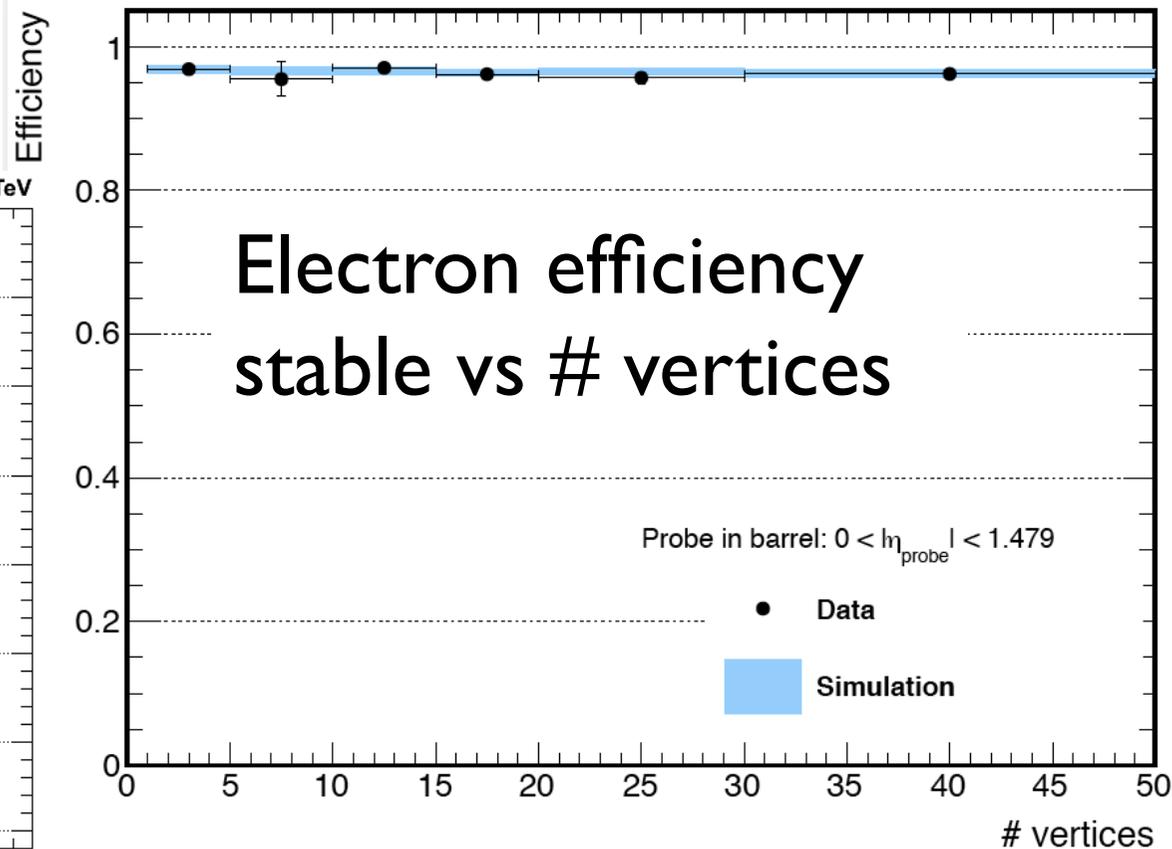
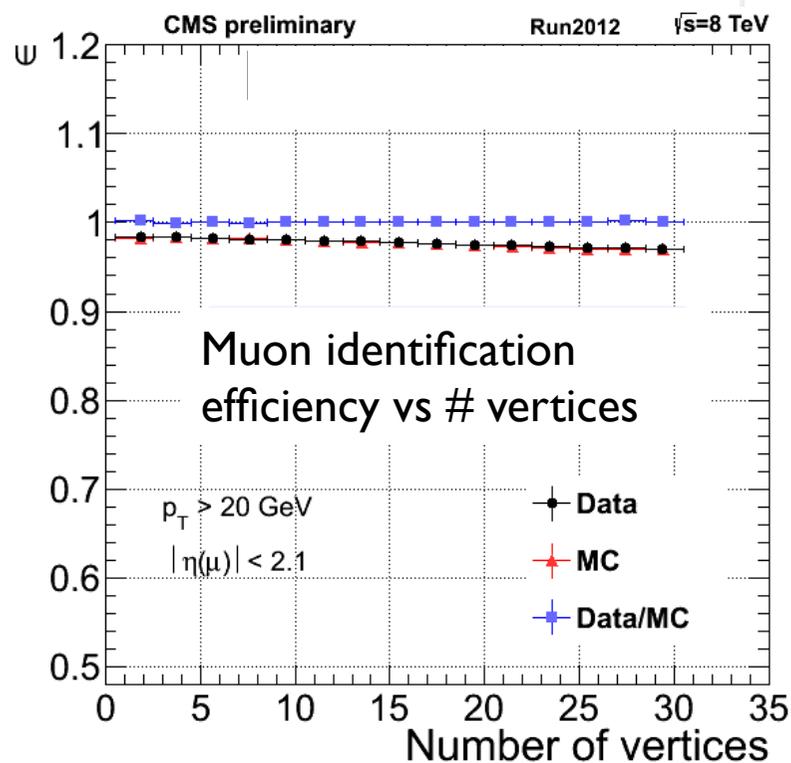


Particle flow



leptons

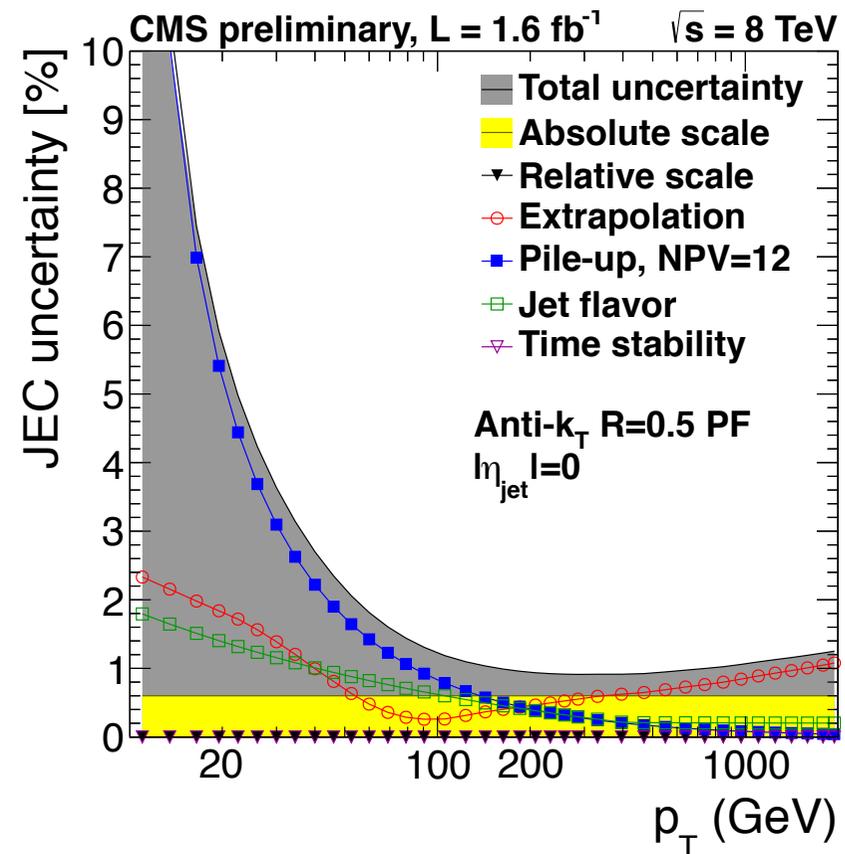
CMS Preliminary 2012 $\sqrt{s} = 8 \text{ TeV}$, $L = 19.6 \text{ fb}^{-1}$



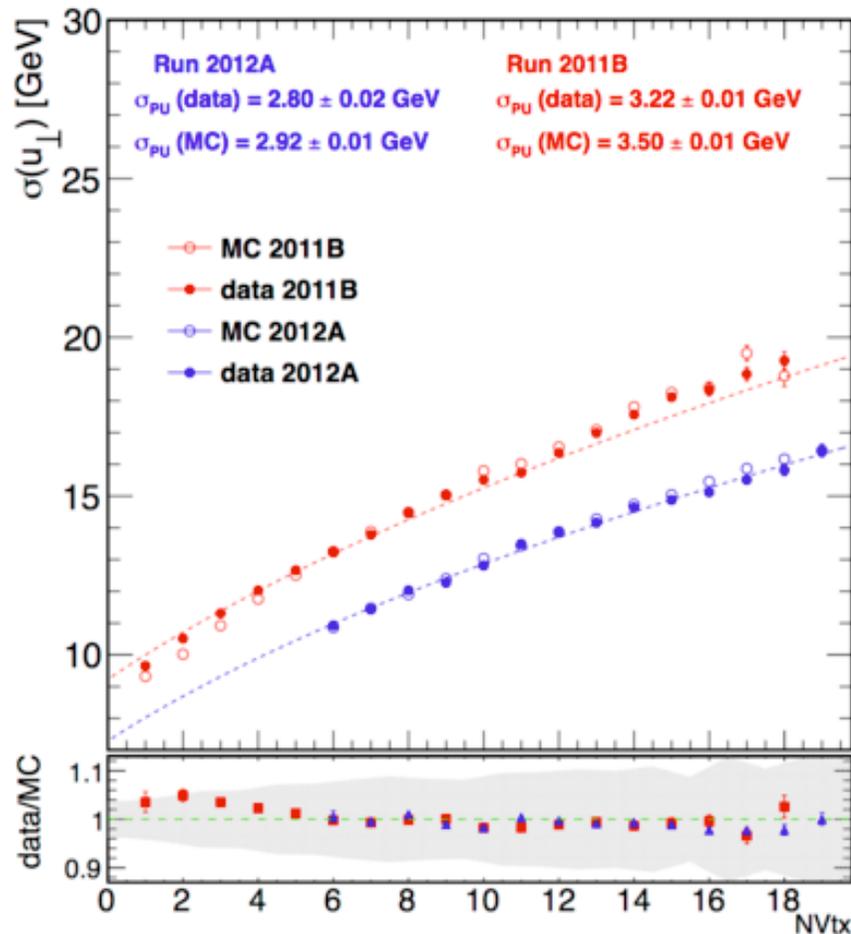
- Substantial effort necessary to achieve this stability

Jets

- For most analyses, CMS uses anti- k_T jets with a distance parameter of 0.5
- Particle flow algorithm allows very good agreement between data and MC with small jet energy scale uncertainties

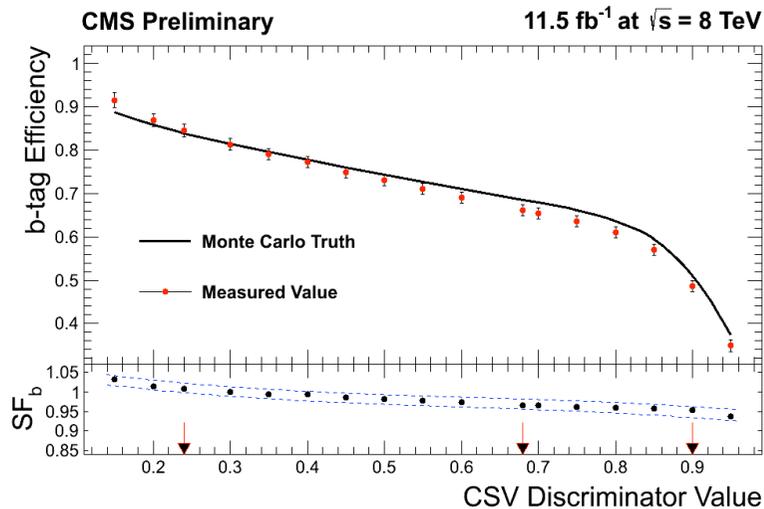
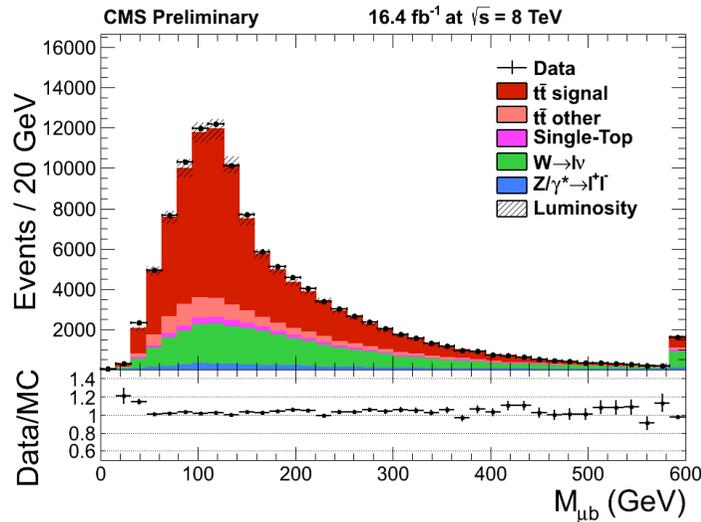


Missing ET



- Particle flow extremely powerful approach for missing ET reconstruction
- Missing ET sensitivity to PU irreducible
 - But well reproduced in MC

Jets with b-tagging



- Long lifetime of b-hadrons in b-jets

- $\tau = 1.512 \times 10^{-12}$ s

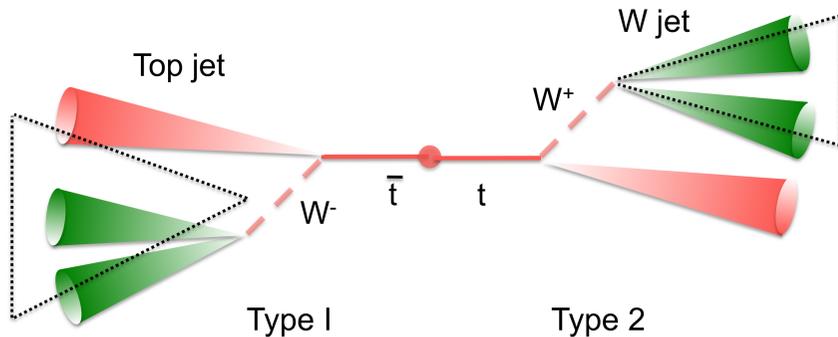
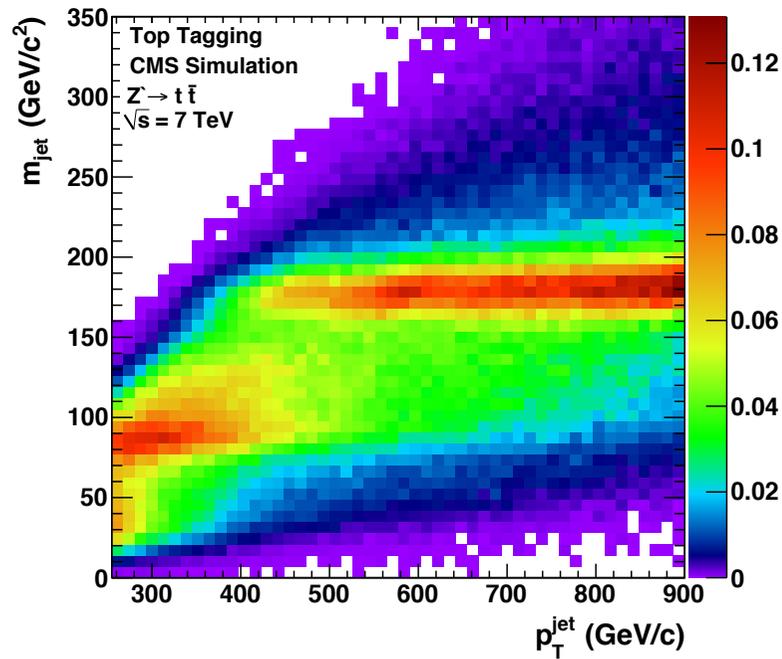
- $c\tau = 455.4$ μm

