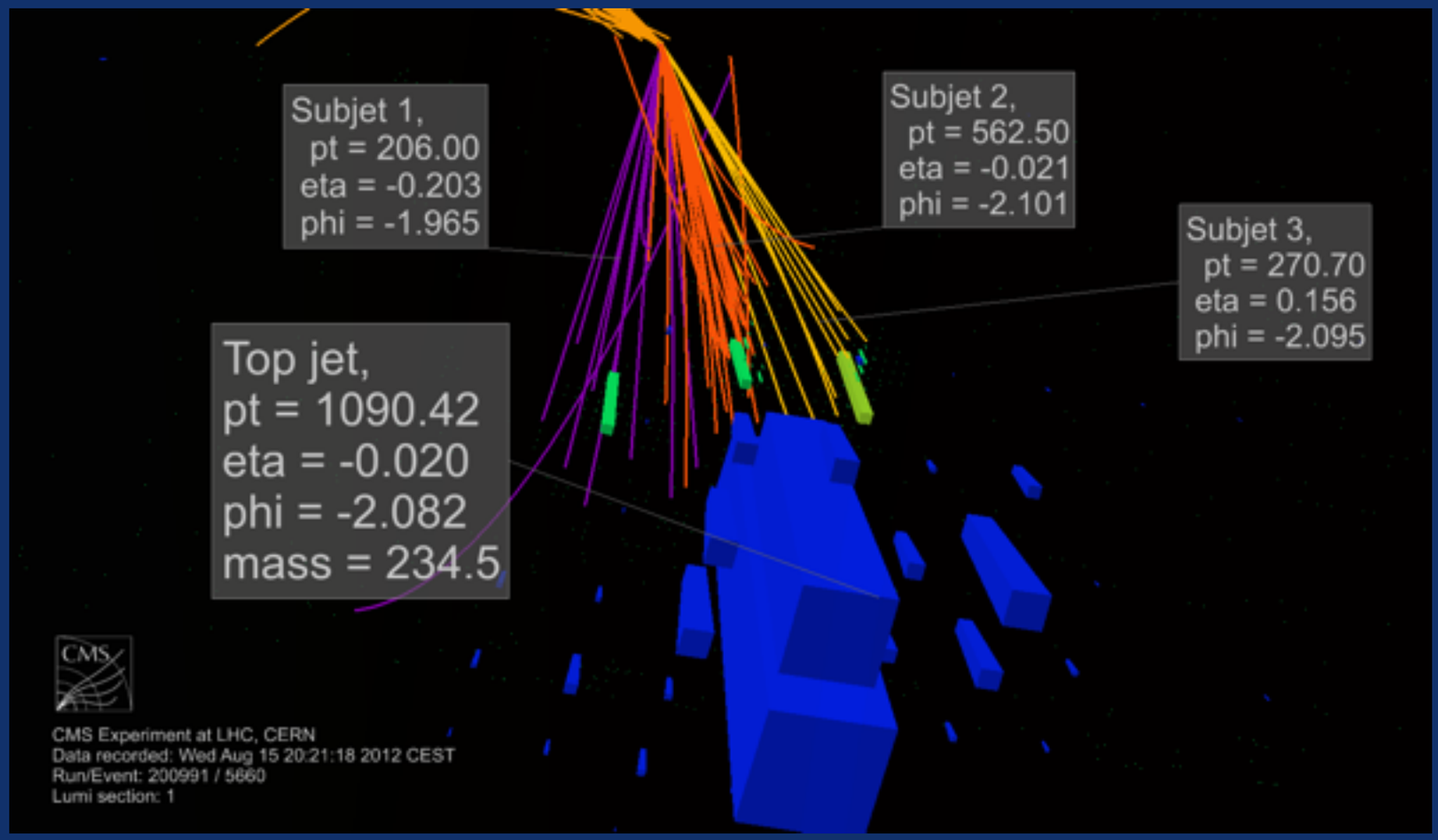
Recent Searches for New Physics With Top Quarks at CMS



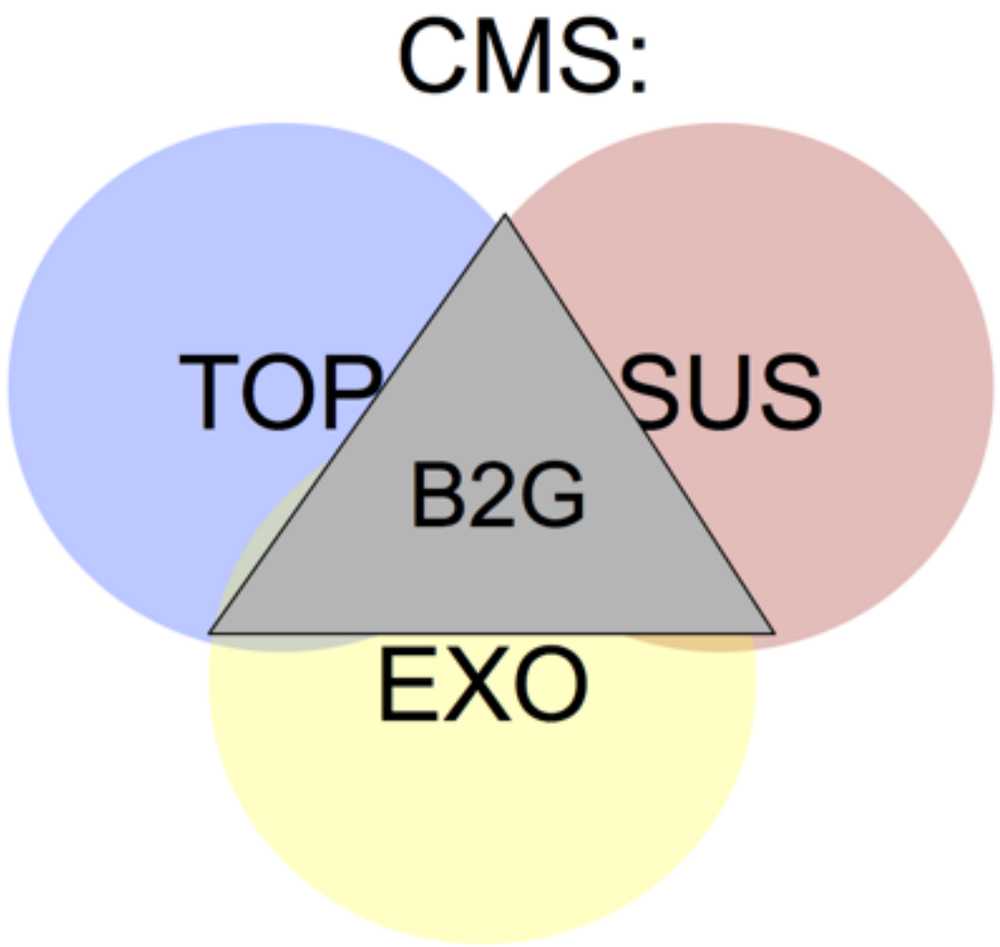
Wine+Cheese Seminar

Salvatore Rappoccio
(State University of New York at Buffalo)

6 June 2014

Beyond Two Generations (B2G)

- For physics including top quarks in the final state, CMS has four different Physics Analysis Groups (PAGs)
- B2G is essentially “non-SUSY searches with top-like final states”
- https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsB2G



Beyond This Talk (BTT)

- Building upon two previous W+C seminars :
  - Freya Blekman (Apr. 2013)
    - http://theory.fnal.gov/jetp/talks/FNAL_WnC_B2G_fblekman.pdf
  - Nhan Tran (Apr. 2014)
    - http://theory.fnal.gov/jetp/talks/wc_ntran_140425.pdf
- There will be tasty new things, I promise

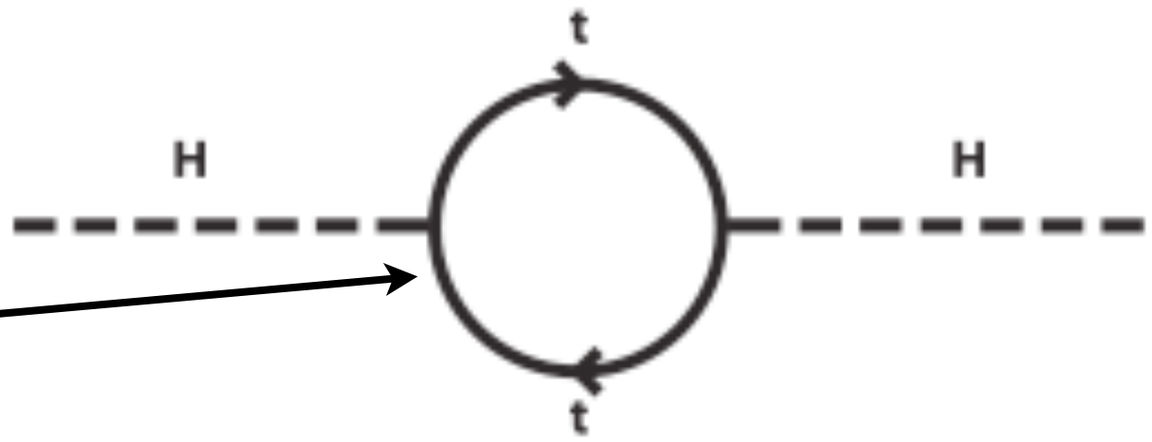
The Big Picture

- The H is great, but even if it solves some problems, it leaves a new puzzle

Diverges $\sim \mathcal{O}(\ln \Lambda^2)$

(max scale of the model)

- Quantum mechanically, H mass "wants" to be enormous
  - Coupling to top, W/Z/H causes logarithmic divergence



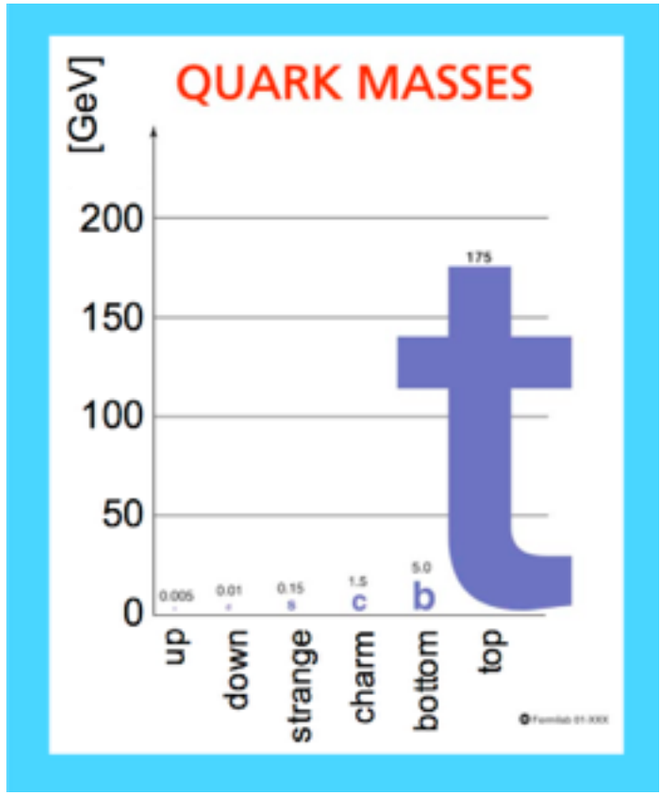
- Yet, we see it at 125 GeV
  - Accident? Necessity?

The (little) Hierarchy Problem : "Is Naturalness a Thing?"

Is Naturalness a Thing?

