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

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Top-Like Beyond-the-Standard-model physics at CMS

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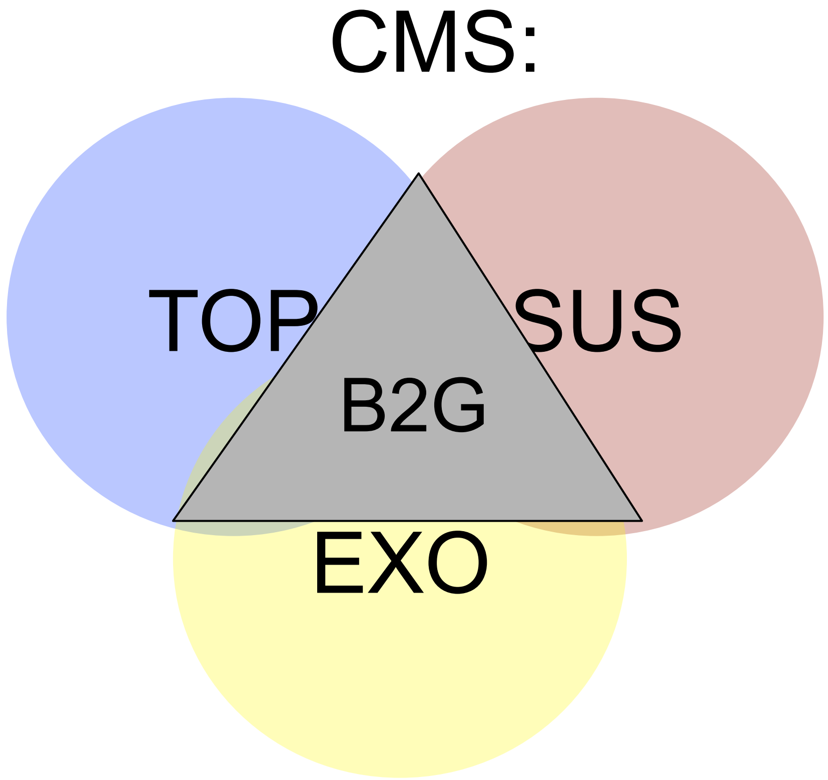
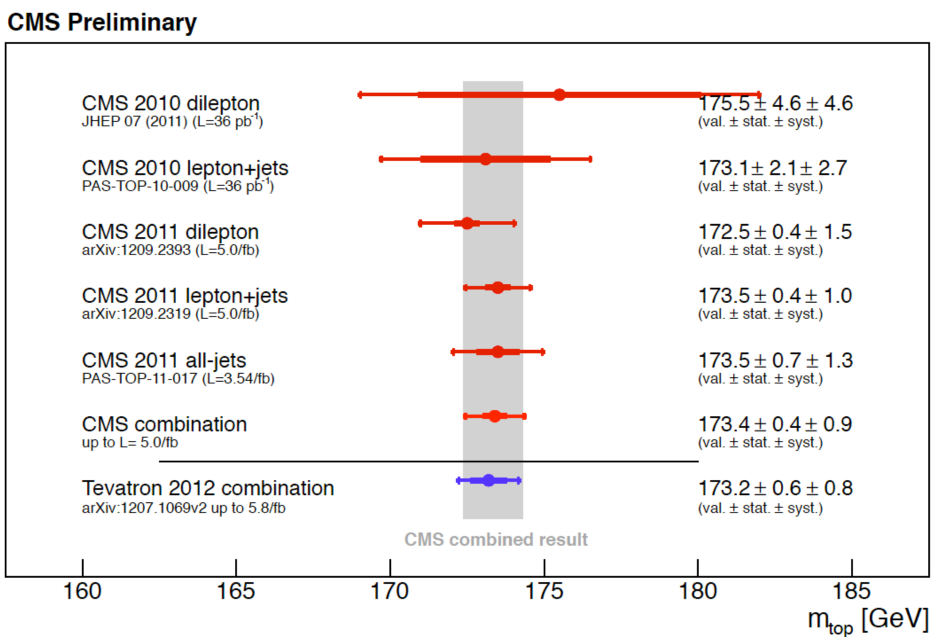
Beyond two Generations group

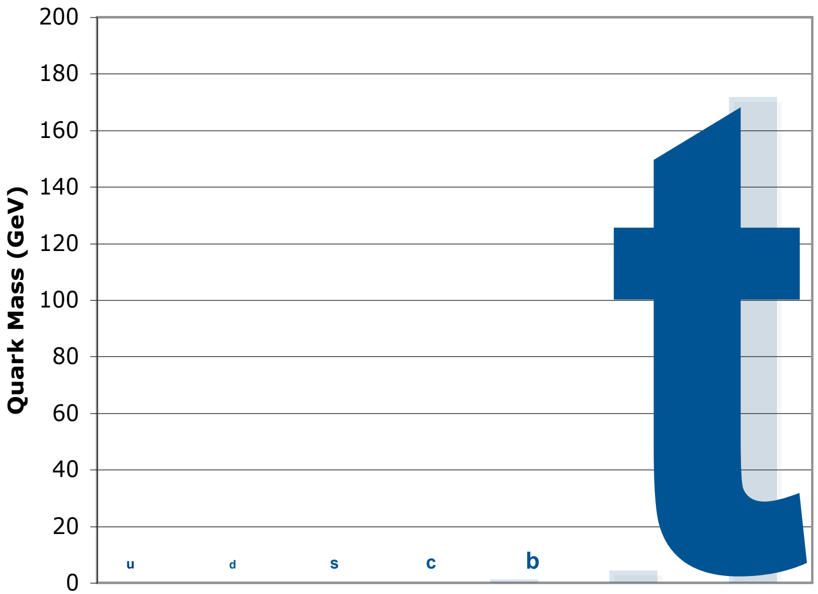


- Gives interesting insight in how collaborations work in practice
- ATLAS has found different solution to same problem

The top quark

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

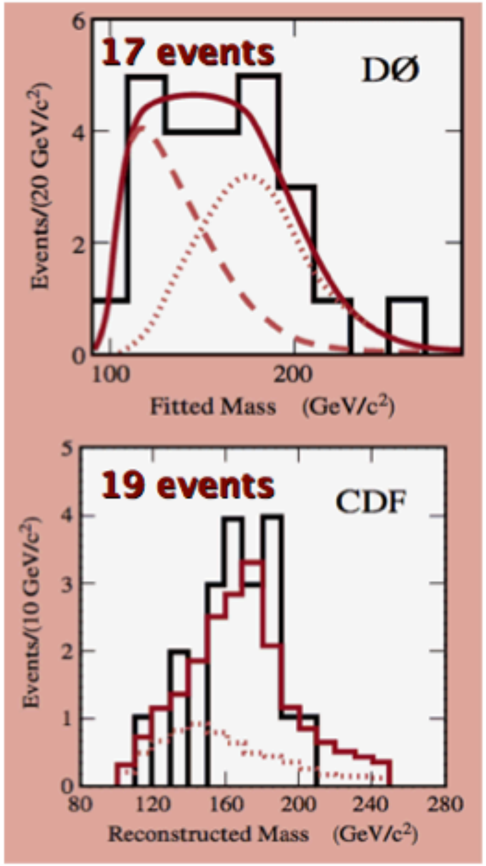




History of the top quark

discovery

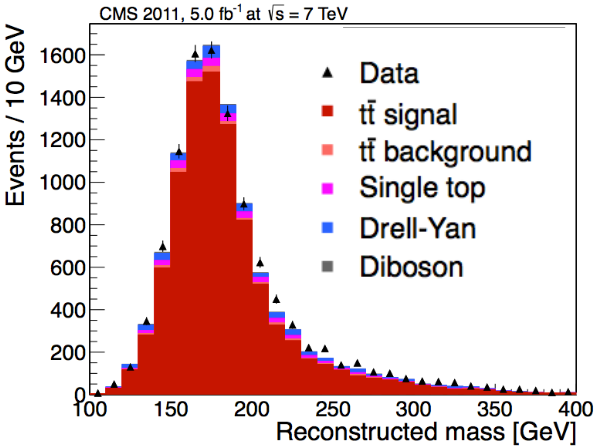
PRL 74, 2632 (1995)
PRL 74, 2626 (1995)



1995, CDF and DØ experiments, Fermilab

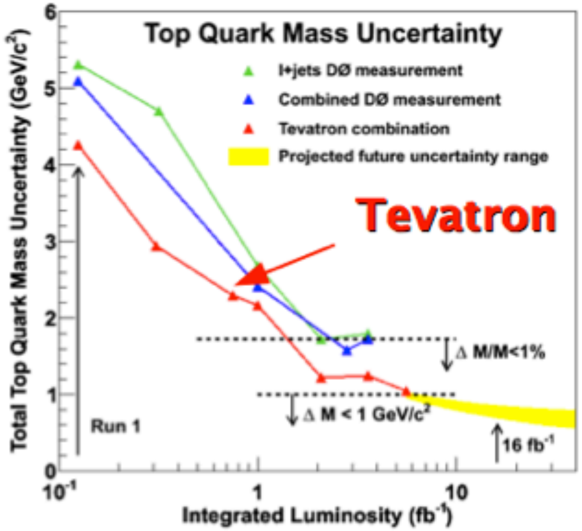
today

10000s of events



LHC: top quark factory

precision



searches

History of the top quark

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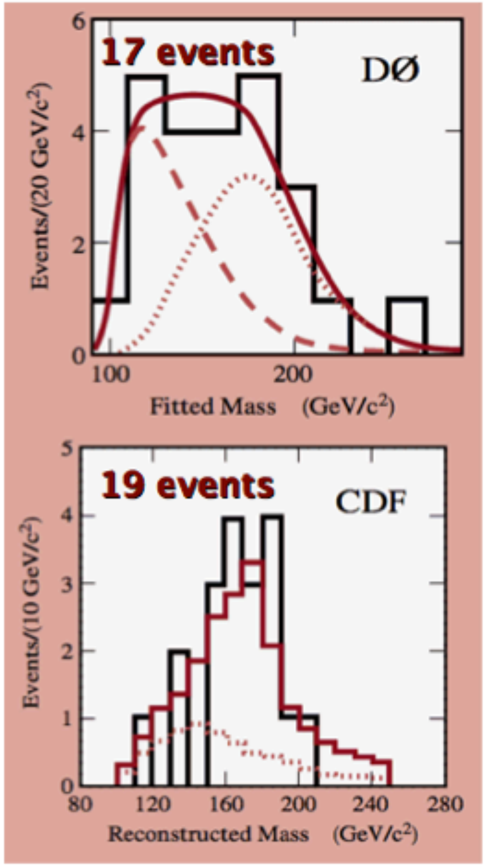

1995, CDF and DØ experiments, Fermilab

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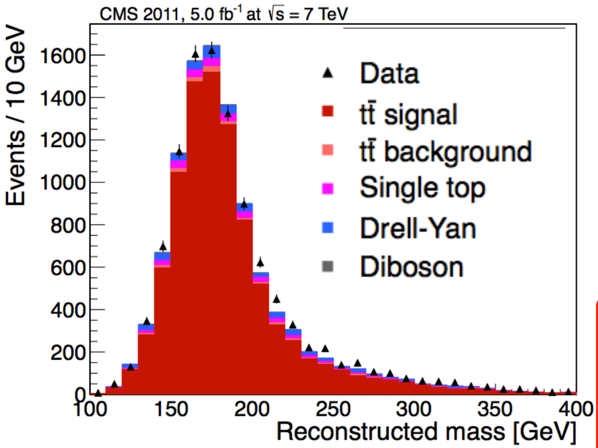

LHC: top quark factory

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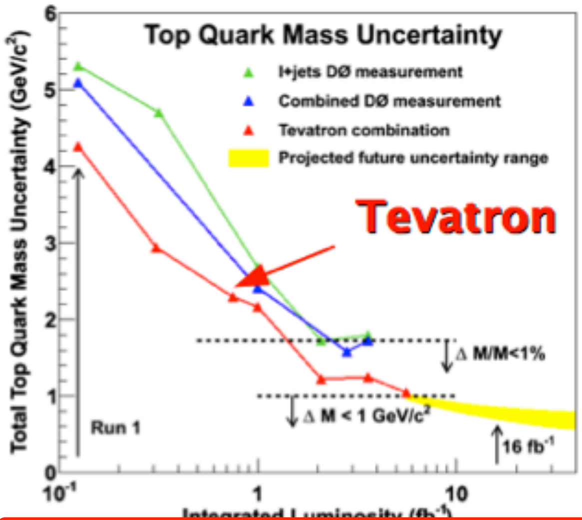
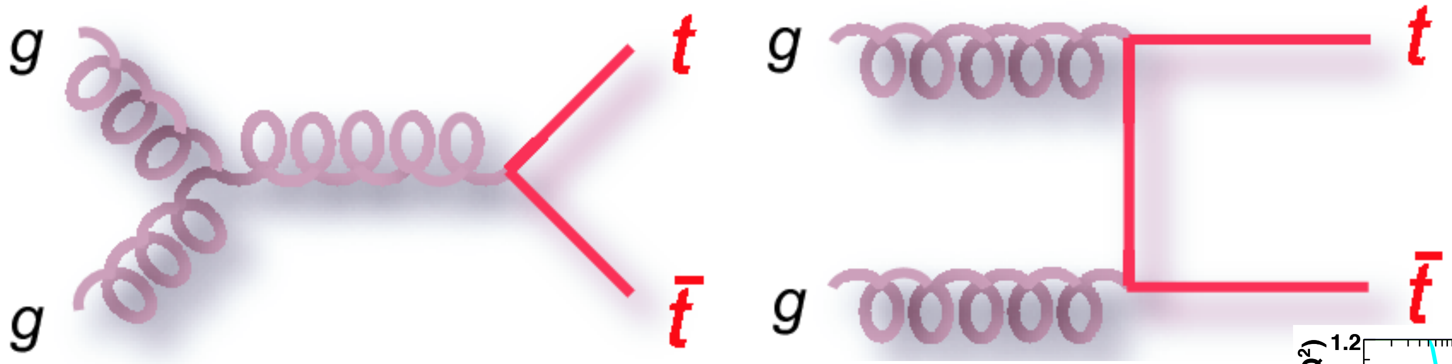


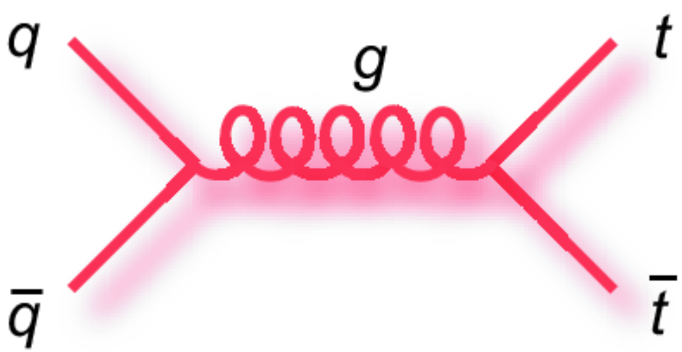
searches

Top pair production at the LHC

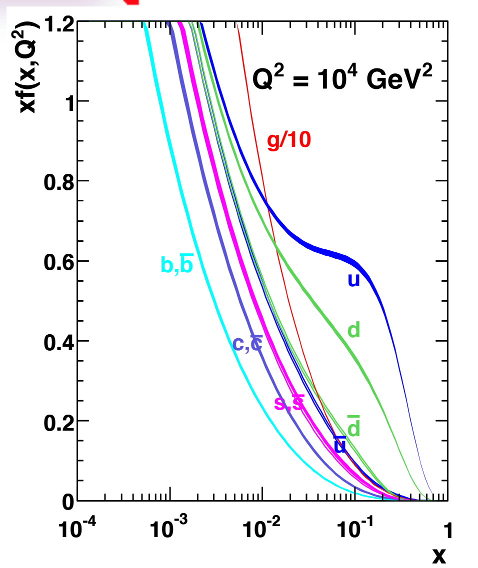
- Pair production in 8 TeV pp collisions:



~90%

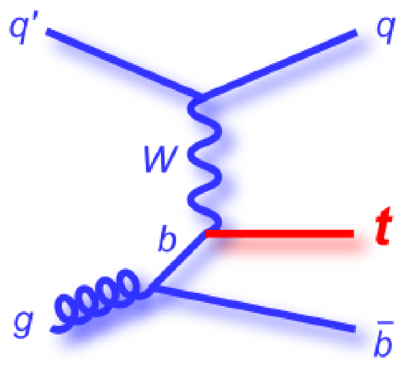


~10%

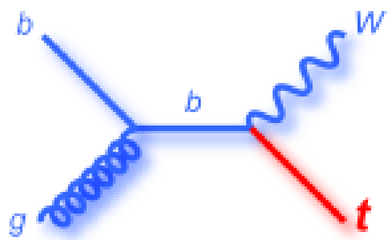


MSTW08:Eur.Phys.J.C63:189-285

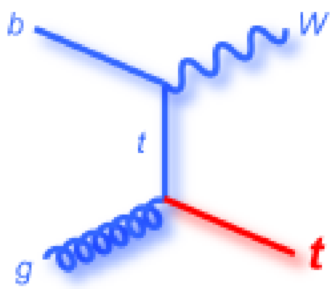
Single Top production

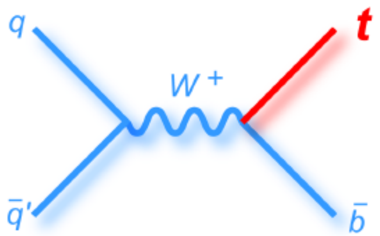


t-channel



tW-channel



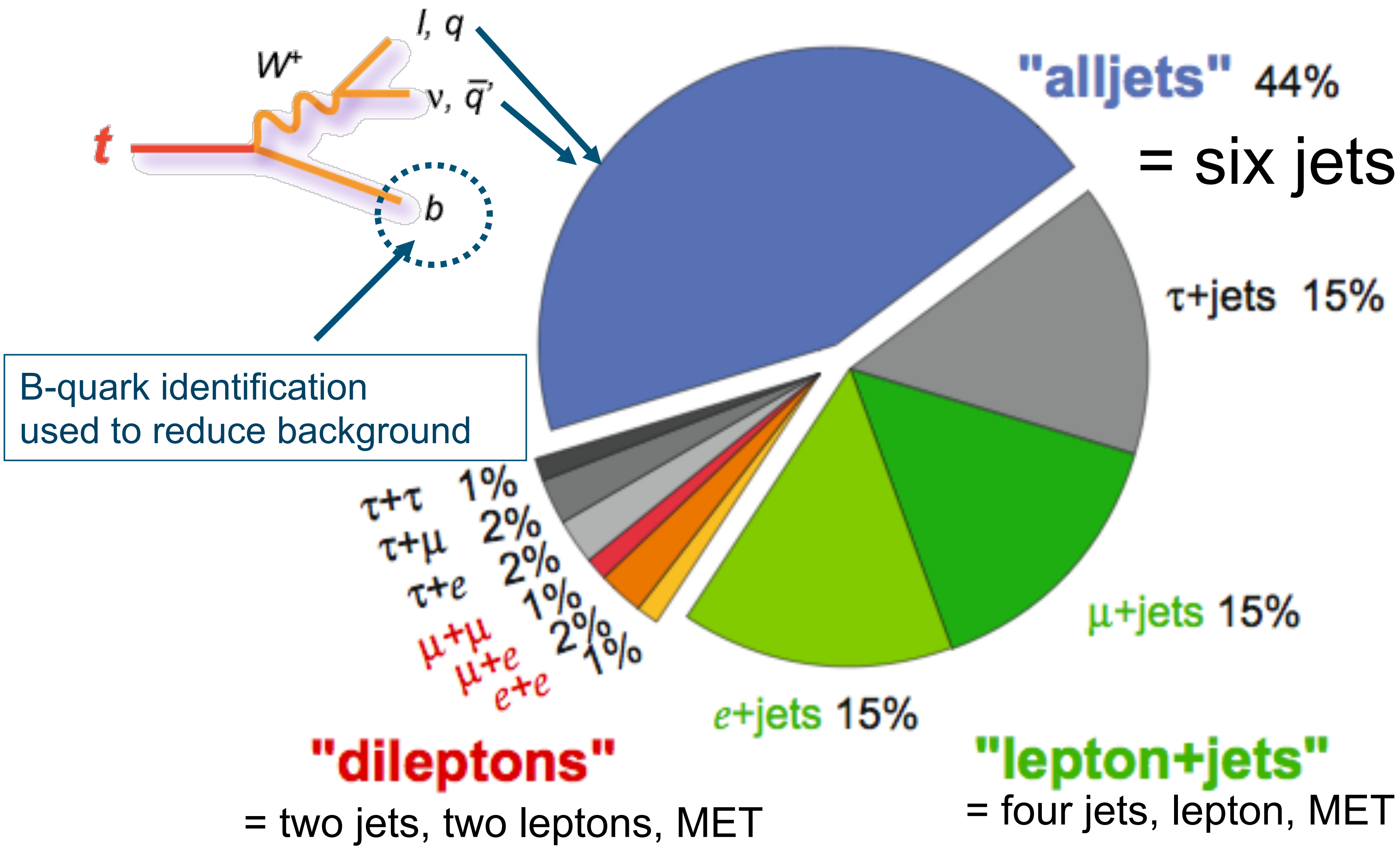


s-channel

- Electroweak production of top quarks

- Dominant channels at LHC @ 8 TeV:
  - t-channel: 87 pb
  - tW channel: 22 pb
  - s-channel: 5.6 pb

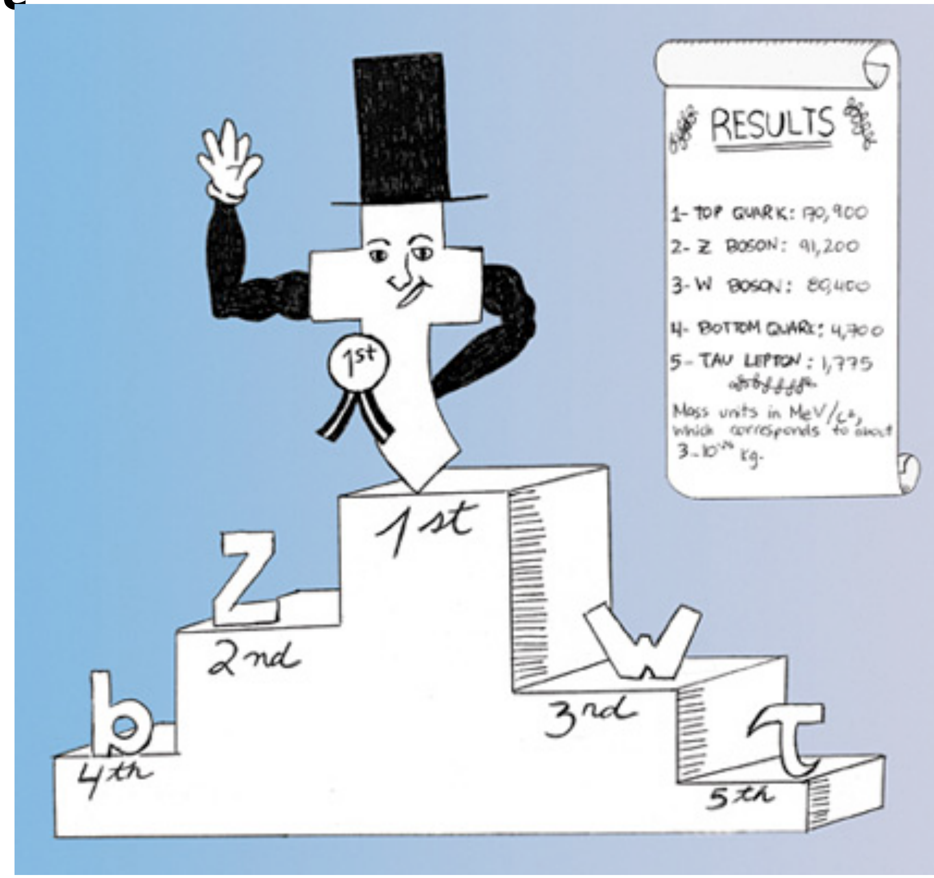
Top pair branching fractions



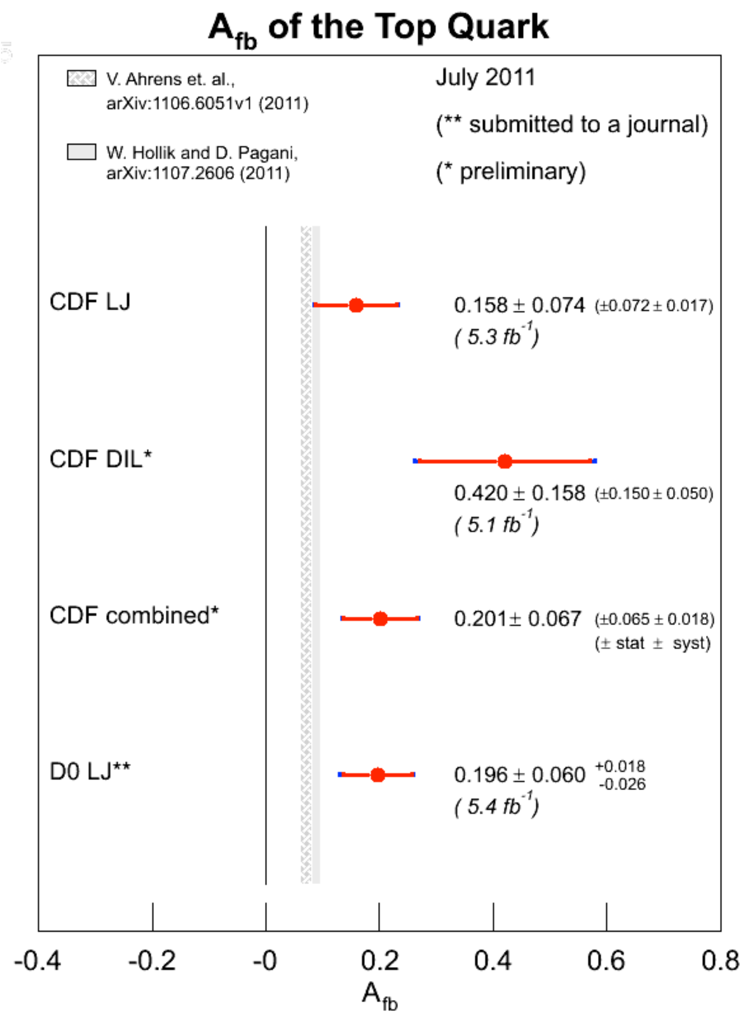
Top quark – special?