- Combination of lifetime information in MVA

- Efficiency measured in top and QCD events (data) using multiple methods

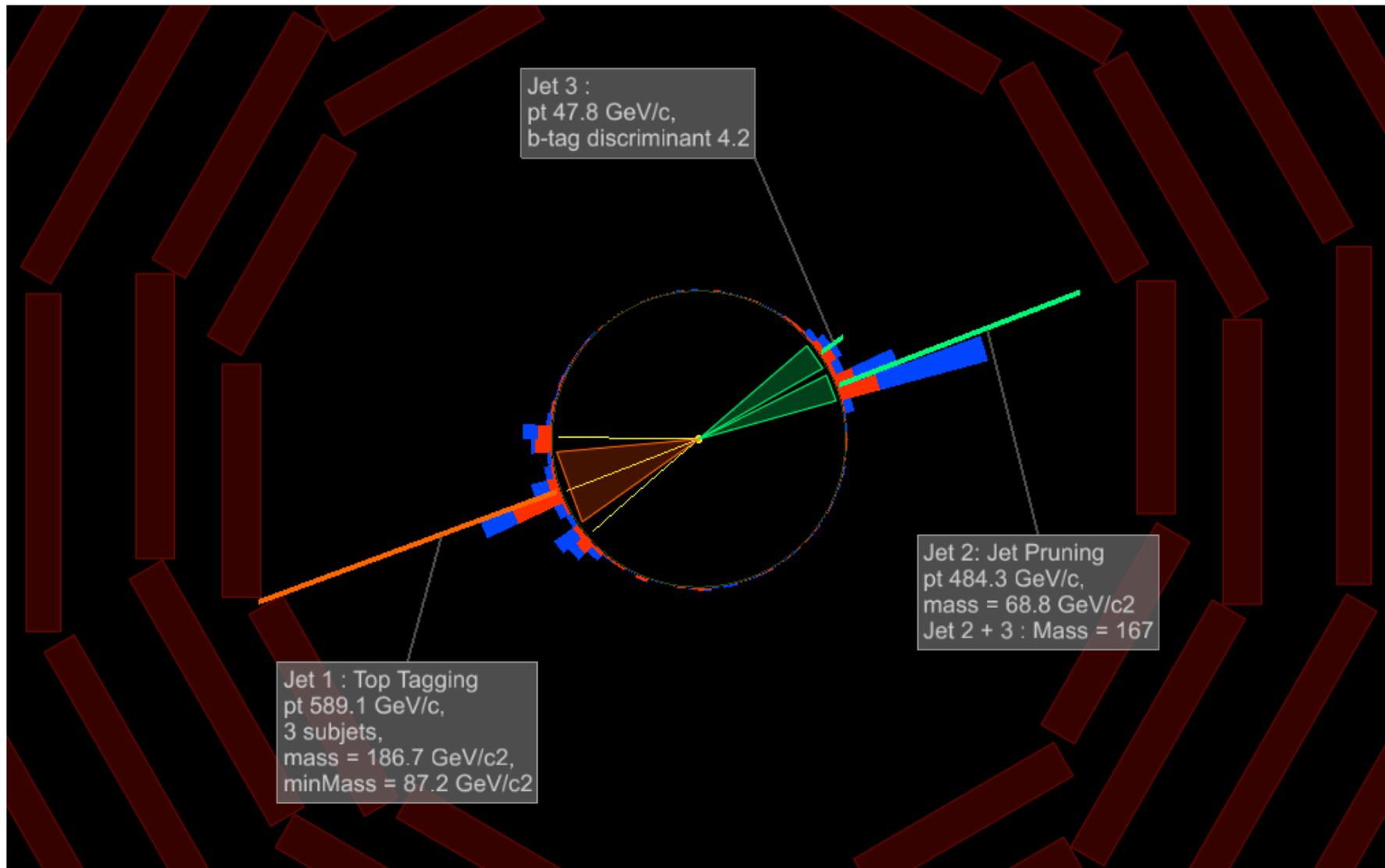
On the momentum of top quarks

PAS JME-10-013

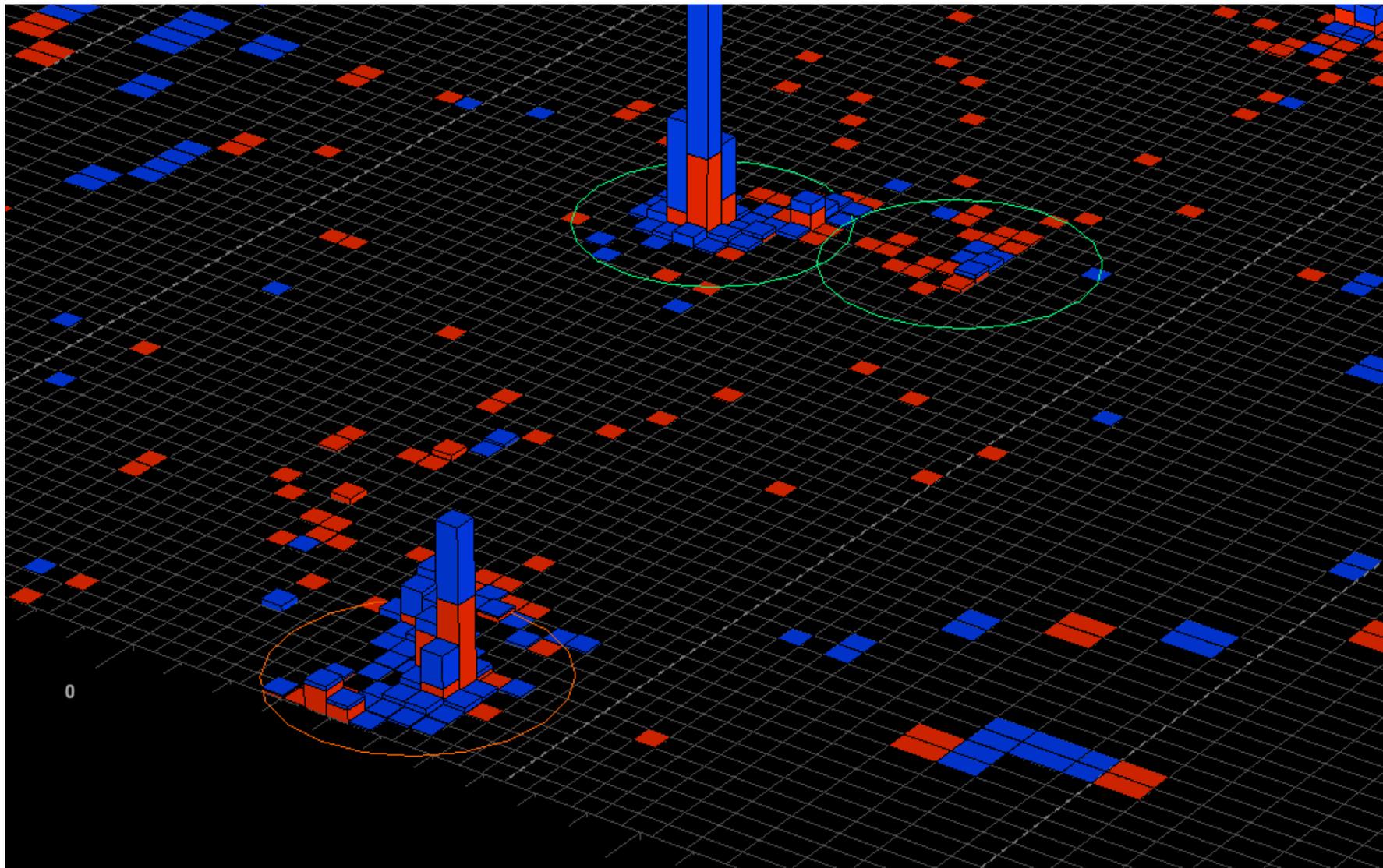


- Once boost of top quarks high enough
- Decay products become collimated
 - $W \rightarrow qq$ in one jet
 - Or $t \rightarrow bqq$ in one jet
- Special reconstruction algorithms needed:
 - Cambridge-Aachen algorithm with distance parameter 0.8

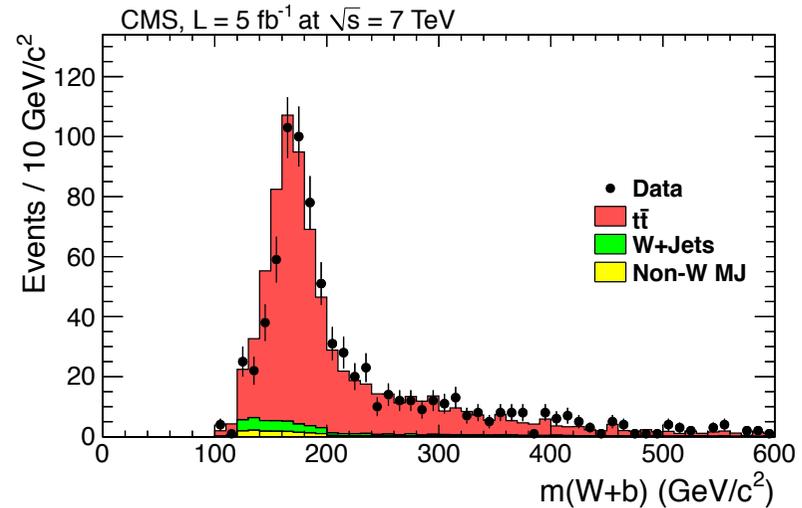
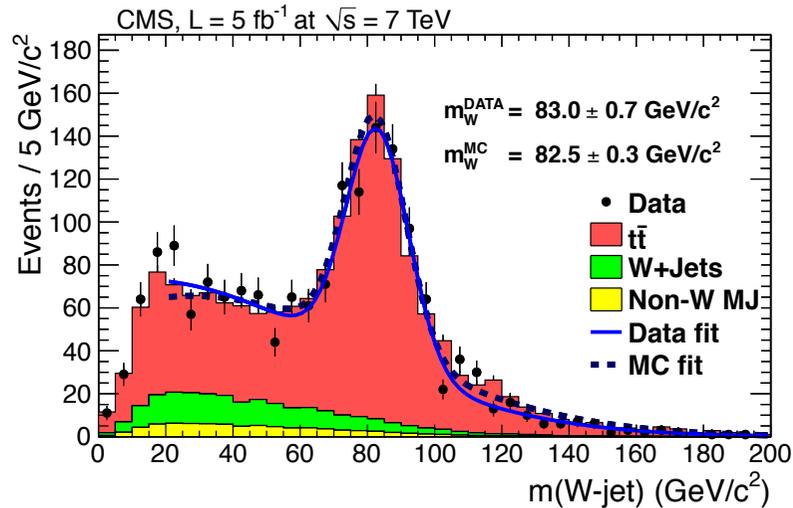
Jets with substructure



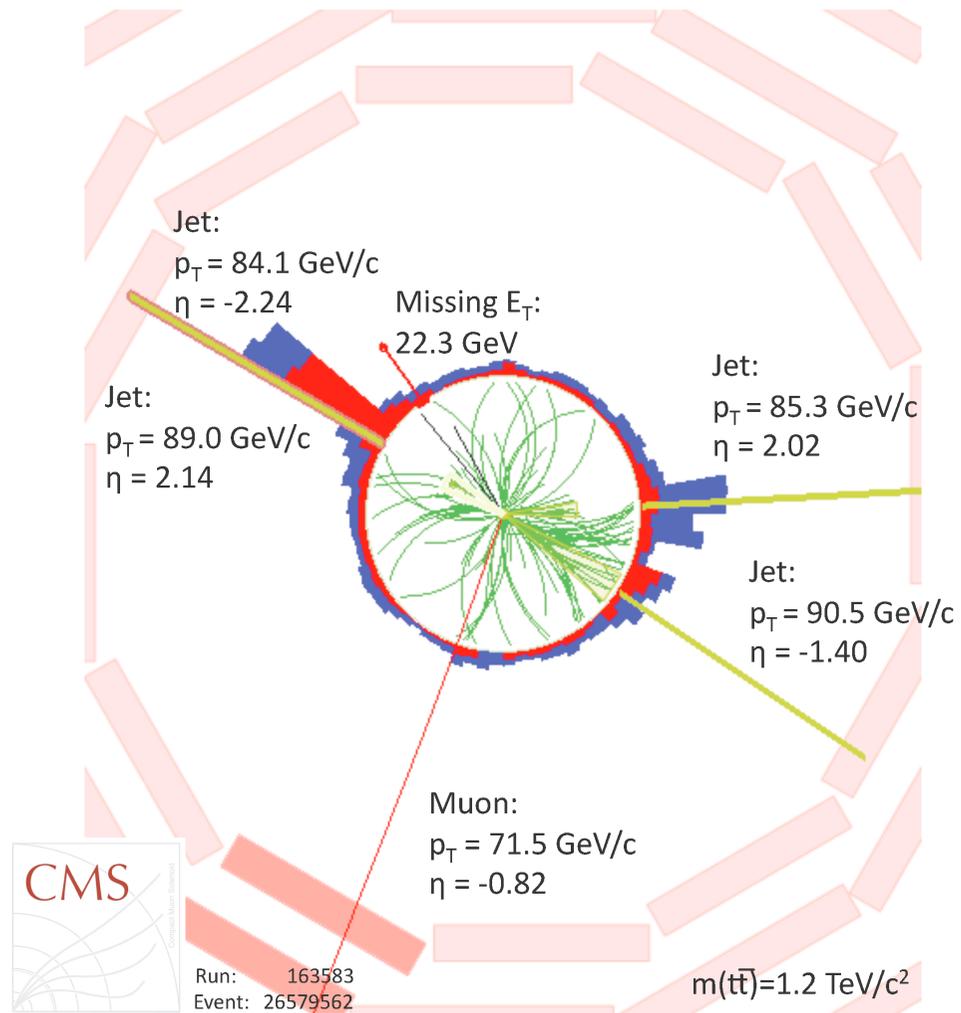
Jets with substructure



Validation in lepton+jets events

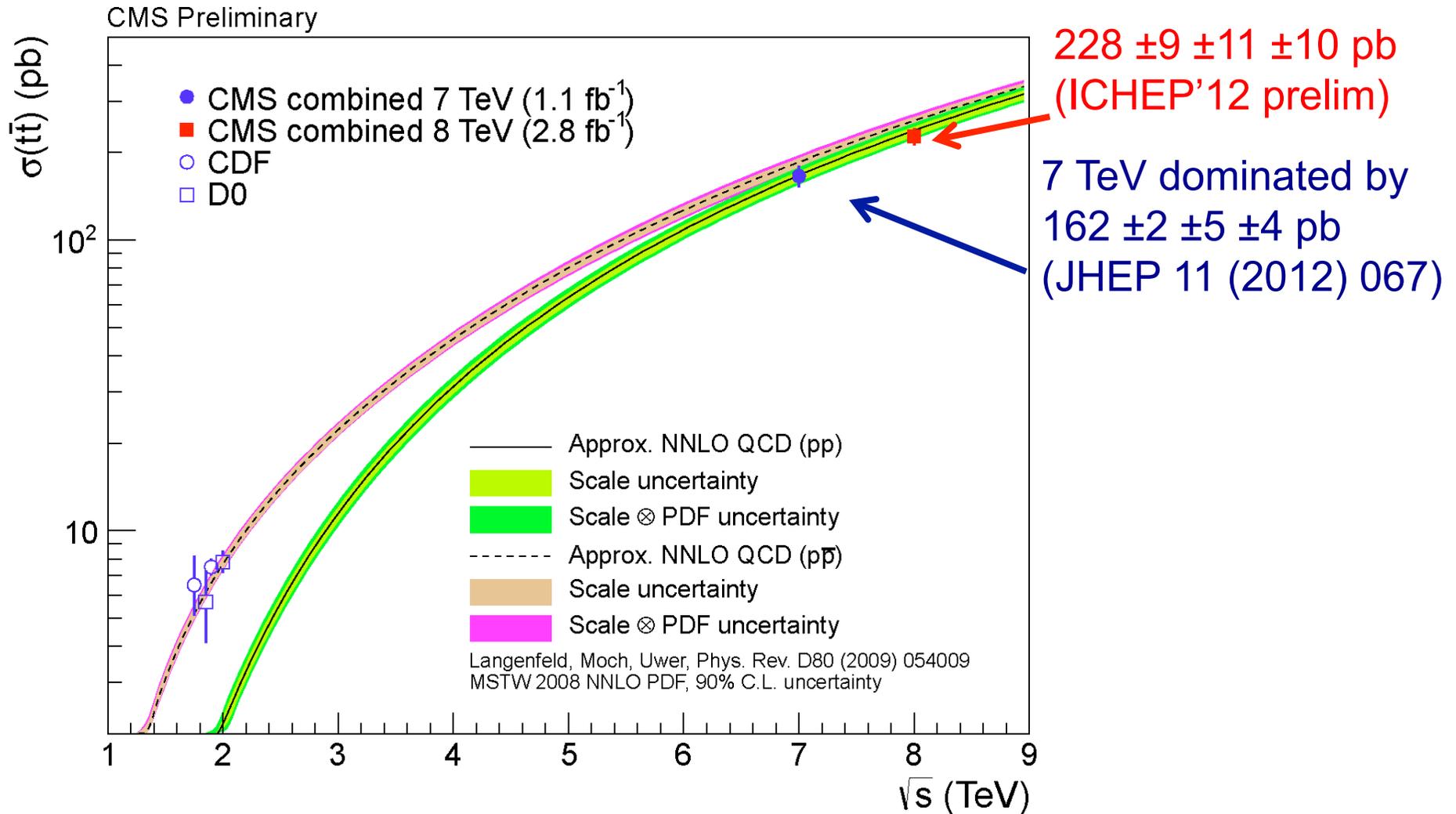


- Algorithm validated using muon+jets selection
- Data shows that W boson and top quark (using di-jet events) can be reconstructed this way and is reasonably well modeled



Top pair production

Production cross section overview



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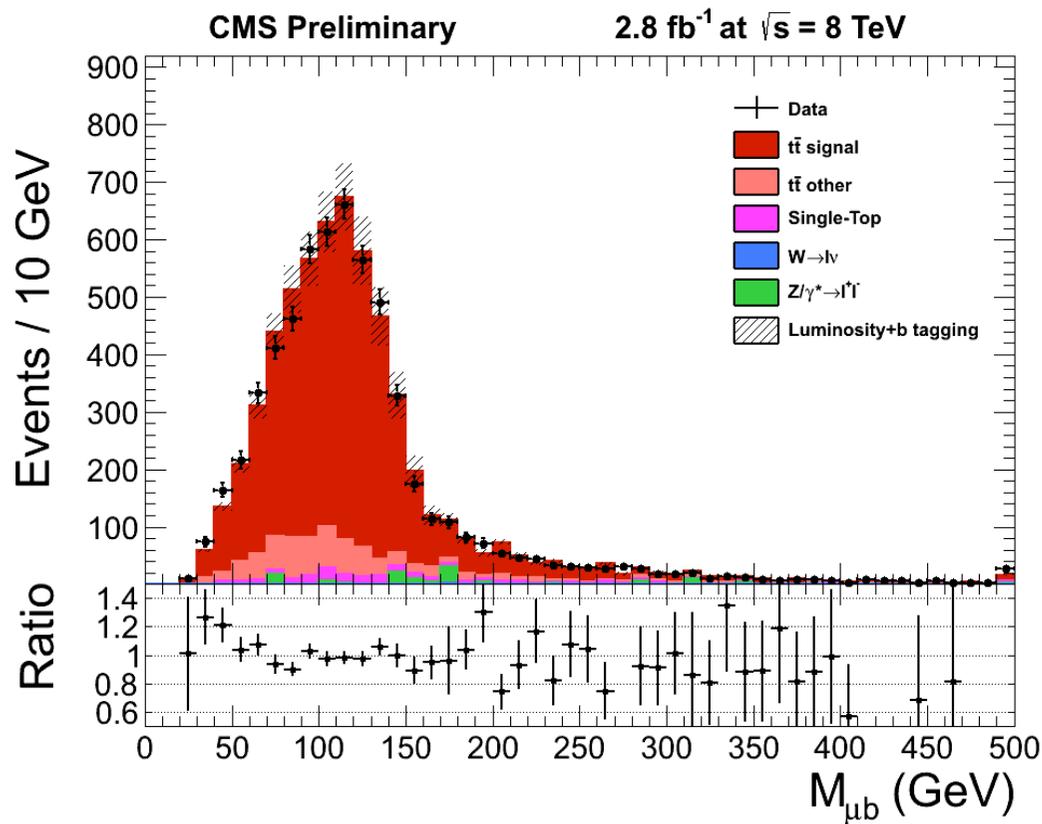


LHC: Top quark pair factory

- Cross sections ~ 225 pb
- In combination with 20 /fb datasets:

– LHC is a top factory

– Very productive program of Standard Model precision top physics



src: CMS TOP-12-006



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Heavy resonances decaying to top+bottom

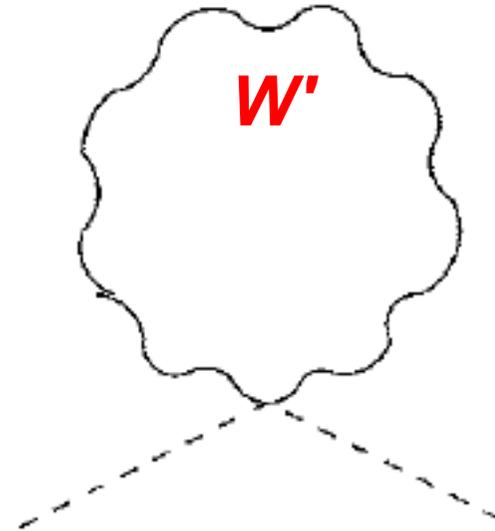


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W' to tb

- Another way to cancel fine-tuning problems in top, gauge and Higgs self-coupling loops
- Couplings similar to standard model?