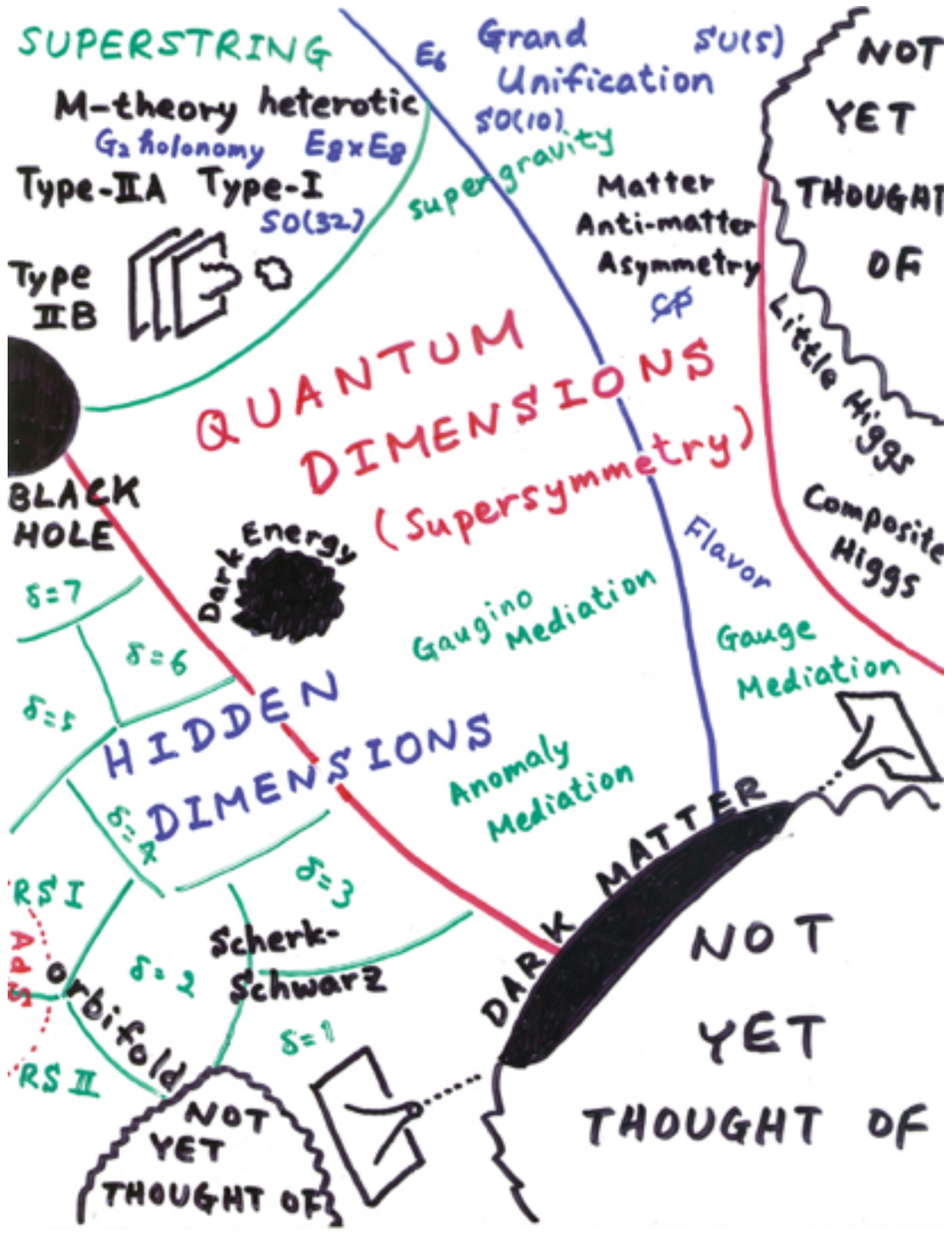
- Assume that it is :
  - Lots of options to achieve it
- Many involve quantum corrections that depend on the **mass of the particle**

Is the top quark special?



"Which one of these is not like the others?"

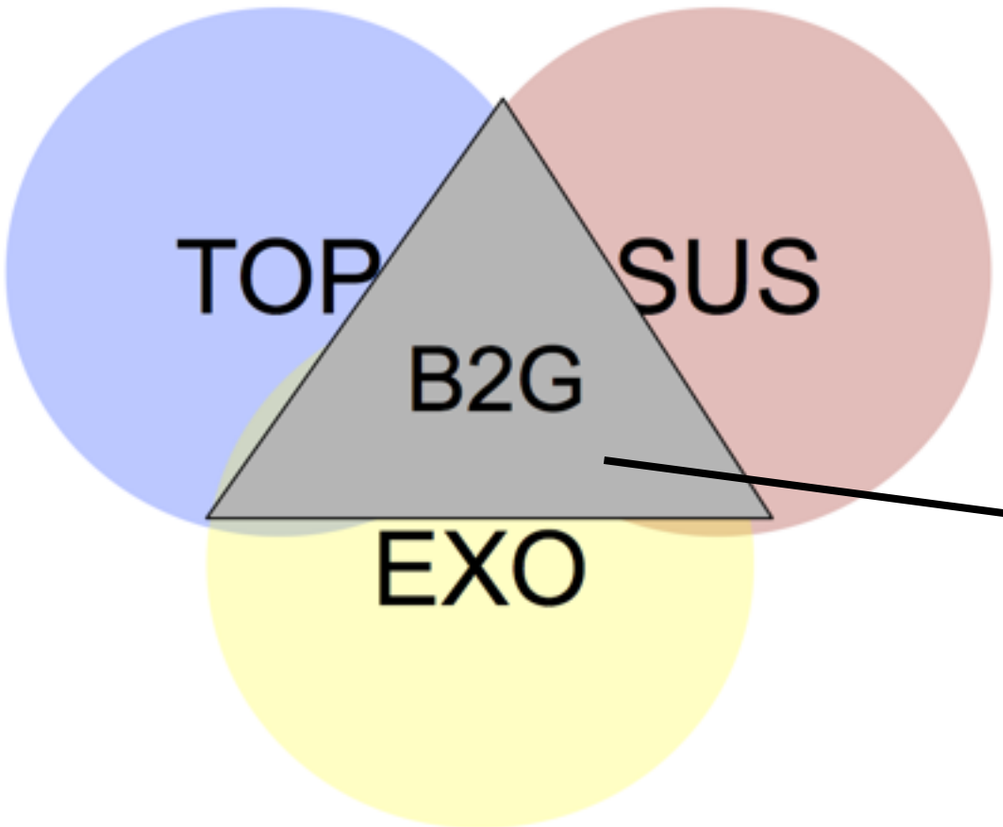
image : Hitoshi Murayama



Is Naturalness a Thing?

Focus of Today:

CMS:



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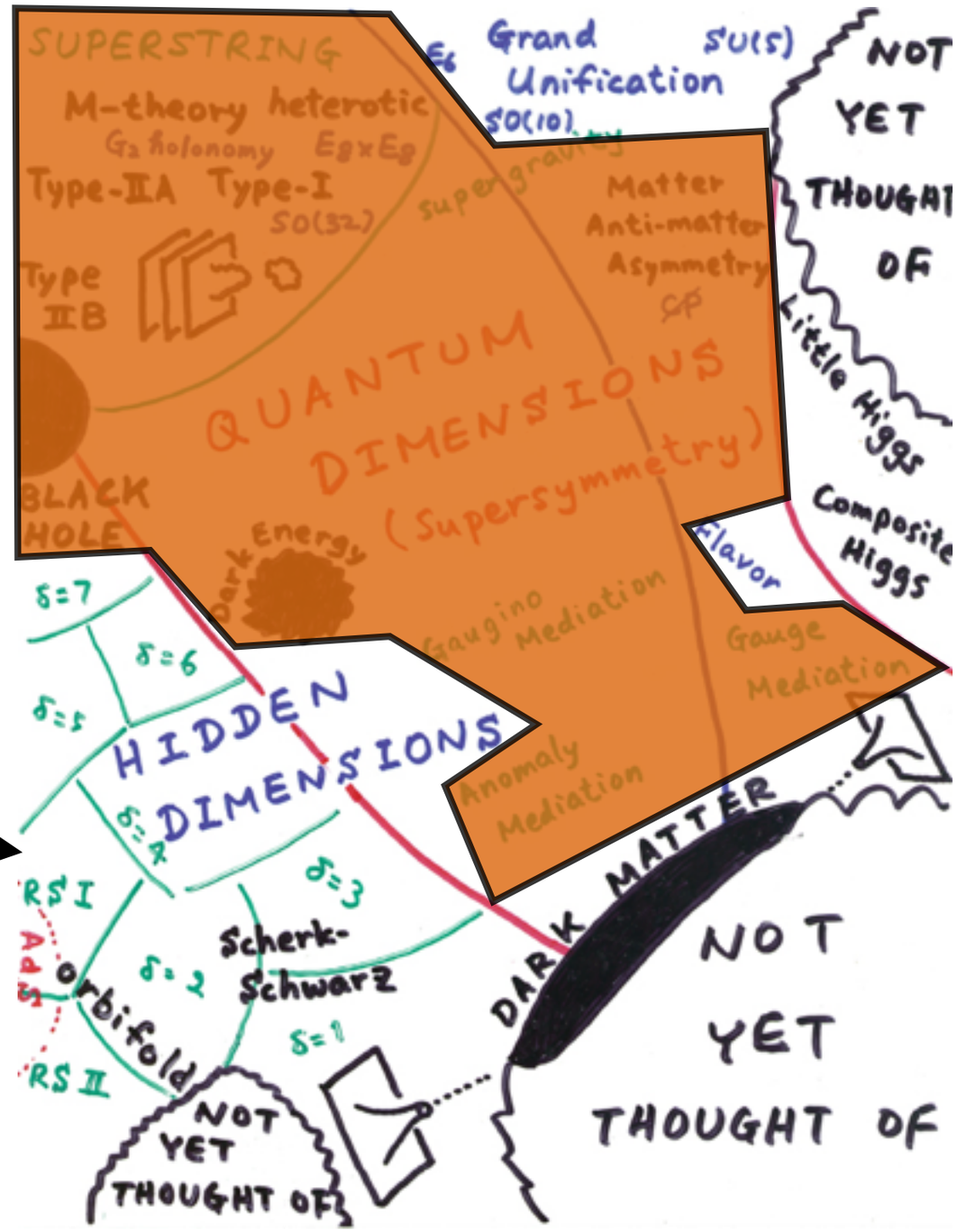
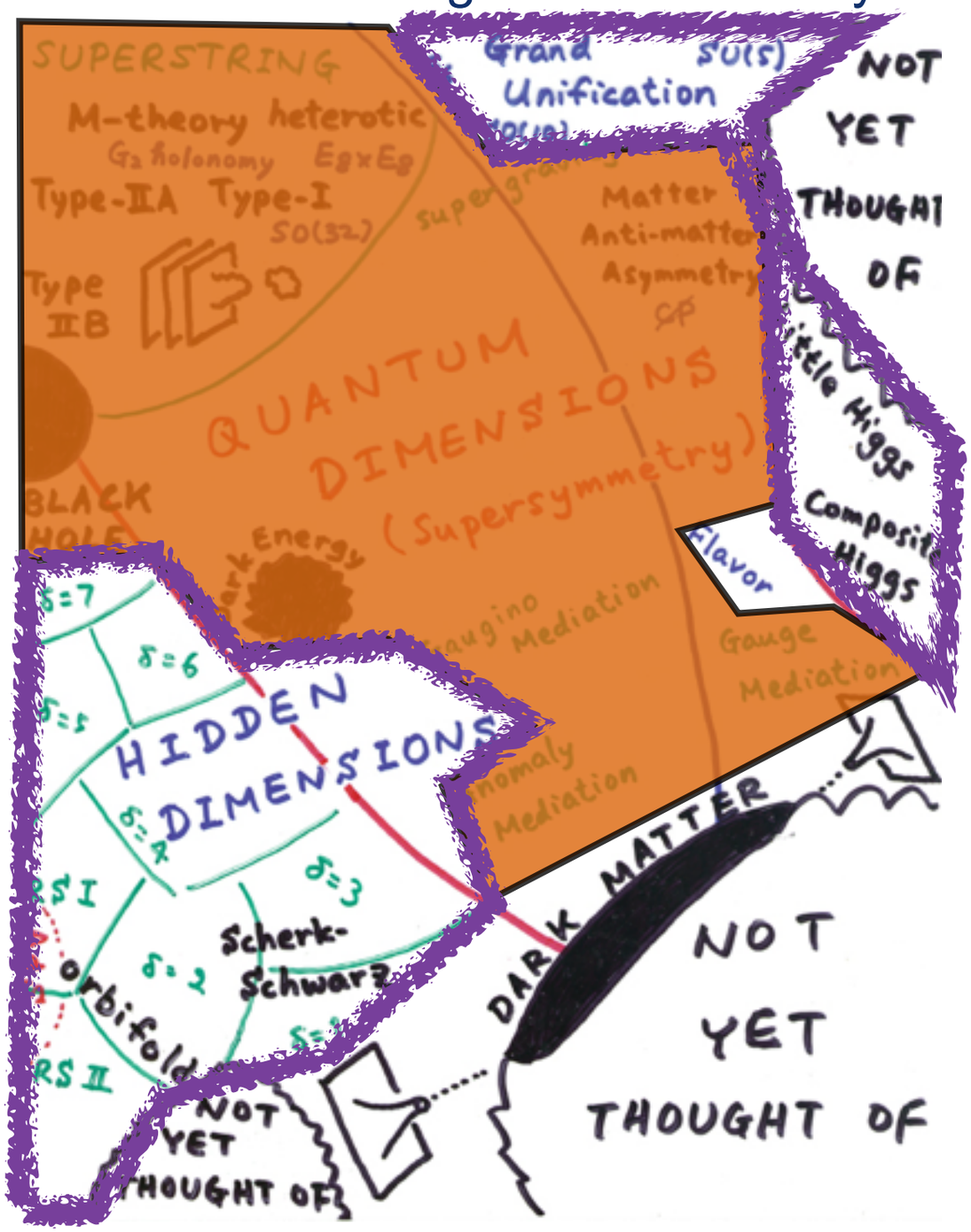