- Many models predict that top is special in order to explain large mass

- Or top quark has special role because of its large mass



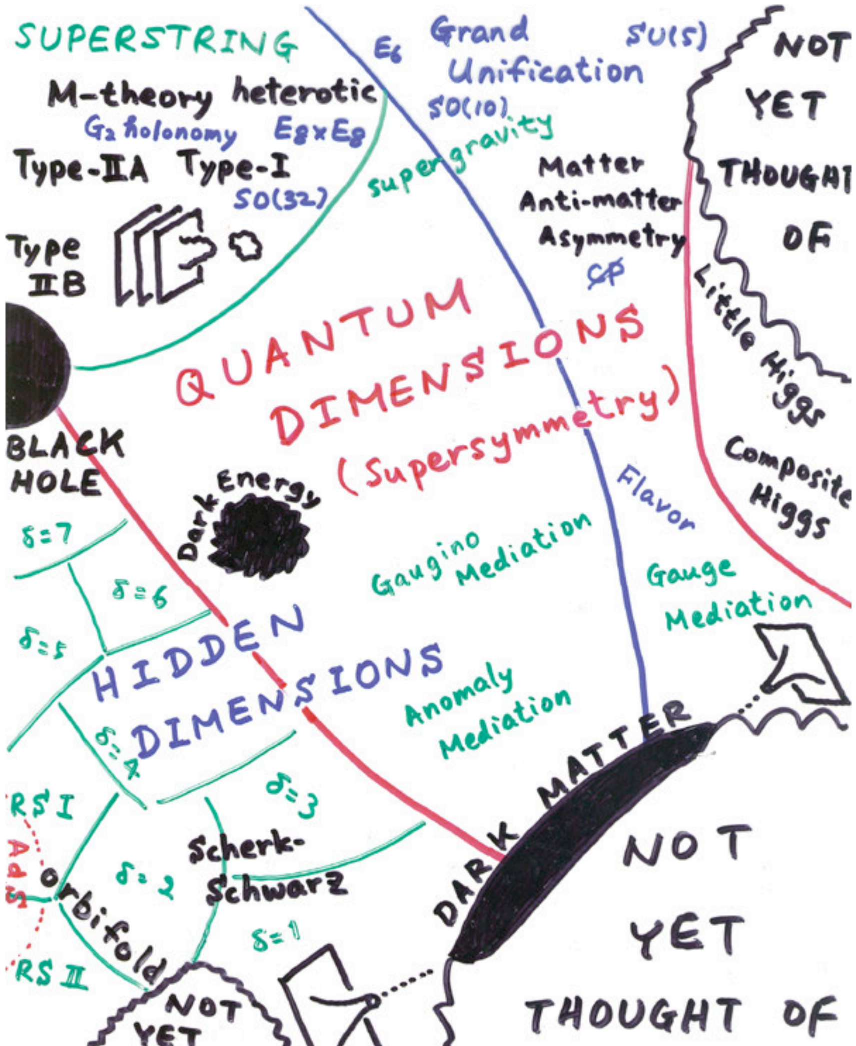
A_{FB} – portal to new physics?



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

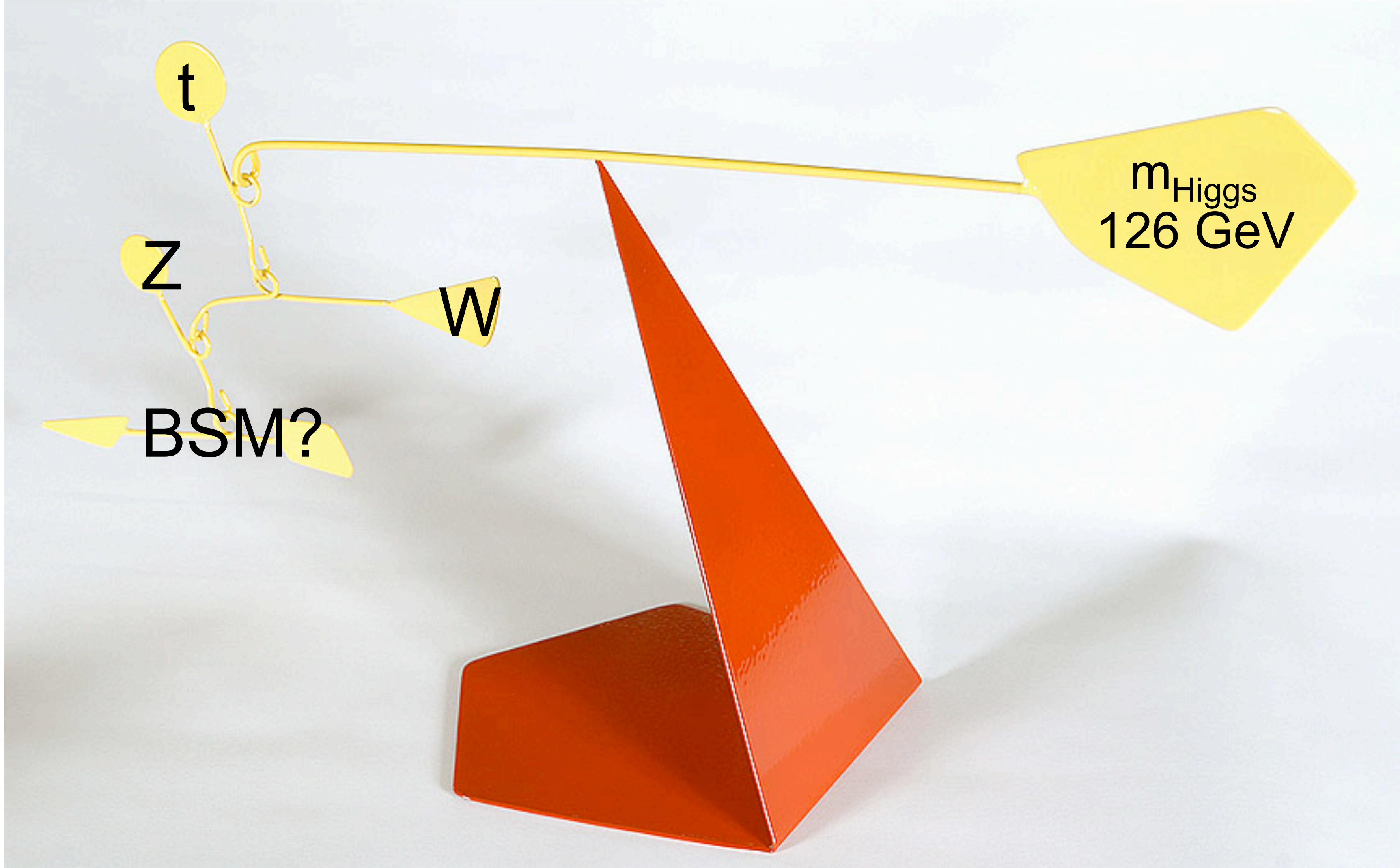
17 SM parameters do not constrain creativity

- SUSY in all it's 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"?



src: H.Murayama

Little Hierarchy problem, Naturalness



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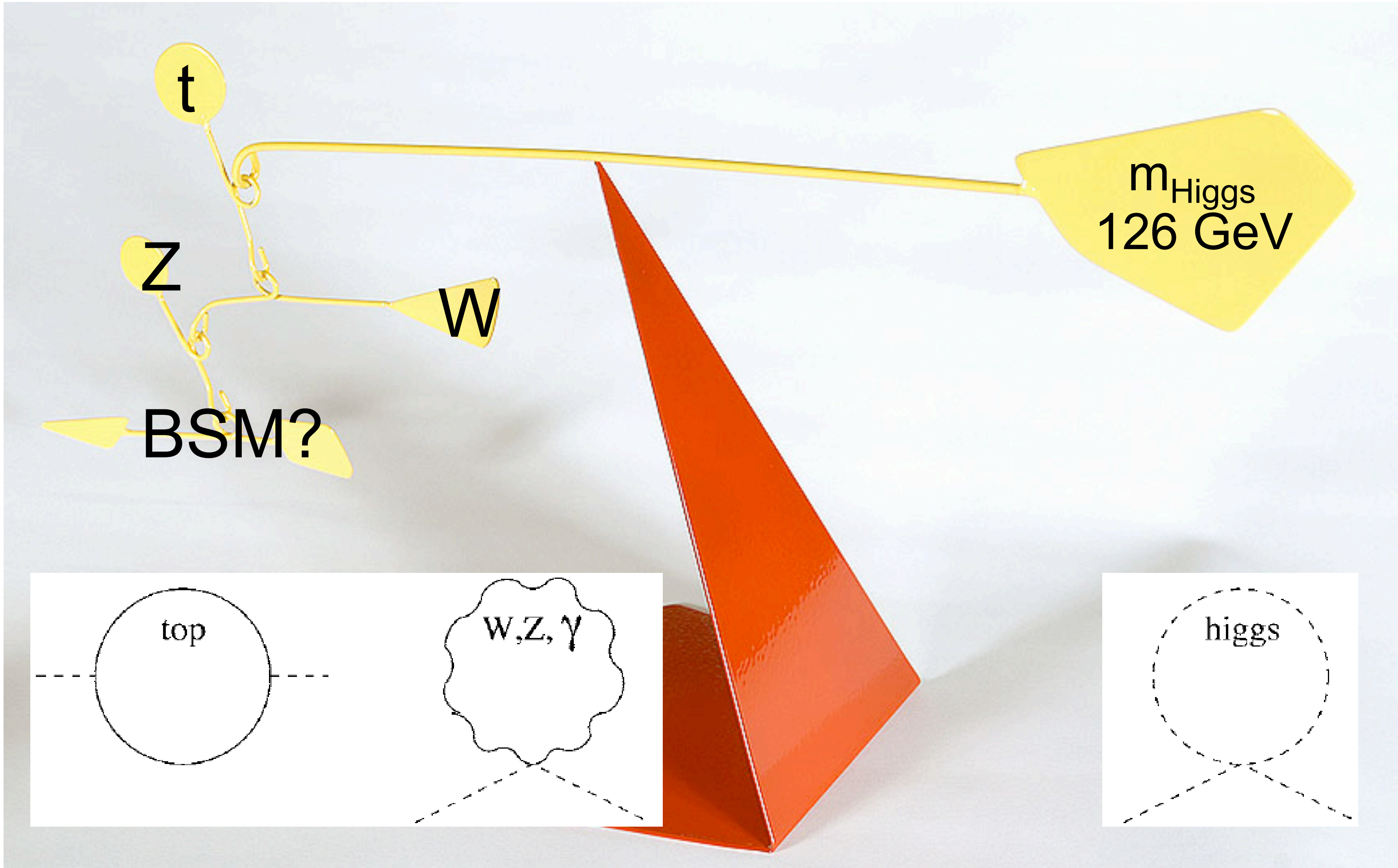

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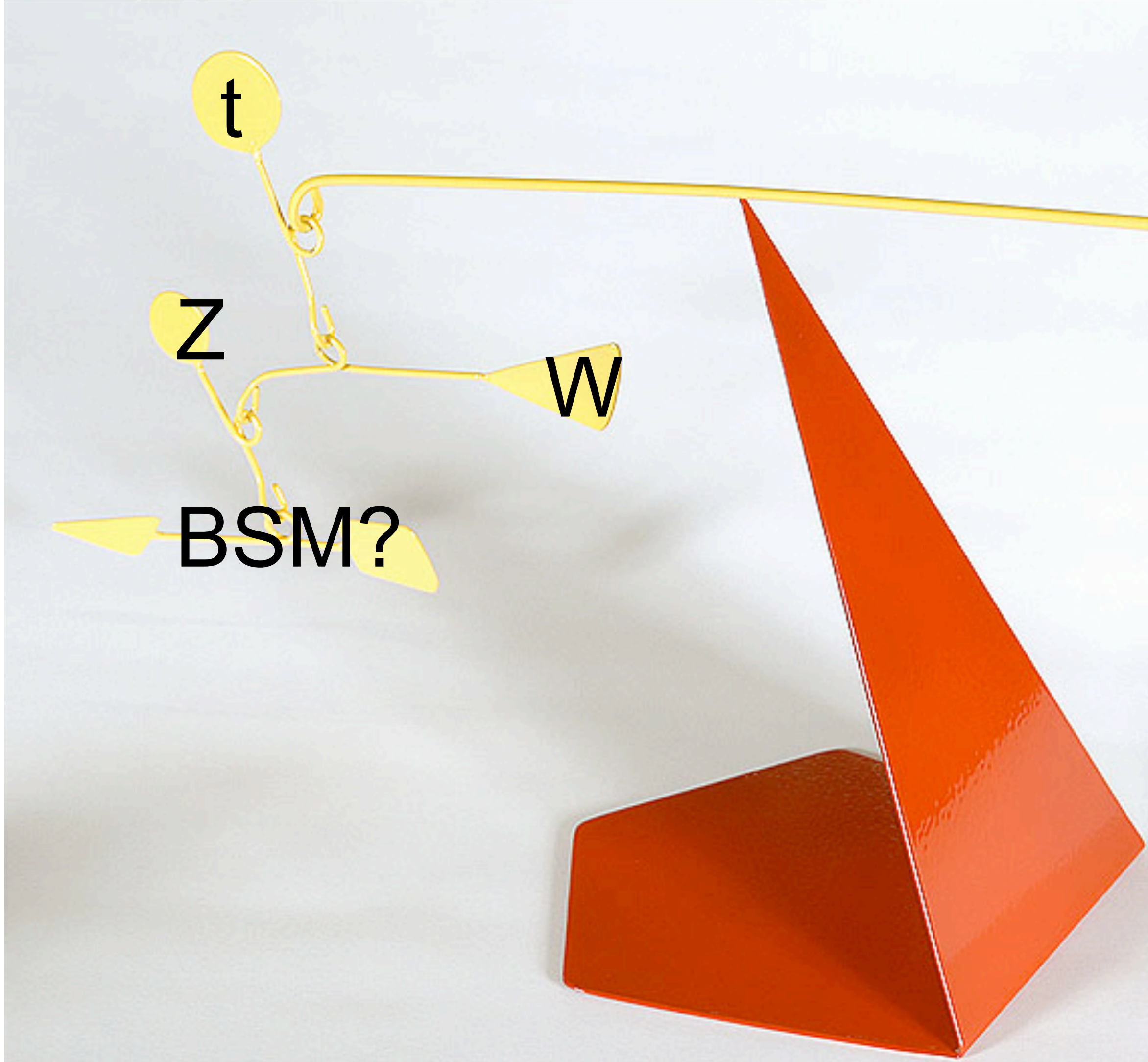
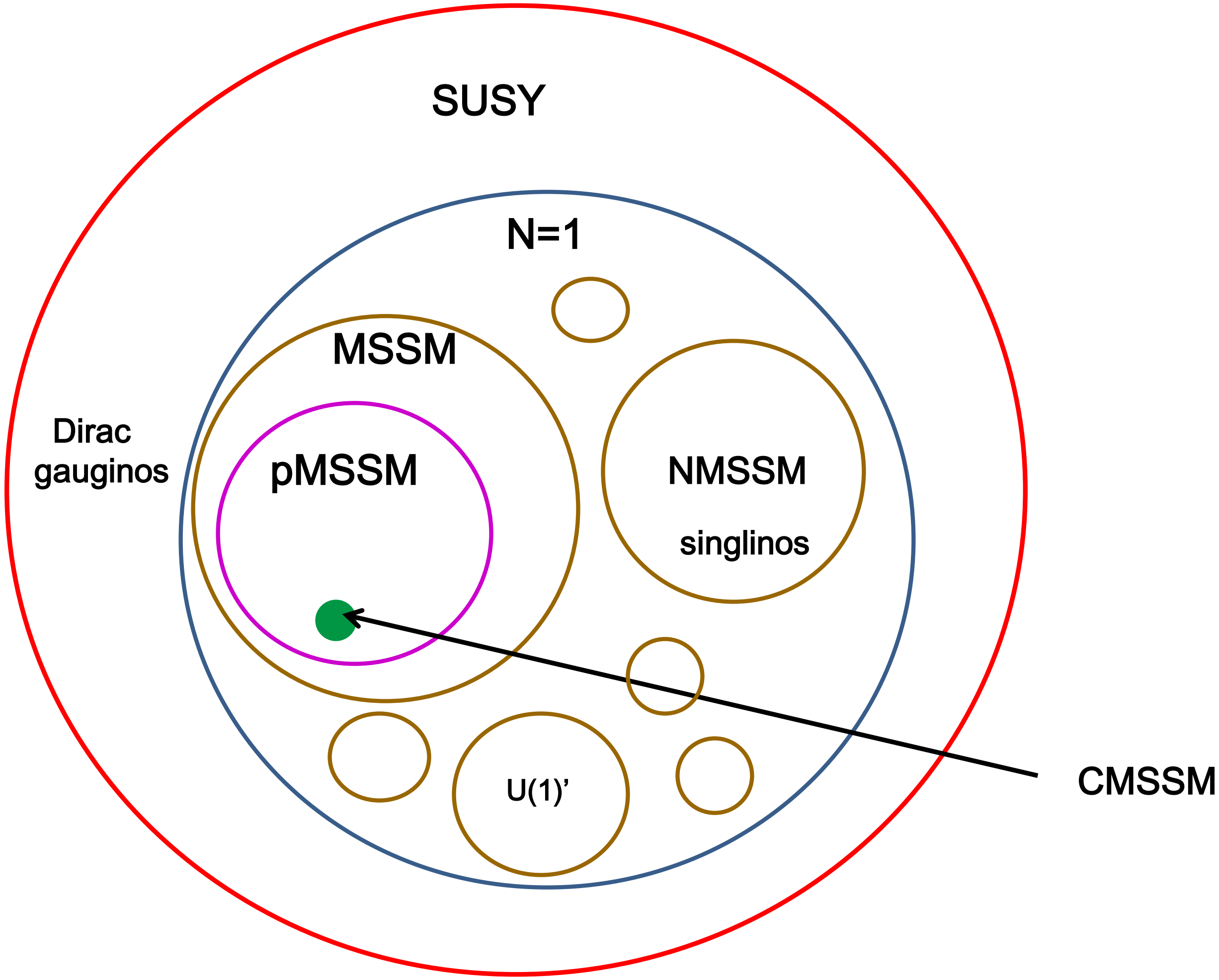


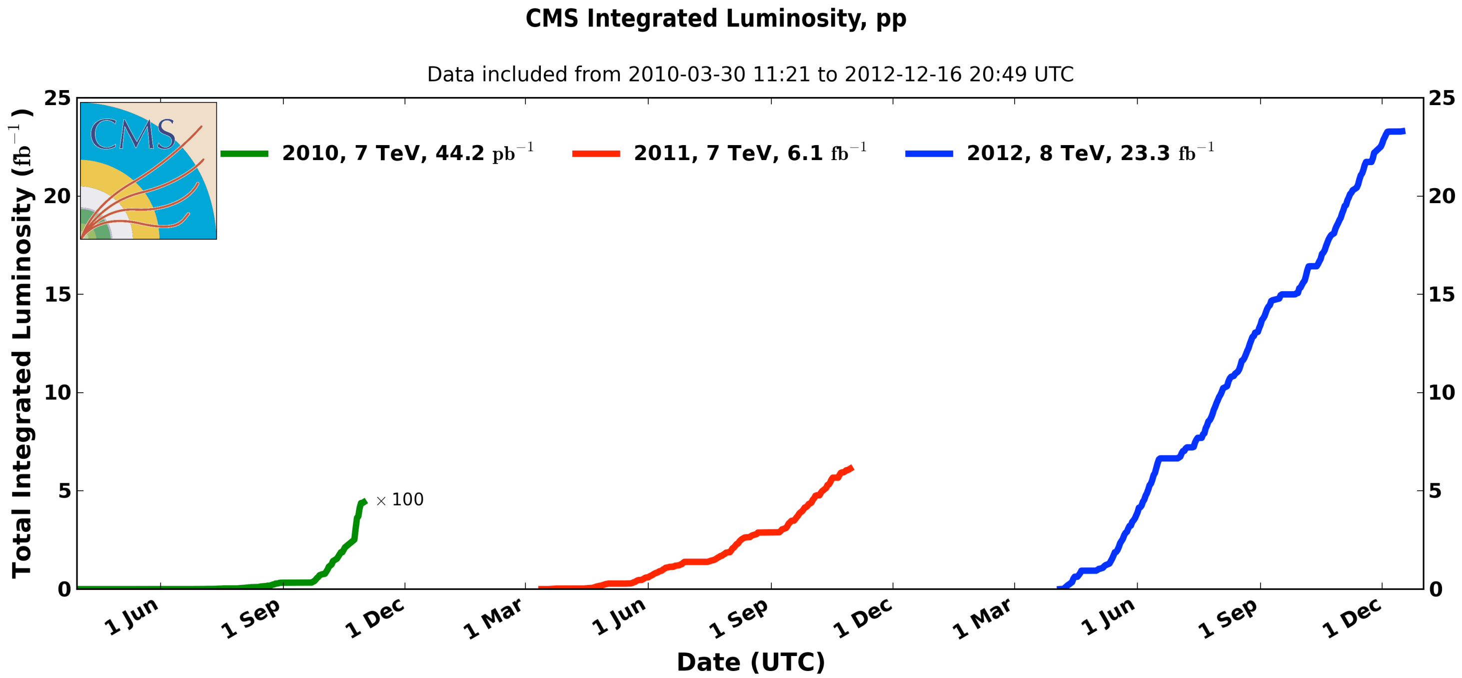
If fine tuning <=10%:
Restrictions:
Λ_{quarks} ~< 2 TeV
Λ_{gauge} ~< 5 TeV