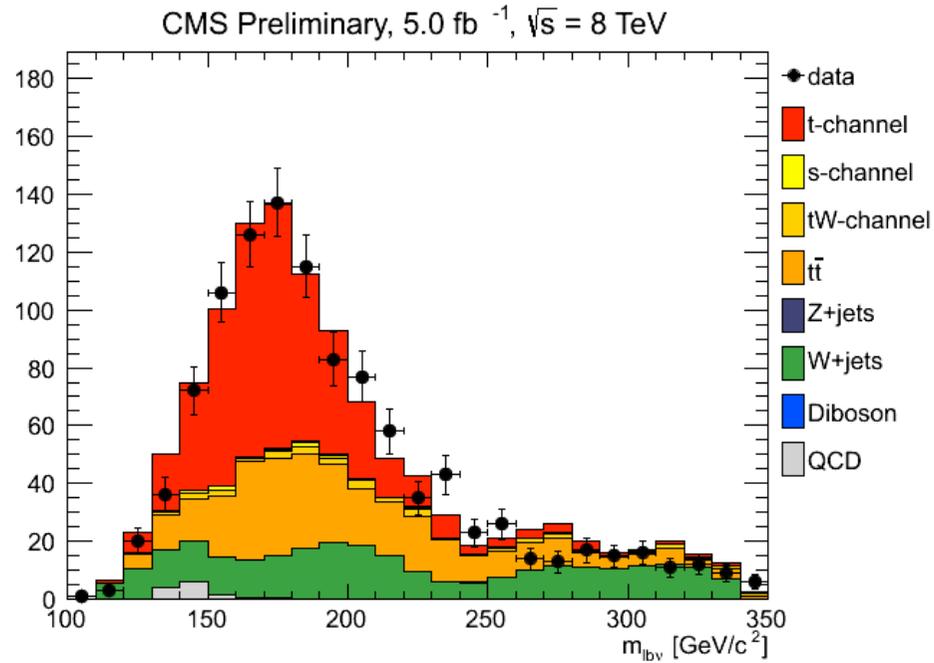


$$\mathcal{L} = \frac{V_{f_i f_j}}{2\sqrt{2}} g_w \bar{f}_i \gamma_\mu (a_{f_i f_j}^R (1 + \gamma^5) + a_{f_i f_j}^L (1 - \gamma^5))^\mu f_j + \text{H.c.}$$

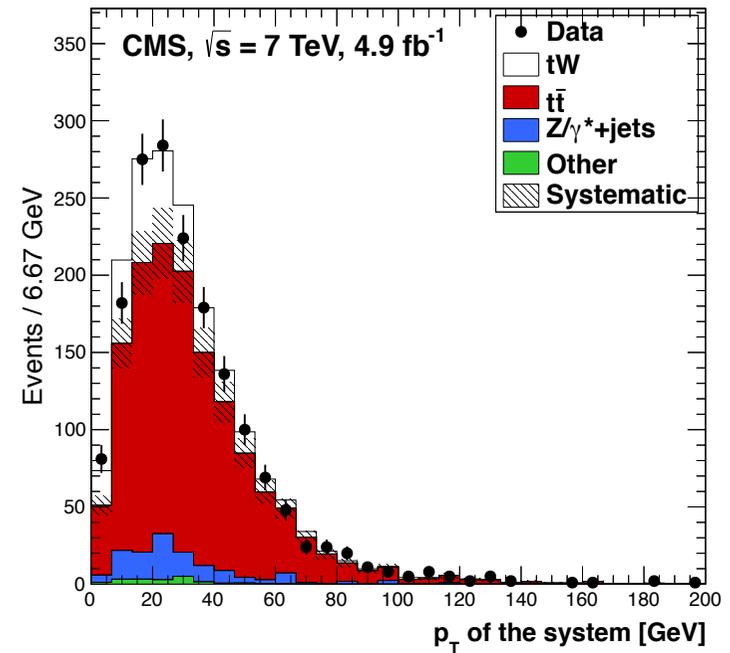
Non-0 → interference with SM

src:Z.Sullivan, Phys.Rev.D 66 075011

Single top production



src: CMS TOP-12-011



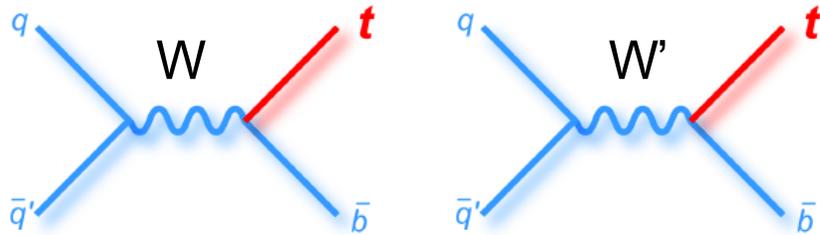
src: Phys.Rev.Lett.110 (2013)022003



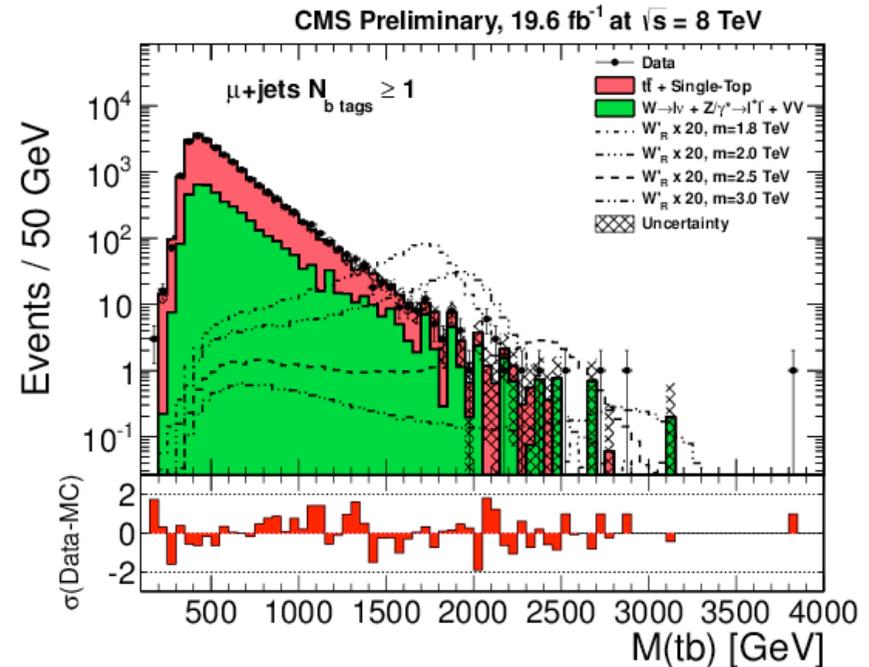
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W' to tb



- analogue to single top s-channel production
- Leptonic top decay:
 - Final state of lepton+MET+2 b jets
- Mass reconstruction also used in SM top physics, using W boson mass to constrain MET
 - With additional top mass constraint



- Interpret in left and right handed W' scenarios

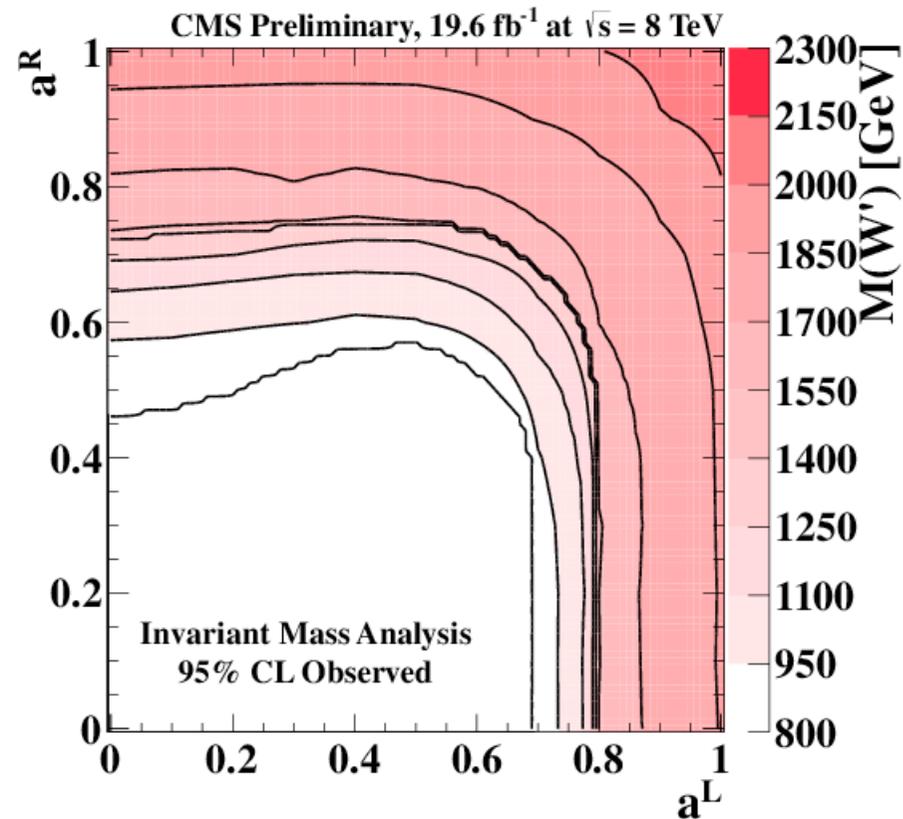
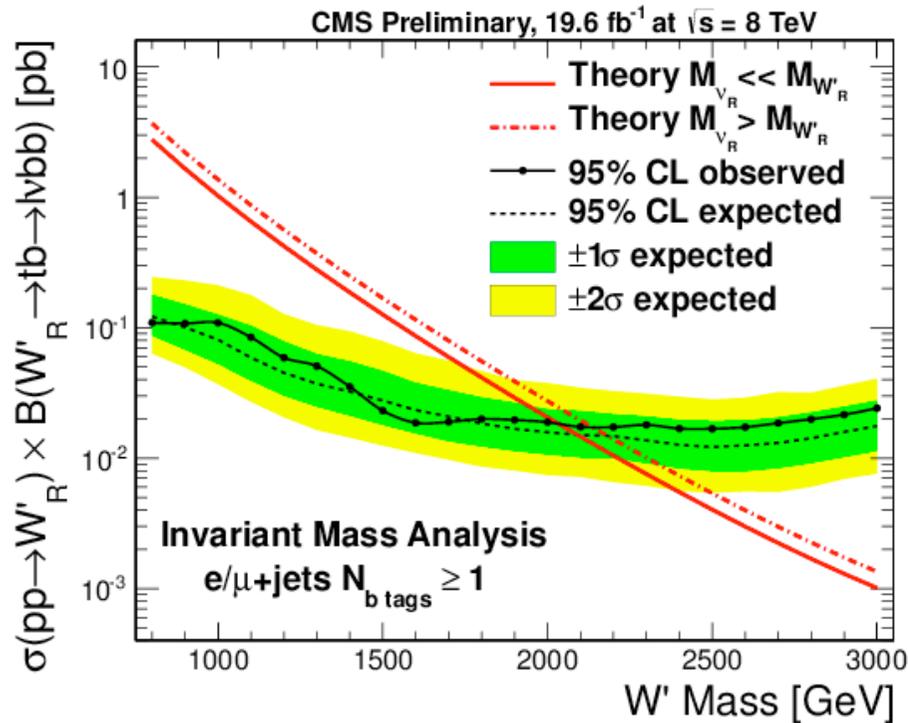
src: B2G-12-010 PAS



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W' to tb



- No excess over SM predictions
- Limit on mass W'_R : 2.03 TeV
- Expected limits very similar

src: B2G-12-010 PAS



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Heavy resonances decaying to top quark pairs

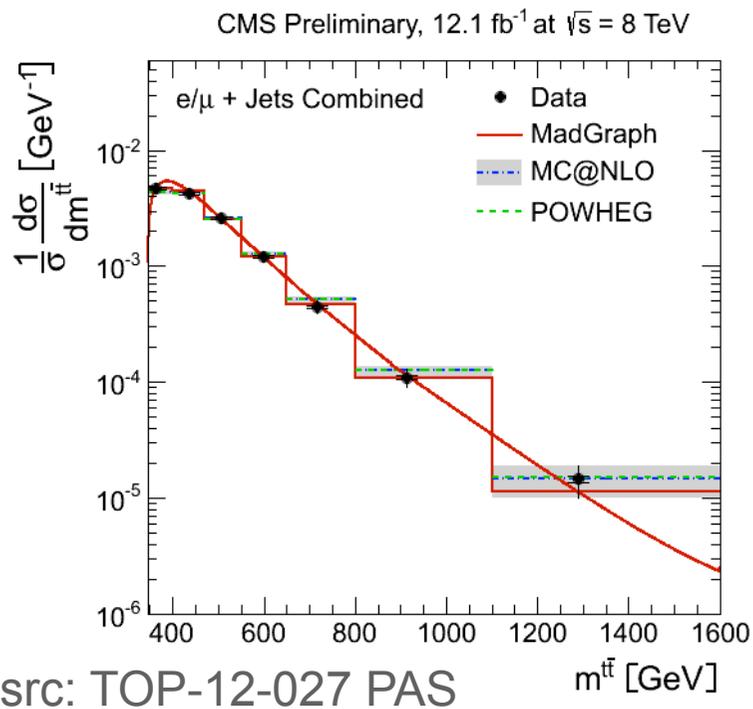
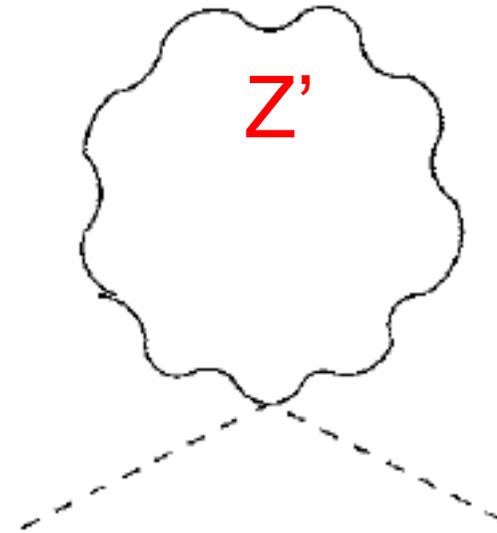


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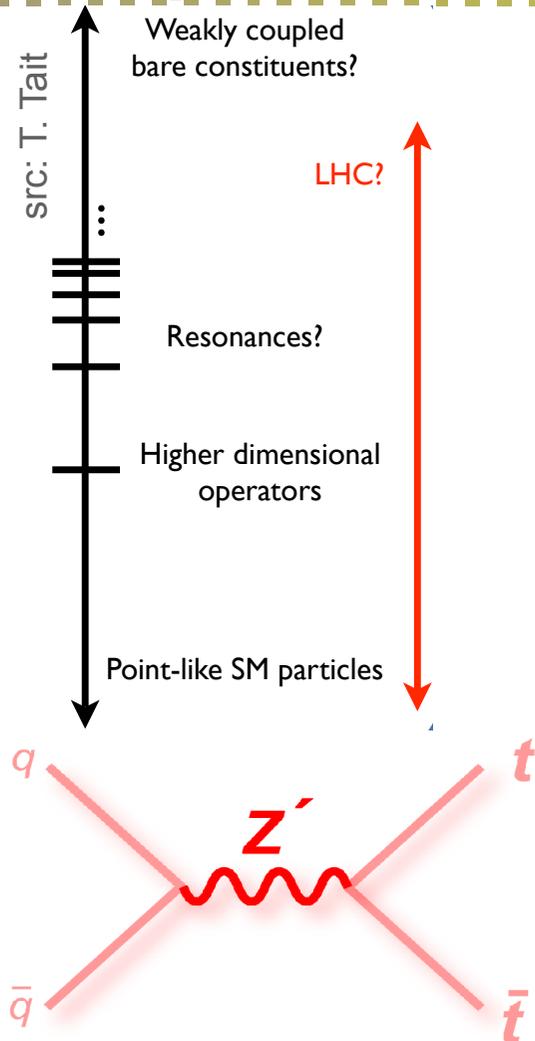
Investigating $t\bar{t}$ invariant mass distribution

- Differential cross sections now available for 8 TeV sub-set
- Searches in tails of distributions ongoing for 8 TeV full sample
 - Expect results very soon



- Z' scenarios interwoven with natural EXO solutions and A_{FB}^- explaining models
- $M_{t\bar{t}}$ distribution sensitive to many new physics scenarios