Is Naturalness a Thing?

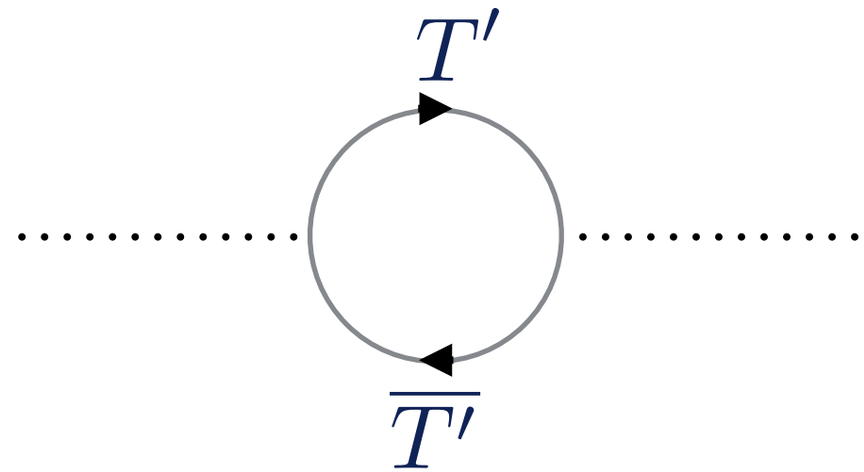
- Much of what we do in B2G focuses on pheno. from strong dynamical models, RS KK particles, Little Higgs, Composite Higgs, etc
- Often leads to vector-like quarks, tops and bottoms in the final state
  - Some are resonant, some are not

image : Hitoshi Murayama



Is Naturalness a Thing?

- Interesting case : **vector-like quarks**
- Solve the hierarchy problem similarly to the stop squark
- Why “vector-like”?



  - L and R chiralities transform the same way under

$$SU(3)_C \times SU(2)_L \times U(1)_Y$$

  - Quantum numbers for “chiral” quarks are

$$(u,d) \iff (3,2)_{1/6}$$
$$\overline{u} \iff (\overline{3},1)_{-2/3}$$
$$\overline{d} \iff (\overline{3},1)_{1/3}$$

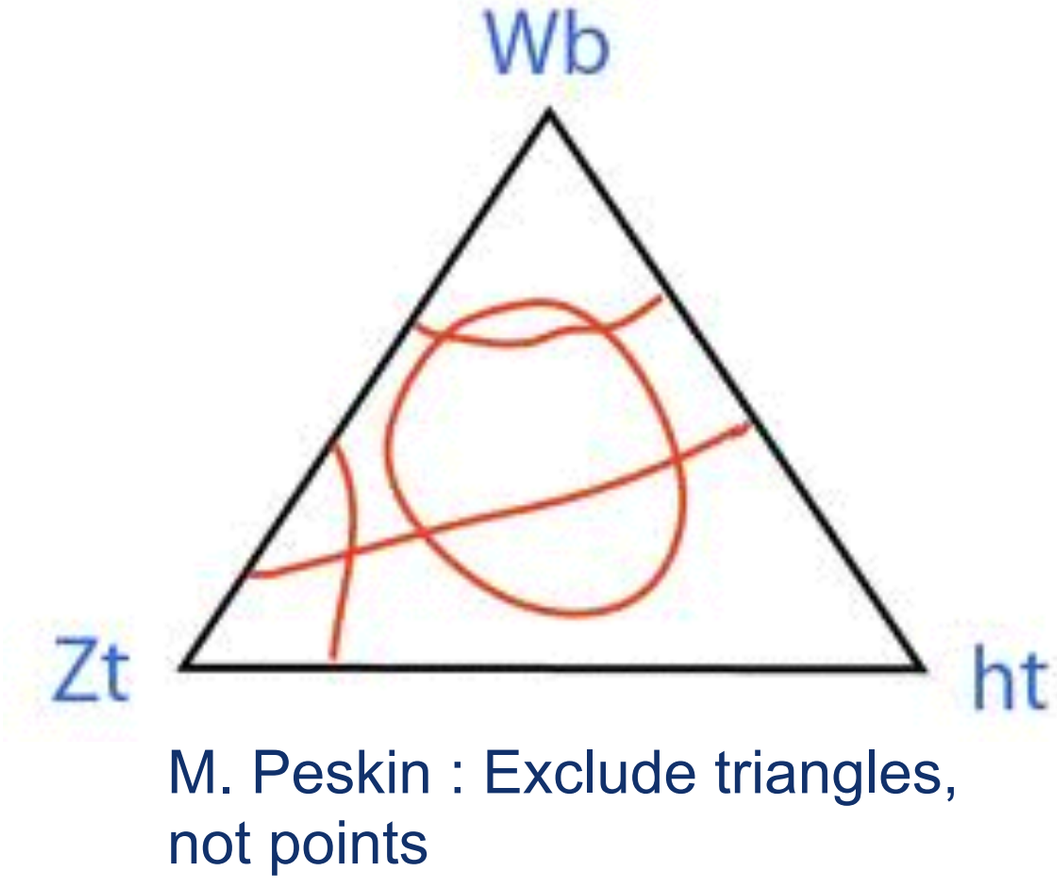
V - A

  - Quantum numbers for vector-like quarks are

$$X \iff (3,1)_{-1/3} + (\overline{3},1)_{1/3}$$

V

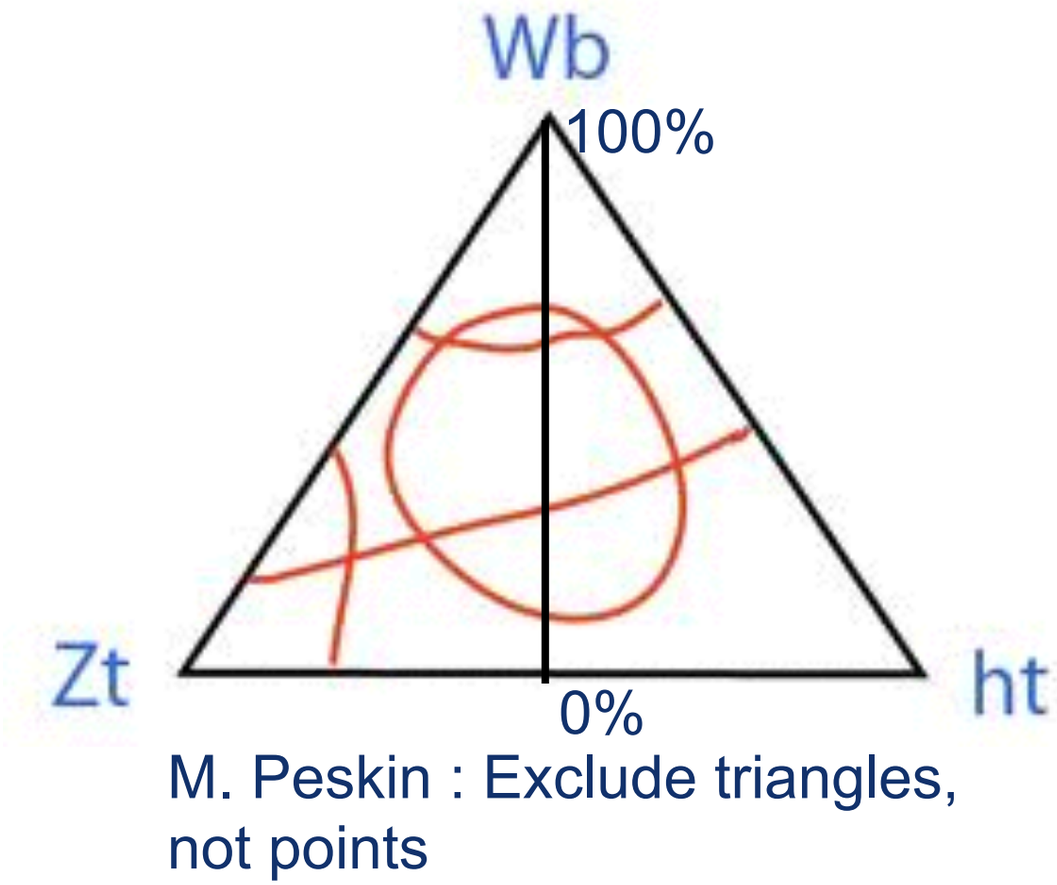
Is Naturalness a Thing?



M. Peskin : Exclude triangles,
not points

- Will present lots of “triangle” plots that are read as branching fractions along each axis

Is Naturalness a Thing?