LHC: search engine

MSSM vs SUSY

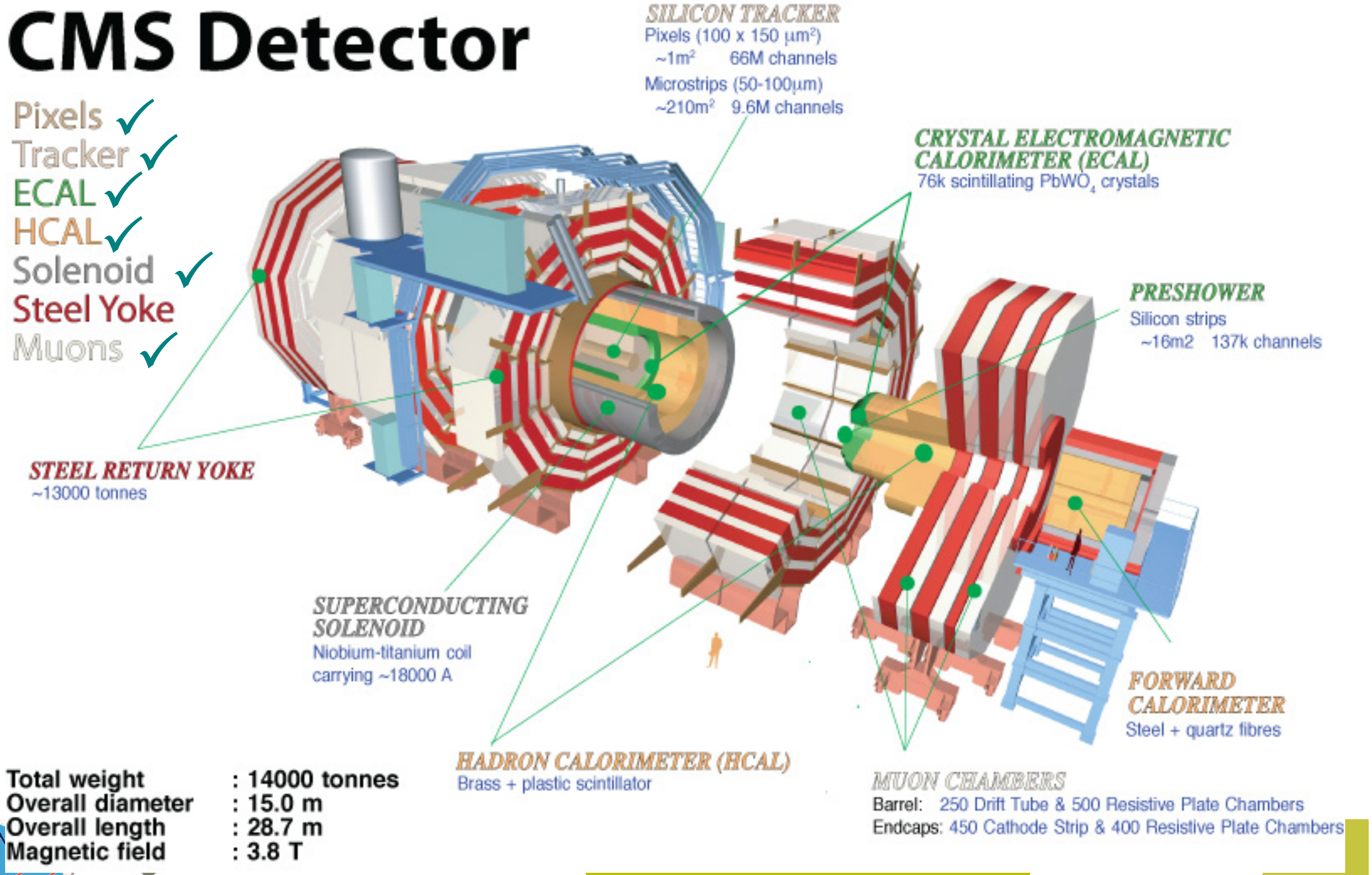


LHC performance

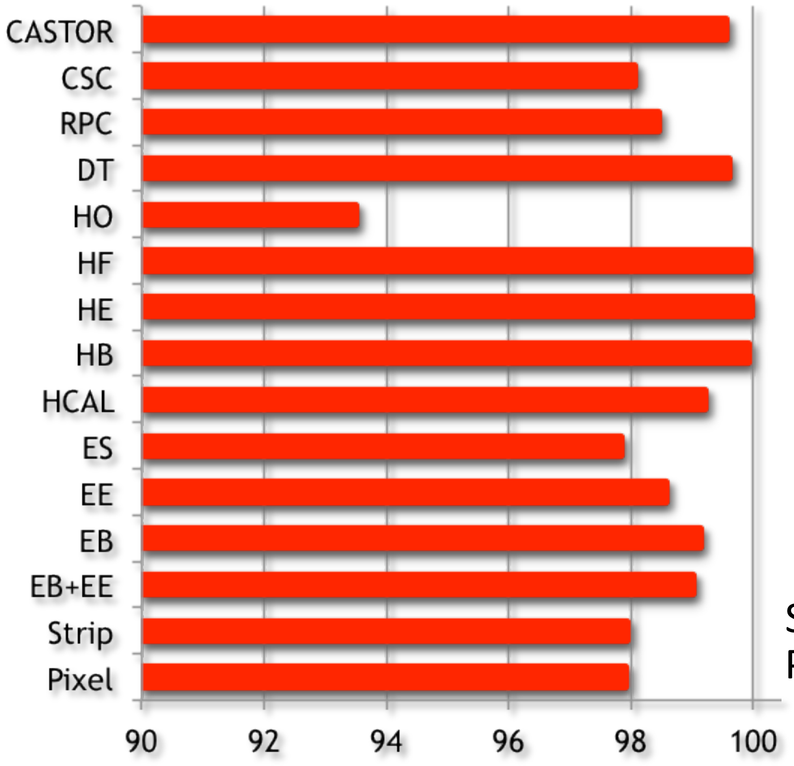


- The LHC and CMS: outstanding performance during LHC Run 1
- Detector performance

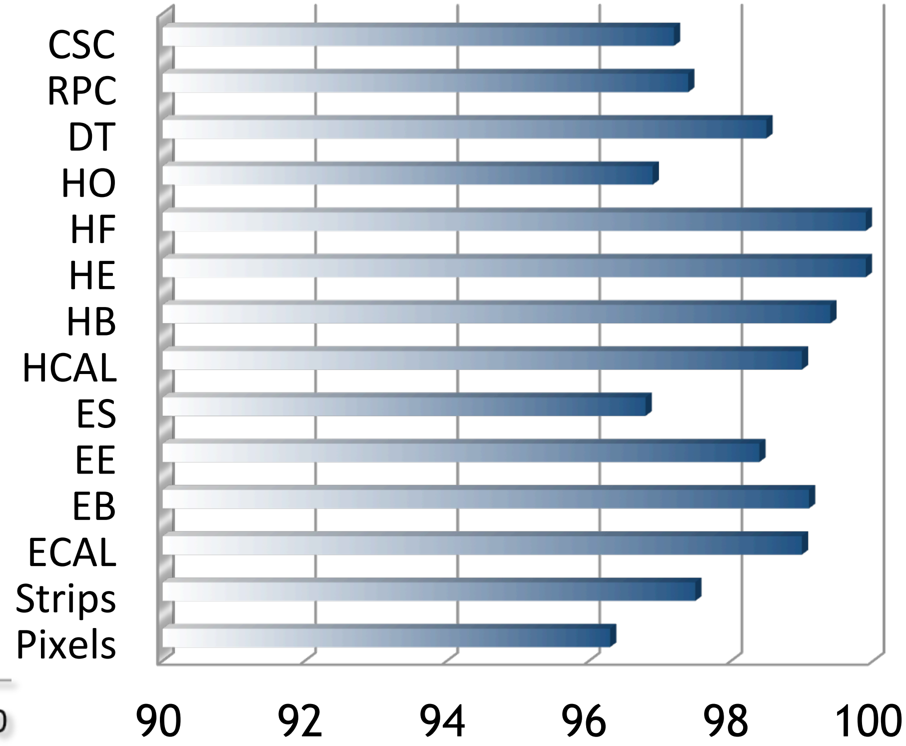
Compact Muon Solenoid



CMS detector performance



December 2010



February 2013

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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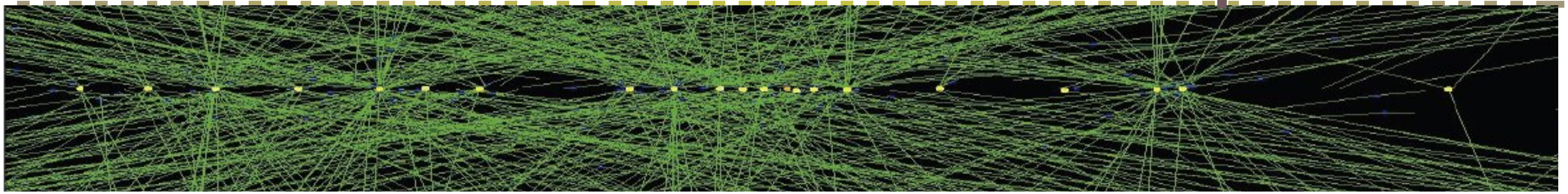
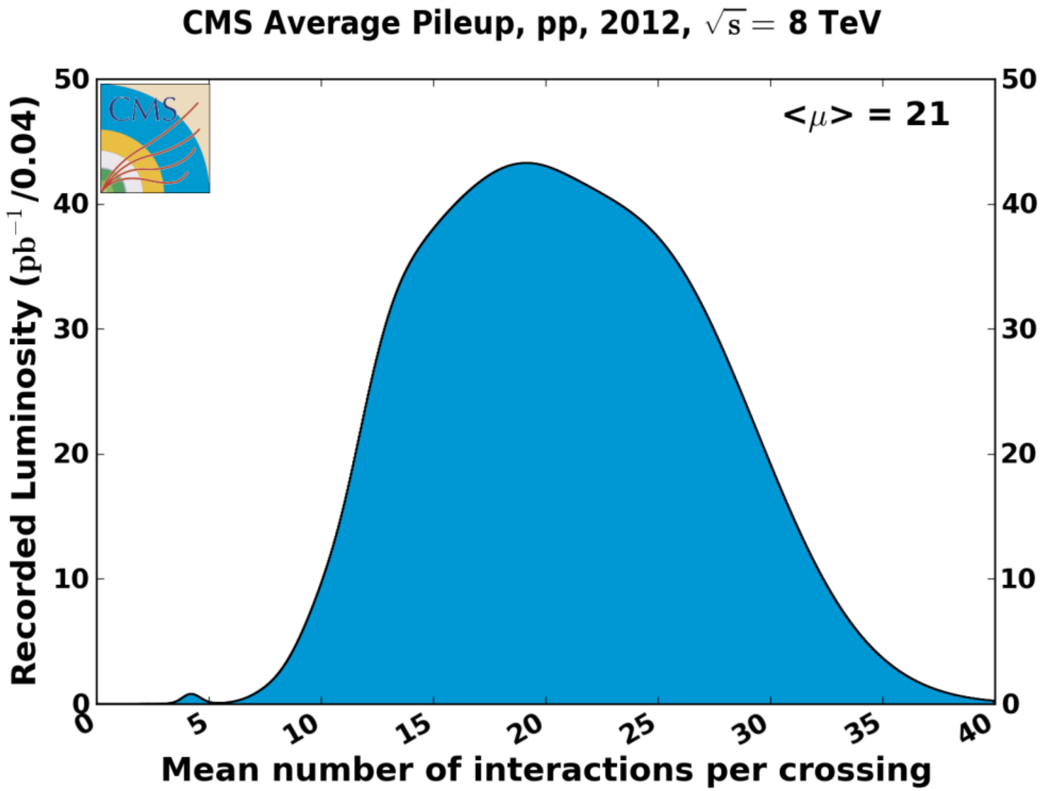
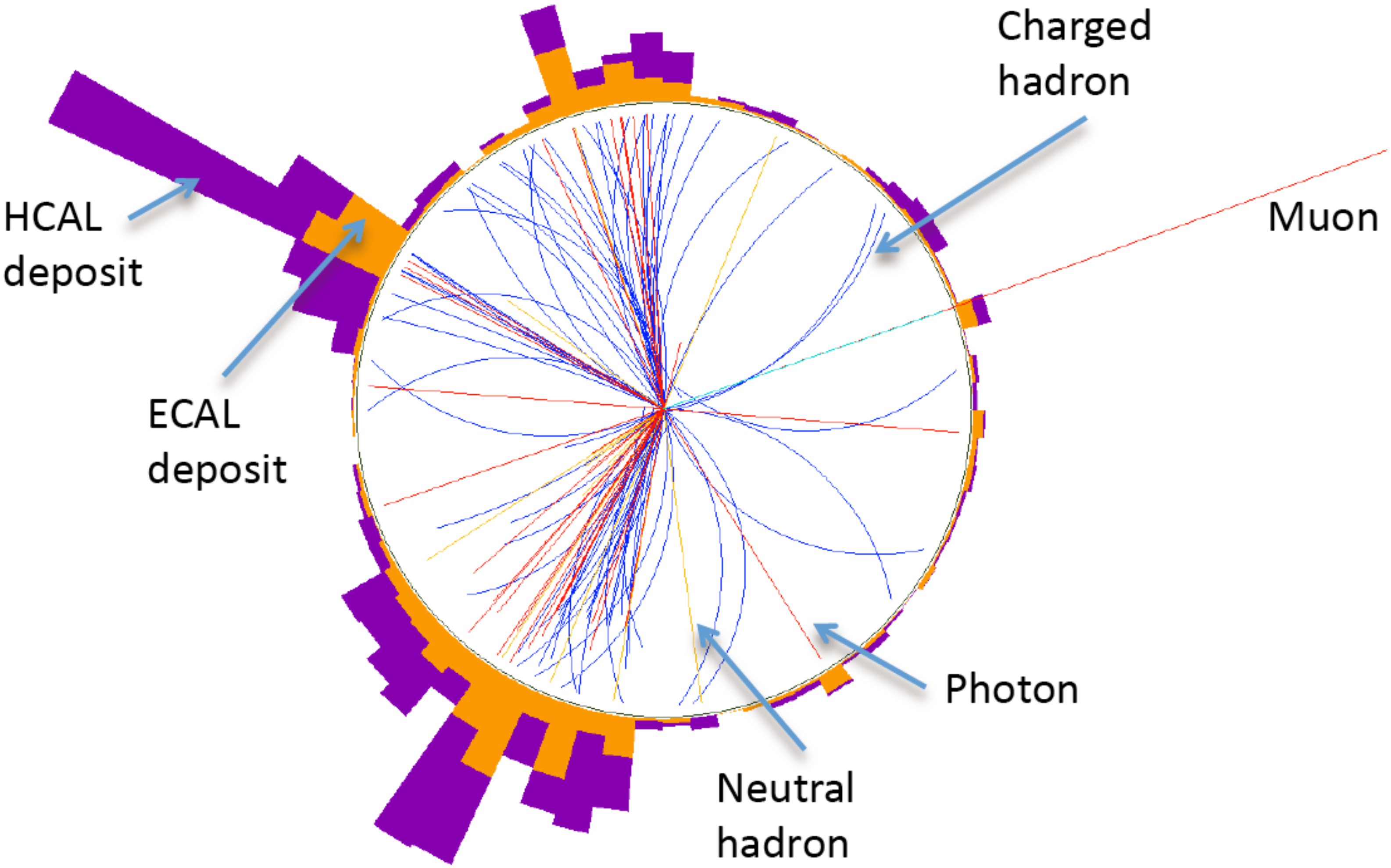
LHC 2012 run: Pile-Up



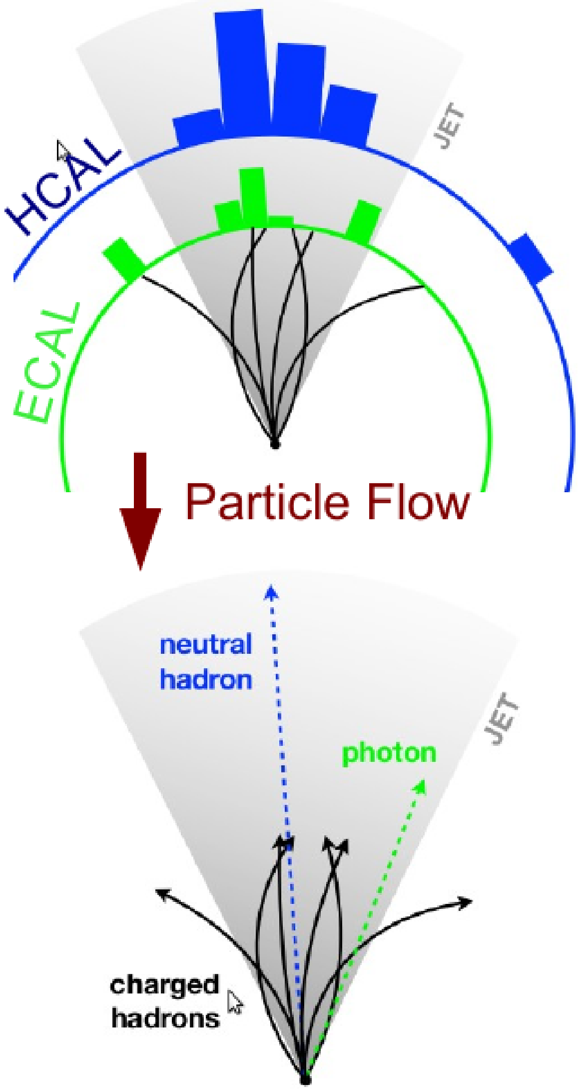
- Outstanding LHC performance comes at a price:
- 2011:
  - Run A: 5 PU
  - Run B: 8 PU
- 2012:
  - Average: 21 PU



Particle flow

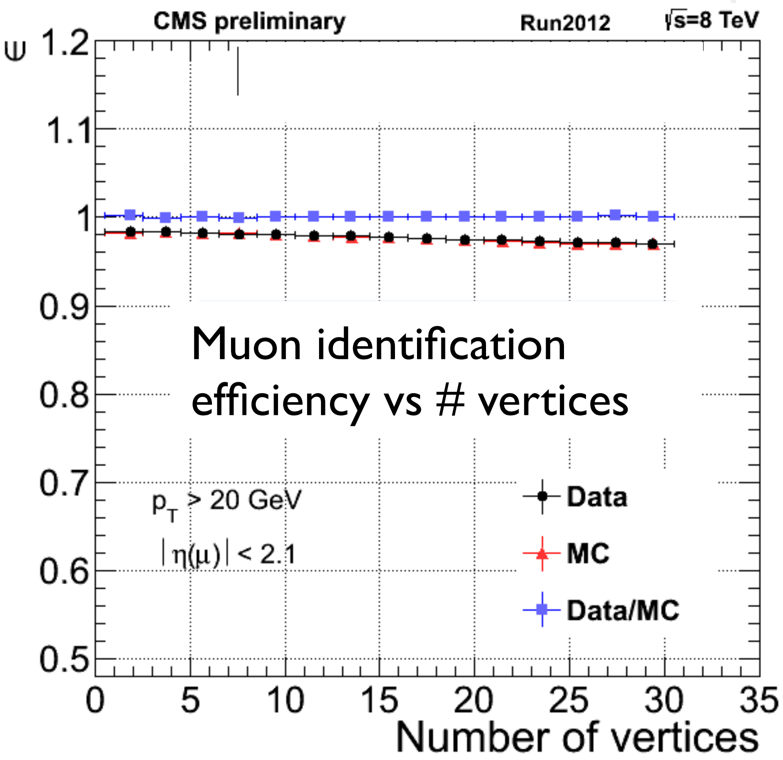


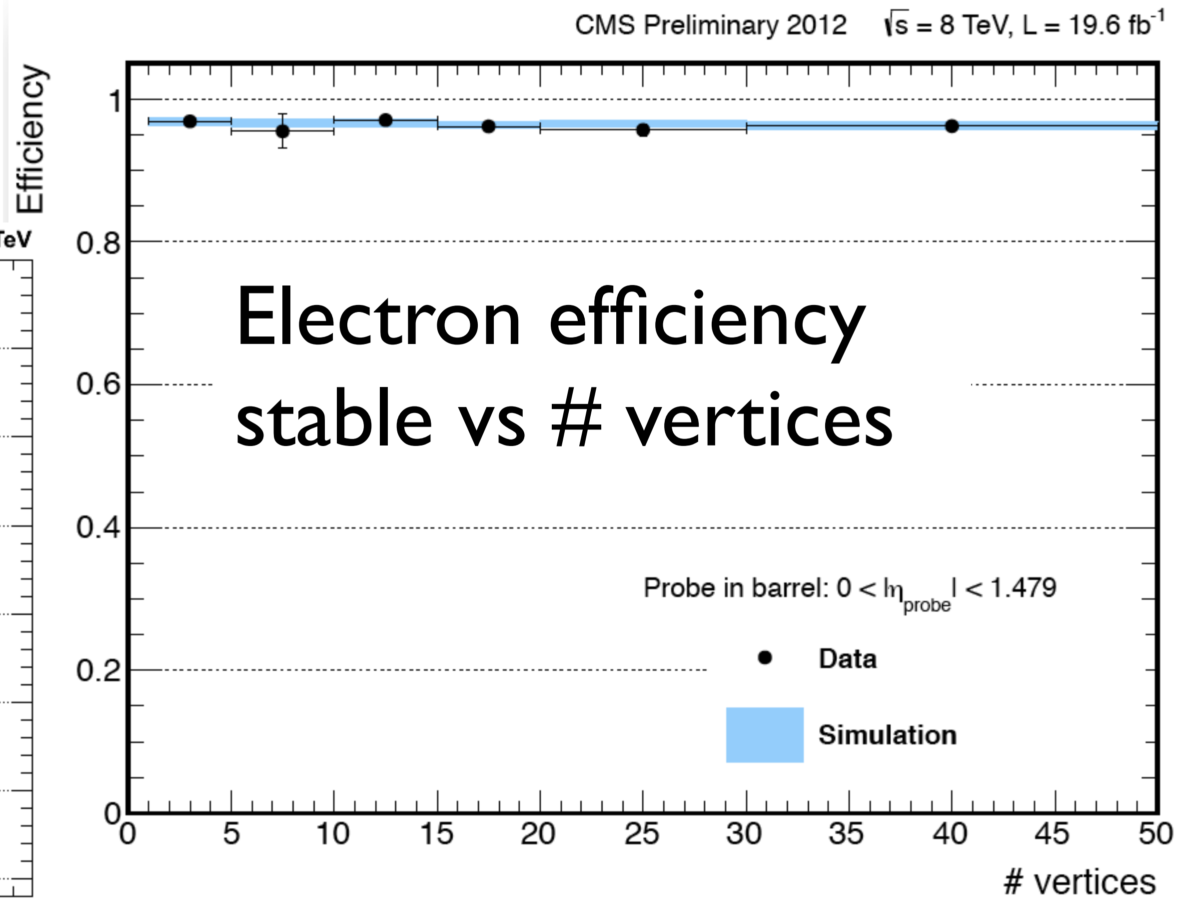
Particle flow in practice



- PF combines information from all subdetectors in a global event description
  - reconstruct 'particles' such as charged/neutral hadrons, photons, muons, electrons
- These particles are used to construct composite objects such as jets, taus, missing transverse energy
  - Reject tracks from non-leading collisions before creating composite objects
  - And make assumptions for background from neutral particles
- Widely used in CMS, LHCb
  - CMS: big improvements in energy resolution jets, MET, tau identification,