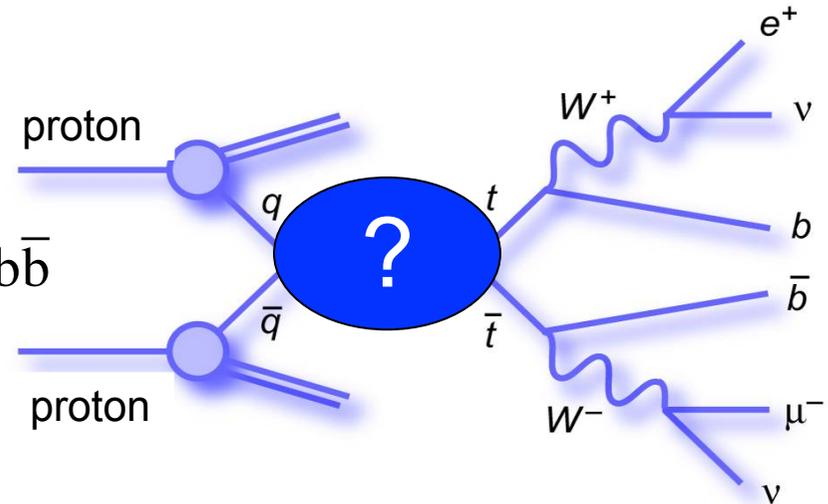
Top resonances physics motivation



- Many new physics models predict extra exchange of massive particles in top quark production
 - Would be observed in a peaked or general excess/dip in the top-antitop invariant mass spectrum
 - Substantial number of theoretical models
 - Z' , colorons, axiguons, Randall-Sundrum/ADD gravitons, Pseudo-scalar Higgs to $t\bar{t}$
 - And many more
- Searches presented can be interpreted in any of these
 - For general comparison, “Topcolor-assisted technicolor” model: hep-ph/991.1288: Hill, Parke, Harris

analysis strategy

- Searches in different top decay channels
 - Dileptons $t\bar{t} \rightarrow \ell^- \ell^+ \nu \bar{\nu} b \bar{b}$
 - Semileptonic \equiv lepton+jets $t\bar{t} \rightarrow \ell \nu q \bar{q} b \bar{b}$
 - Hadronic \equiv alljets $t\bar{t} \rightarrow q \bar{q} q \bar{q} b \bar{b}$
- And in different regimes
 - Close to $2x(\text{top mass})$ threshold
 - Sensitive to shape of SM $M(t\bar{t})$ distribution
 - Conventional top physics techniques may be used
 - More boosted
 - Sensitive to more massive $M(t\bar{t})$ BSM physics
 - Dedicated reconstruction techniques may be necessary



8 TeV
l+jets

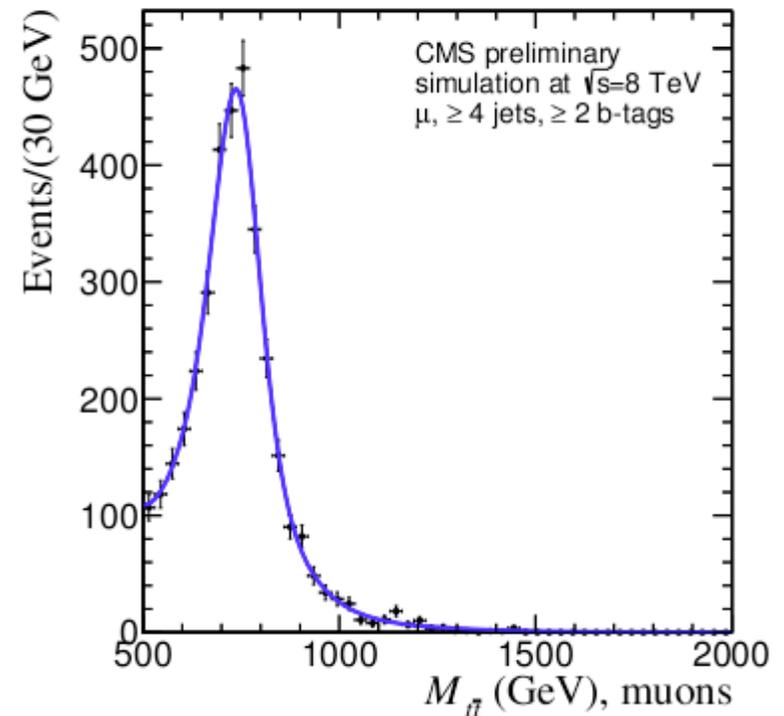
NEW!

Preliminary TODAY

NEW!

Semileptonic, threshold

- Require only one lepton, ≥ 4 jets and split in b-tag multiplicity
- χ^2 sorting used to select best jet combination
- Using data-driven estimates for falling distribution of top pair mass spectrum above 500 GeV/c²
- Systematic uncertainties take into account rate and shape changes for signal and background model



src: CMS PAS B2G-12-006



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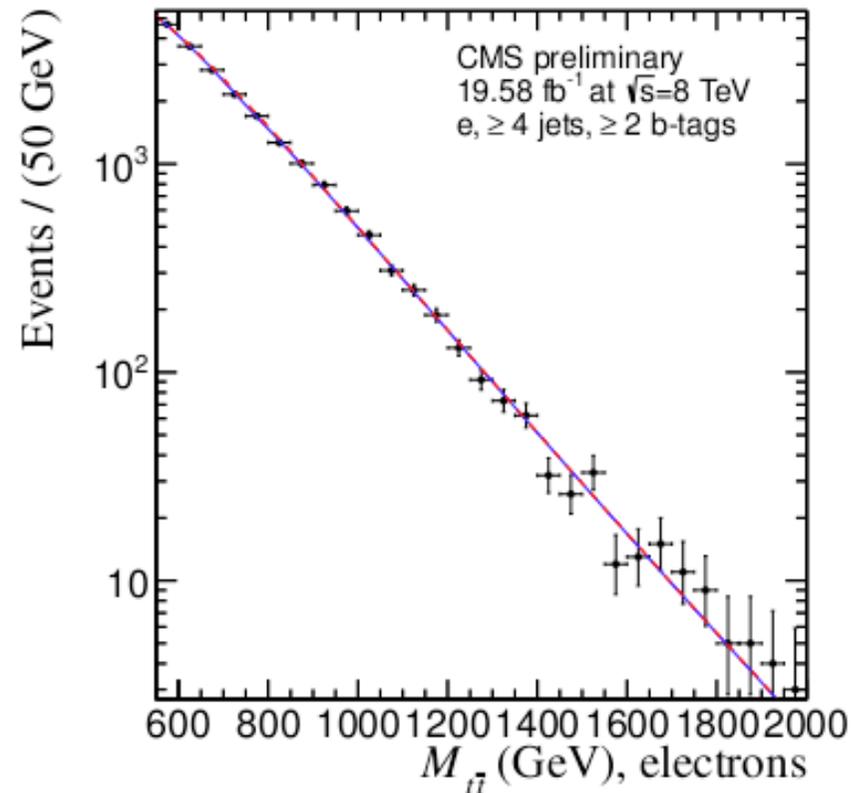
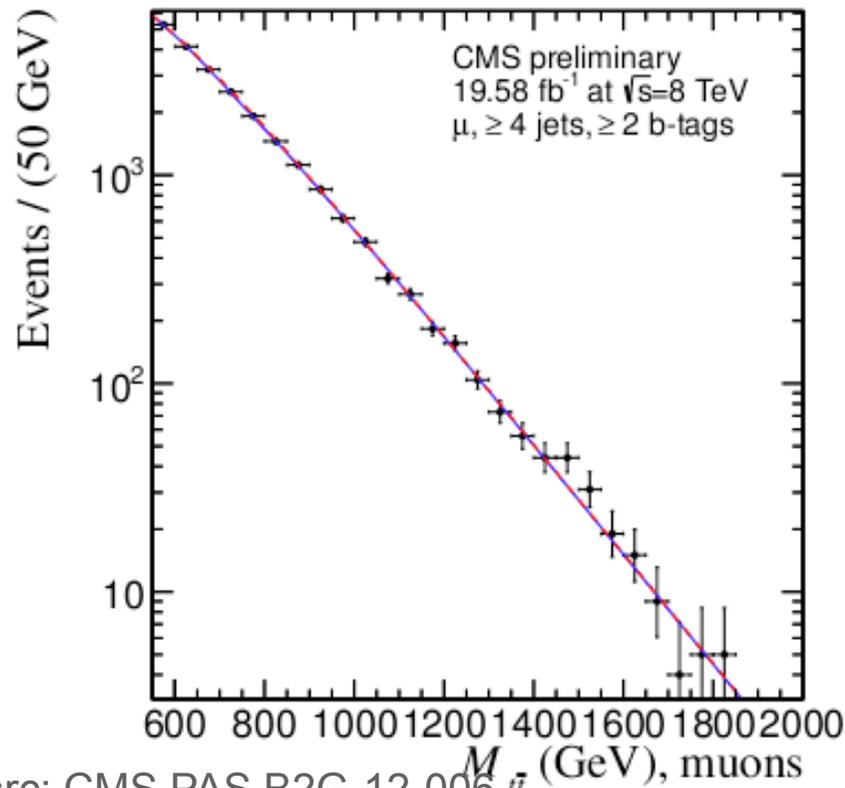


Ref:CMS TOP-11-009

NEW!

Semileptonic, threshold

- Fit to falling distribution in electron/muon final states used to set limits (1 and ≥ 2 b-tag regions fit simultaneously)
 - **Fully data-driven method, only makes assumptions on resonant shape of signal**



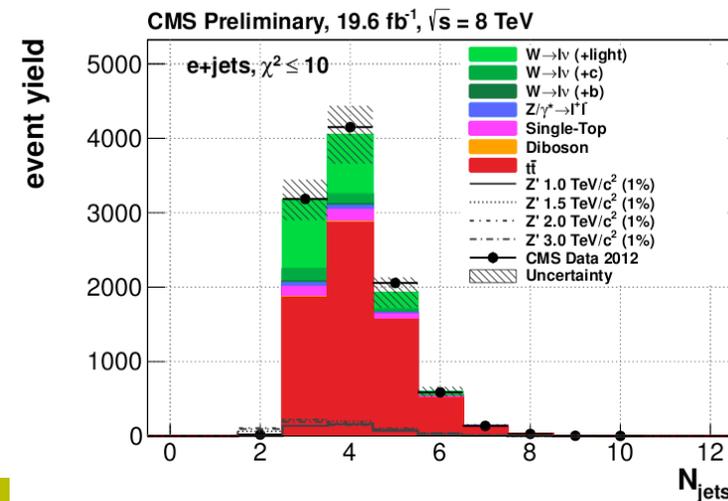
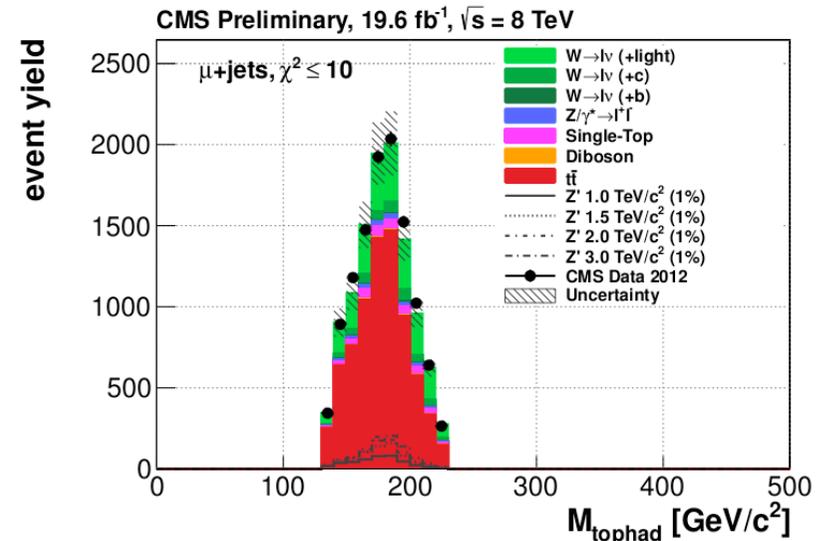
src: CMS PAS B2G-12-006
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NEW!

Semileptonic, non-isolated

- Alternate analysis: Loosened lepton isolation criteria allow jet/lepton overlap
- Focus on mass tail: require harder cuts on leptons and jets
- Only at least 2 jets+lepton required
- χ^2 sorting used to select best jet combination
- Simultaneous template fit to $M(\text{ttbar})$ in different b-tag multiplicities and electron/muon final states used to set limits
- Backgrounds normalized to control region where SM ttbar is dominant



src: CMS PAS B2G-12-006

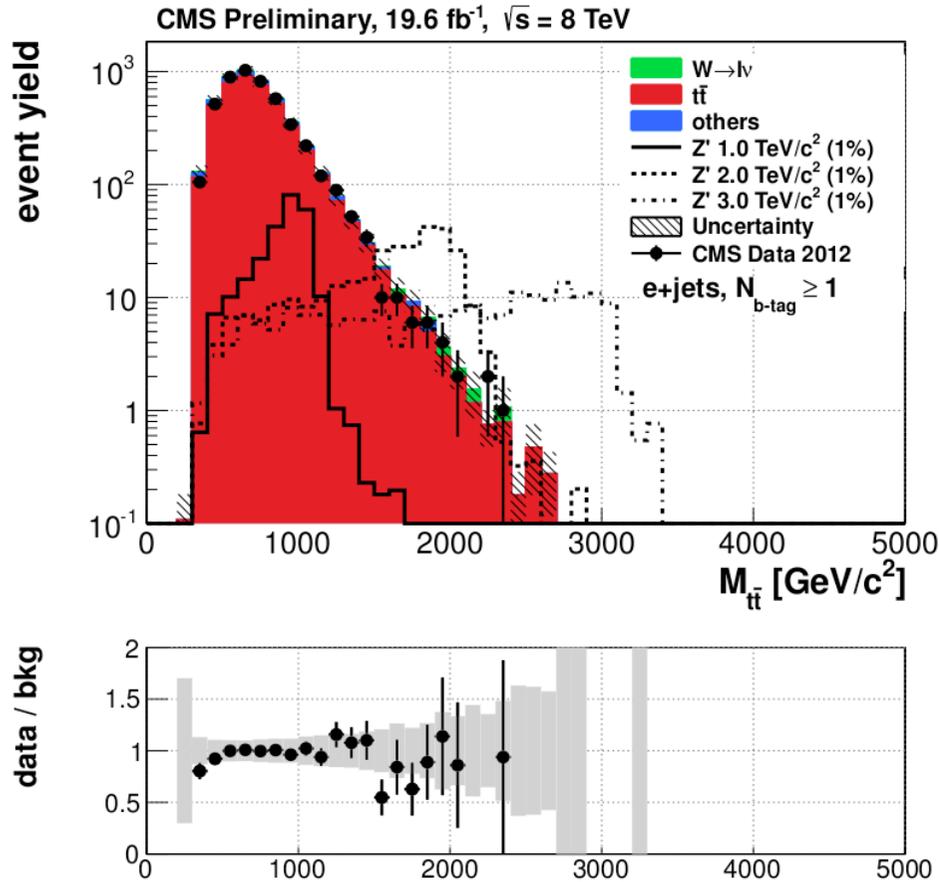


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NEW!

Semileptonic, non-isolated

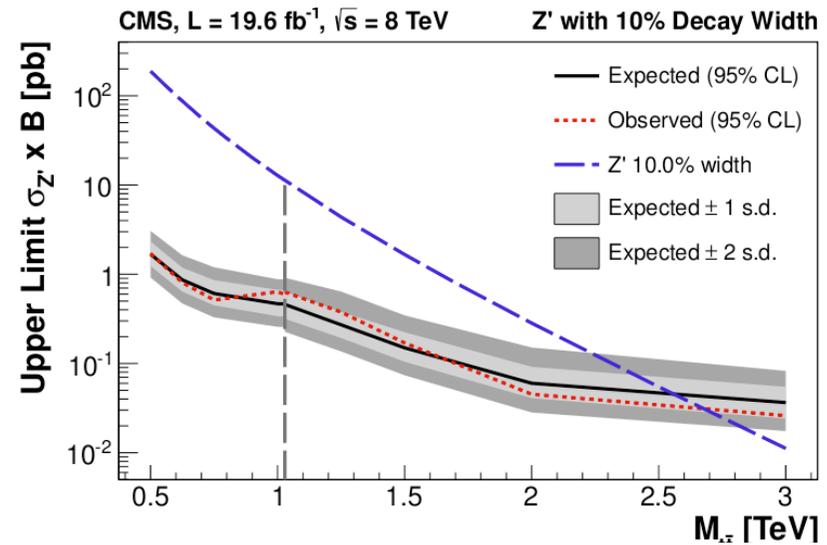


- Multiple scenarios considered

- Worlds best limit on production of resonant t \bar{t} bar:

- Z' (width 1.2%): m > 2.10 TeV
- Z' (width 10%): m > 2.68 TeV
- KK gluons: m > 2.69 TeV
- Resonances in low-mass region:

excluded with xsec > 1-2 pb!!



src: CMS PAS B2G-12-006



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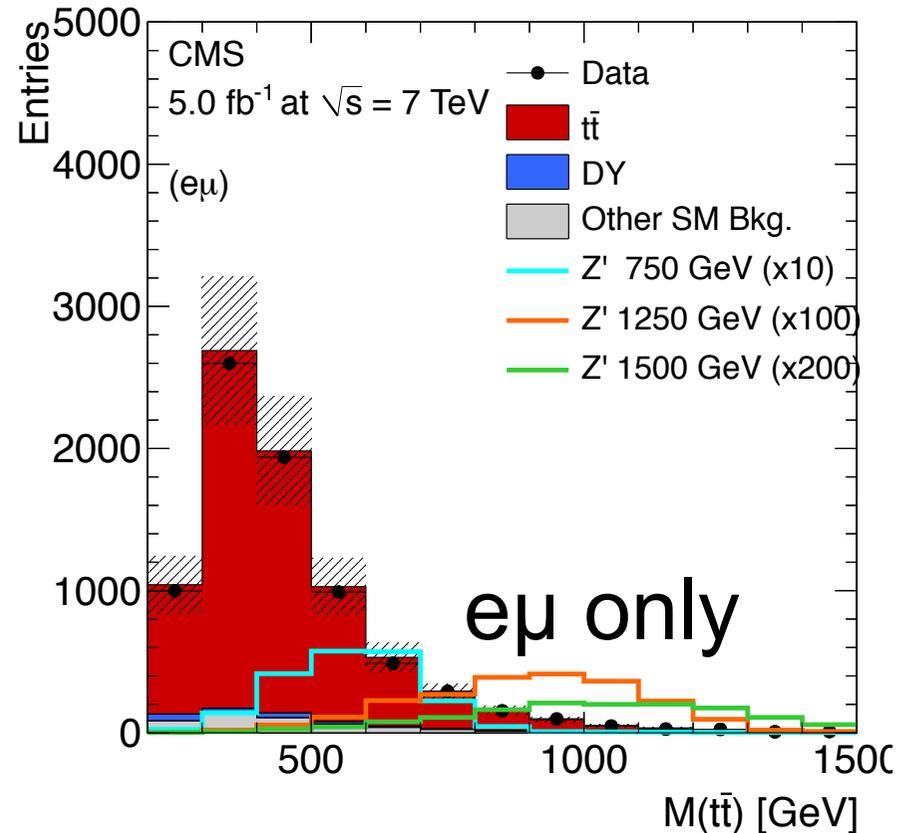
Dilepton, threshold, 7 TeV