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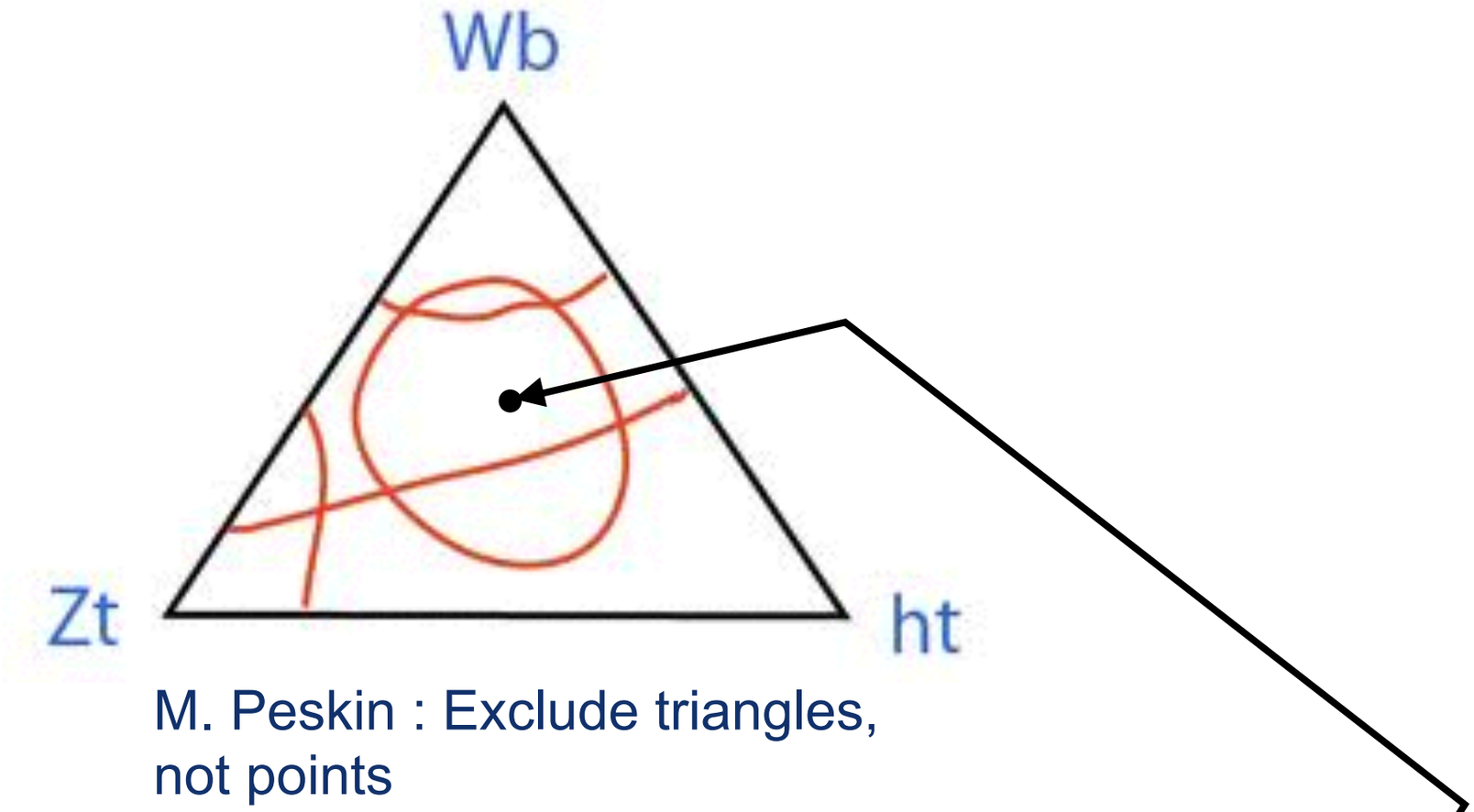
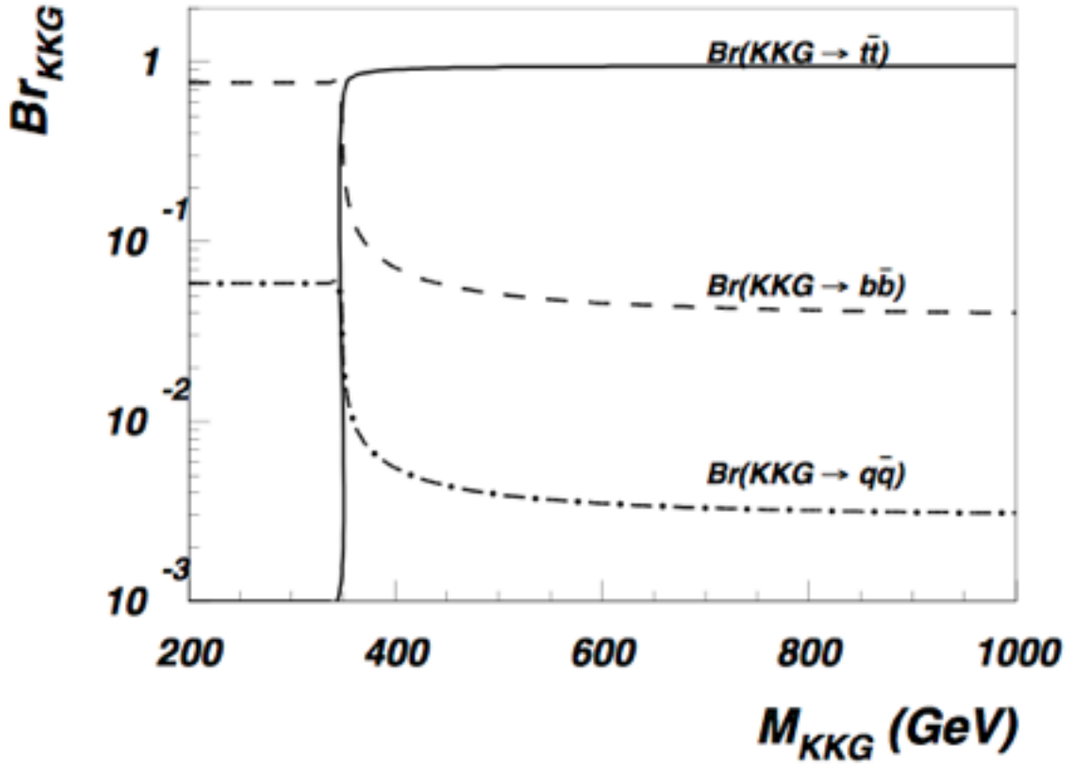


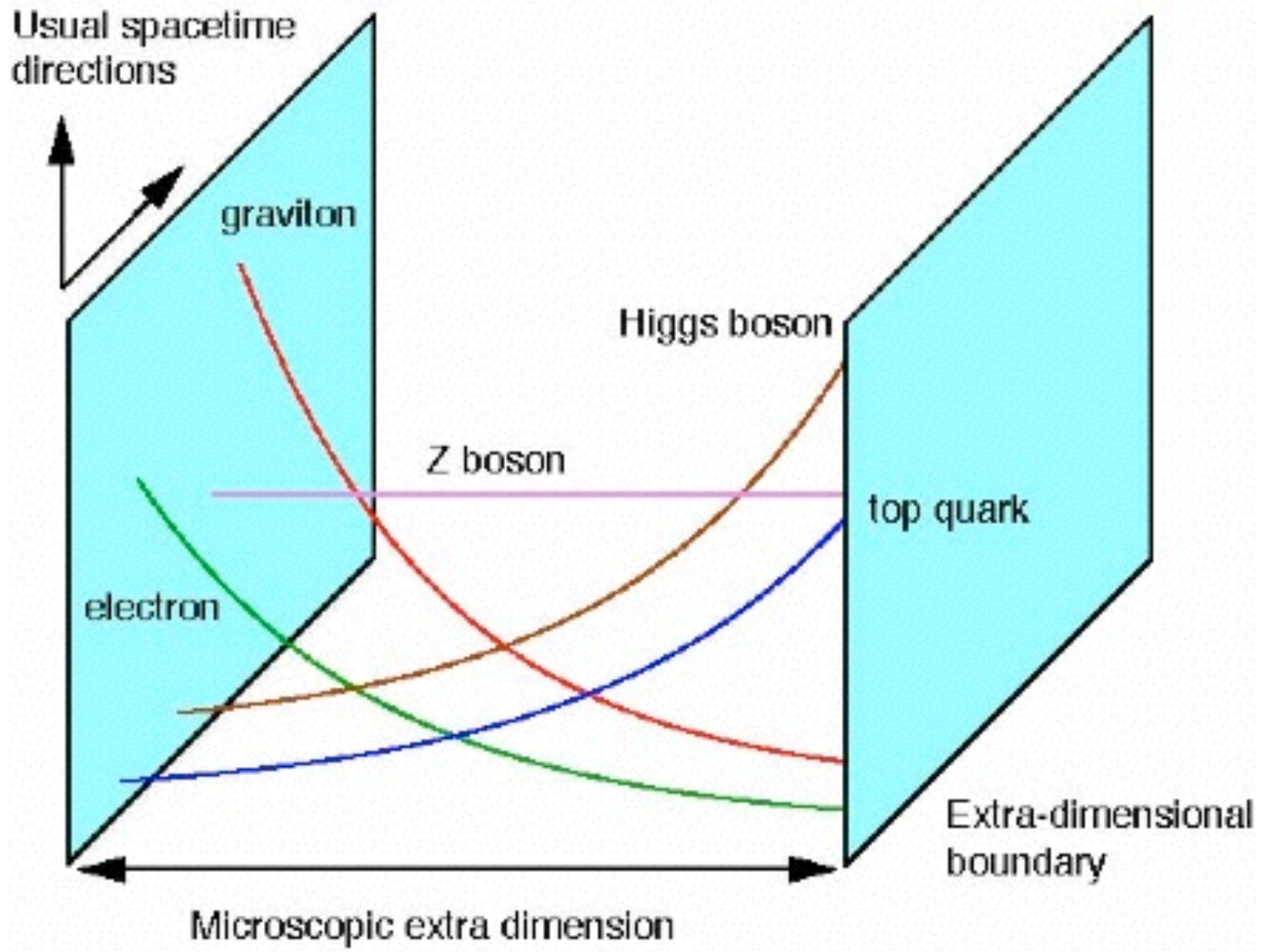
- Will present lots of “triangle” plots that are read as branching fractions along each axis
- For instance, (Wb,Zt,ht) = (0.5, 0.25, 0.25) is here

Is Naturalness a Thing?

- Interesting case : **ttbar and tb resonances**



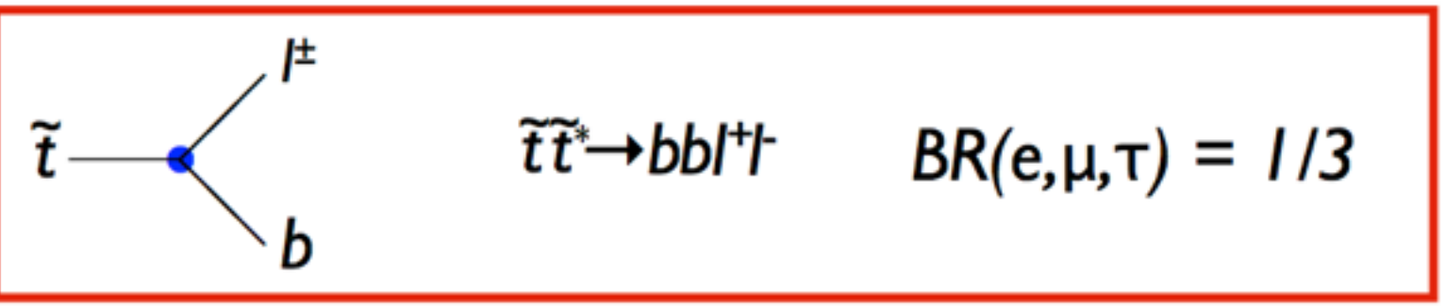
Tops may be “special” in extra dimensional scenarios, KK gluons have strong coupling to top quarks!