leptons

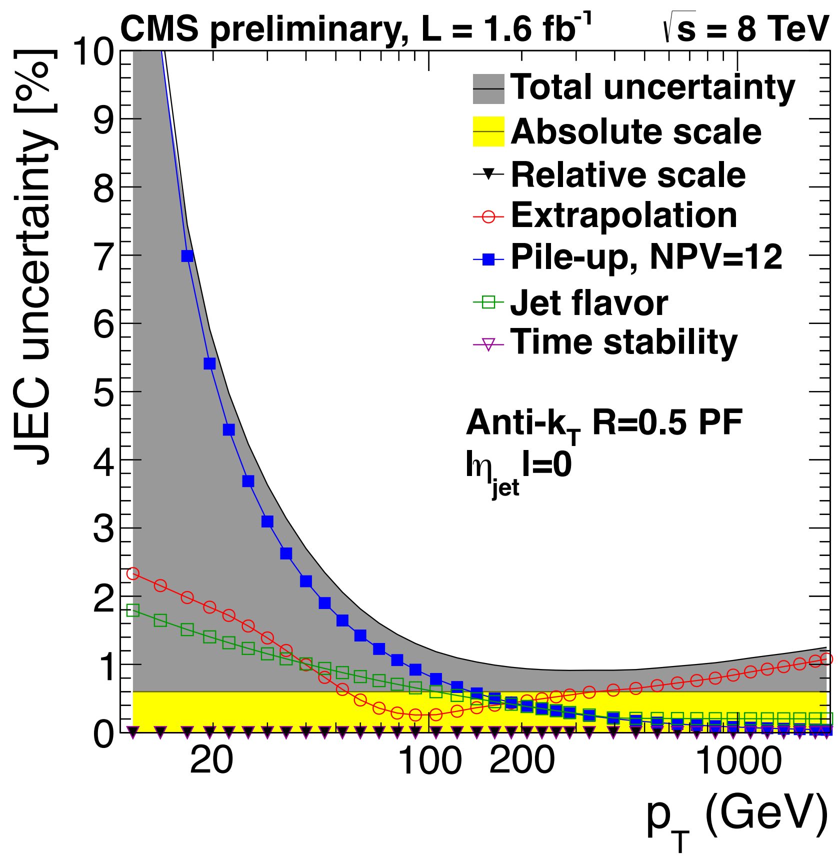




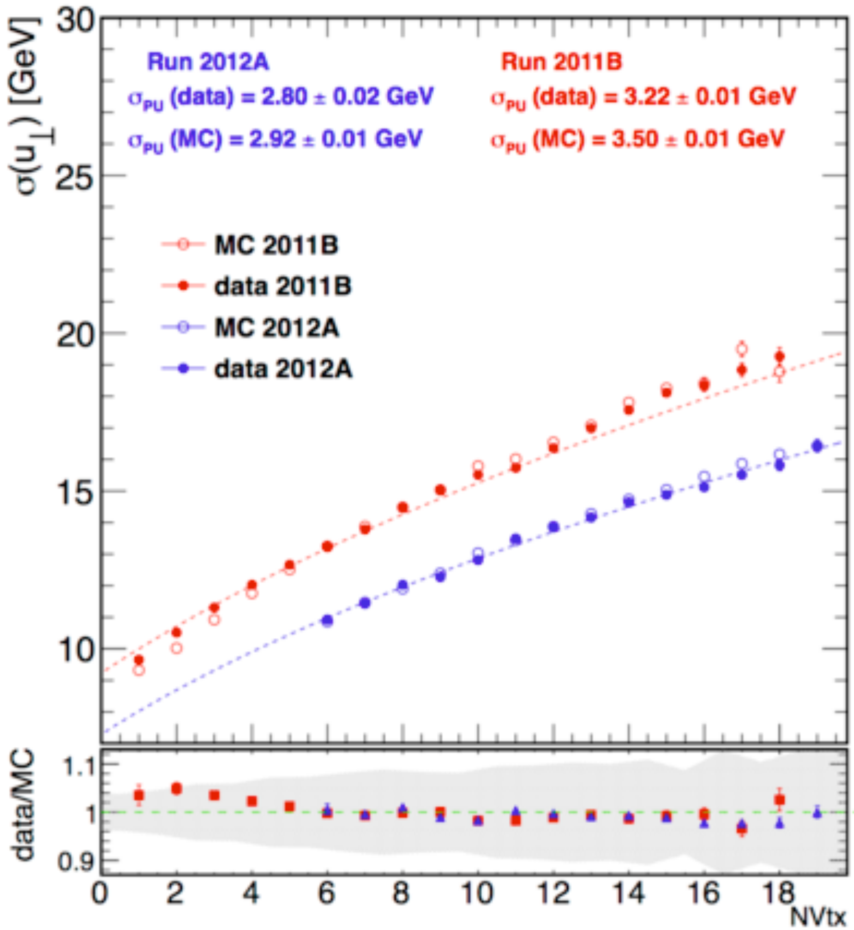
- Substantial effort necessary to achieve this stability

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

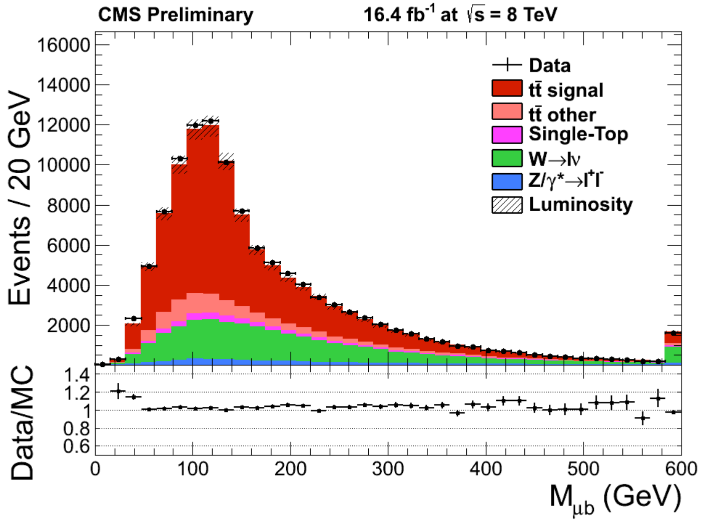


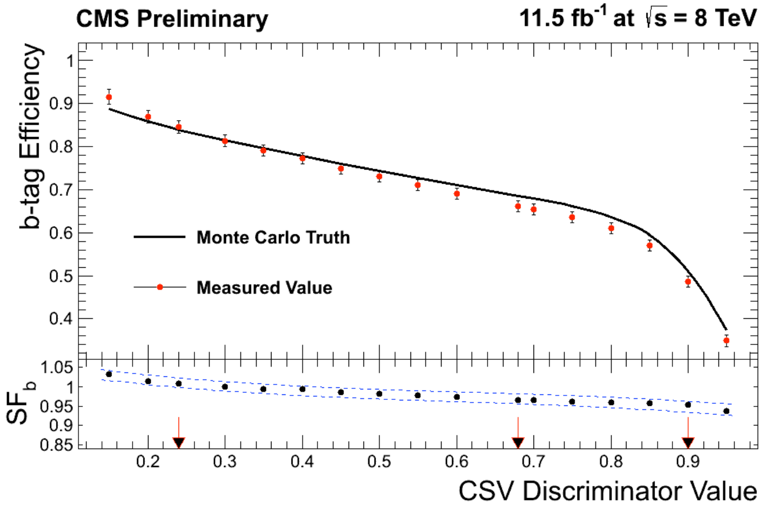
Missing ET



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

Jets with b-tagging

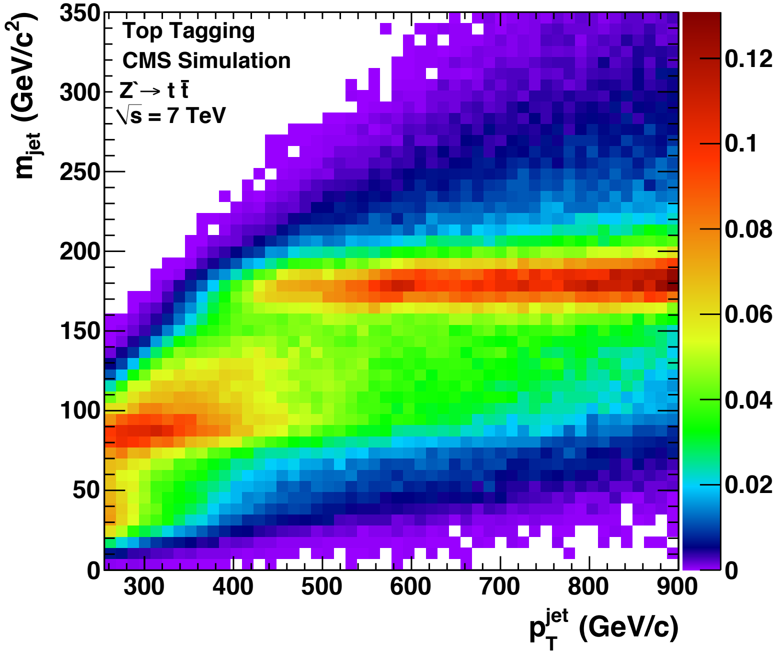


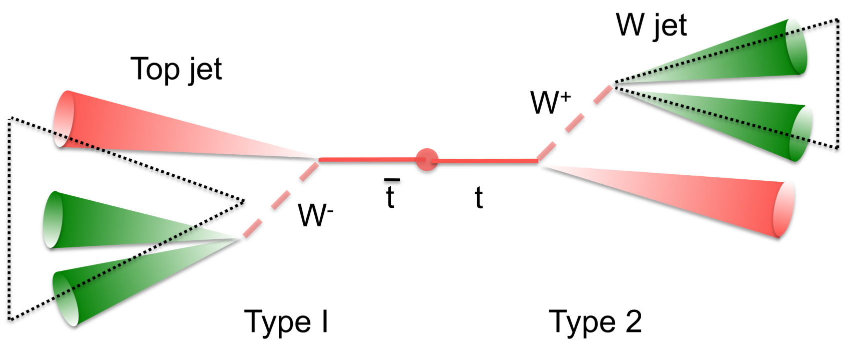


- Long lifetime of b-hadrons in b-jets
  - τ= 1.512 x 10^{-12} s
  - $c\tau$ = 455.4 μm
- Combination of lifetime information in MVA
- Efficiency measured in top and QCD events (data) using multiple methods

On the momentum of top quarks

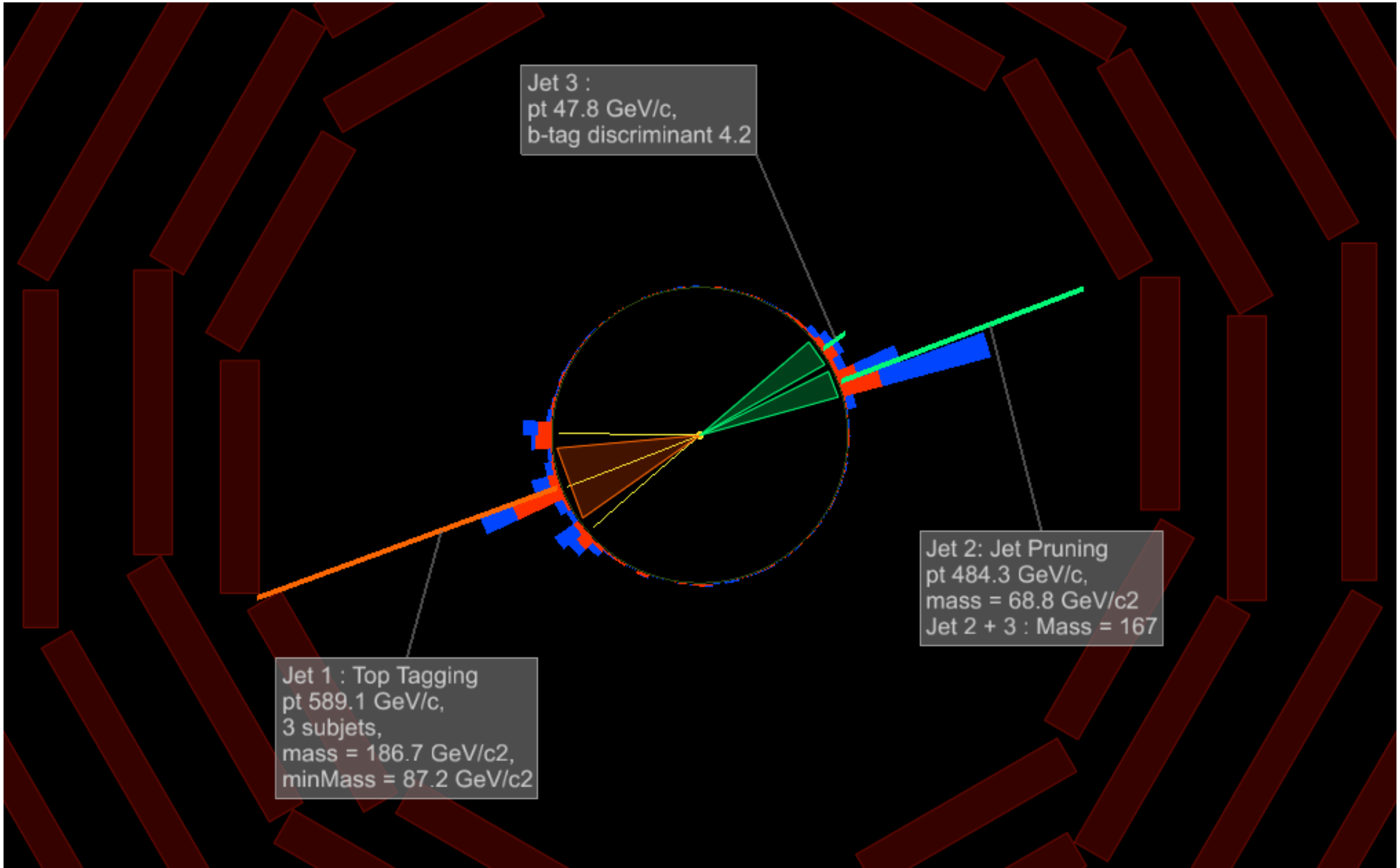
PAS JME-10-013



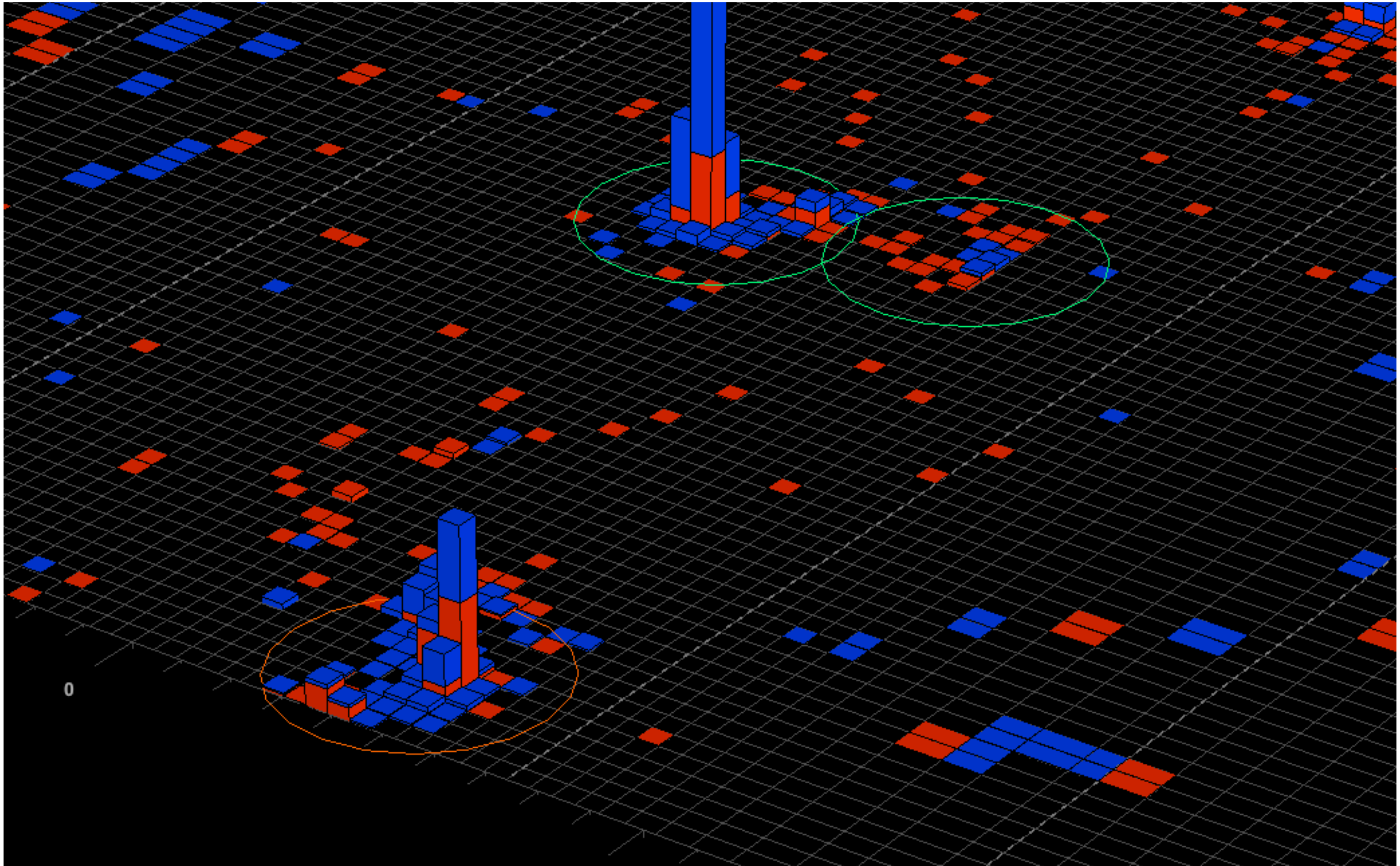


- Once boost of top quarks high enough
- Decay products become collimated
  - W->qq in one jet
  - Or t->bqq in one jet
- Special reconstruction algorithms needed:
  - Cambridge-Aachen algorithm with distance parameter 0.8

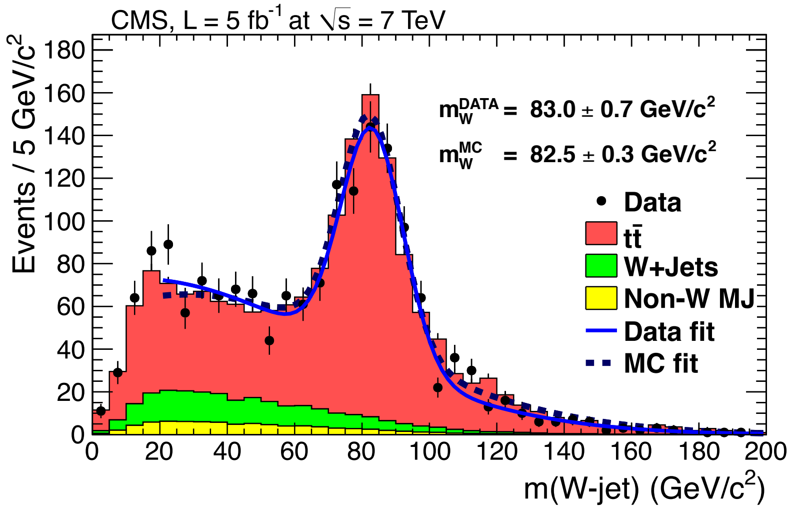
Jets with substructure

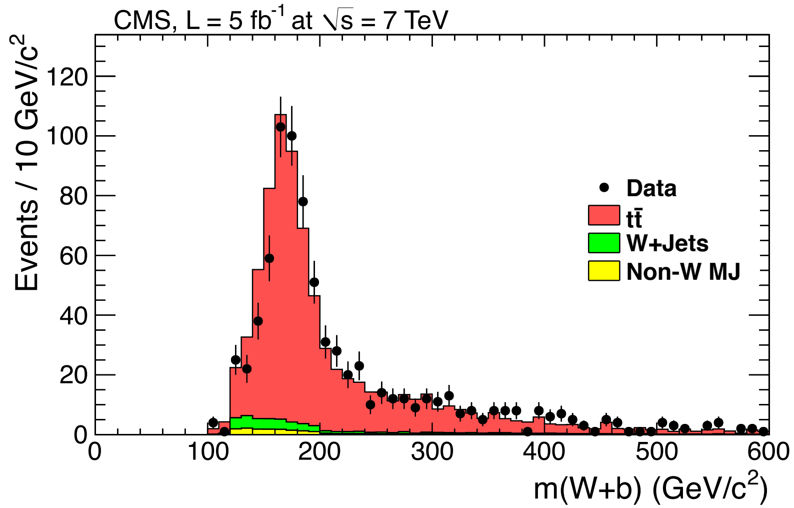


Jets with substructure



Validation in lepton+jets events

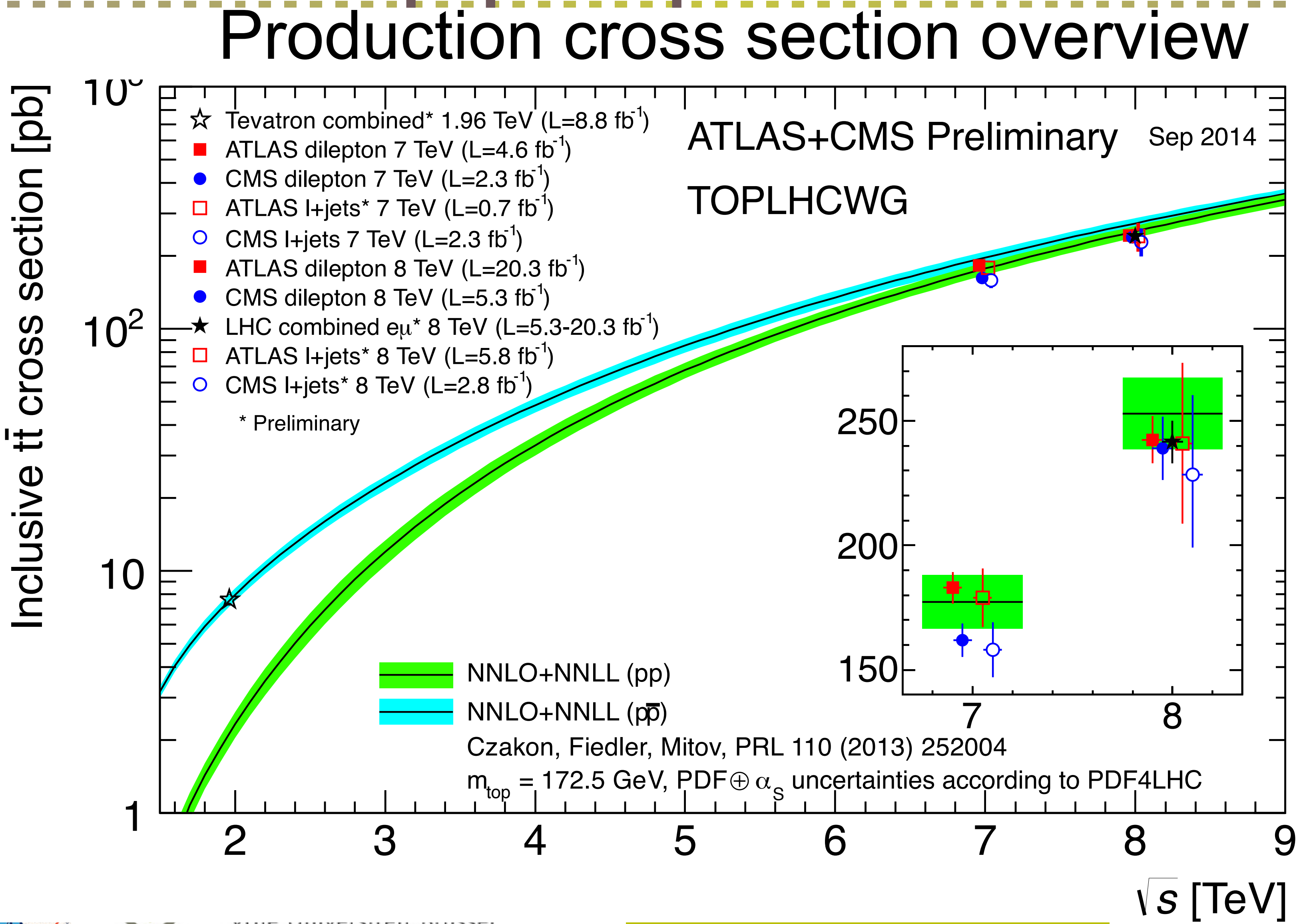




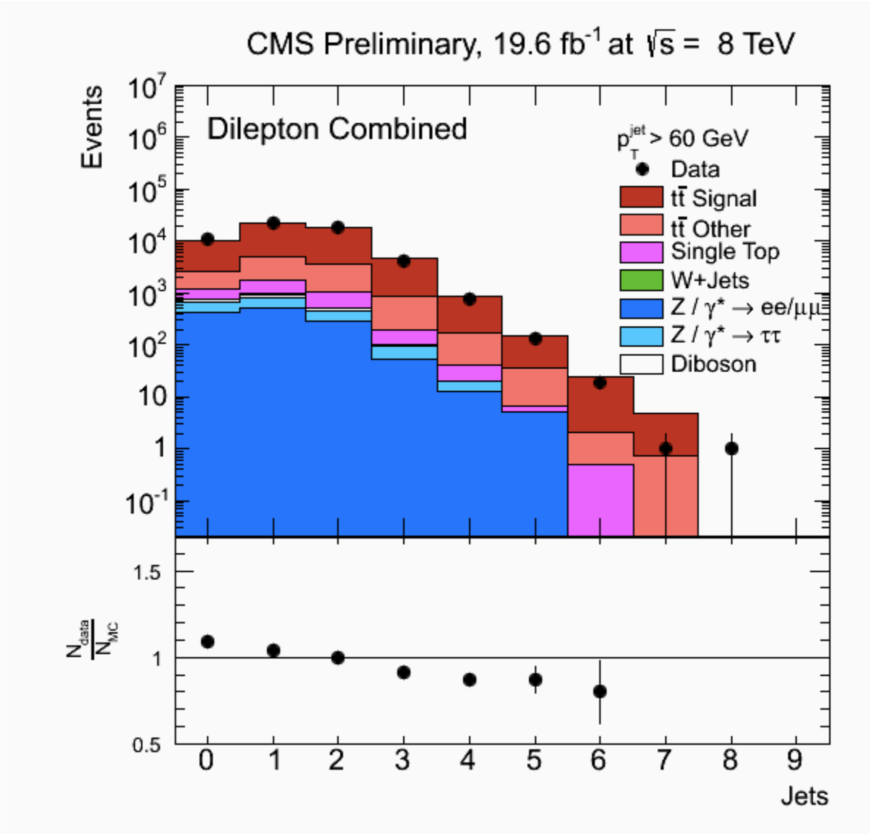
- Algorithm validated using muon+jets selection