Selection requirements:

$ee/e\mu/\mu\mu$ final state

- two isolated leptons, opp.charge, $p_T > 20$ GeV, $|\eta| < 2.5$
- Missing $E_T > 30$ GeV
- Veto on DY at low/Z peak
- ≥ 2 jets, one b-tag (Secondary vertex)
 $p_T > 30$ GeV, $|\eta| < 2.5$

Analysis uses Bayesian NN to gain more sensitivity



src:CMS TOP-11-010



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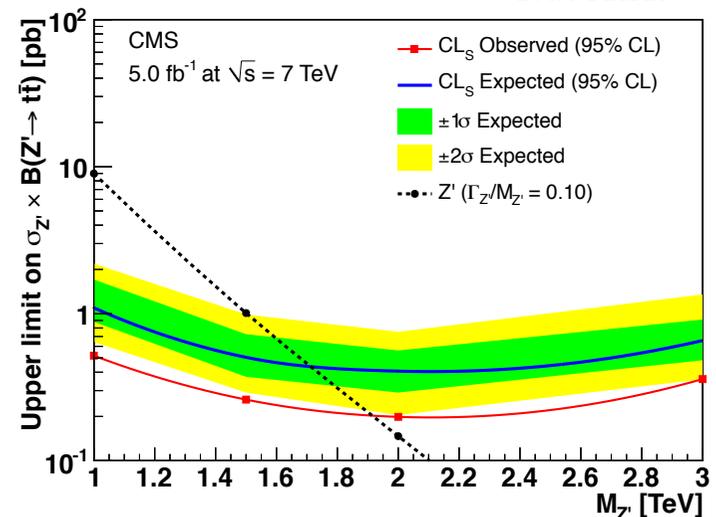
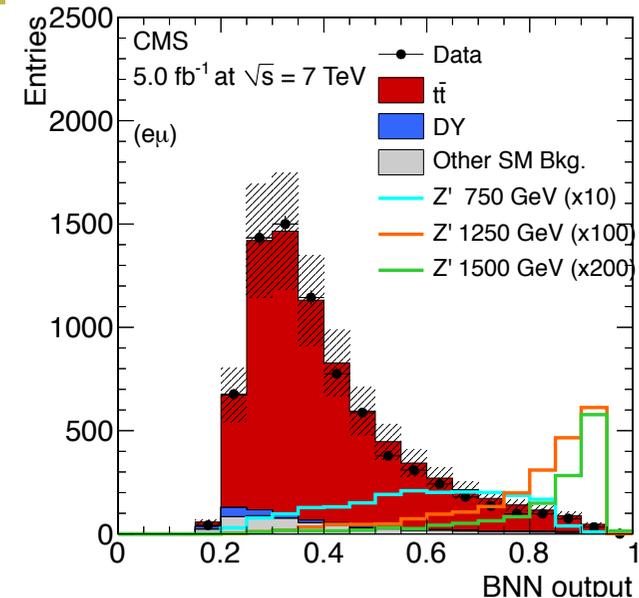


Dilepton, threshold, 7 TeV

- After selection dominated by $t\bar{t}$ production (75%)
- Good agreement between MC (Madgraph) and data.
- BNN trained for 750 GeV Z'
- Input variables: all available four-vectors and angles wrt missing E_T , b-tag multiplicity and angles wrt b-jet
- Systematic uncertainty on rates and shapes of SM contribution total: 18%

$M(Z', 1.3\%) < 1.3$ TeV excluded

$M(Z', 10\%) < 1.9$ TeV excluded



src:CMS TOP-11-010

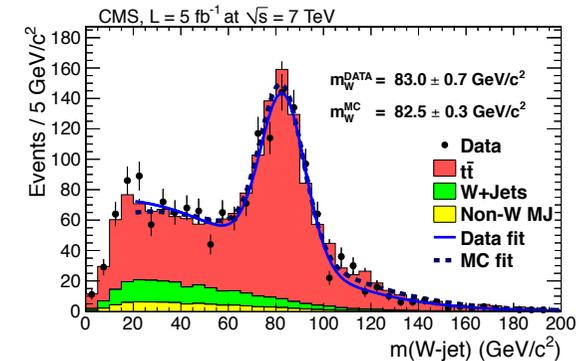


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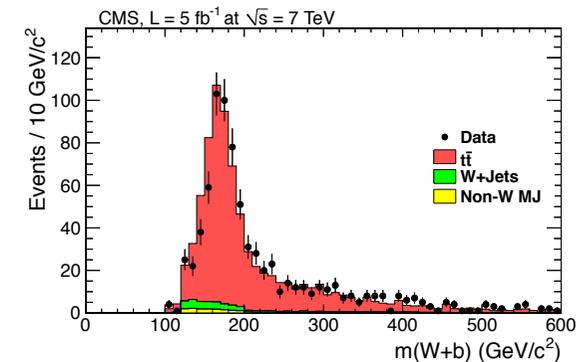


All hadronic, boosted, 7 TeV

- Using boosted objects and jet pruning to identify substructure
 - Full merged and semi-merged topologies
- Cambridge-Aachen jets
 - 'top jets'
 - 'W boson jets'



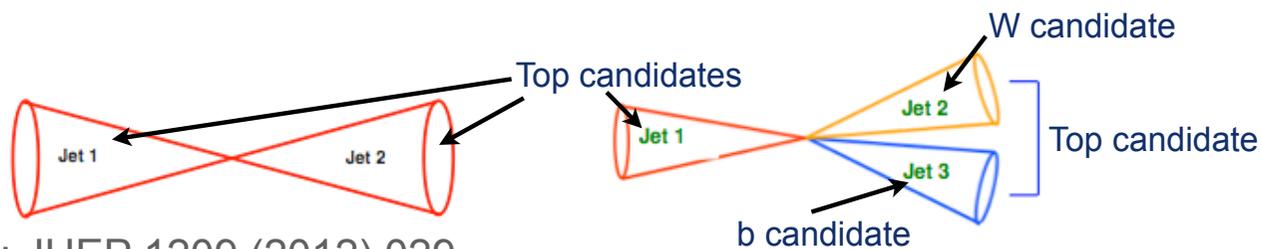
(a)



(b)

Type 1 + Type 1

Type 1 + Type 2



src: JHEP 1209 (2012) 029

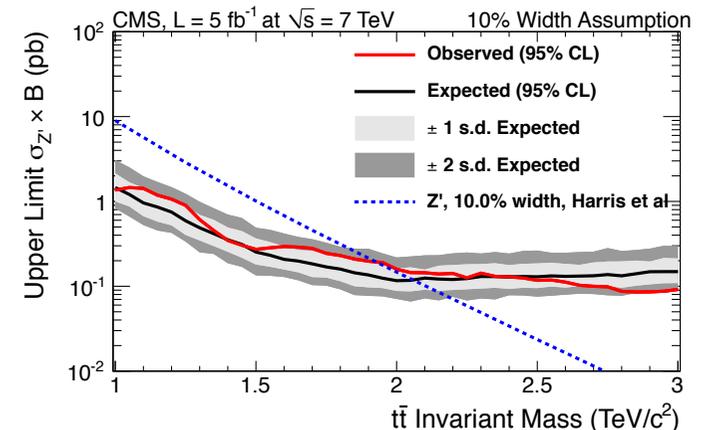
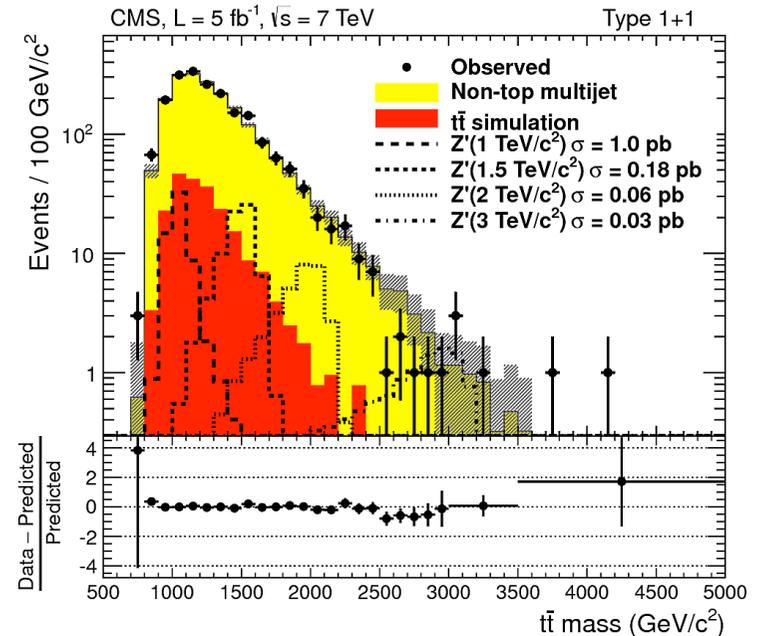


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All hadronic, boosted, 7 TeV

- LLH fit to bumps in mass spectrum used to set limits
- Narrow (1.2%) Z' limit: **$M(Z') > 1.3-1.5 \text{ TeV}$**
- intermediate (3%) Z' limit: **$M(Z') > 1.6 \text{ TeV}$**
- Wide (10%) Z' limit: **$M(Z') > 2.0 \text{ TeV}$**
- RS Kaluza-Klein gravitons: **$M(KKG) > 1.4-1.5 \text{ TeV}$**
- 95% CL upper limits on increased cross section at high mass:
 - ~1 pb for intermediate mass (1 TeV)
 - ~50 fb for higher mass (2 TeV)



src: JHEP 1209 (2012) 029



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Heavy top partners



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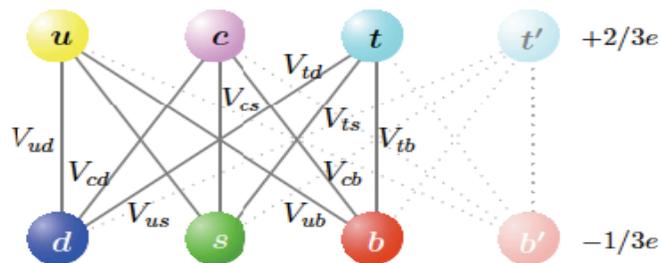


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Fourth Generation



- Fourth generation one of more compelling SM extensions
 - Direct and indirect limits on simplest SM4: excluded!



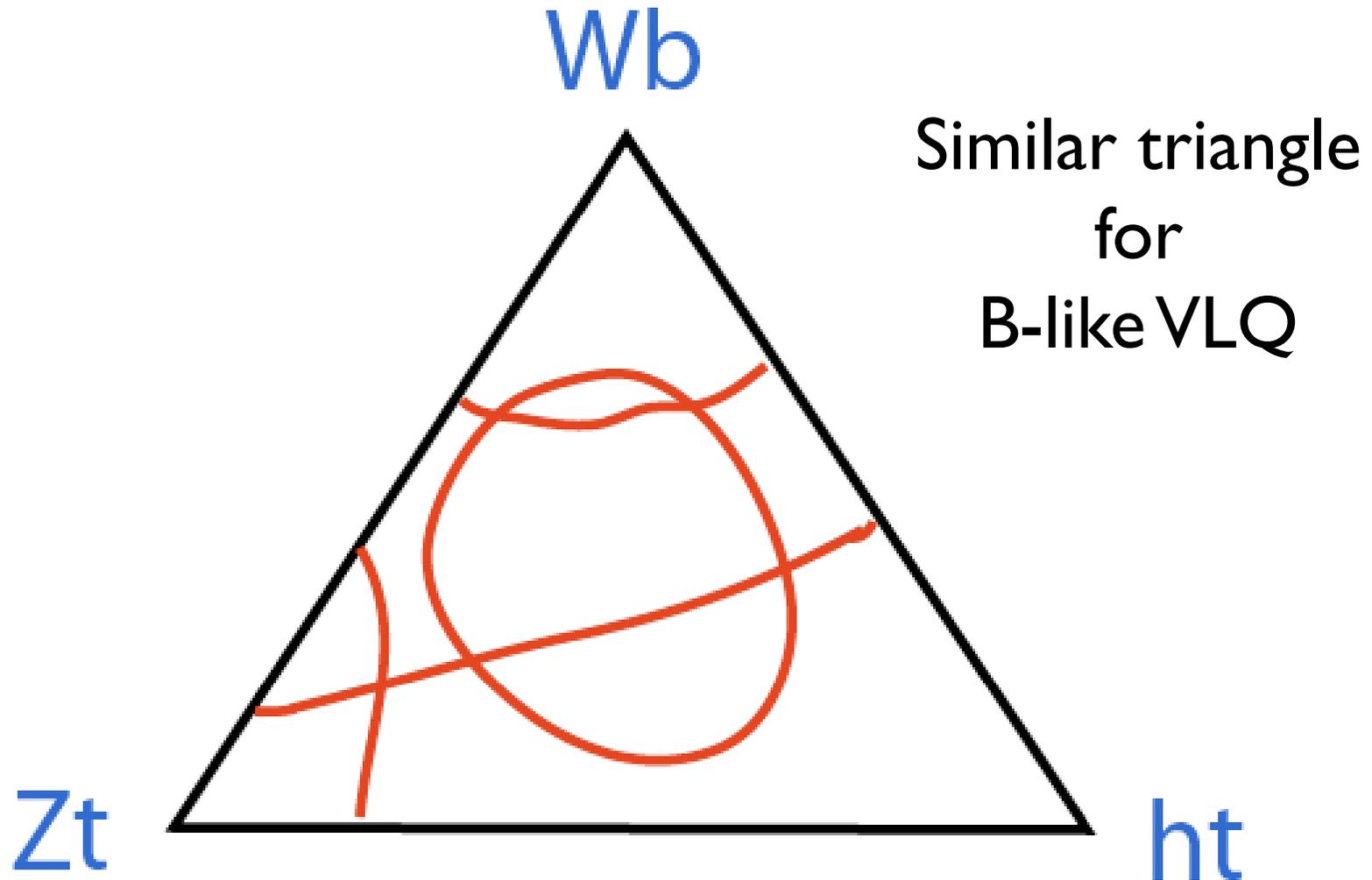
- More elaborate fourth generation models still alive
 - Any SM extension with a Higgs doublet and fourth generation
 - Any models predicting other heavy top partners such as 2HDM
 - Vector-like quarks that are top quark/b quark partners
 - Exotic top partners with different charge

Fourth Generation

- Still compelling topic even if simplest extension excluded
 - Can enhance CP violation
 - Heavy neutrino as DM candidate
- Vector-like fermions (non-chiral fermions):
 - Not excluded by Higgs cross sections
 - Little Higgs models
Nucl.Phys.Proc.Suppl.117 (2003)40
 - Warped extra dimensions
Phys.Rev.Lett.83:3370-3373,1999
- Models benchmark for new physics decaying top-like:
 - Extremely rich phenomenology with final states with multiple gauge bosons, b and t quarks:
 - $T \rightarrow bW, tZ, th$
 - $B \rightarrow tW, bZ, bh$
 - Current searches mostly pair production
 - Single production also possible

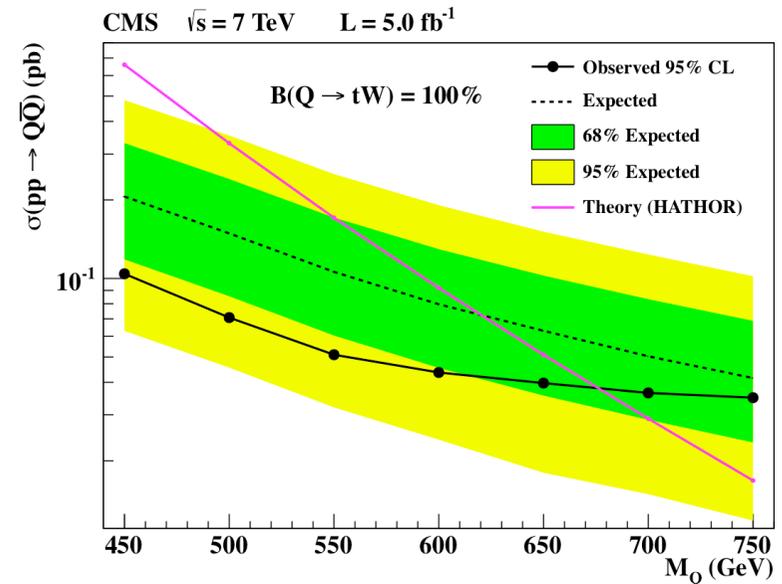
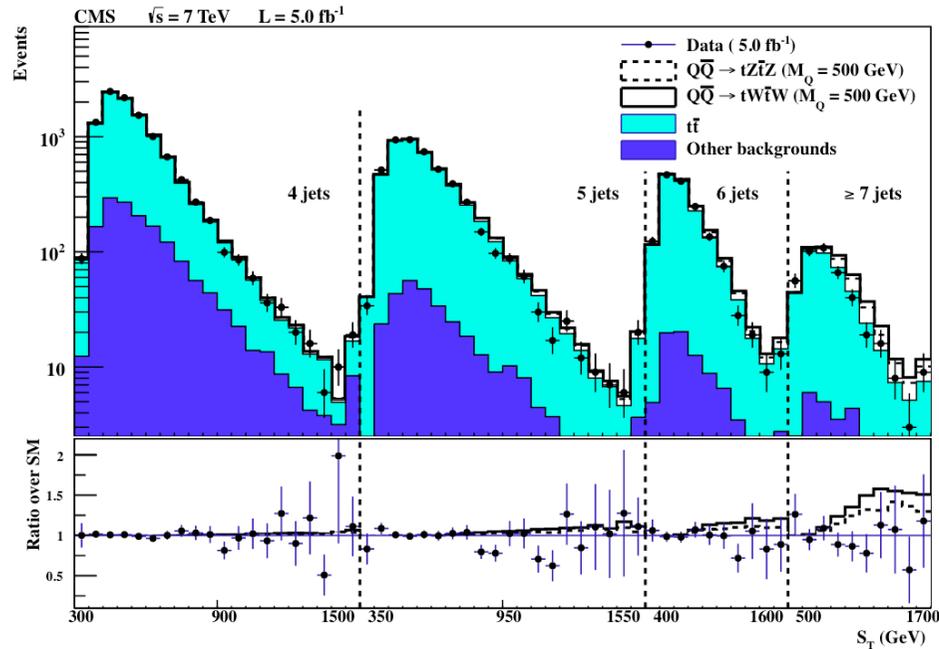