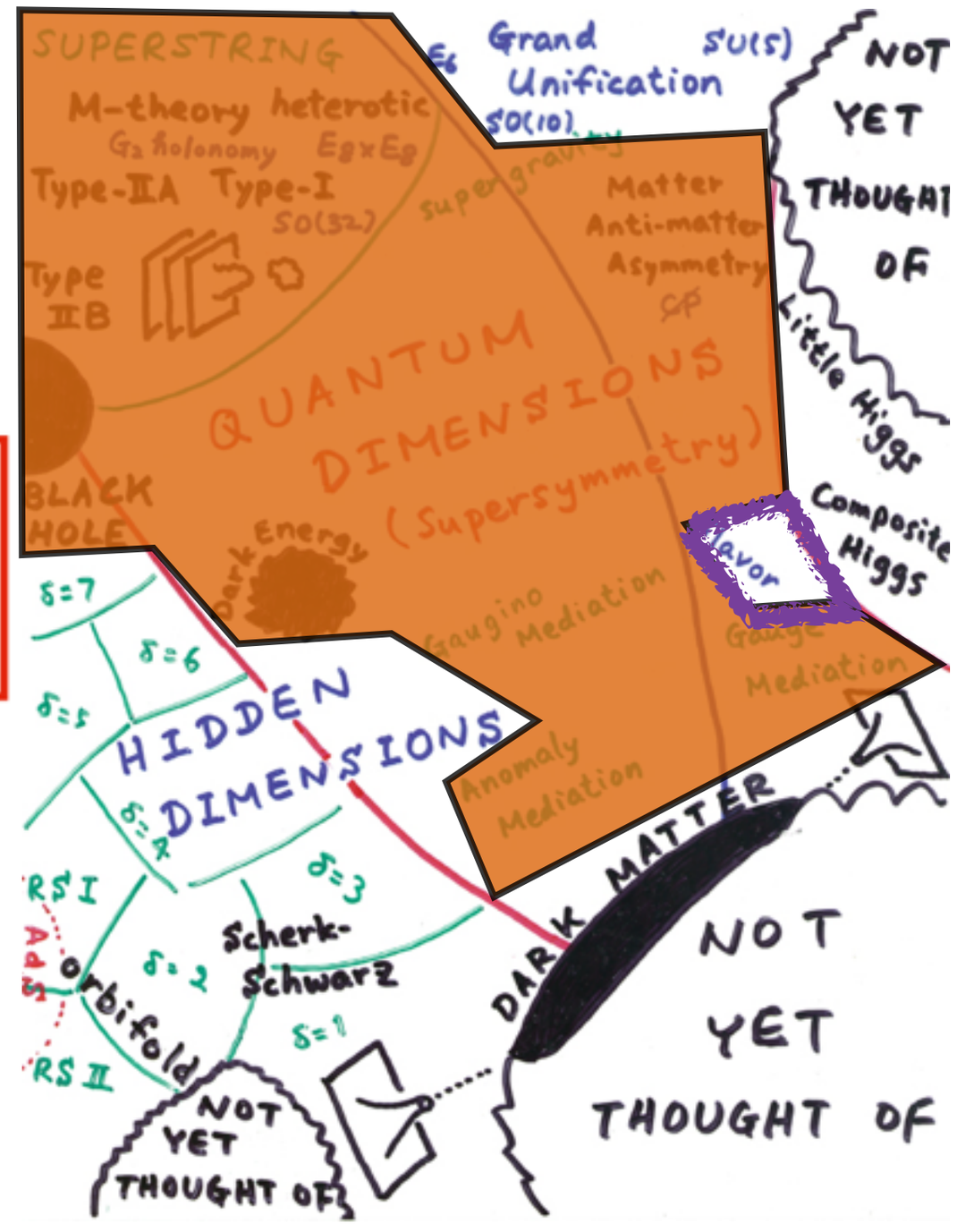


http://www.pha.jhu.edu/~morris/jhu_hep/theory.html

Is Naturalness a Thing?

- RPV SUSY can have **displaced particles**
  - For instance consider the displaced MSSM (JHEP 1207 (2012) 149)



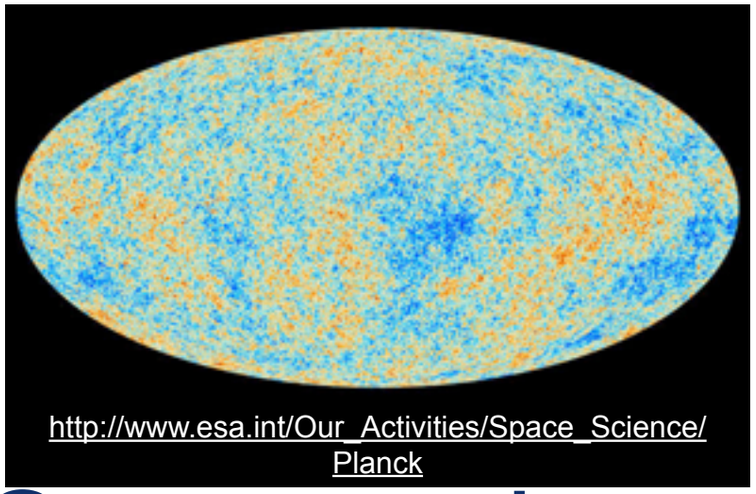


- CMS has lots of searches for very long-lived, but not moderately-lived displaced particles
- Higgs at 126 GeV favors moderate lifetimes

($\langle c\tau \rangle$ ~100 μm - 1 cm)

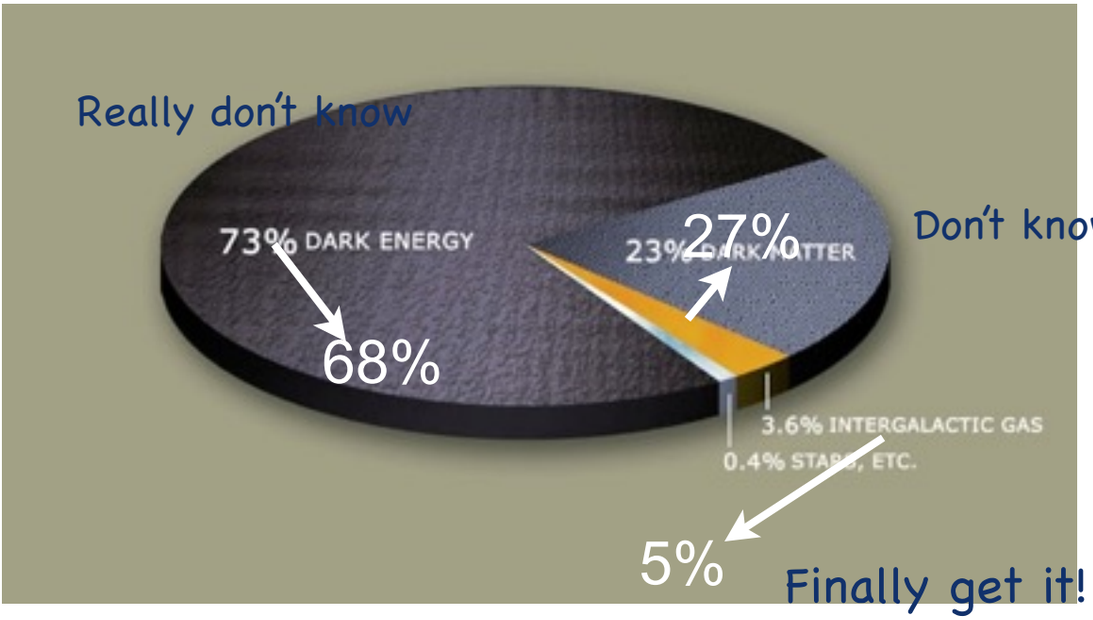
Content of the Universe?

Our Universe :

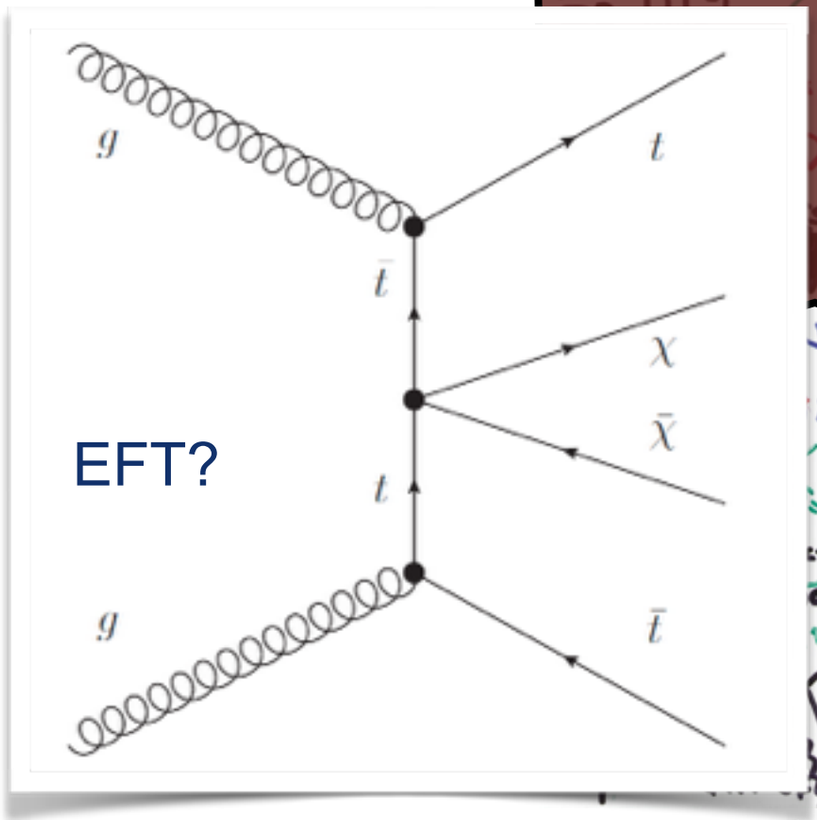


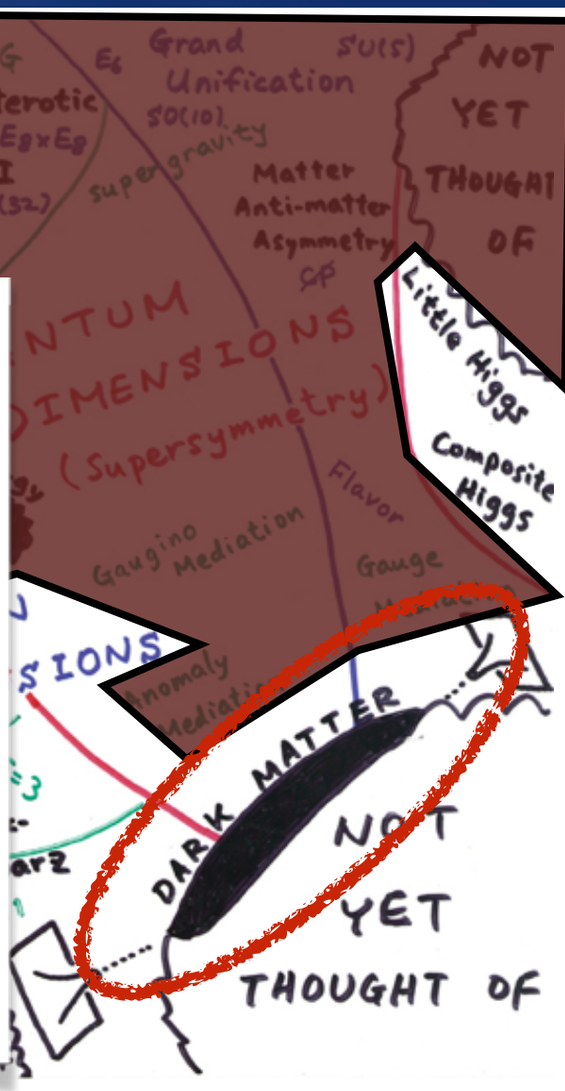
http://www.esa.int/Our_Activities/Space_Science/Planck