- 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



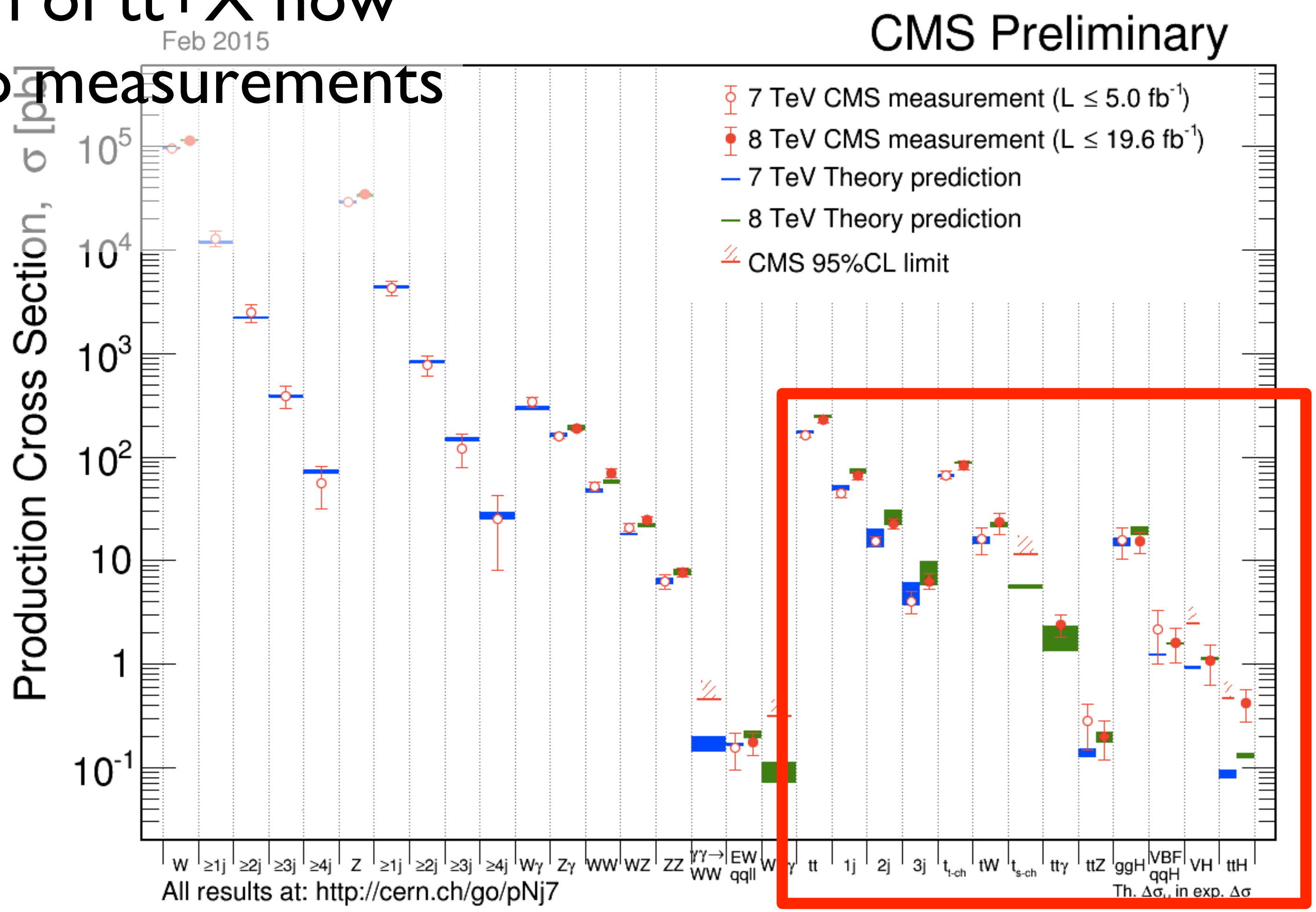
LHC: Top quark pair factory



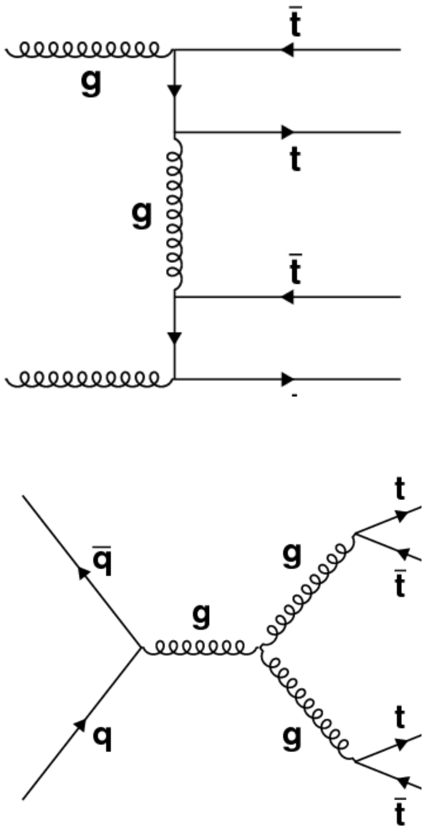
- Cross sections ~225 pb
- In combination with 20 /fb datasets:
  - LHC is a top factory
  - Very productive program of Standard Model precision top physics

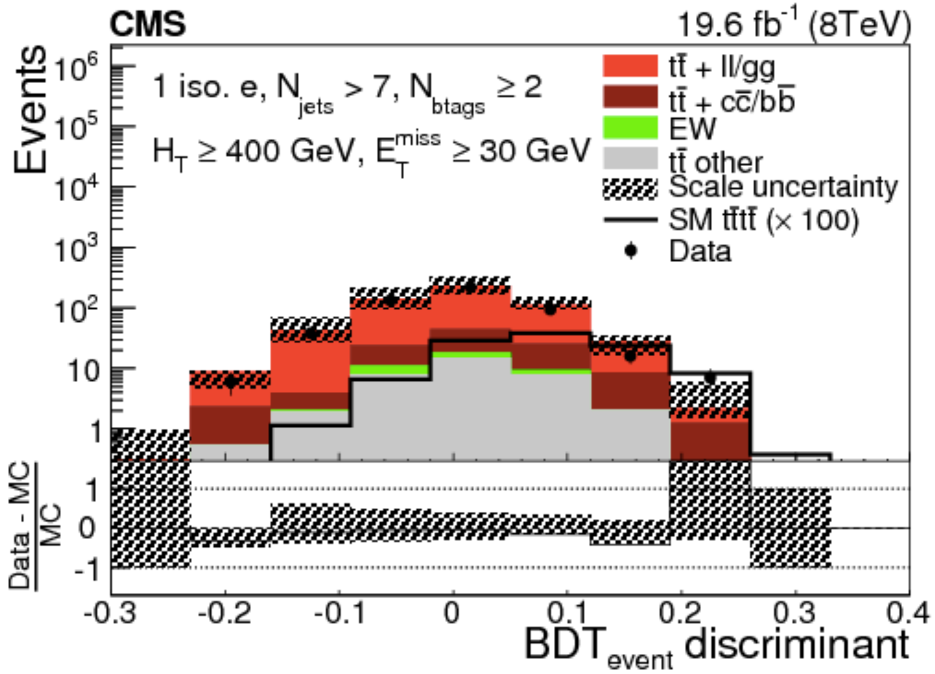
Top physics: rare decays

- Production of tt+X now used to do measurements to test SM



Next: undiscovered ttbar+X final states





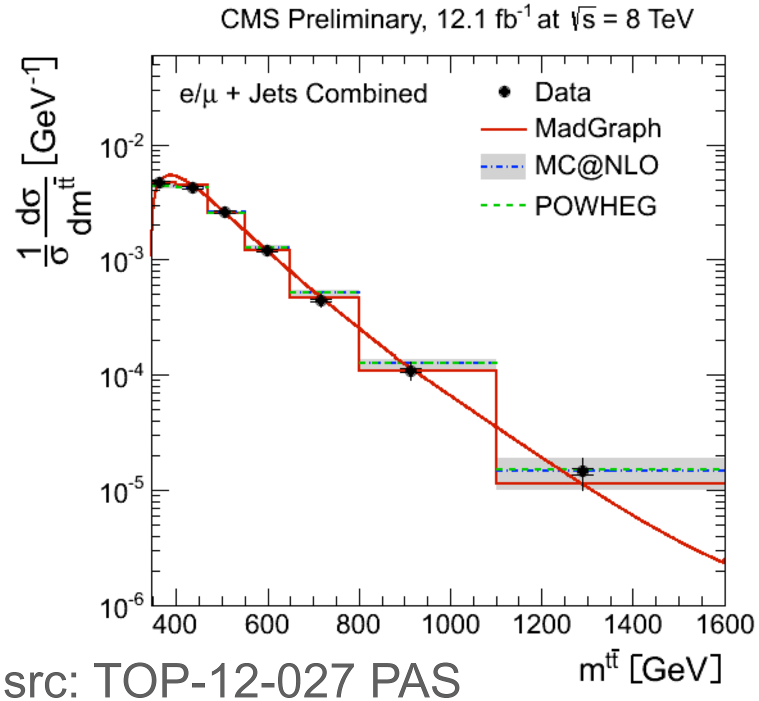
Production of tttt in SM: 1 fb!
Limits now at xsec<32 fb
Very sensitive to QCD-BSM

Src: TOP-13-012: JHEP 11 (2014) 154

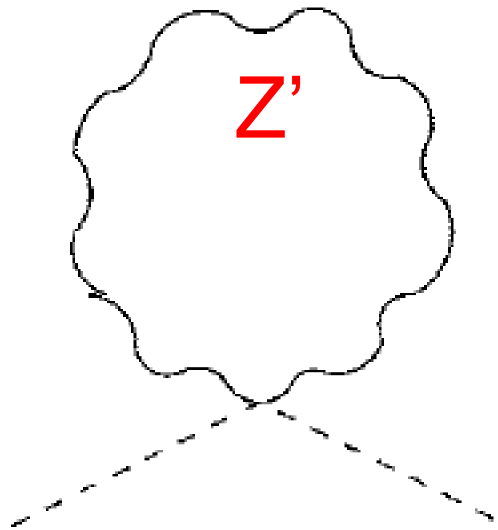
Heavy resonances decaying to top quark pairs

Investigating ttbar 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



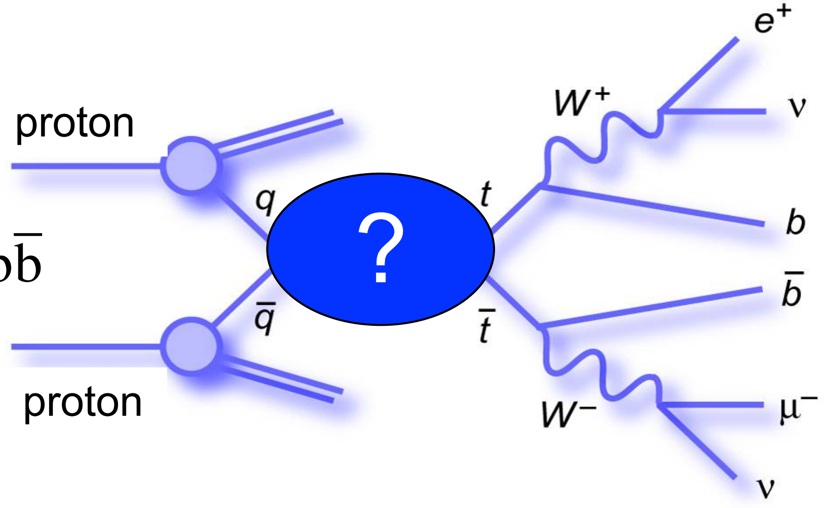
src: TOP-12-027 PAS



- Z' scenarios interwoven with natural EXO solutions and A_{FB}-explaining models
- M_{ttbar} distribution sensitive to many new physics scenarios

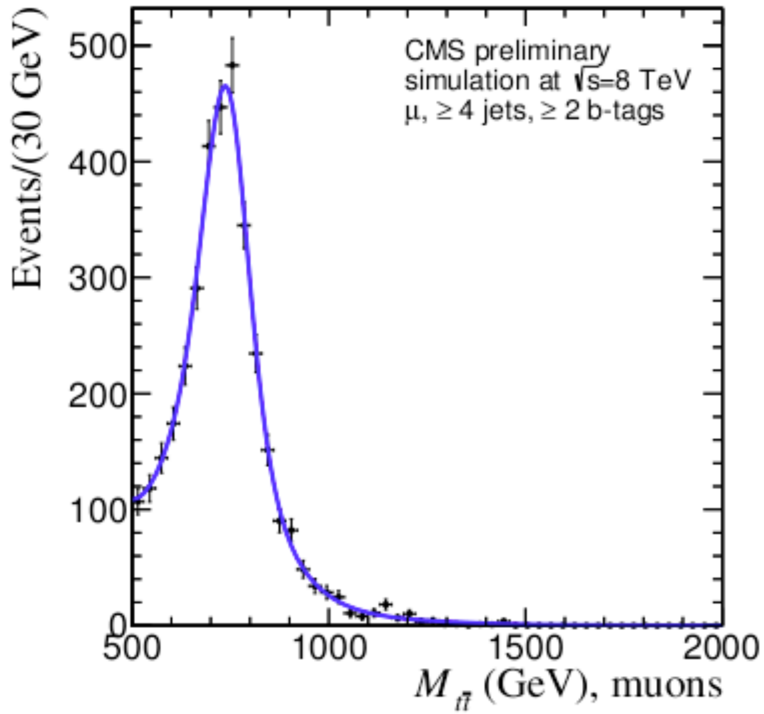
analysis strategy

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



Semileptonic, threshold

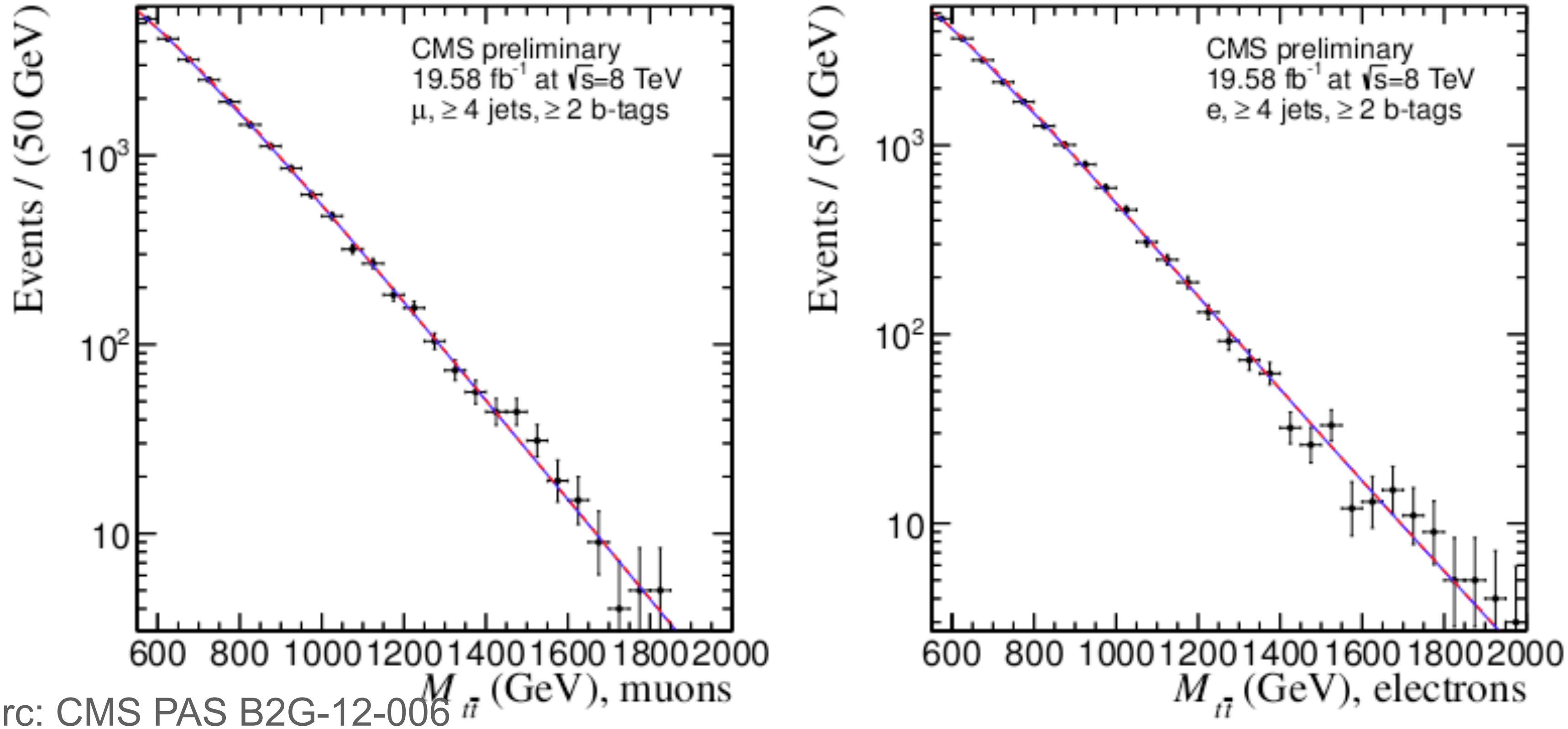
- Require only one lepton, >= 4 jets and split in b-tag multiplicity
- χ^2 sorting used to select best jet combination
- Using data-driven estimates for falling distribution of top pair mass spectrum above 500 GeV/c^2
- Systematic uncertainties take into account rate and shape changes for signal and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



src: CMS PAS B2G-12-006

Semileptonic, threshold

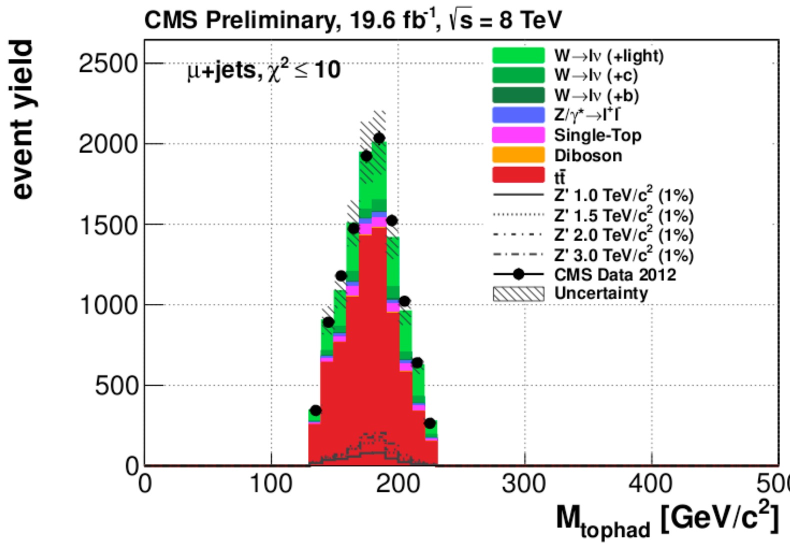
- Fit to falling distribution in electron/muon final states used to set limits (1 and ≥2 b-tag regions fit simultaneously)
  - **Fully data-driven method, only makes assumptions on resonant shape of signal**