Vector-like quarks:



src: M. Peskin

Search for Bottom/top partners in 7 TeV data



- Investigate $S_T = \text{sum } p_T \text{ of jets+lepton+MET}$ as a function of jet multiplicity
- $tZtZ$ and $tWtW$ final states examined (similar limits)

src: JHEP 01 (2013) 154



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Zoo of 7 TeV direct searches

Search	Channel	Lower mass limit
$t' \rightarrow bW$ pair	lepton+jets	570 GeV/c ²
	dileptons	557 GeV/c ²
$b' \rightarrow tW$ pair	lepton+jets	675 GeV/c ²
	trilepton and same-sign dilepton	611 GeV/c ²
$T \rightarrow tZ$ pair	lepton+jets	625 GeV/c ²
	trileptons	475 GeV/c ²
$B \rightarrow bZ$ pair	two leptons	550 GeV/c ²
Model-Dependent t'/b'	lepton(s)+jets	685 GeV/c ²

src: S. Khalil

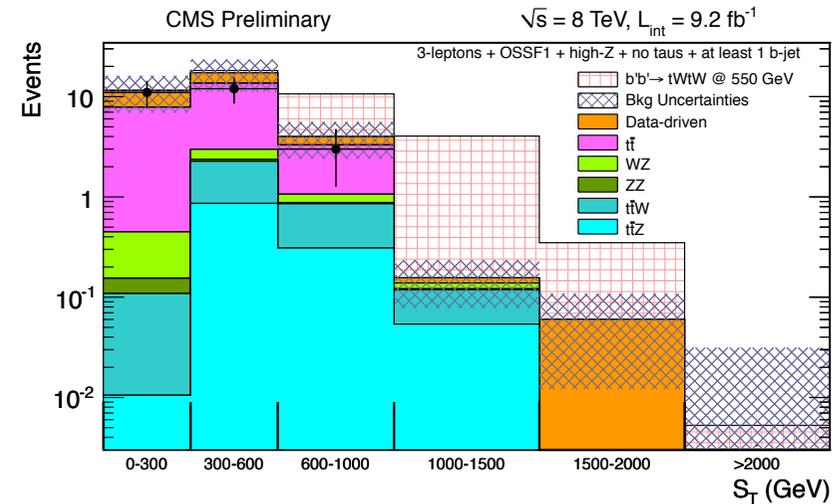
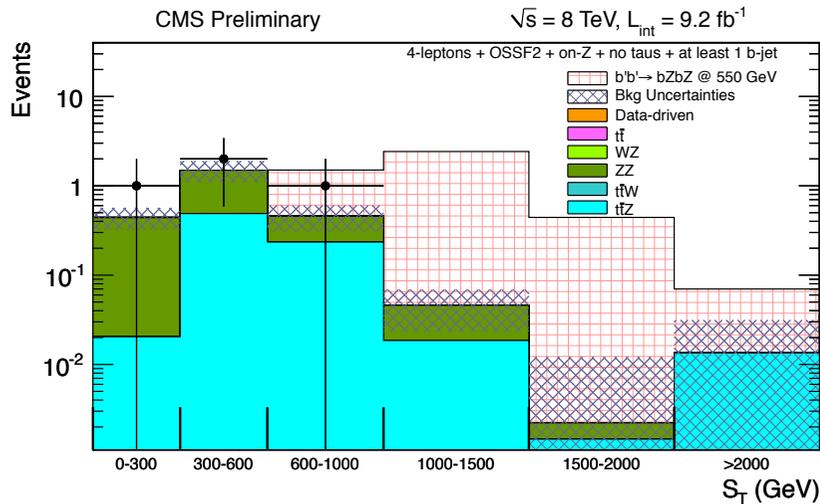


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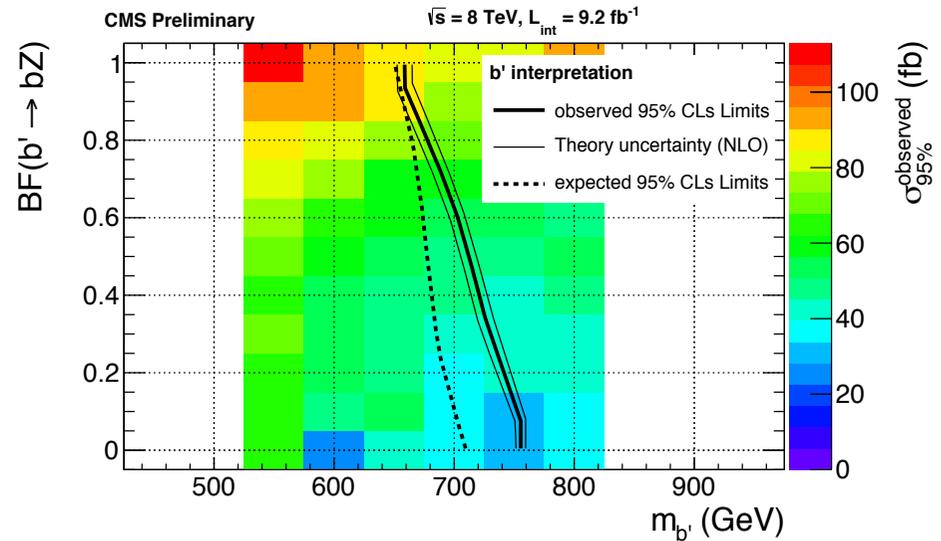


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First limits on 8 TeV data



- Multilepton SUSY search using half of 2012 dataset
 - Reinterpretation in $BB \rightarrow bZbZ$ and $BB \rightarrow tWtW$ scenarios



src: CMS PAS SUS-12-027

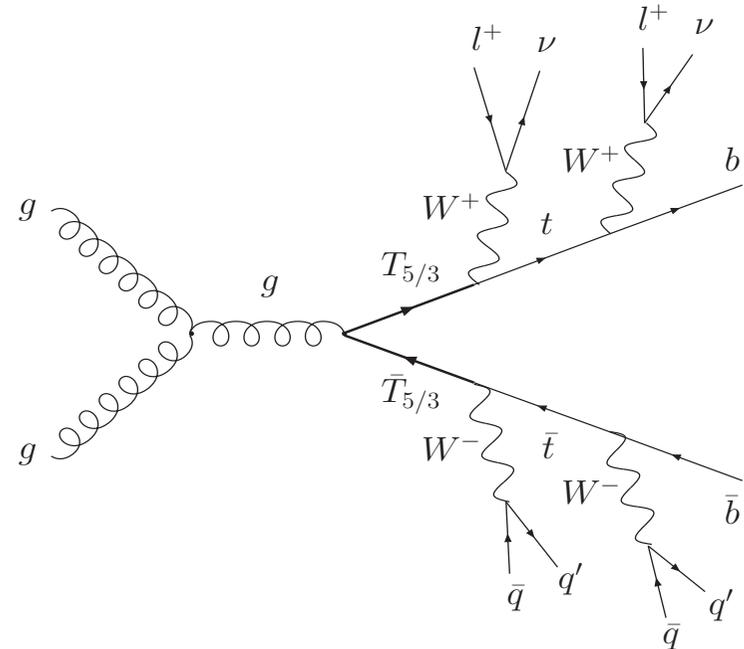


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Top partner with charge 5/3e

- Focus on same-sign dilepton channel
 - Leptonic W bosons from same $T_{5/3}$
- Understanding same-sign fake and prompt lepton background
 - Non-prompt background determined on data
 - Prompt: rare decays from MC:
 - WW , ZZ , $t\bar{t}W$, $t\bar{t}Z$, WWW



src: CMS PAS B2G-12-012

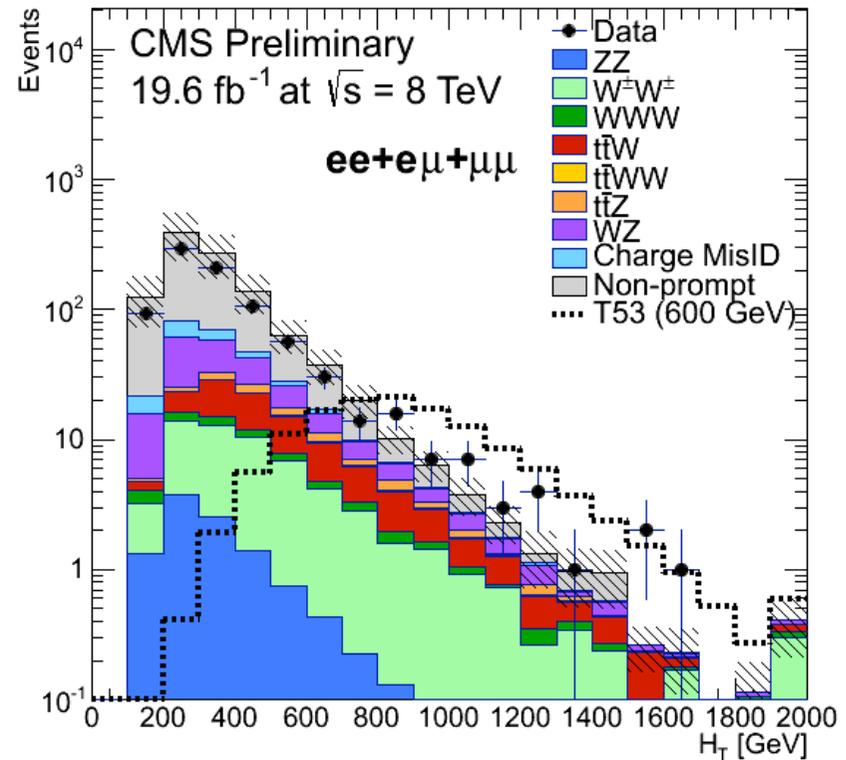


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Top partner with charge $5/3e$

- Very busy environment: require same-sign leptons outside Z boson window and $HT > 900$ GeV
- High-mass leads to merging of objects:
 - Substructure considered as V-tagged jets or top-tagged jets



src: CMS PAS B2G-12-012



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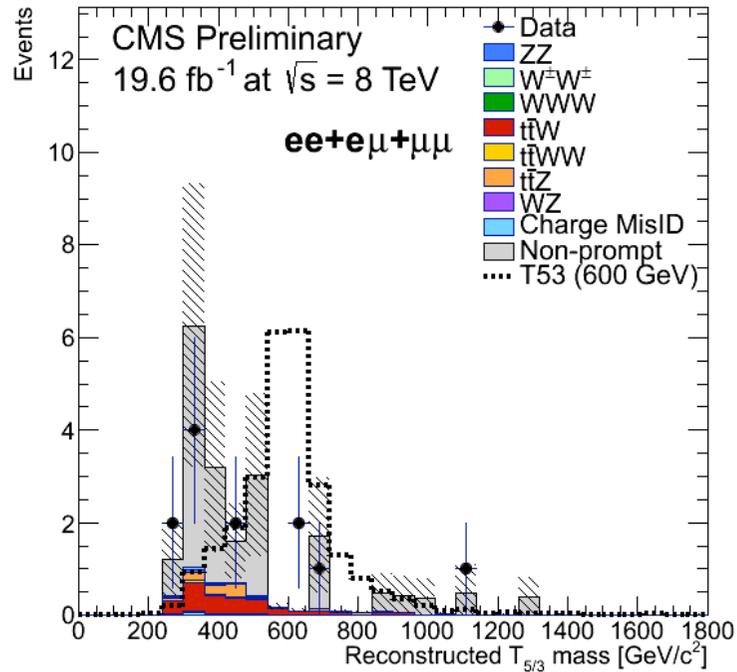


Freya Blekman - Wine & Cheese Seminar - Fermi National Accelerator Laboratory

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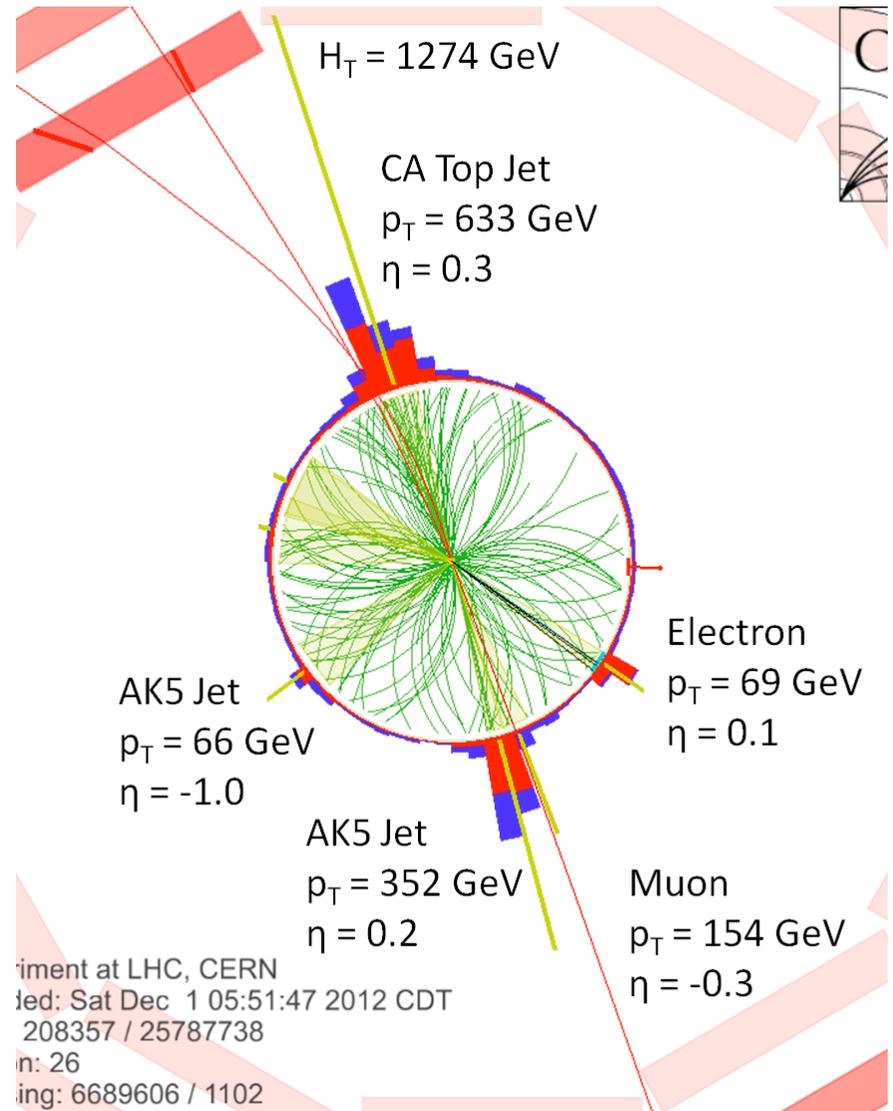
59

Top partner with charge 5/3e



Reconstructed T5/3 mass
considered also from
substructure tools

src: CMS PAS B2G-12-012



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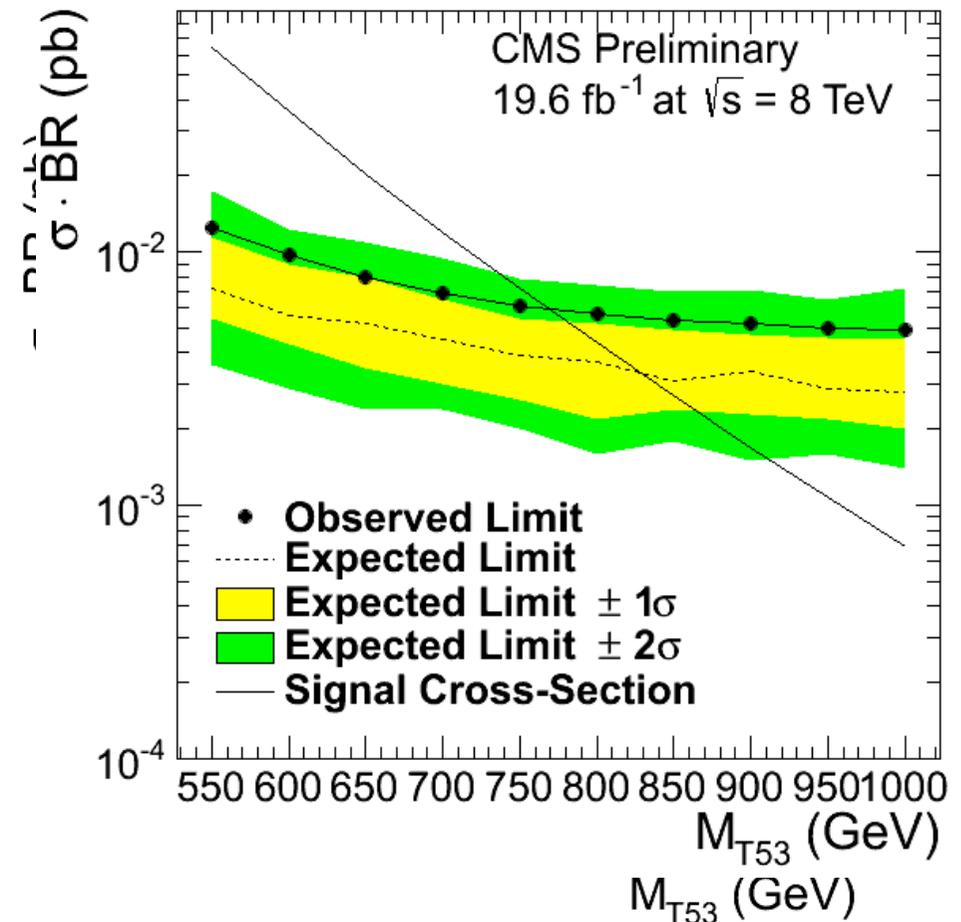