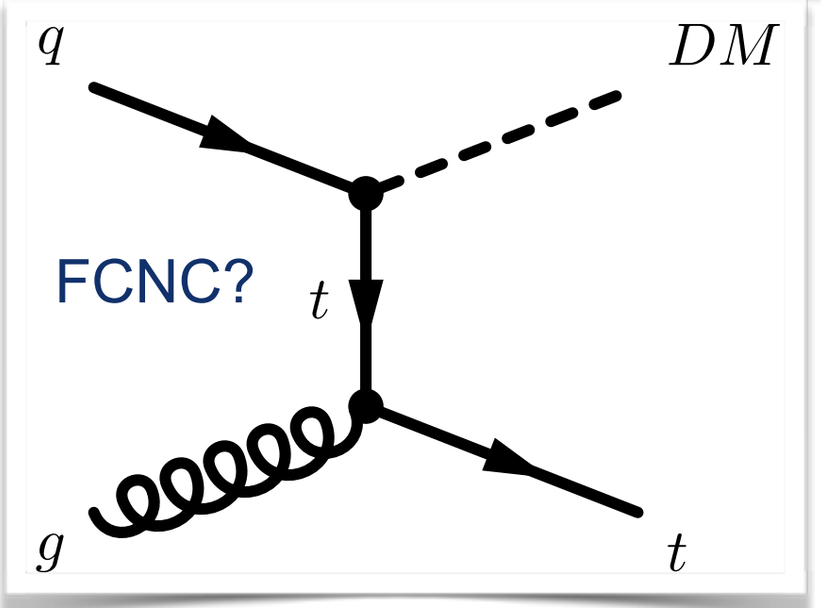
Scorecard :



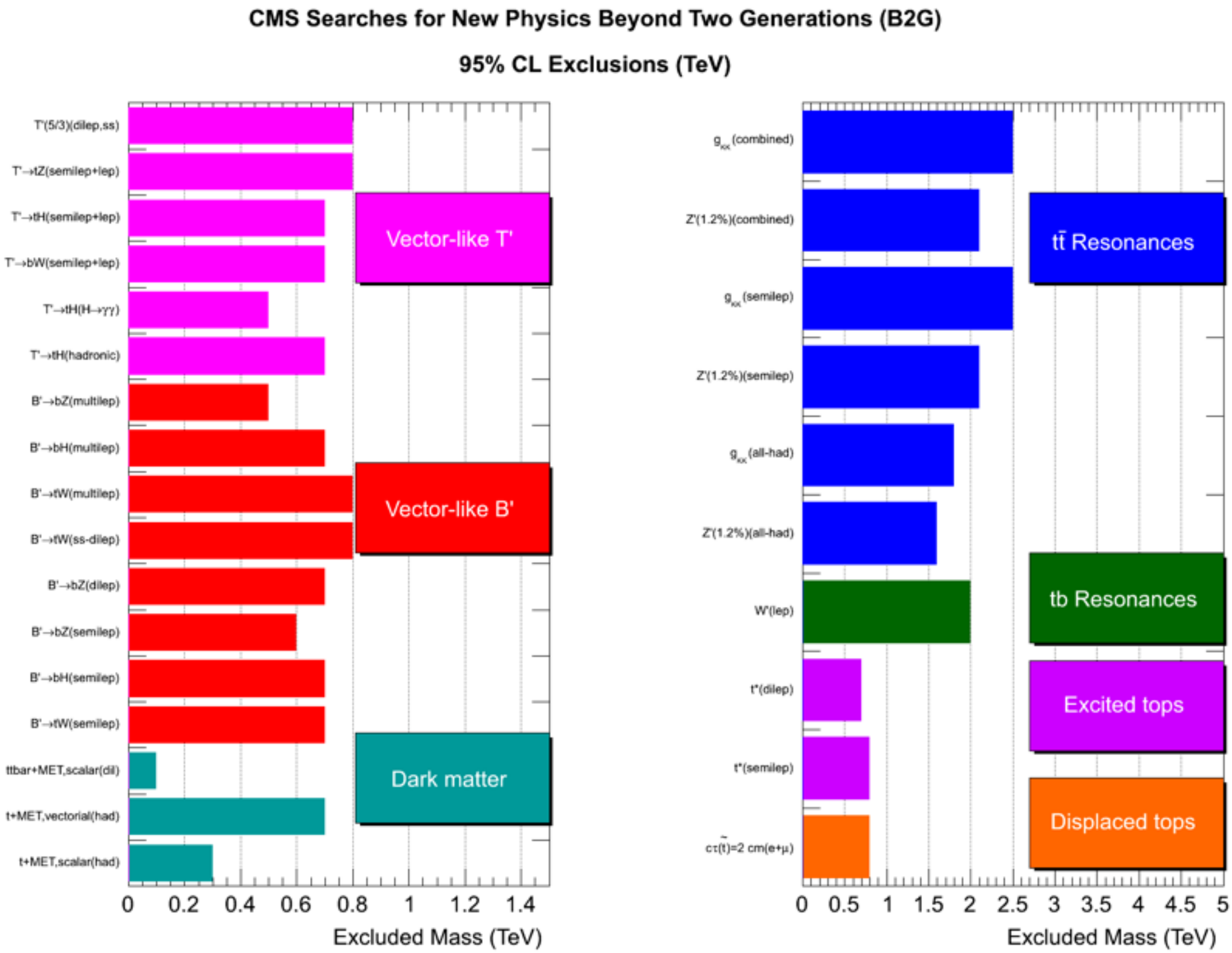
Are tops involved?





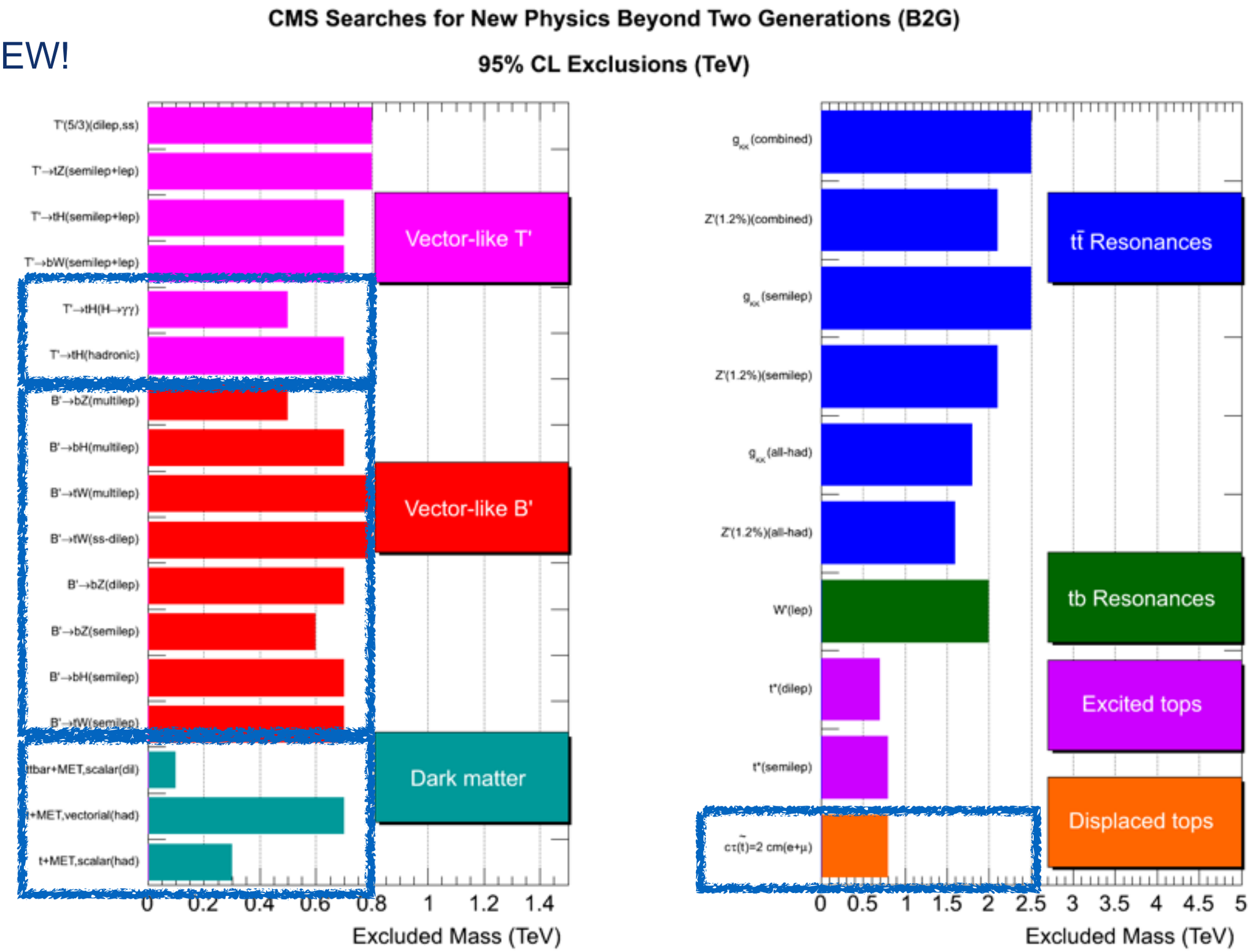


B2G Results


CMS Searches for New Physics Beyond Two Generations (B2G)
95% CL Exclusions (TeV)
T'(5/3)(dilep,ss)
T'→tZ(semilep+lep)
T'→tH(semilep+lep)
T'→bW(semilep+lep)
T'→tH(H→γγ)
T'→tH(hadronic)
B'→bZ(multilep)
B'→bH(multilep)
B'→tW(multilep)
B'→tW(ss-dilep)
B'→bZ(dilep)
B'→bZ(semilep)
B'→bH(semilep)
B'→tW(semilep)
ttbar+MET,scalar(dil)
t+MET,vectorial(had)
t+MET,scalar(had)
Vector-like T'
Vector-like B'
Dark matter
0 0.2 0.4 0.6 0.8 1 1.2 1.4
Excluded Mass (TeV)
g_KK (combined)
Z'(1.2%)(combined)
g_KK (semilep)
Z'(1.2%)(semilep)
g_KK (all-had)
Z'(1.2%)(all-had)
W'(lep)
t*(dilep)
t*(semilep)
cτ(t̃)=2 cm(e+μ)
tt̄ Resonances
tb Resonances
Excited tops
Displaced tops
0 0.5 1 1.5 2 2.5 3 3.5 4 4.5 5
Excluded Mass (TeV)