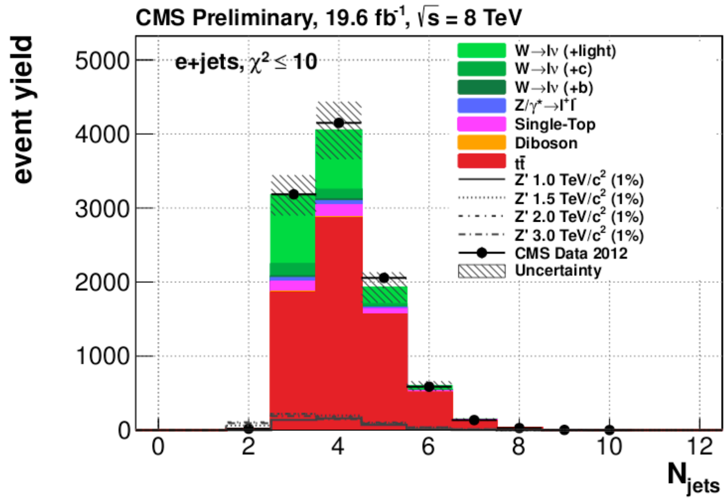


src: CMS PAS B2G-12-006

Semileptonic, non-isolated

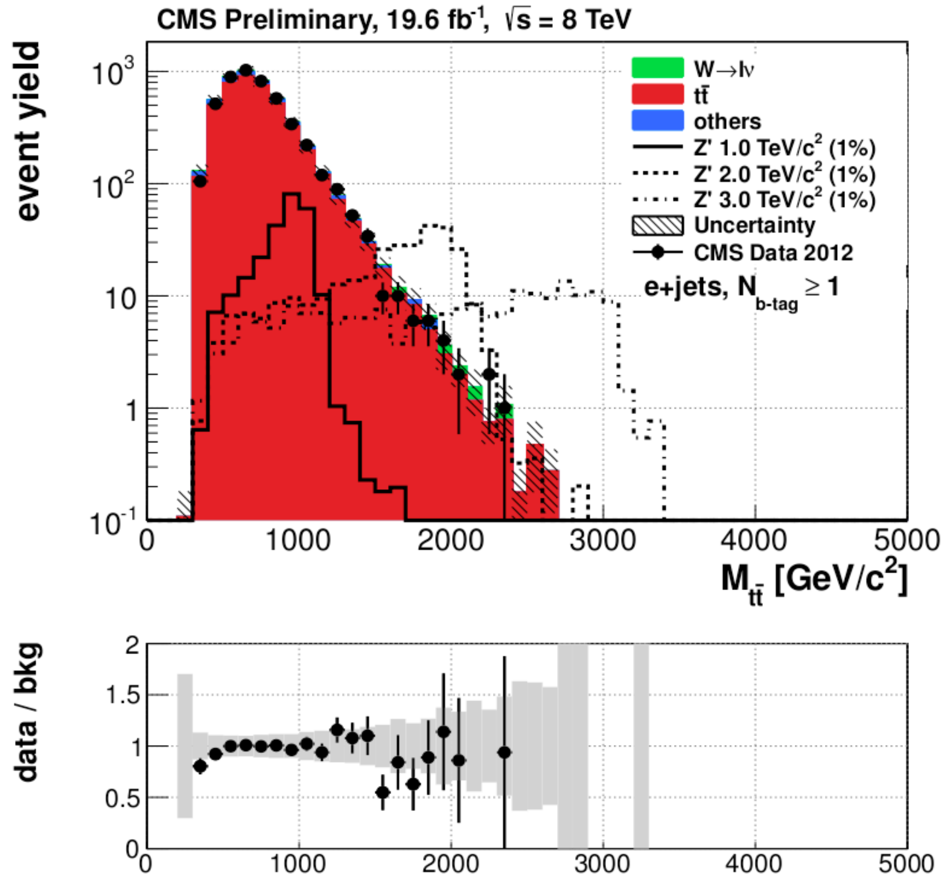
- Alternate analysis: Loosened lepton isolation criteria allow jet/lepton overlap
- Focus on mass tail: require harder cuts on leptons and jets
- Only at least 2 jets+lepton required
- χ^2 sorting used to select best jet combination
- Simultaneous template fit to M(ttbar) in different b-tag multiplicities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





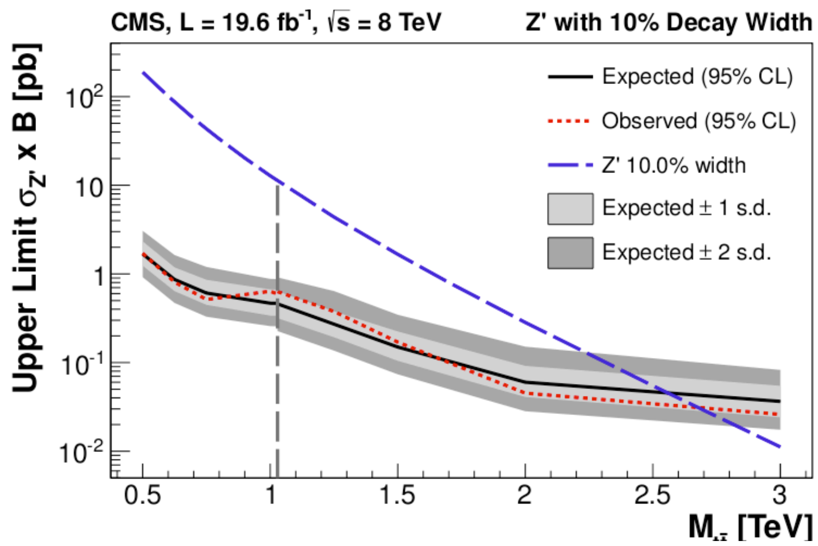
src: CMS PAS B2G-12-006

Semileptonic, non-isolated



- Multiple scenarios considered
  - Worlds best limit on production of resonant ttbar:
    - 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:

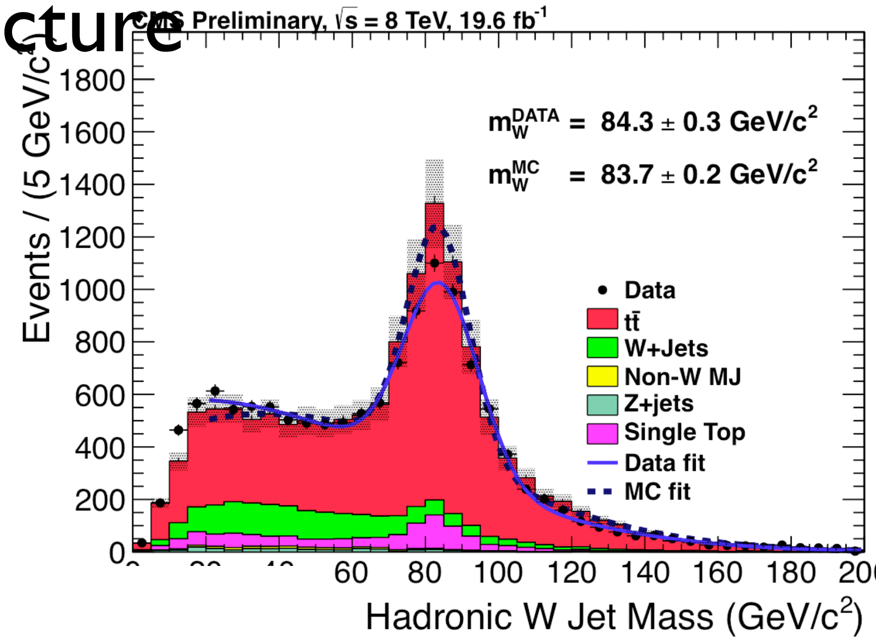
      excluded with xsec > 1-2 pb!!

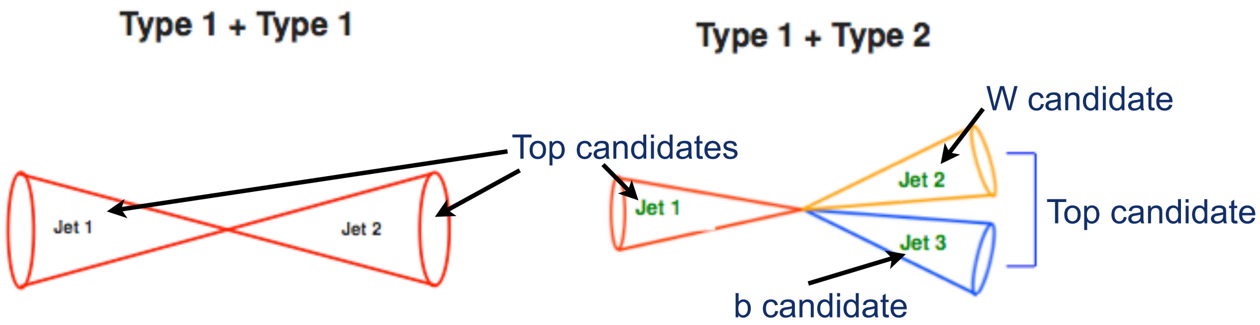


B2G-13-001, Phys. Rev. Lett. 111, 211804

All hadronic, boosted, 8 TeV

- Using boosted objects and jet pruning to identify substructure
  - Full merged topology
- Cambridge-Aachen jets
  - ‘top jets’
  - ‘W boson jets’





B2G-13-001, Phys. Rev. Lett. 111, 211804

All hadronic, boosted, 8 TeV

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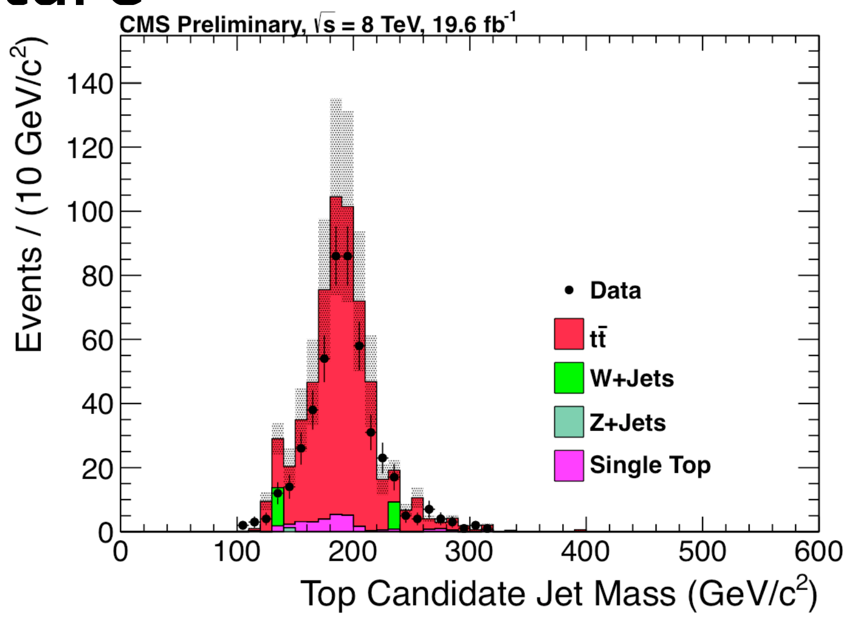
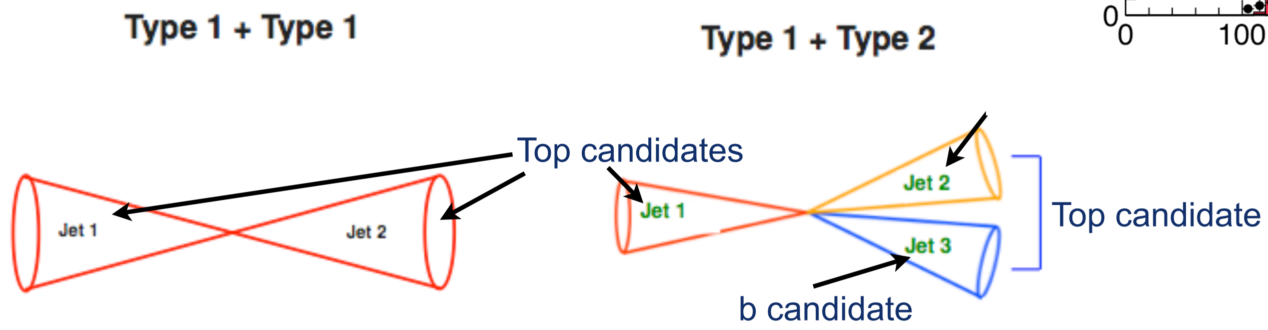
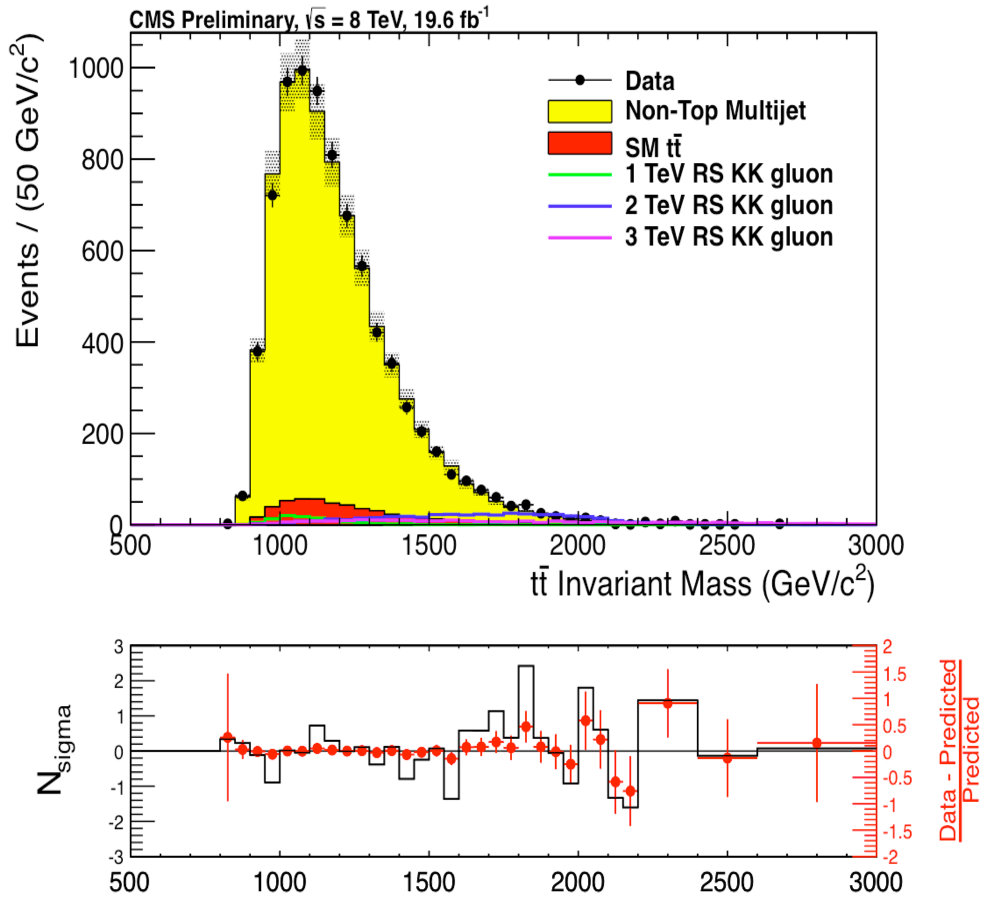




B2G-13-001, Phys. Rev. Lett. 111, 211804

All hadronic, boosted, 8 TeV

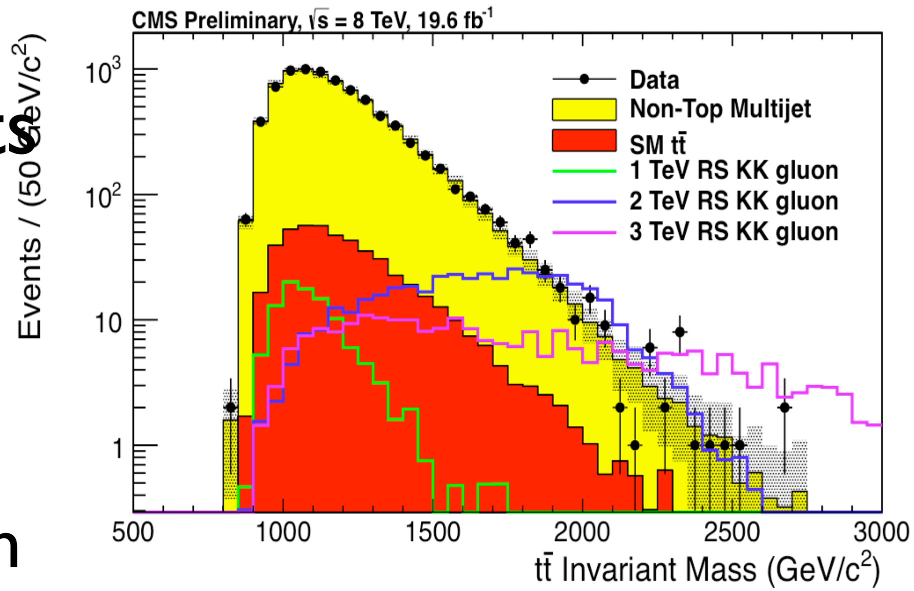
- LLH fit to bumps in mass spectrum used to set limits



B2G-13-001, Phys. Rev. Lett. 111, 211804

All hadronic, boosted, 8 TeV

- LLH fit to bumps in mass spectrum used to set limits

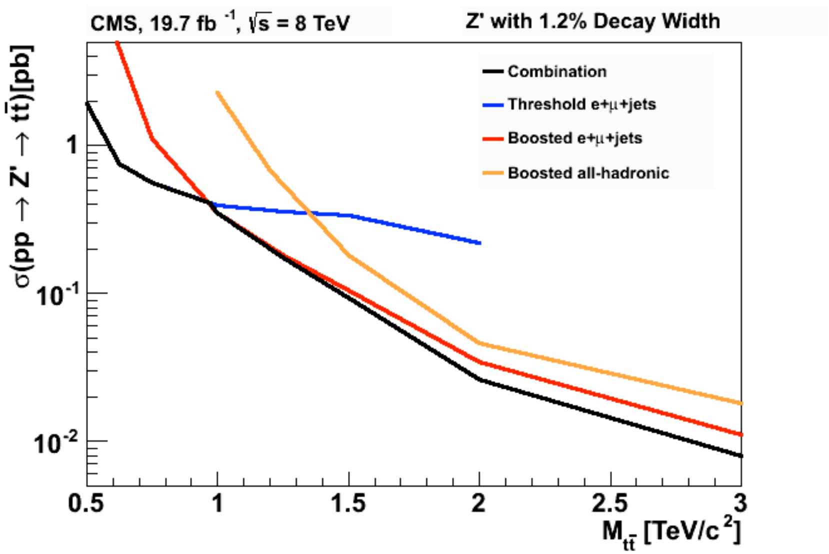


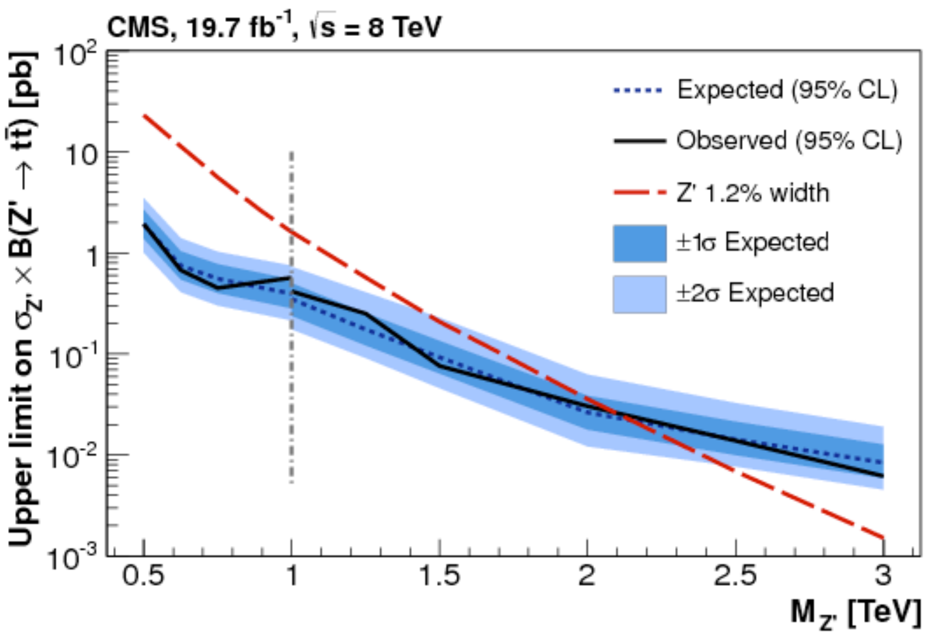
- 95% CL upper limits on increased cross section at high mass:

  $\sigma_{NP+SM} < 1.2\ \sigma_{SM}$ for masses above 1 TeV

B2G-13-001, Phys. Rev. Lett. 111, 211804

Combined limits



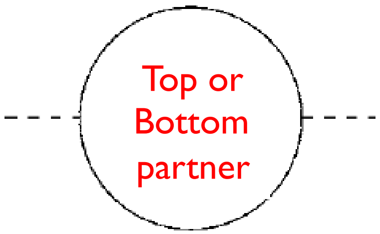


- Combining results gives more sensitivity in high mass regime

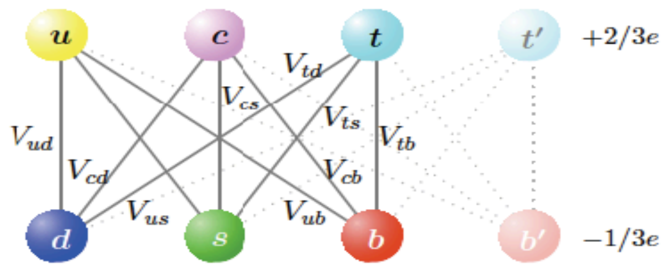
B2G-13-001, Phys. Rev. Lett. 111, 211804

Heavy top partners

Fourth Generation



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

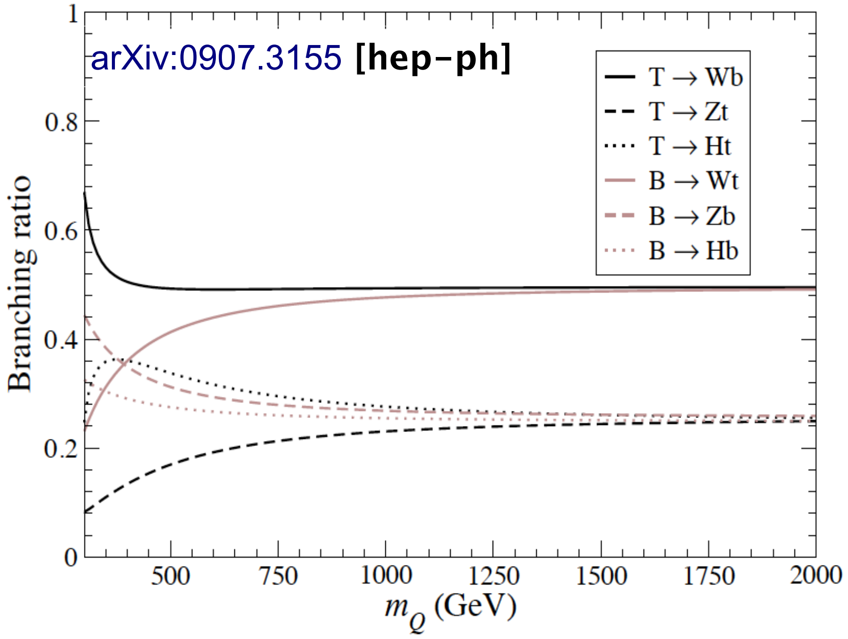


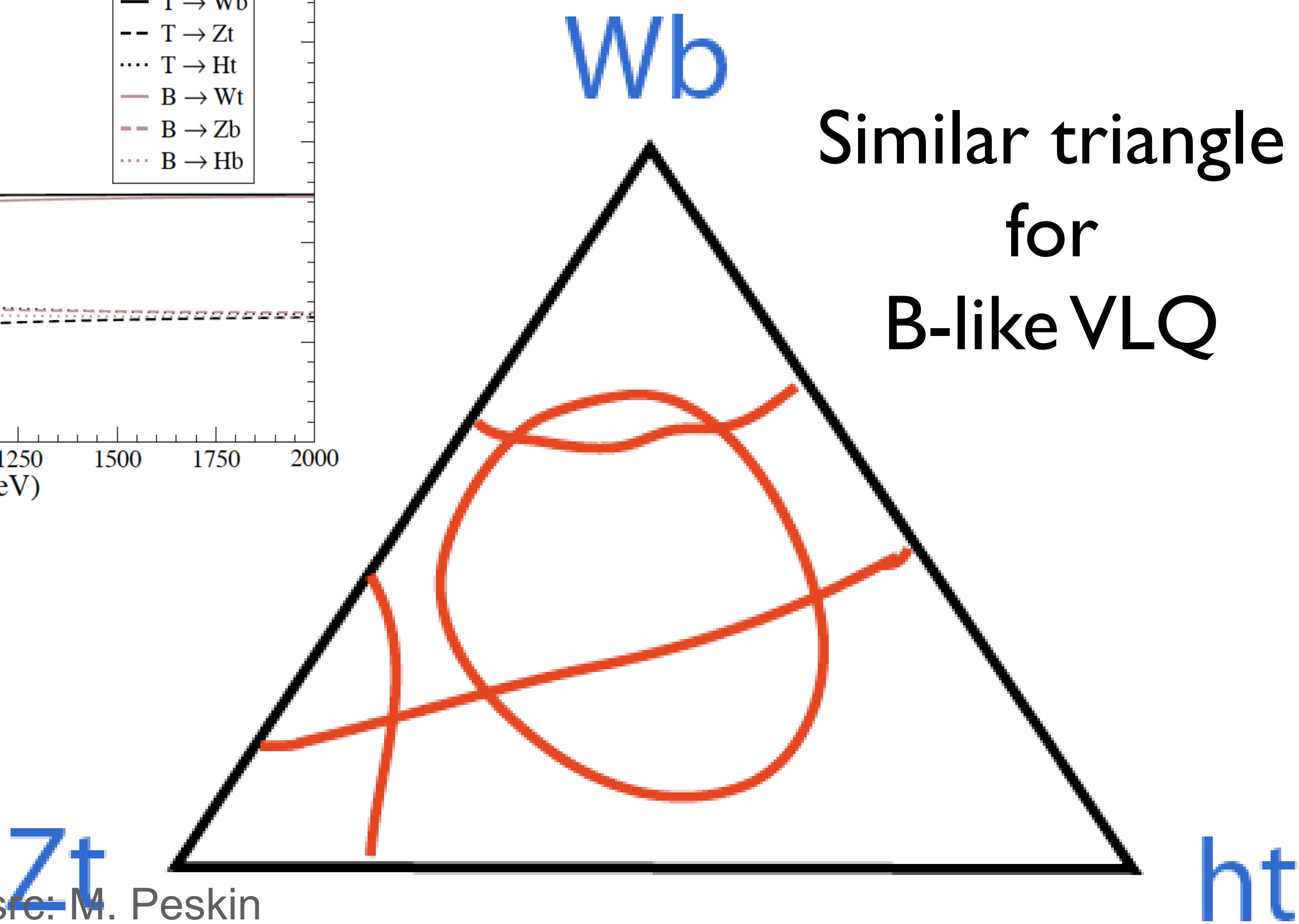
- More elaborate fourth generation models still alive
  - Any SM extension with a Higgs doublet and fourth generation
  - Any models predicting other heavy top partners such as 2HDM
  - Vector-like quarks that are top quark/b quark partners
  - Exotic top partners with with different charge