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Top partner with charge 5/3e

- SS lepton events with $H_T > 900$ GeV:
 - 11 observed
 - 6.6 ± 2 expected
- Cross section limits exclude $q=5/3e$ top partners with mass up to $770 \text{ GeV}/c^2$



src: CMS PAS B2G-12-012



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Composite top



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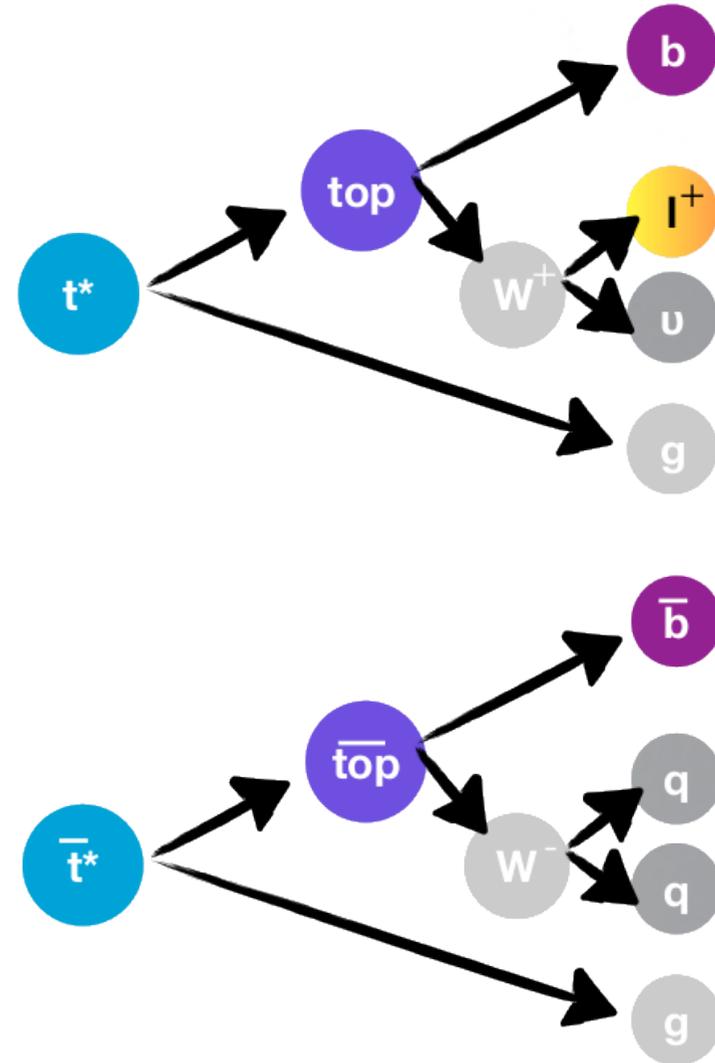
$(t+j)(t+j)$ resonant search

- Composite top quark would mean excited states possible

- Pair produced spin 3/2 fermion
- 100% decay t^* to tg assumed

- References:

- Dicus, Gibbons, and Nandi, arXiv:hep-ph/9806311
- Hassanain, March-Russel, and Rosa, JHEP 0907 (2009)
- Stirling and Vryonidou, JHEP 1201 (2012)



src: CMS PAS B2G-12-014



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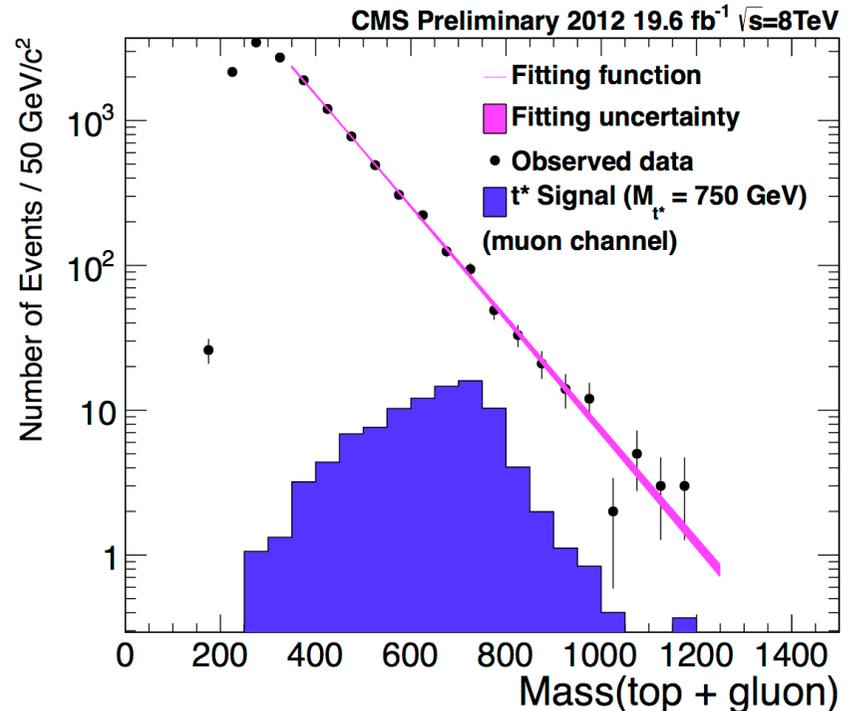


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$(t+j)(t+j)$ resonant search

- $top+j$ mass as discriminating variable
- Modified version of HitFit mass fitter with additional constraints on $t+j$ mass
- Fully data-driven: Fitting to resonance on falling mass distribution



src: CMS PAS B2G-12-014

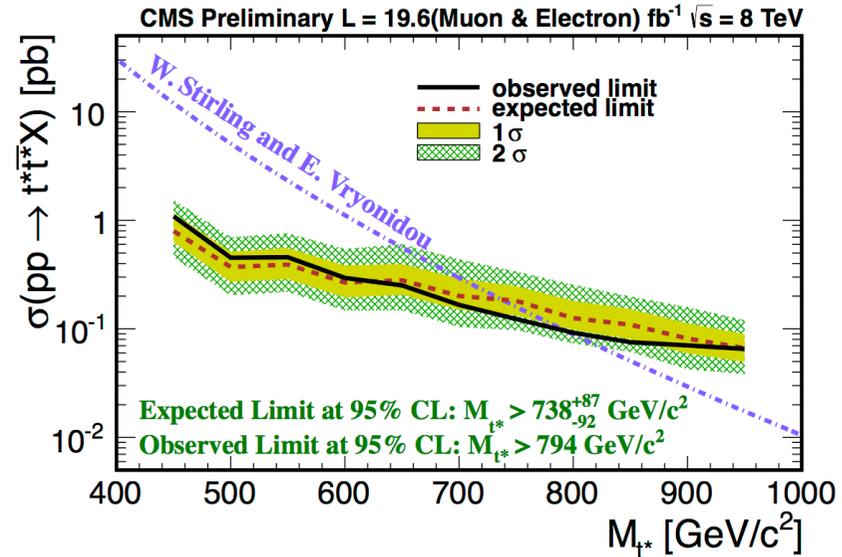


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$(t+j)(t+j)$ resonant search

- First search for particle decaying to $(t+j)(t+j)$
- data driven method
 - Leading systematic uncertainties are JES & MC statistics of signal and parton density functions
- Many possible interpretations



- Welcome feedback from pheno community on interpretation for paper currently in preparation

src: CMS PAS B2G-12-014



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Short advertisement

- The Beyond-two-generations group is a small physics group in CMS
- We have open topics for experimentalists
 - Including nice thesis topics and analyses a postdoc can make a visible contribution
 - CMS internal B2G page has more details (linked from iCMS)
- In addition, we are seeking more interaction with the pheno community
 - Particularly feedback on how to best present our results is extremely welcome



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References:

Search for Z' to $t\bar{t}$ in $l+jets$, CMS PAS B2G-12-006, Preliminary 8 TeV 19.6 /fb 
Search for $5/3e T'$, CMS PAS B2G-12-012, Preliminary 8 TeV 19.6 /fb
Search for W' in $l+jets$ events, CMS PAS B2G-12-010, Preliminary 8 TeV 19.6 /fb
Search for t^*t^* production, CMS PAS B2G-12-014, Preliminary 8 TeV 19.6 /fb
Search for T'/B' in tri/multilepton events, CMS PAS SUS-12-027, Preliminary 8 TeV 9.2 /fb

Search for B'/T' in $l+jets$ events, JHEP 01 (2013) 154, B2G-12-004, 7 TeV 5 /fb
Search for Z' to $t\bar{t}$ in dileptons, Submitted to Phys. Rev. D, TOP-11-010, 7 TeV 5 /fb
Search for Z' to $t\bar{t}$ in all-jets, JHEP 1209 (2012) 029, EXO-11-006, 7 TeV 5 /fb

<https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsB2G>

Expect many more results in the very near future!

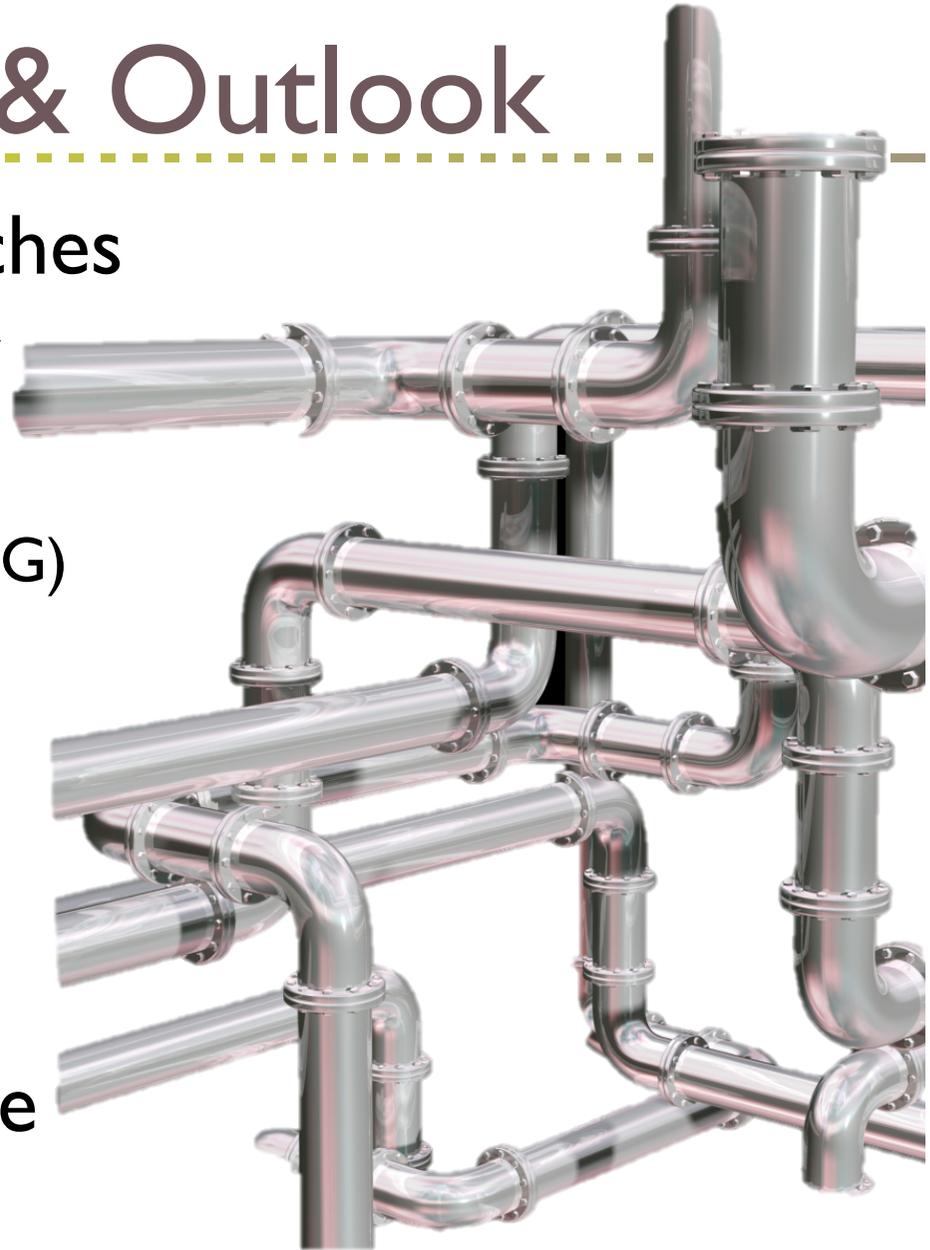


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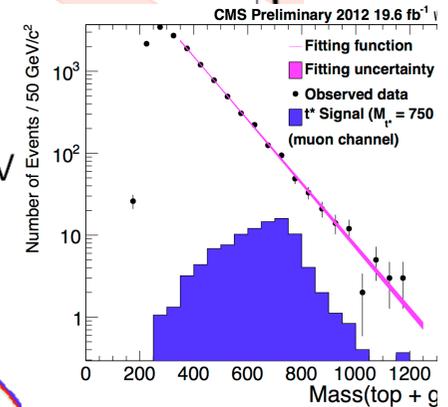
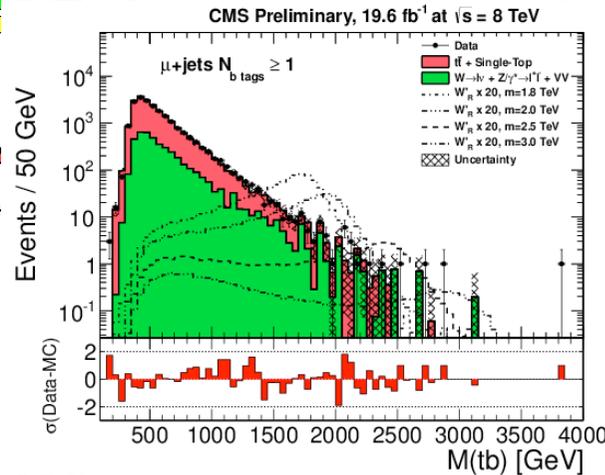
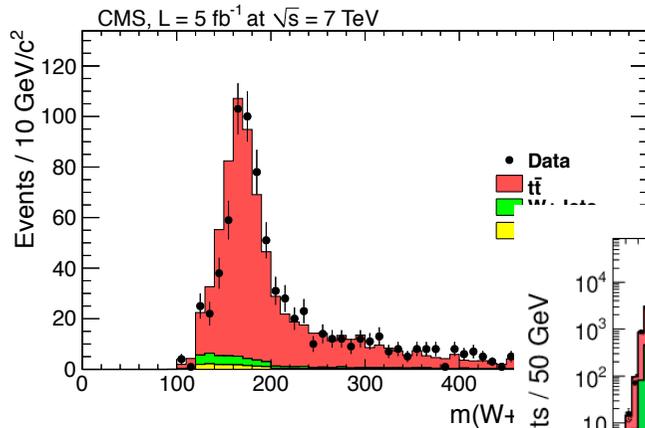


Conclusion & Outlook

- CMS has established searches program in the top sector
 - Top-like Exotica
 - = Beyond two generations (B2G)
- Pushing the envelope:
 - very stringent limits
 - spearheading new reconstruction techniques
- Many 8 TeV analyses in the pipeline.