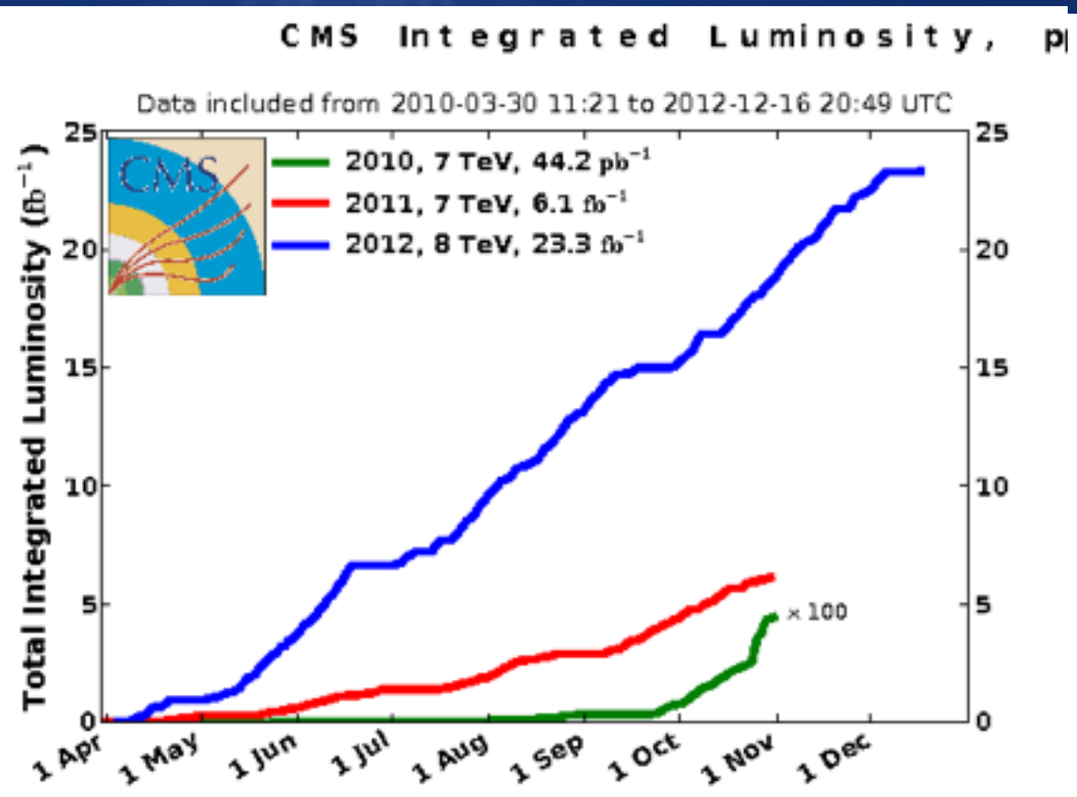
B2G Results

= NEW!



LHC

- Thanks to the tireless efforts of many, LHC Run 1 was a resounding success!
- Runs >= 2 listed as a top priority by P5 in all scenarios :
  - *"The enormous physics potential of the LHC, entering a new era with its planned high-luminosity upgrades, should be fully exploited."*



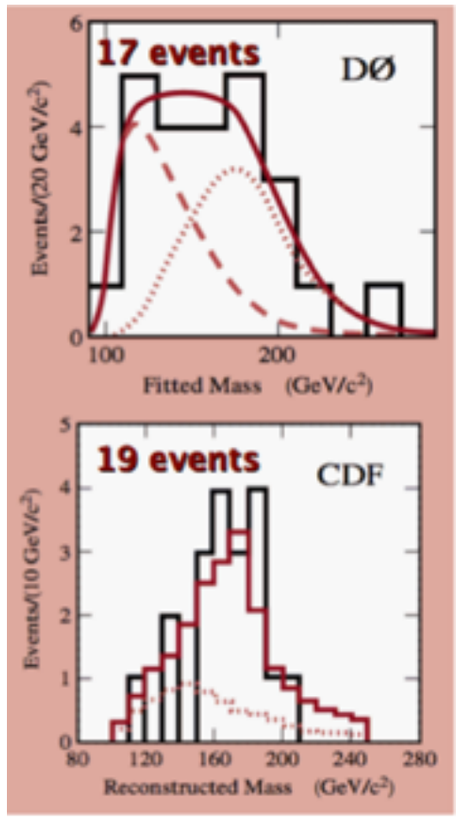
- We can expect continued excellent participation in the LHC program by the US for years to come

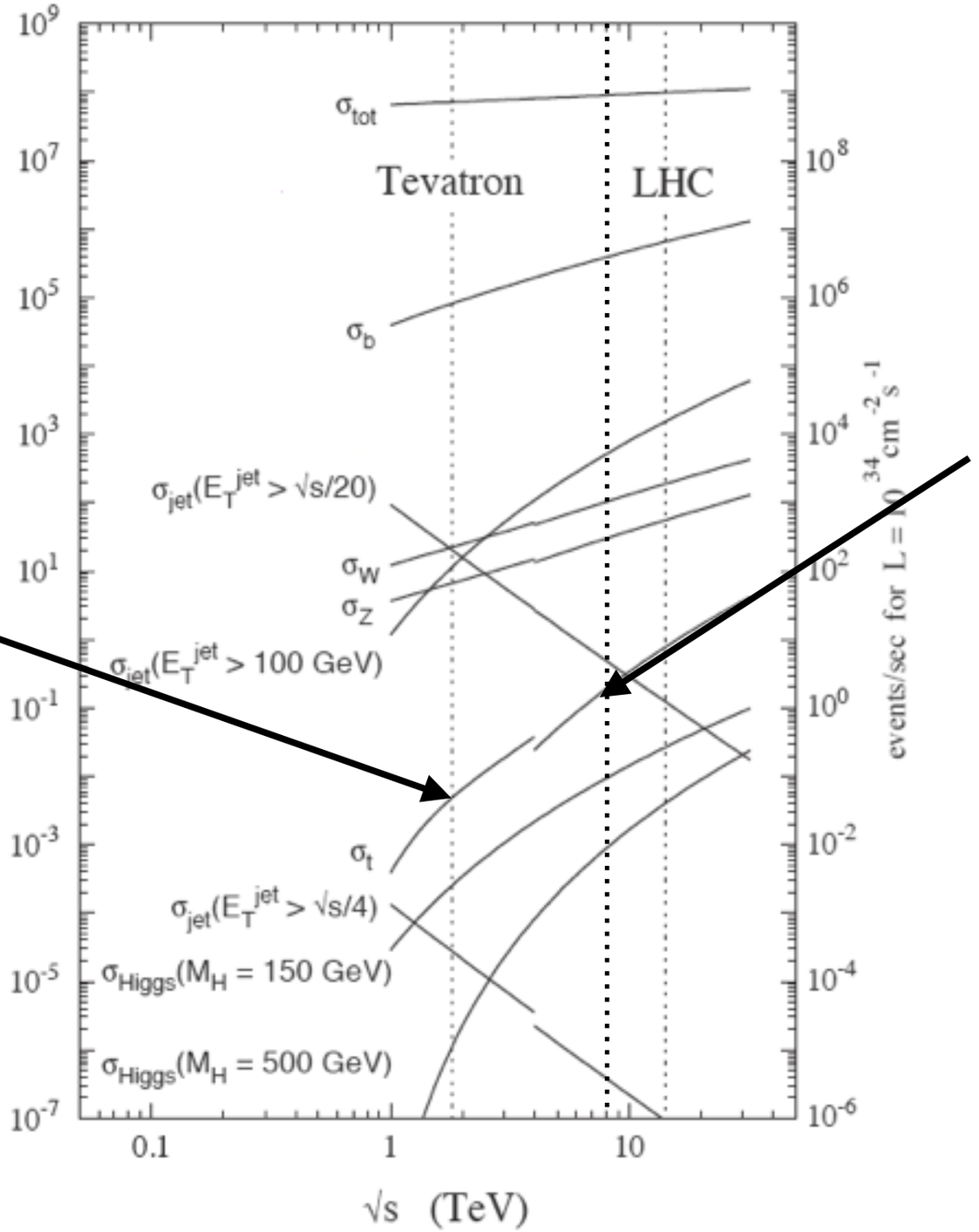
Table 1
Summary of Scenarios

Project/Activity	Scenario A	Scenario B	Scenario C	Science Drivers: Higgs	Neutrinos	Dark Matter	Cosm. Accel.	The Unknown	Technique (Frontier)
Large Projects									
Muon program: Mu2e, Muon g-2	Y, Mu2e small reprofile needed	Y	Y					✓	I
HL-LHC	Y	Y	Y	✓		✓		✓	E
LBNF + PIP-II	Y, delayed relative to Scenario B.	Y	Y, enhanced		✓			✓	I,C
ILC	R&D only	R&D, possibly small hardware contributions. See text.	Y	✓		✓		✓	E
NuSTORM	N	N	N		✓				I
RADAR	N	N	N		✓				I

LHC : Top Factory

Run 1 :





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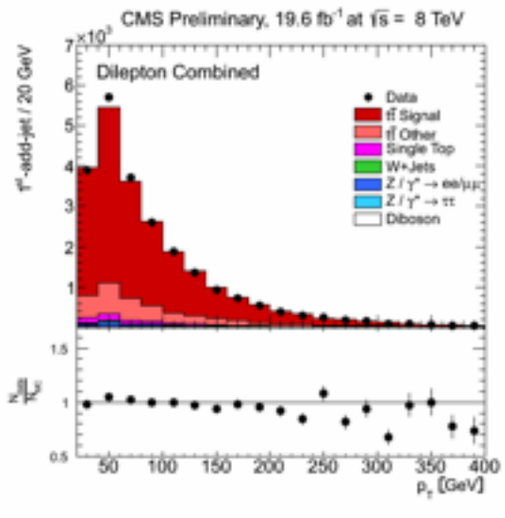
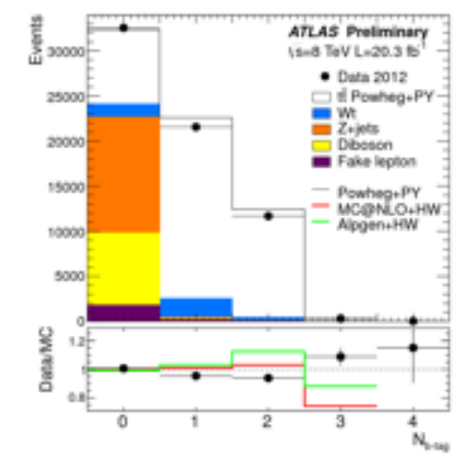
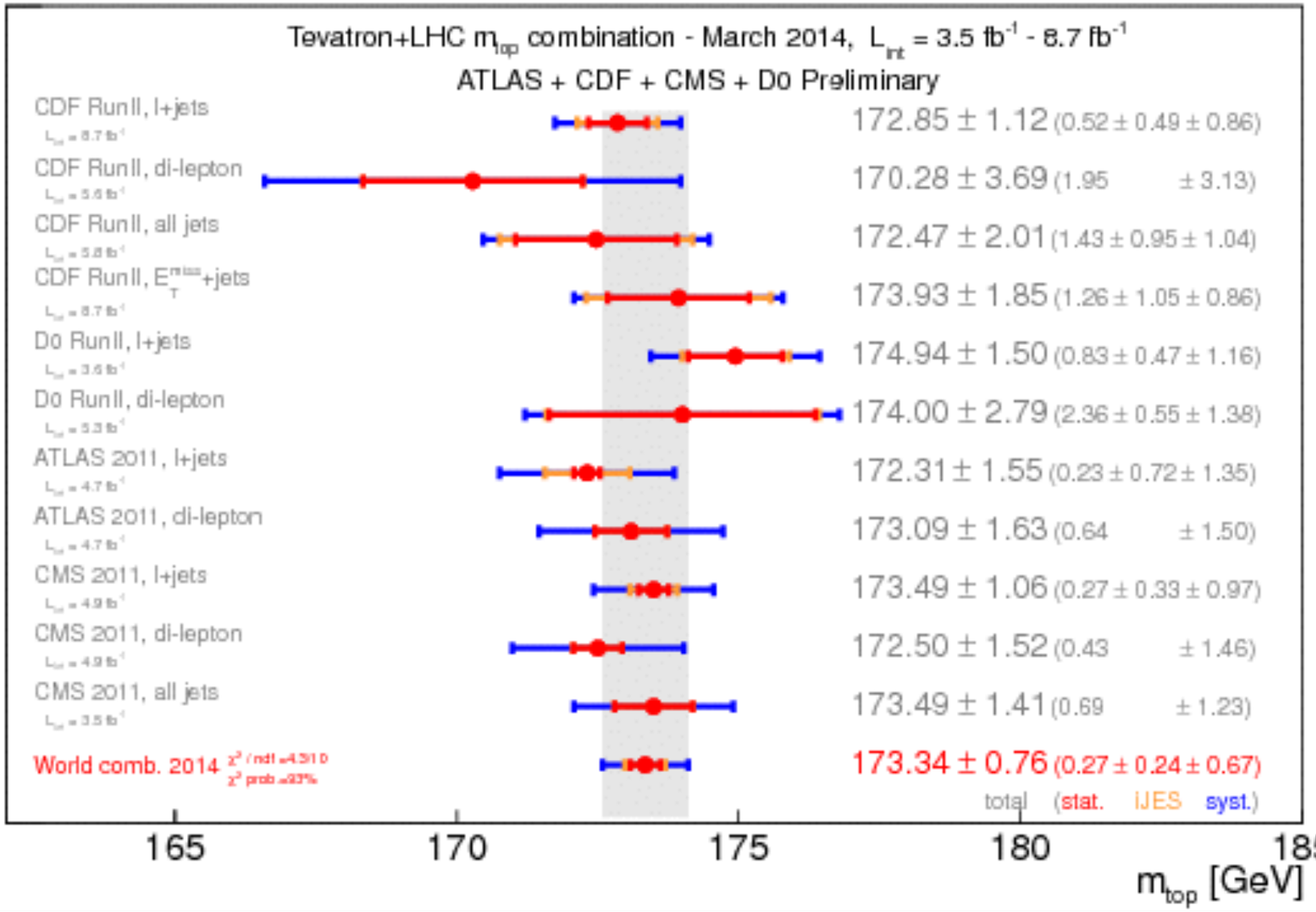