Vector like quarks

- Non- SM fourth generation very hot topic
  - 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->bW,tZ, th
    - B->tW,bZ,bh
  - Current searches mostly pair production
  - Single production also possible

Vector-like quarks:



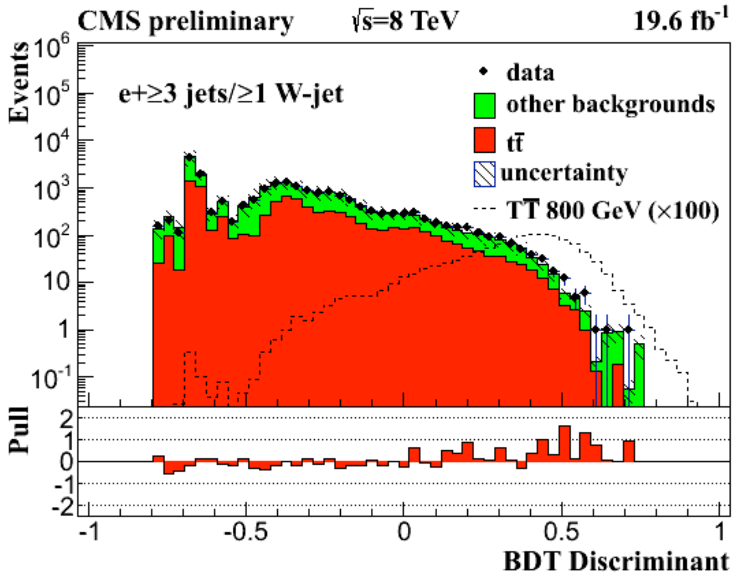


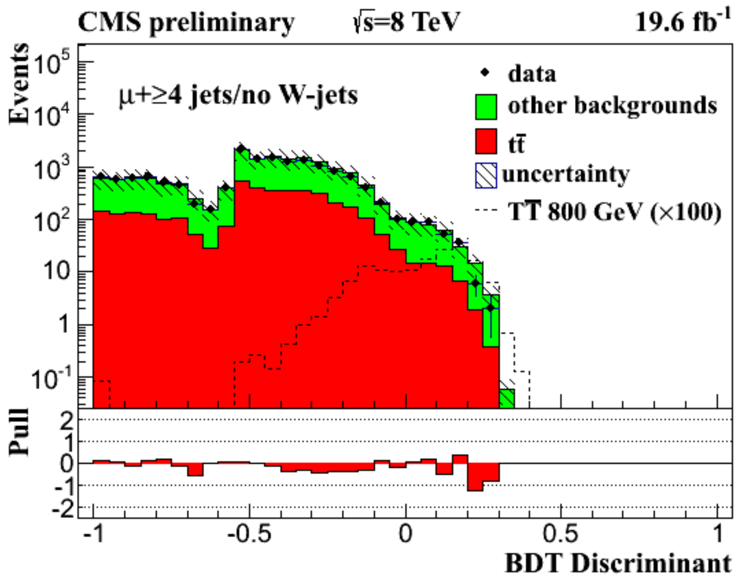
Similar triangle
for
B-like VLQ

src: M. Peskin

Combined t' search in l+jets and multileptons

- Require one isolated lepton pT> 32 GeV
- And at least 3 jets plus:
  - Fourth jet
  - W-tagged CA8 jet in first 3 jets
- L+jets analysis employs Boosted Decision Tree to reach maximum sensitivity

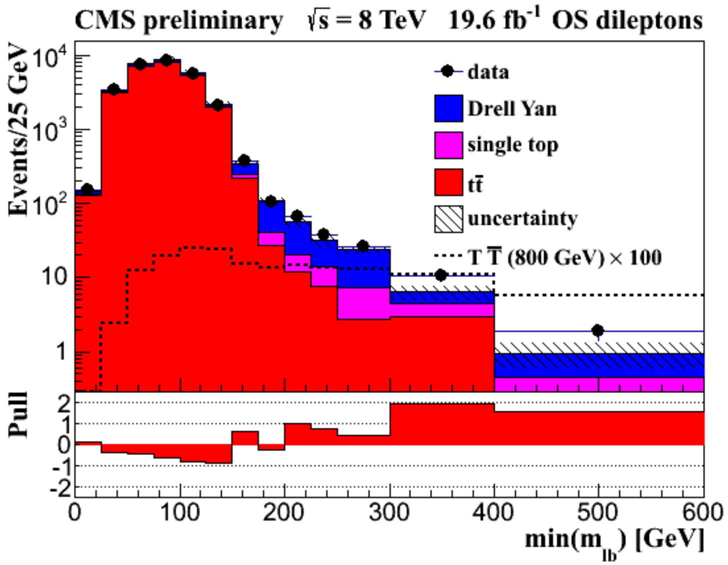


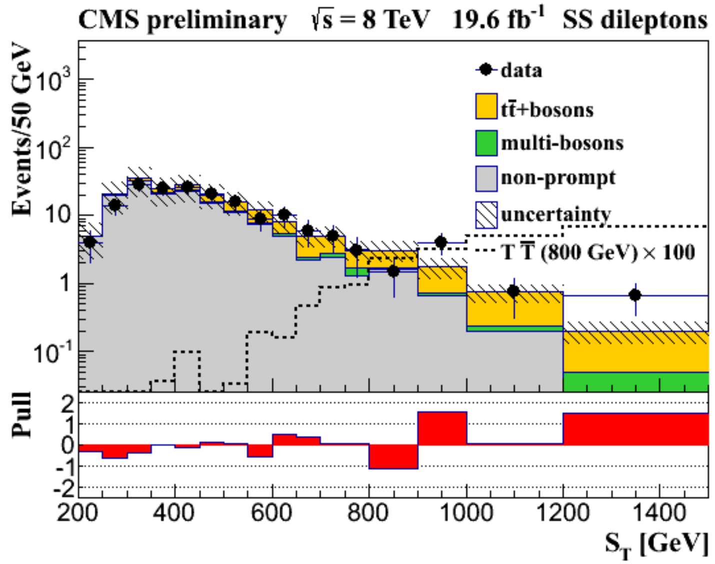


src: B2G-12-015, JHEP 06(2014) 125

Combined t' search in l+jets and multileptons

- In multilepton channels events are separated by backgrounds
  - 12 cathegories, cut and count experiment in each
- Example:
  - same-sign dilepton events
  - Opposite sign same flavor leptons + one extra lepton

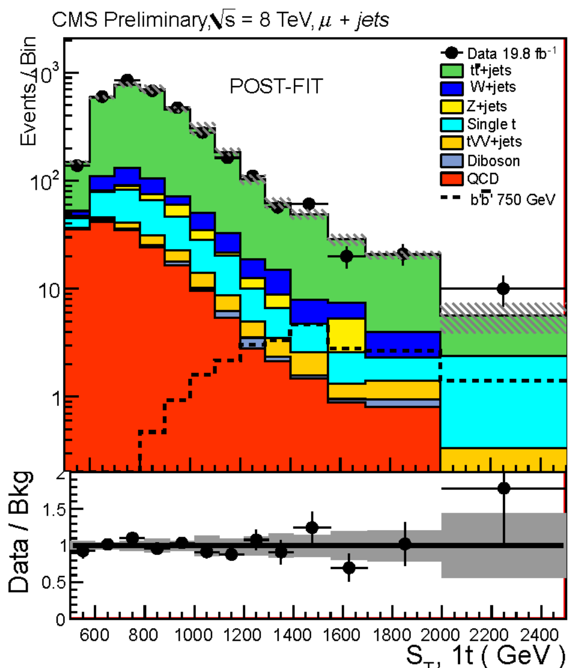


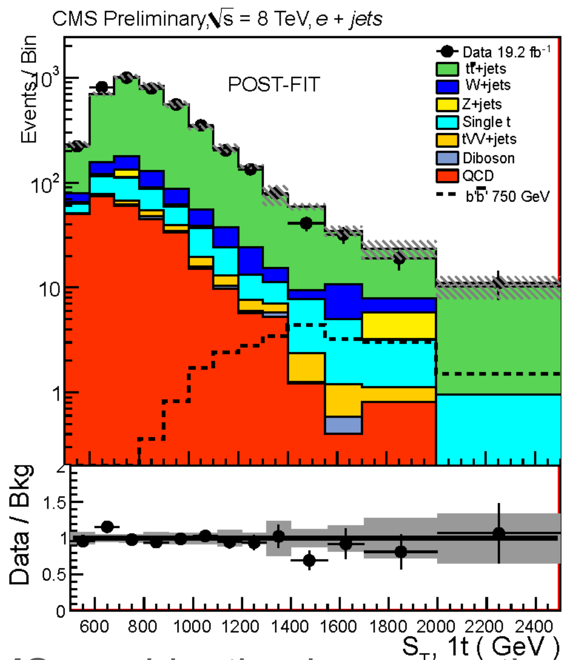


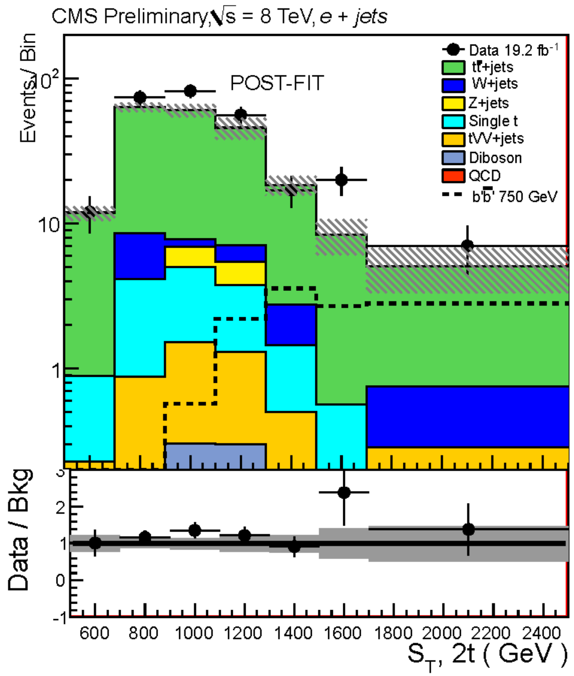
src: B2G-12-015, JHEP 06(2014) 125

Search for b' pair production in l+jets

- Single lepton, at least 4 jets, one b-tag
- Again, focus on boosted (vector-boson-tagged) jets
- Only ST considered to be more model-independent
- Sensitive to tWtW, tWbZ, tWbH, bZbZ, bZbH, bHbH final states

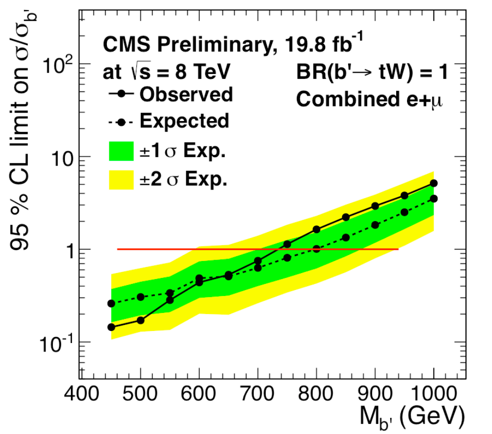




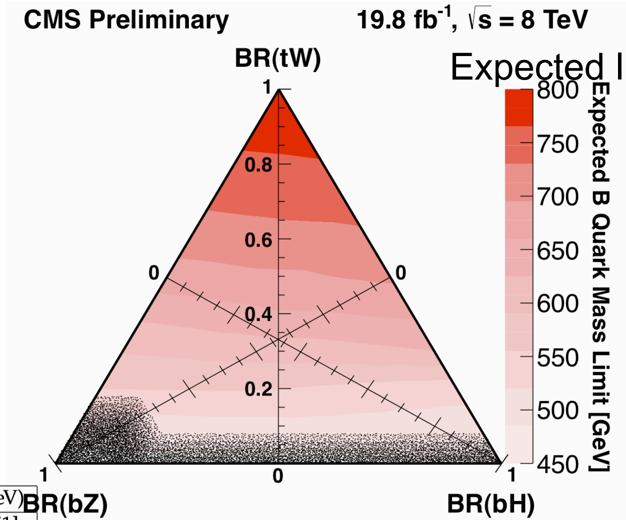


src: CMS PAS B2G-12-019 – CMS combination in preparation

Combined result in BR plane: b’

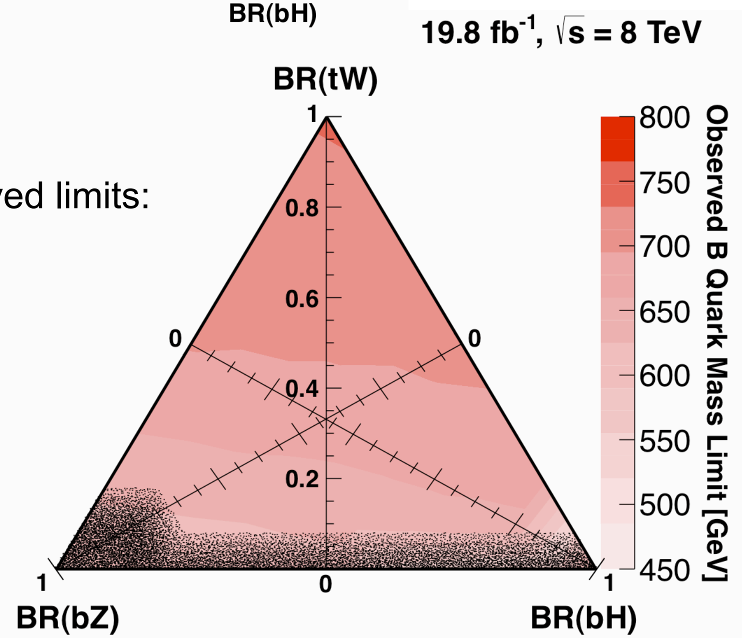


Expected limits:



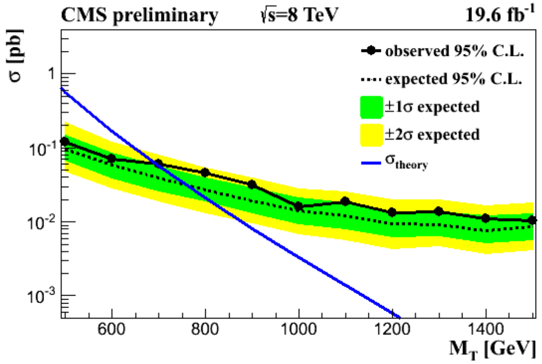
Comb#	Br(tW)	Br(bH)	Br(bZ)	Obs (GeV)	Exp (GeV)	±1σ (GeV)	±2σ(GeV)
(0)	0.5	0.25	0.25	700	689	[586,782]	[516,851]
(1)	0.0	0.0	1.0	582	<450	[<450,495]	[<450,566]
(2)	0.0	0.2	0.8	601	<450	[<450,502]	[<450,565]
(3)	0.0	0.4	0.6	606	<450	[<450,506]	[<450,557]
(4)	0.0	0.6	0.4	546	<450	[<450,504]	[<450,530]
(5)	0.0	0.8	0.2	523	<450	[<450,501]	[<450,515]
(6)	0.0	1.0	0.0	634	454	[<450,514]	[<450,599]
(7)	0.2	0.0	0.8	639	555	[476,633]	[<450,721]
(8)	0.2	0.2	0.6	647	557	[484,645]	[<450,728]
(9)	0.2	0.4	0.4	653	555	[494,657]	[<450,732]
(10)	0.2	0.6	0.2	665	543	[500,664]	[<450,748]
(11)	0.2	0.8	0.0	671	532	[501,672]	[<450,755]
(12)	0.4	0.0	0.6	678	633	[557,741]	[473,810]
(13)	0.4	0.2	0.4	686	648	[560,745]	[486,814]
(14)	0.4	0.4	0.2	686	657	[562,754]	[493,825]
(15)	0.4	0.6	0.0	695	666	[555,760]	[503,830]
(16)	0.5	0.5	0.0	707	702	[594,792]	[522,861]
(17)	0.6	0.0	0.4	706	710	[599,802]	[537,866]
(18)	0.6	0.2	0.2	709	717	[609,810]	[542,875]
(19)	0.6	0.4	0.0	712	722	[625,816]	[544,879]
(20)	0.8	0.0	0.2	720	757	[666,845]	[567,905]
(21)	0.8	0.2	0.0	725	762	[671,852]	[574,908]
(22)	1.0	0.0	0.0	732	797	[700,873]	[589,934]

Observed limits:



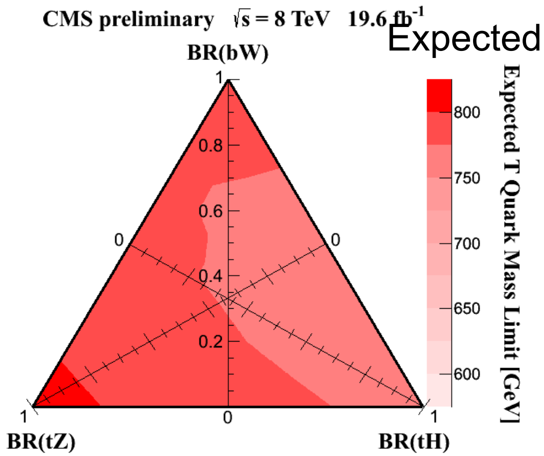
src: CMS PAS B2G-12-019 – CMS combination in preparation

Combined result in BR plane: t'

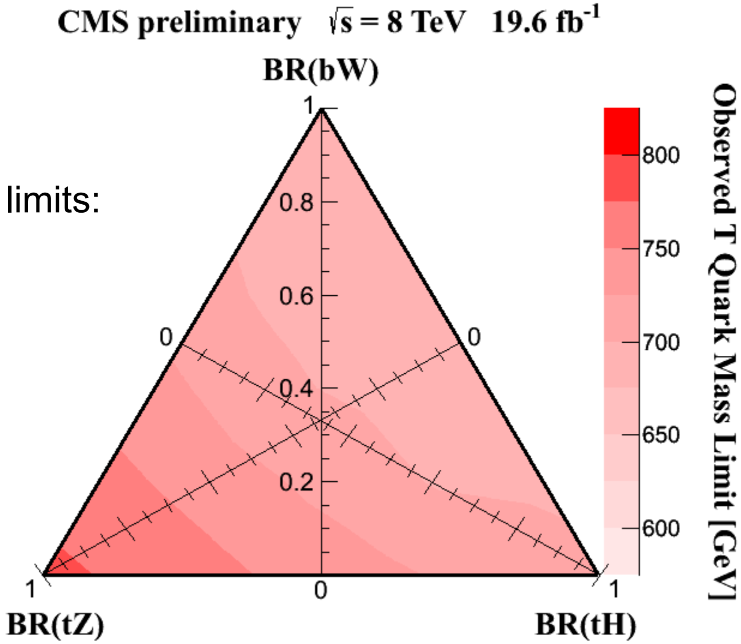


Scenario	Branching Fractions T→bW	T→tH	T→tZ	expected limit (GeV)	observed limit (GeV)
(0)	0.5	0.25	0.25	773	696
(1)	0.0	0.0	1.0	813	782
(2)	0.0	0.2	0.8	798	766
(3)	0.0	0.4	0.6	790	747
(4)	0.0	0.6	0.4	783	731
(5)	0.0	0.8	0.2	773	715
(6)	0.0	1.0	0.0	770	706
(7)	0.2	0.0	0.8	794	758
(8)	0.2	0.2	0.6	786	739
(9)	0.2	0.4	0.4	777	717
(10)	0.2	0.6	0.2	767	698
(11)	0.2	0.8	0.0	766	694
(12)	0.4	0.0	0.6	786	734
(13)	0.4	0.2	0.4	776	705
(14)	0.4	0.4	0.2	766	693
(15)	0.4	0.6	0.0	762	690
(16)	0.6	0.0	0.4	779	703
(17)	0.6	0.2	0.2	771	693
(18)	0.6	0.4	0.0	769	687
(19)	0.8	0.0	0.2	779	695
(20)	0.8	0.2	0.0	777	689
(21)	1.0	0.0	0.0	785	700

Expected limits:



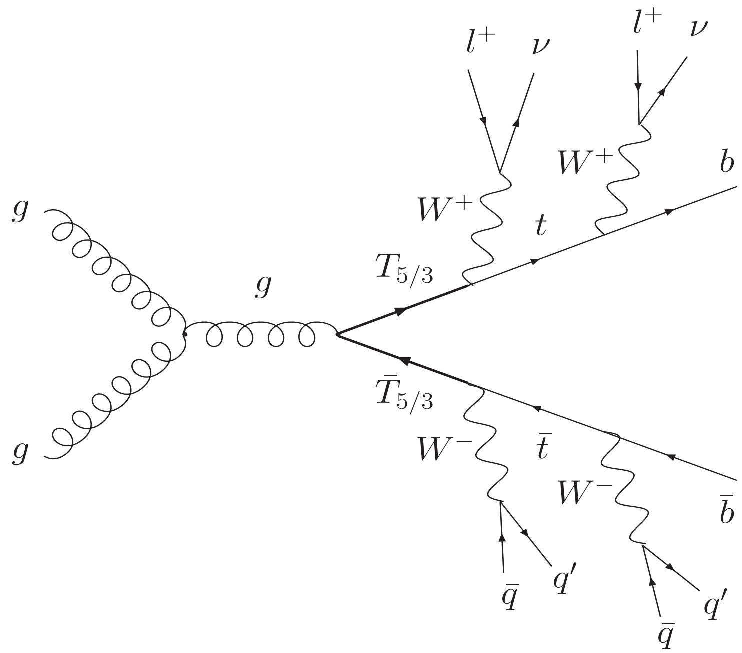
Observed limits:



src: B2G-12-015, JHEP 06(2014) 125

Top partner with charge 5/3e

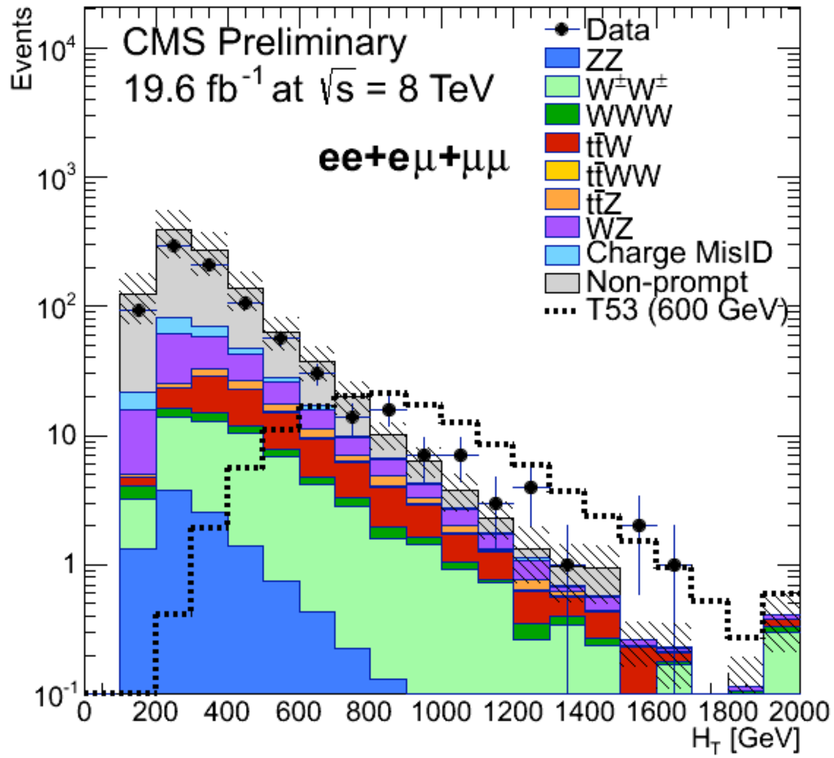
- Focus on same-sign dilepton channel
  - Leptonic W bosons from same $T_{5/3}$
- Understanding same-sign fake and prompt lepton background
  - Non-prompt background determined on data
  - Prompt: rare decays from MC:
    - WW, ZZ, ttbarW, ttbarZ, WWW



src: B2G-12-012,, Phys.Rev.Lett 112 (2014) 171801

Top partner with charge 5/3e

- Very busy environment: requir 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
- Cross section limits exclude q=5/3e top partners with mass up to 770 GeV/c^2

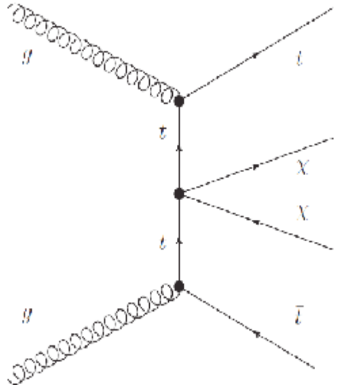


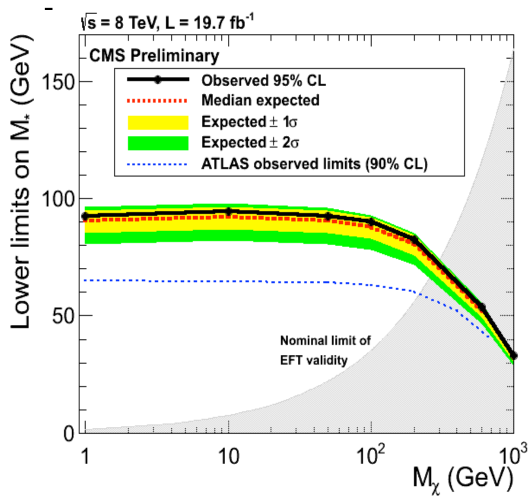
src: B2G-12-012,, Phys.Rev.Lett 112 (2014) 171801

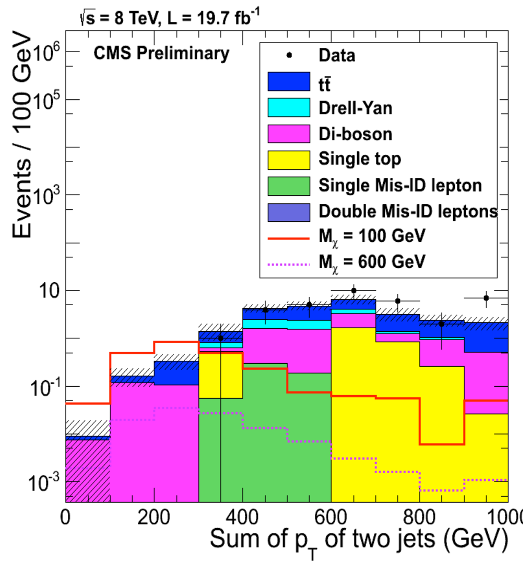
Vrije Universiteit Brussel

CMS ttbar+DM

- Searches for threshold ttbar production with low missing ET
- Complementary to more SUSY-inspire searches that for example focus on stop+LSP pair production

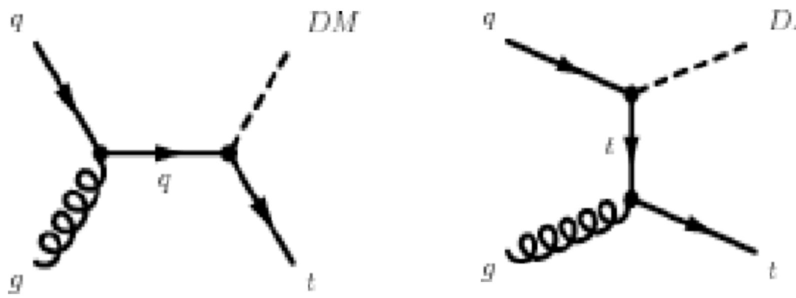




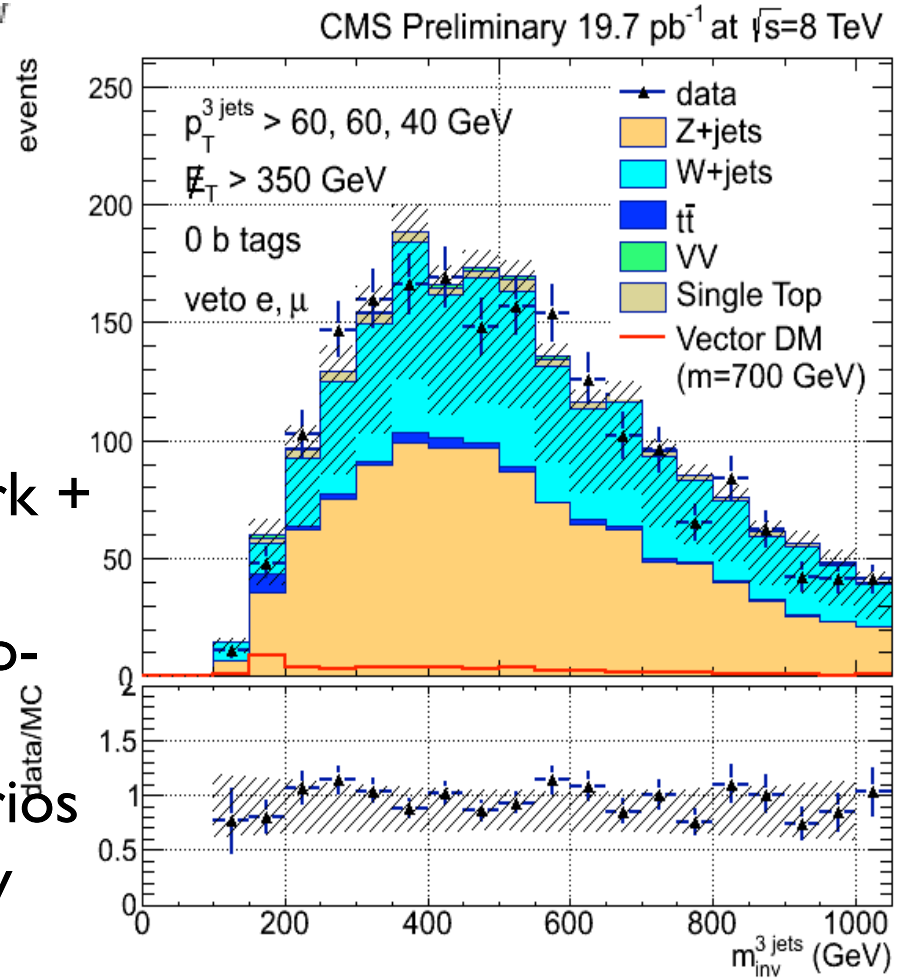


CMS-B2G-13-004, (19.6 fb^{-1}@ 8 TeV)

CMS monotops



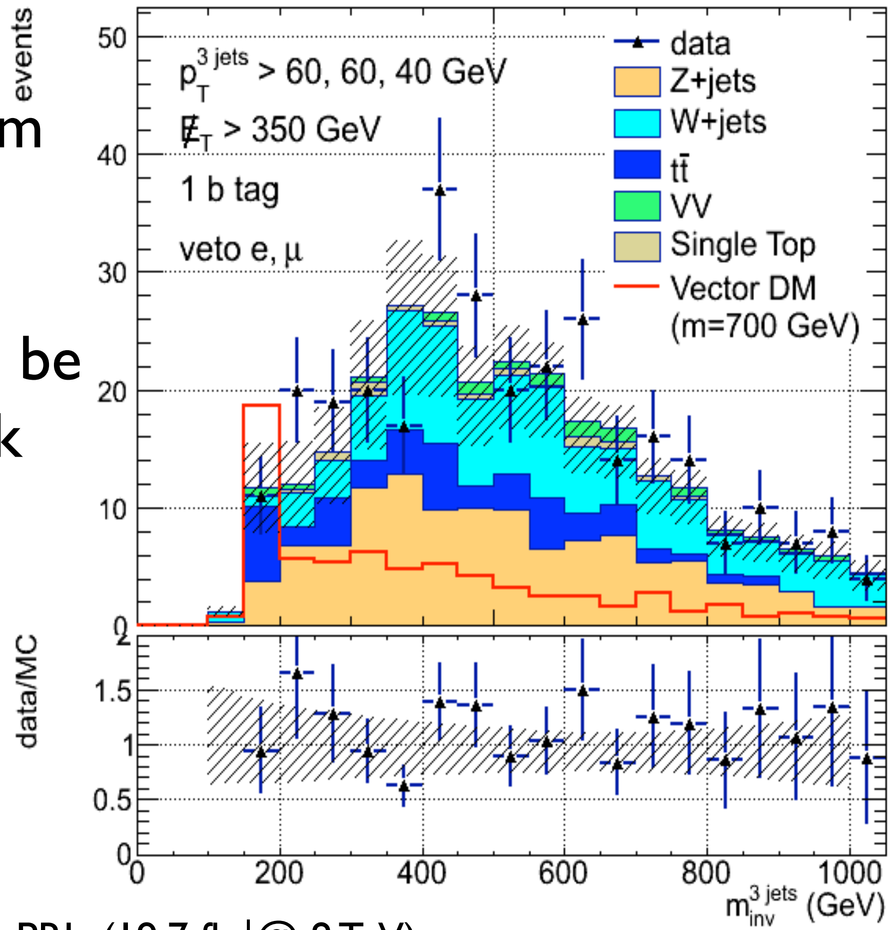
- Production of one top quark recoiling against DM candidate
- Signature: one hadronic top quark + $E_T$miss
- Complementary to typical 'mono-X' signatures
- Signature favoured in DM scenarios with modified couplings to heavy flavour



CMS-B2G-12-022, hep-ex:1410.1149, submitted to PRL, (19.7 fb^{-1}@ 8 TeV)

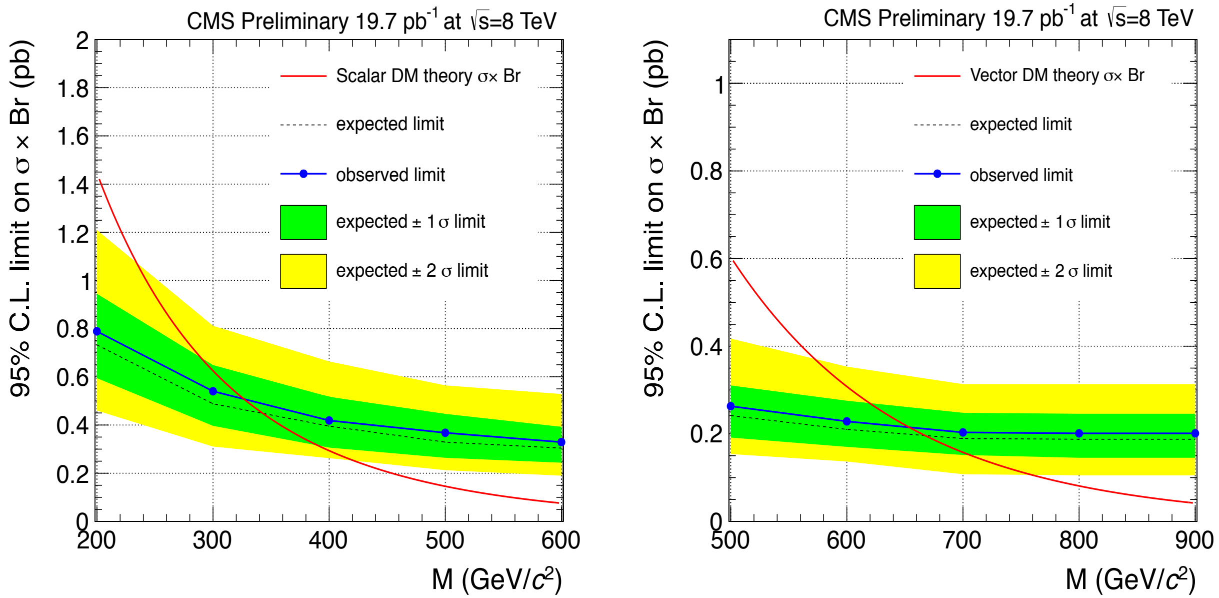
CMS monotops

- Analysis investigates $E_T$miss and invariant mass of three-jet system recoiling against $E_t$miss
- After b-tagging the signal should be visible as a peak at the top quark mass
- No excess observed above SM background, dominated by ttbar and Z boson+3 jet production



CMS-B2G-12-022, hep-ex:1410.1149, submitted to PRL, (19.7 fb^{-1}@ 8 TeV)

CMS monotops

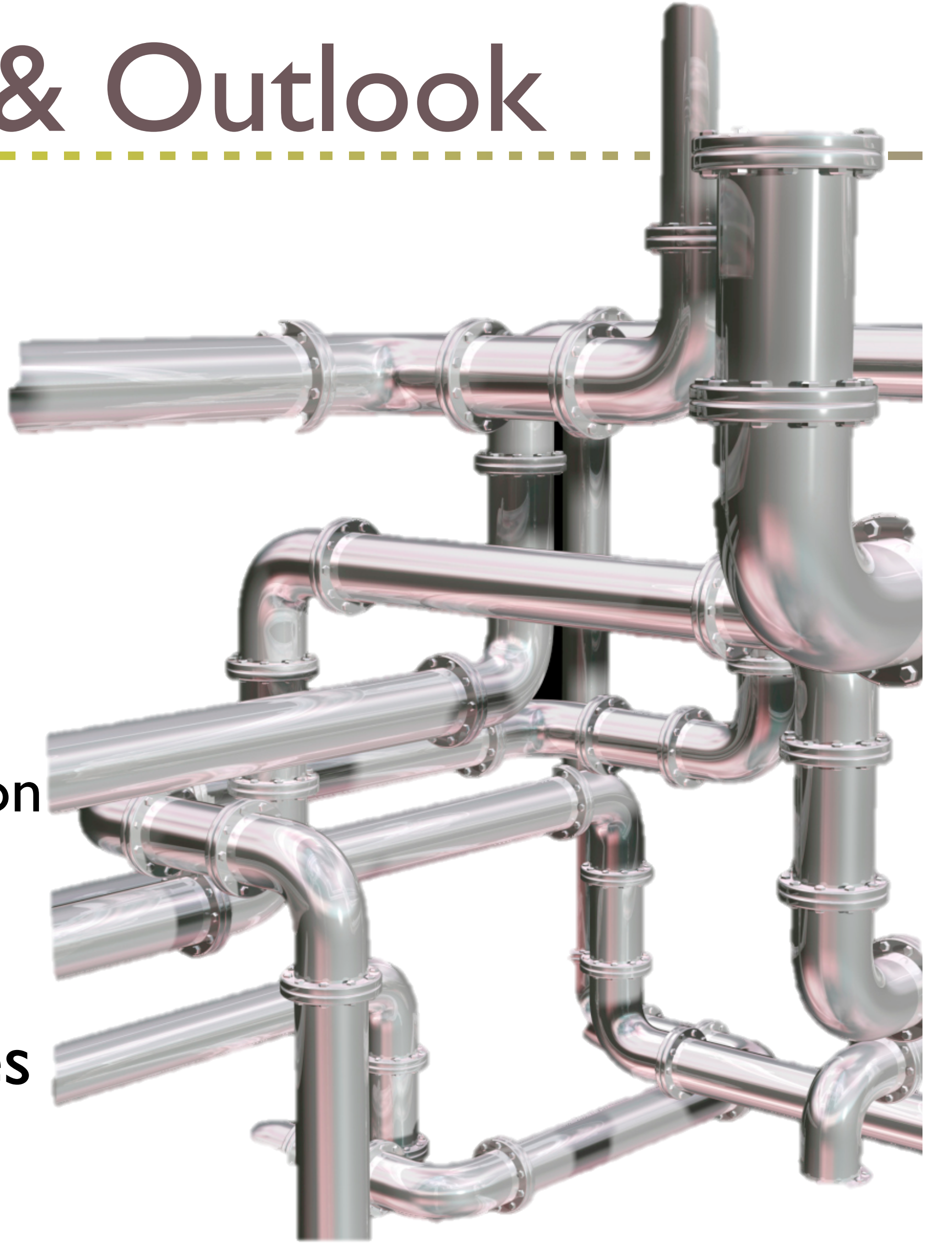


- Limits set for Scalar and vector couplings
- No mapping to flux or coupling strength limits as in monojet/monophoton searches

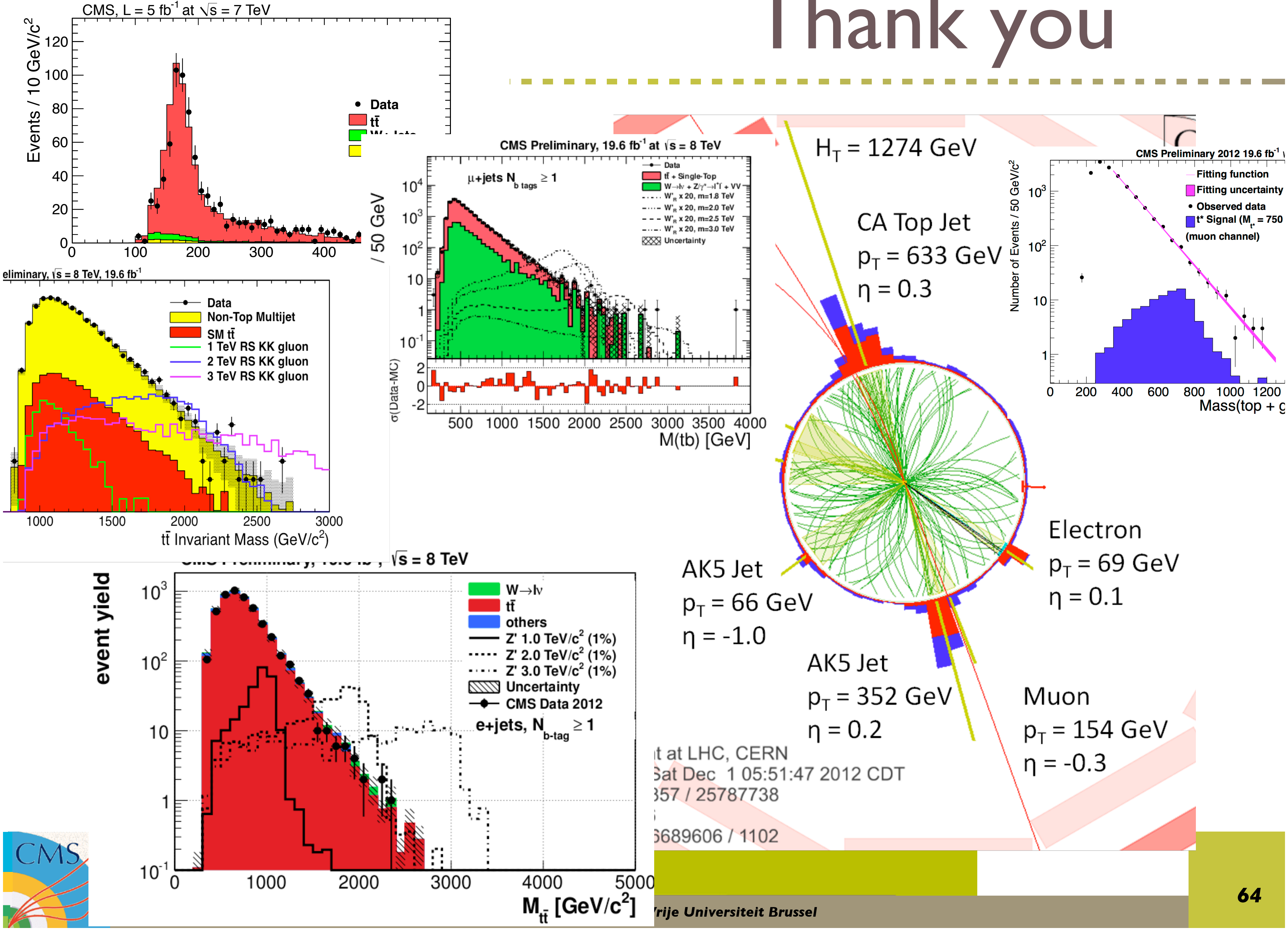
CMS-B2G-12-022, hep-ex:1410.1149, submitted to PRL, (19.7 fb^{-1}@ 8 TeV)

Conclusion & Outlook

- CMS has dedicated searches program in the top sector
  - Top-like Exotica
    - = Beyond two generations (B2G)
- Pushing the envelope:
  - very stringent limits
  - spearheading new reconstruction techniques
- Some 'final word' papers in pipeline – but these techniques will really flourish at 13 TeV



Thank you


CMS, L = 5 fb^{-1} at $\sqrt{s}$ = 7 TeV
Events / 10 GeV/c^2
Data
tt̄
Preliminary, $\sqrt{s}$ = 8 TeV, 19.6 fb^{-1}
Data
Non-Top Multijet
SM tt̄
1 TeV RS KK gluon
2 TeV RS KK gluon
3 TeV RS KK gluon
tt̄ Invariant Mass (GeV/c^2)
CMS Preliminary, 19.6 fb^{-1} at $\sqrt{s}$ = 8 TeV
μ+jets N$_{b\ tags}$ ≥ 1
σ(Data-MC)
M(tb) [GeV]
CMS Preliminary 2012 19.6 fb^{-1}
Fitting function
Fitting uncertainty
Observed data
t* Signal
(muon channel)
Number of Events / 50 GeV/c^2
Mass(top + g
$\sqrt{s}$ = 8 TeV
event yield
W→lν
tt̄
others
Z' 1.0 TeV/c^2 (1%)
Z' 2.0 TeV/c^2 (1%)
Z' 3.0 TeV/c^2 (1%)
Uncertainty
CMS Data 2012
e+jets, N$_{b\text{-}tag}$ ≥ 1
M$_{t\bar{t}}$ [GeV/c^2]
H$_T$ = 1274 GeV
CA Top Jet
p$_T$ = 633 GeV
η = 0.3
Electron
p$_T$ = 69 GeV
η = 0.1
AK5 Jet
p$_T$ = 66 GeV
η = -1.0
AK5 Jet
p$_T$ = 352 GeV
η = 0.2
Muon
p$_T$ = 154 GeV
η = -0.3
t at LHC, CERN
Sat Dec 1 05:51:47 2012 CDT
357 / 25787738
6689606 / 1102