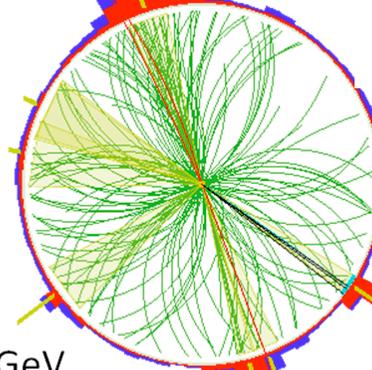


Thank you



$H_T = 1274 \text{ GeV}$

CA Top Jet
 $p_T = 633 \text{ GeV}$
 $\eta = 0.3$

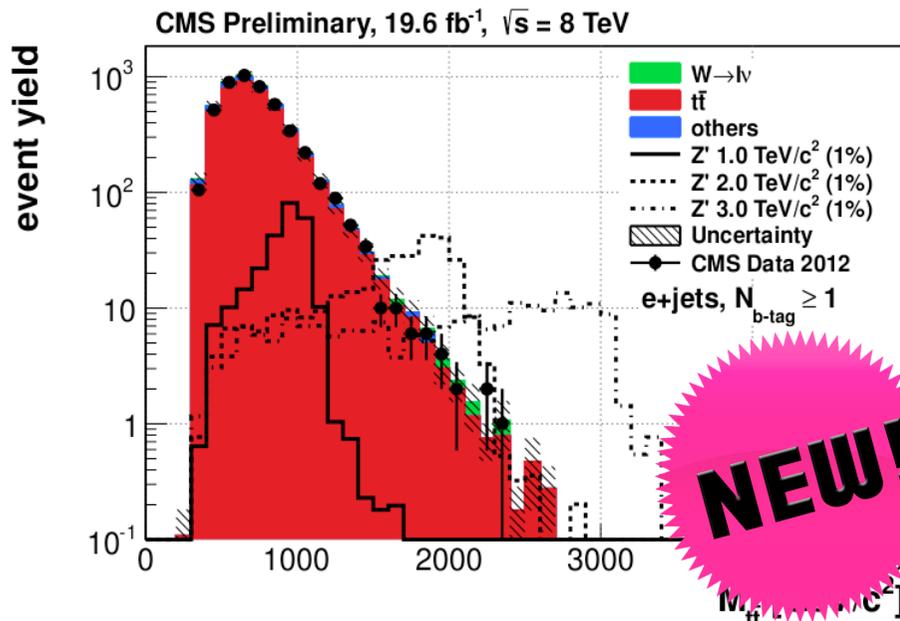


Electron
 $p_T = 69 \text{ GeV}$
 $\eta = 0.1$

AK5 Jet
 $p_T = 66 \text{ GeV}$
 $\eta = -1.0$

AK5 Jet
 $p_T = 352 \text{ GeV}$
 $\eta = 0.2$

Muon
 $p_T = 154 \text{ GeV}$
 $\eta = -0.3$



Experiment at LHC, CERN
 Date: Sat Dec 1 05:51:47 2012 CDT
 ID: 208357 / 25787738
 Time: 00:26
 Group: 6689606 / 1102



April 19, 2013

backup

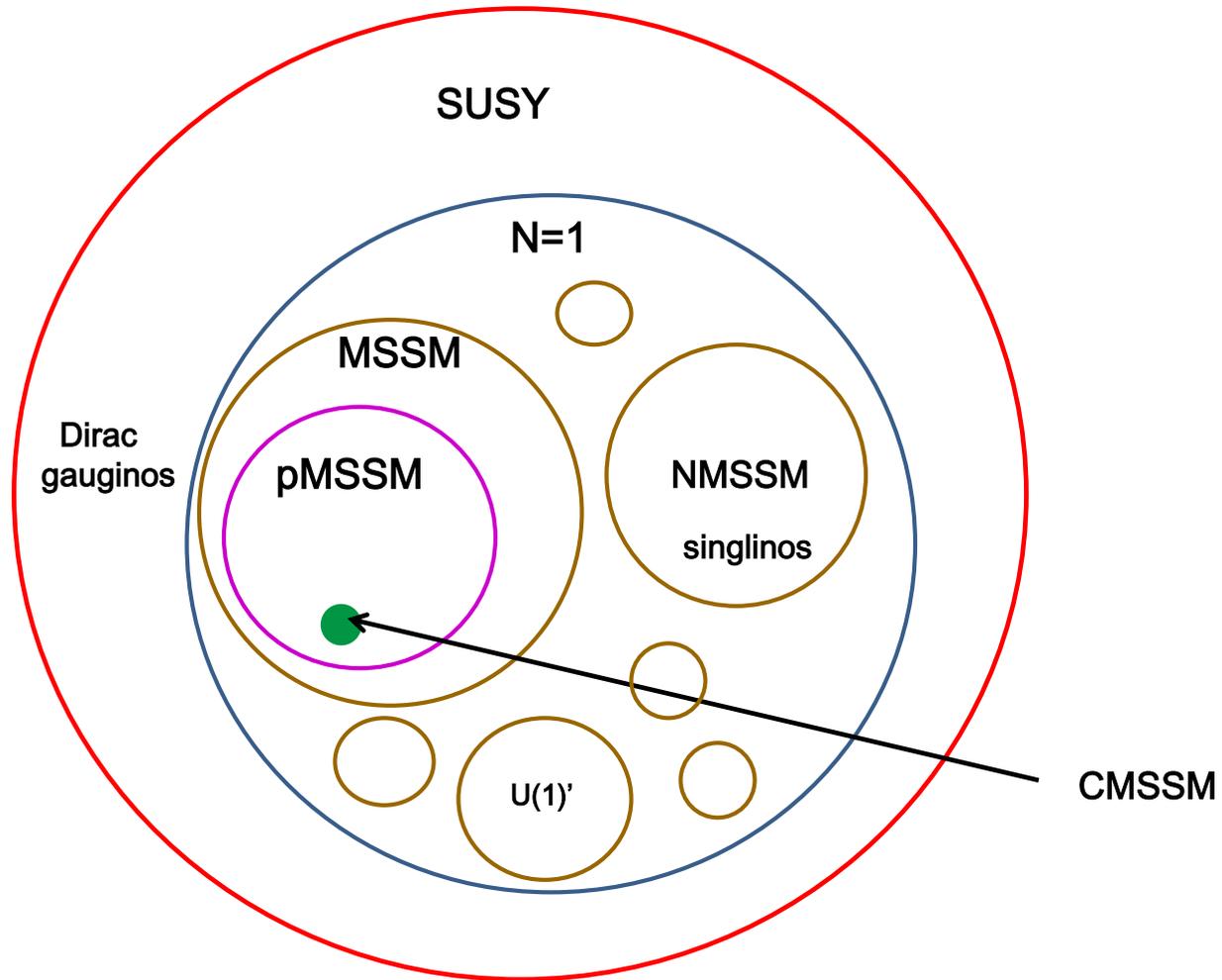


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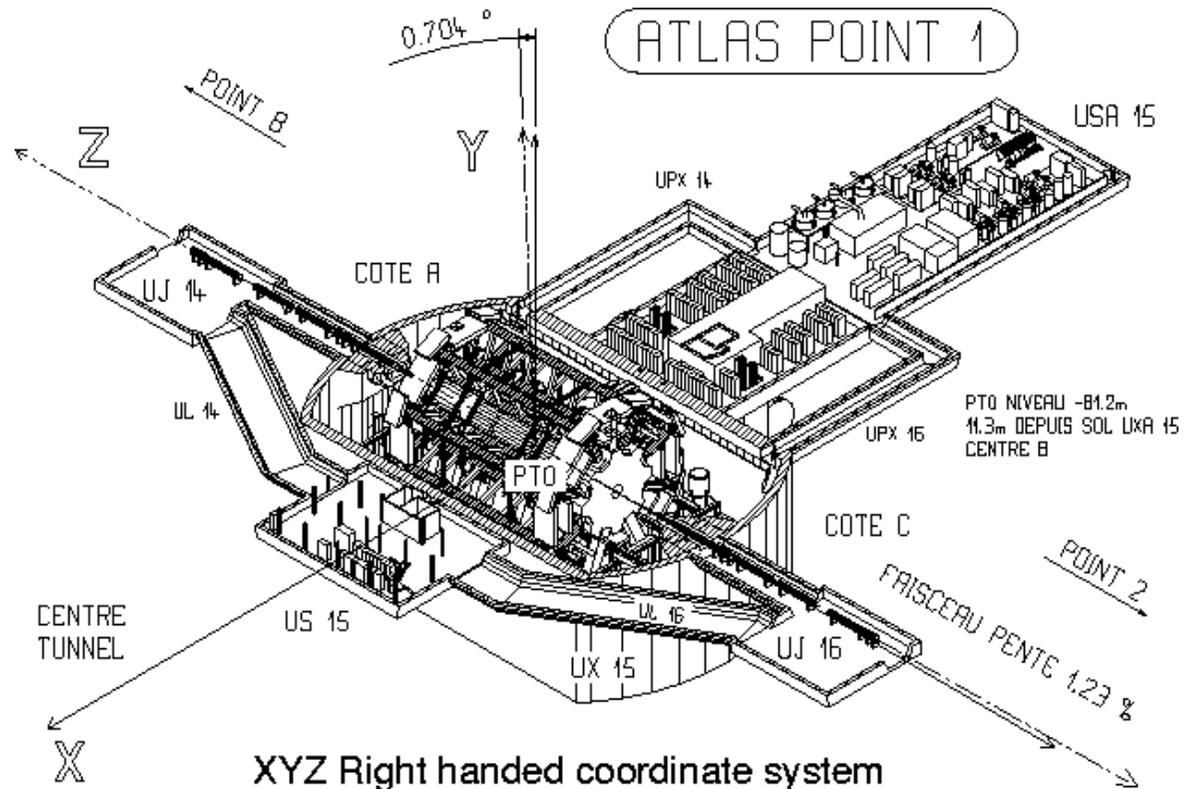
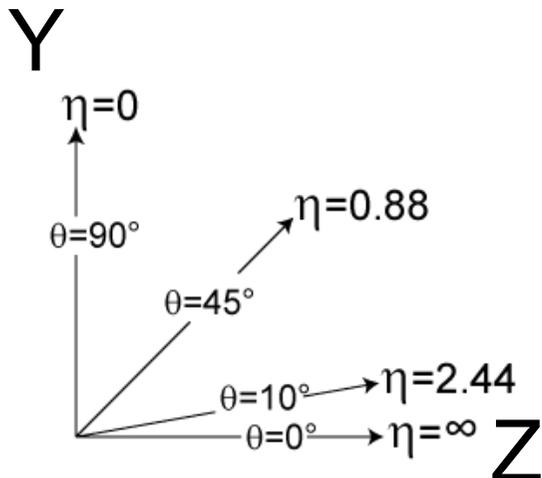
MSSM vs SUSY



Typical GPD coordinate system

$$\eta = -\ln \left[\tan \left(\frac{\theta}{2} \right) \right]$$

$$y = \frac{1}{2} \ln \left(\frac{E + p_L}{E - p_L} \right)$$



XYZ Right handed coordinate system
with z in beam direction

+ cylindrical coordinates around Z axis

Typical inputs of 4-vector:

p_T , ϕ , η , E

Tau ID

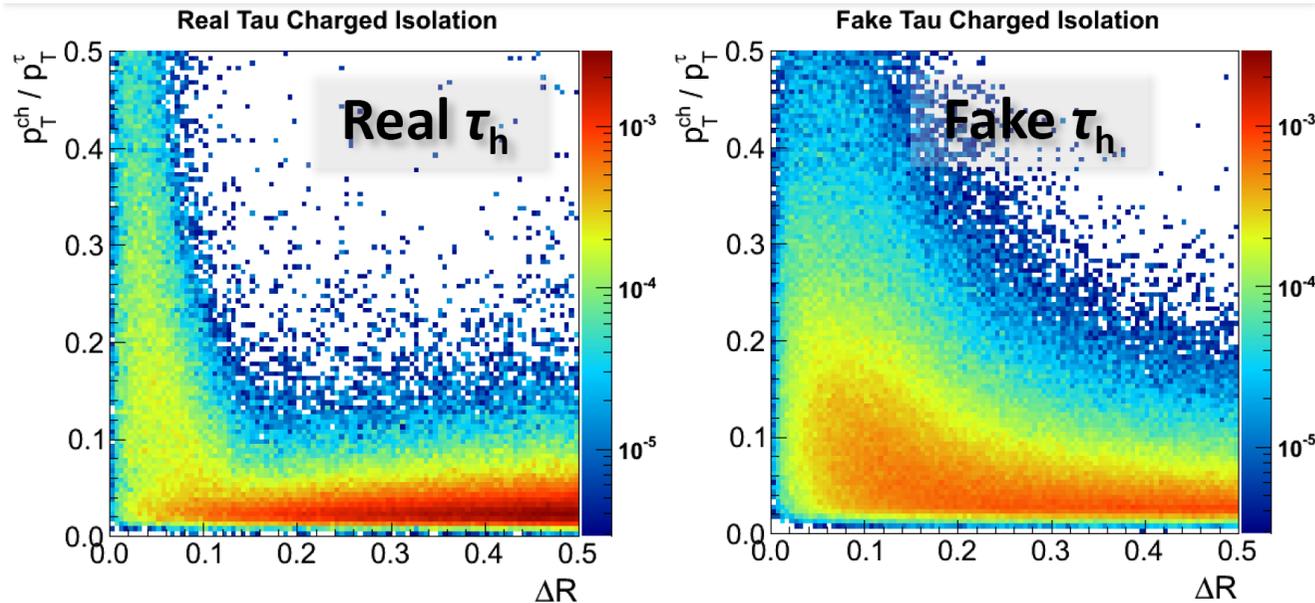
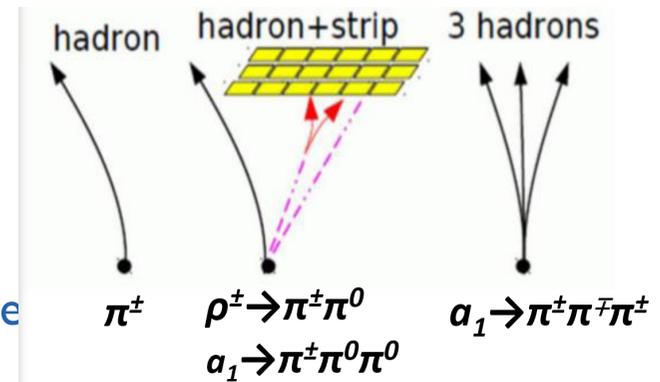
Identification

Hadronic taus reconstructed based on decay modes: charged hadrons + EM strips

Isolation

New in 2012

Multivariate isolation using relative Σp_T of particle flow candidates in concentric rings around the τ



Overview B'/T' (by Sadia Khalil)

Status @ 7 TeV

- CMS 4th generation searches @7 TeV

<https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsB2G>
<https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO>

- ▶ **t'** pair search

- lepton+jets channel
- dilepton channel

$$t't' \rightarrow WbWb \rightarrow l\nu bbq\bar{q}$$

$$t'\bar{t}' \rightarrow WbW\bar{b} \rightarrow l\nu bl\bar{\nu}\bar{b}$$

[PLB.2012.10.038, EXO-11-099](#)

[PLB.2012.07.959, EXO-11-050](#)

- ▶ **b'** search

- lepton+jets channel
- same sign dilepton + trilepton channel

$$b'\bar{b}' \rightarrow WtW\bar{t} \rightarrow bWWbWW$$

[arXiv:1210.7471 \(accept by JHEP\), B2G-12--004](#)

[arXiv:1204.1088 \(sub to JHEP\)](#)

- ▶ **Inclusive t' and b' search**

- singly produced
- pair produced

$$t'b \rightarrow bWb$$

$$b't \rightarrow tWbW \rightarrow bWWbW$$

$$b't' \rightarrow tWbW \rightarrow bWWbW$$

$$t'\bar{t}' \rightarrow bWbW$$

$$b'\bar{b}' \rightarrow tWtW \rightarrow bWWbWW$$

[arXiv:1209.1062 \(accept by PRD\)](#)

- ▶ **T vector like pair**

- lepton+jets
- trilepton channel

$$T\bar{T} \rightarrow tZ\bar{t}Z \rightarrow b\bar{b}WWZZ$$

[arXiv:1210.7471 \(accept by JHEP\), B2G-12--004](#)

[PRL.107.271802 EXO-11-005](#)

- ▶ **B vector-like pair**

$$B\bar{B} \rightarrow bZ\bar{b}Z$$

[CMS-PAS-EXO-11-066](#)

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Thursday, January 17, 2013

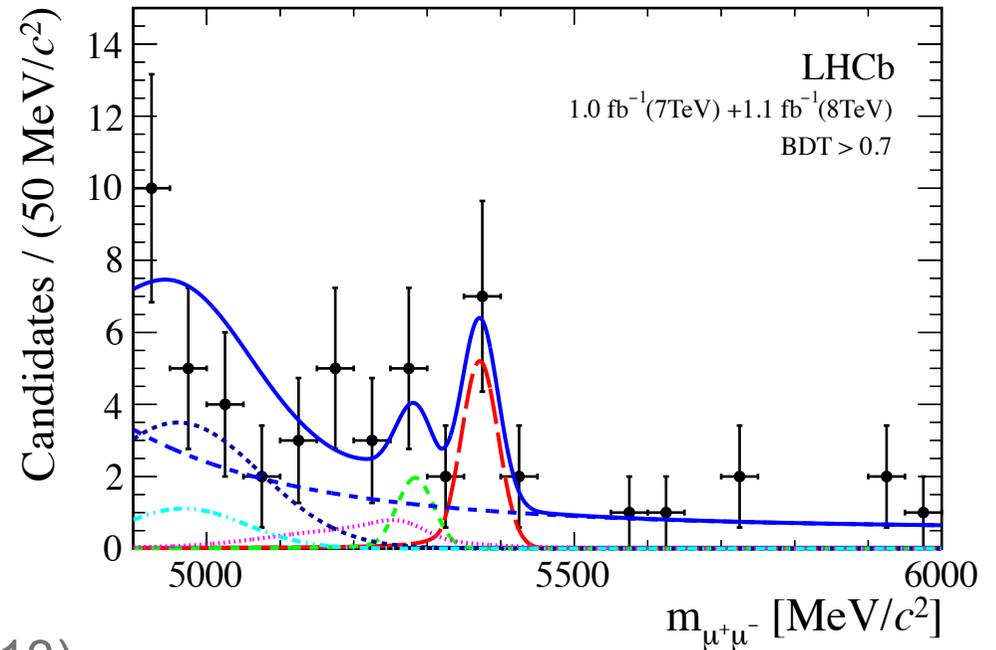
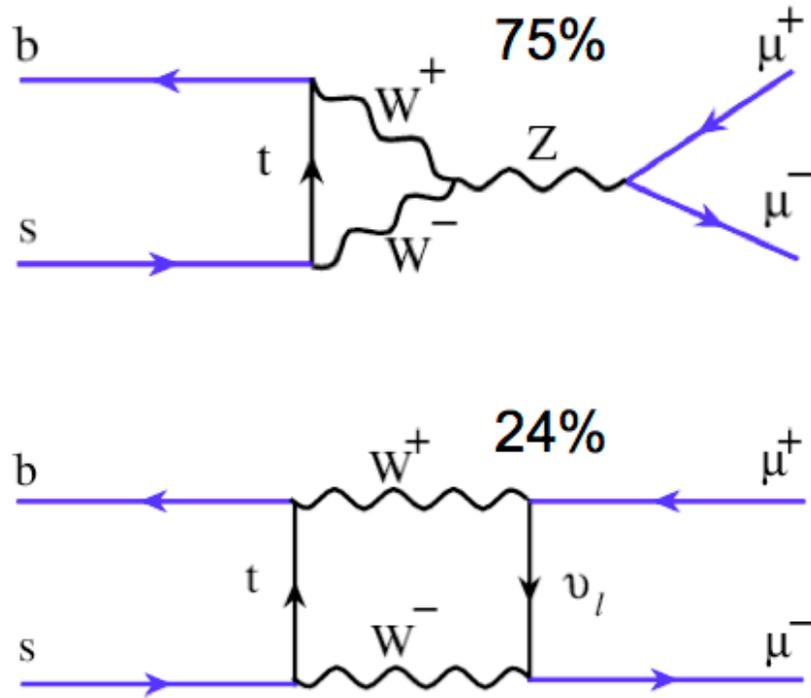


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But not just Higgs...

- B_s to $\mu\mu$ close to SM is extremely strong limit to all top partner-loving model building!



src: Phys. Rev. Lett. 110, 021801 (2013)



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