~5.8M tops produced

Run 2 :
~100k tops produced

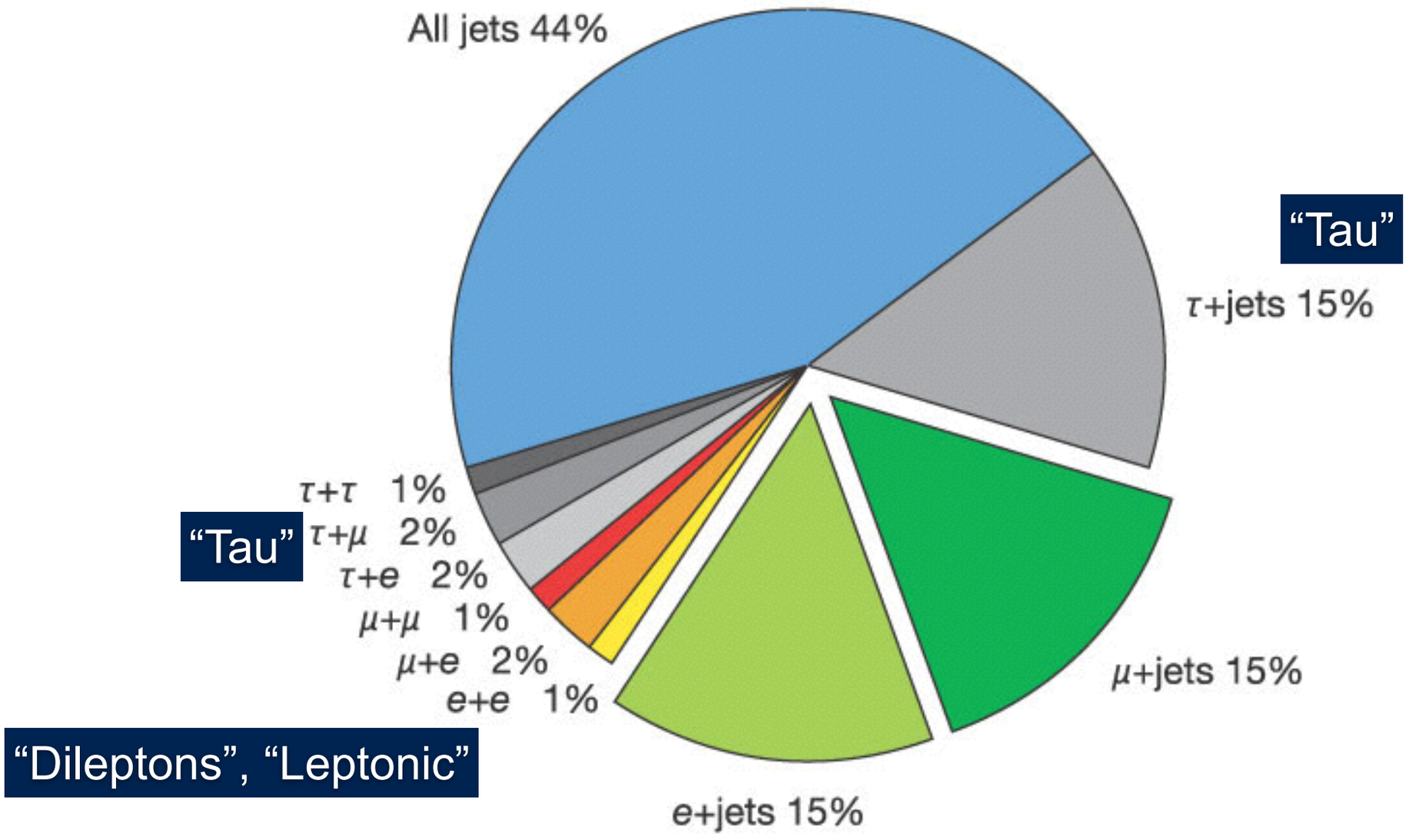
LHC : Top Factory



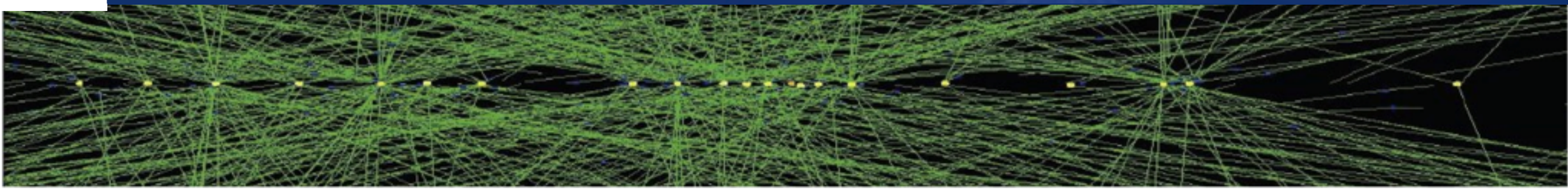
Putting it all together, the era of precision top quark physics is well underway! What else lies in store?

Obligatory Top Quark Nomenclature Slide

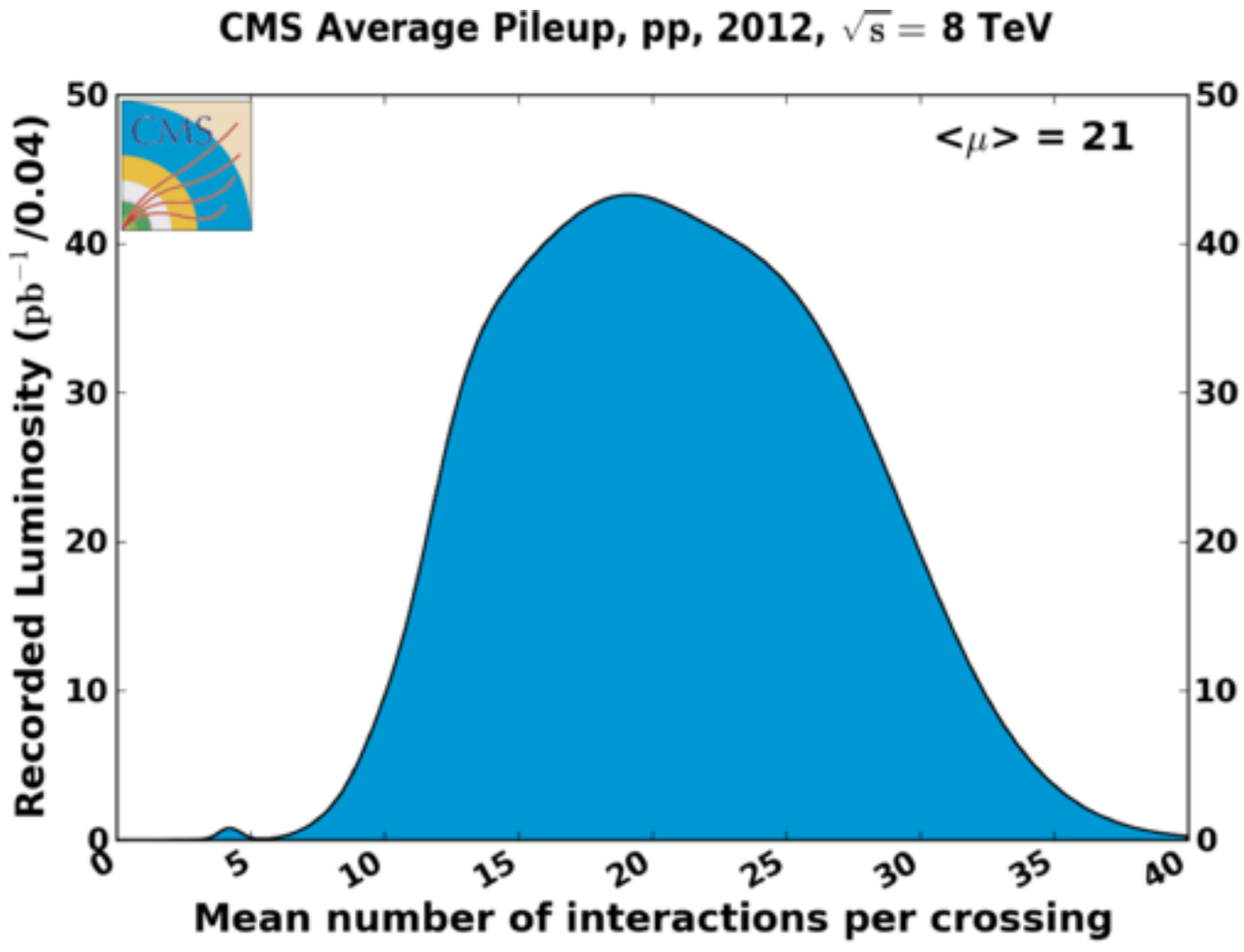
"All jets", "All hadronic"



LHC : Luminosity and Pileup



- Challenge for Run 1 : mitigate 20 interactions per crossing



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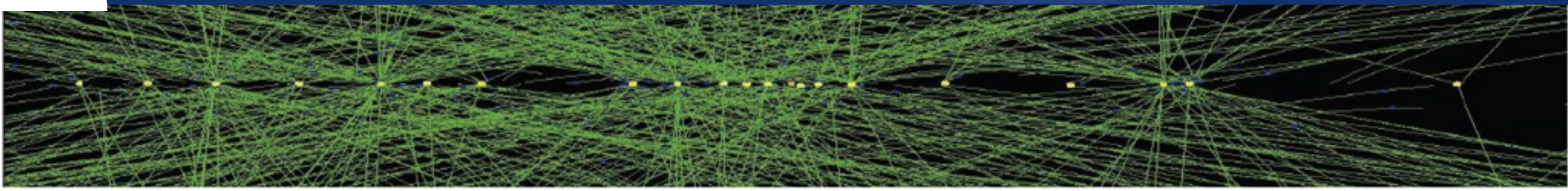
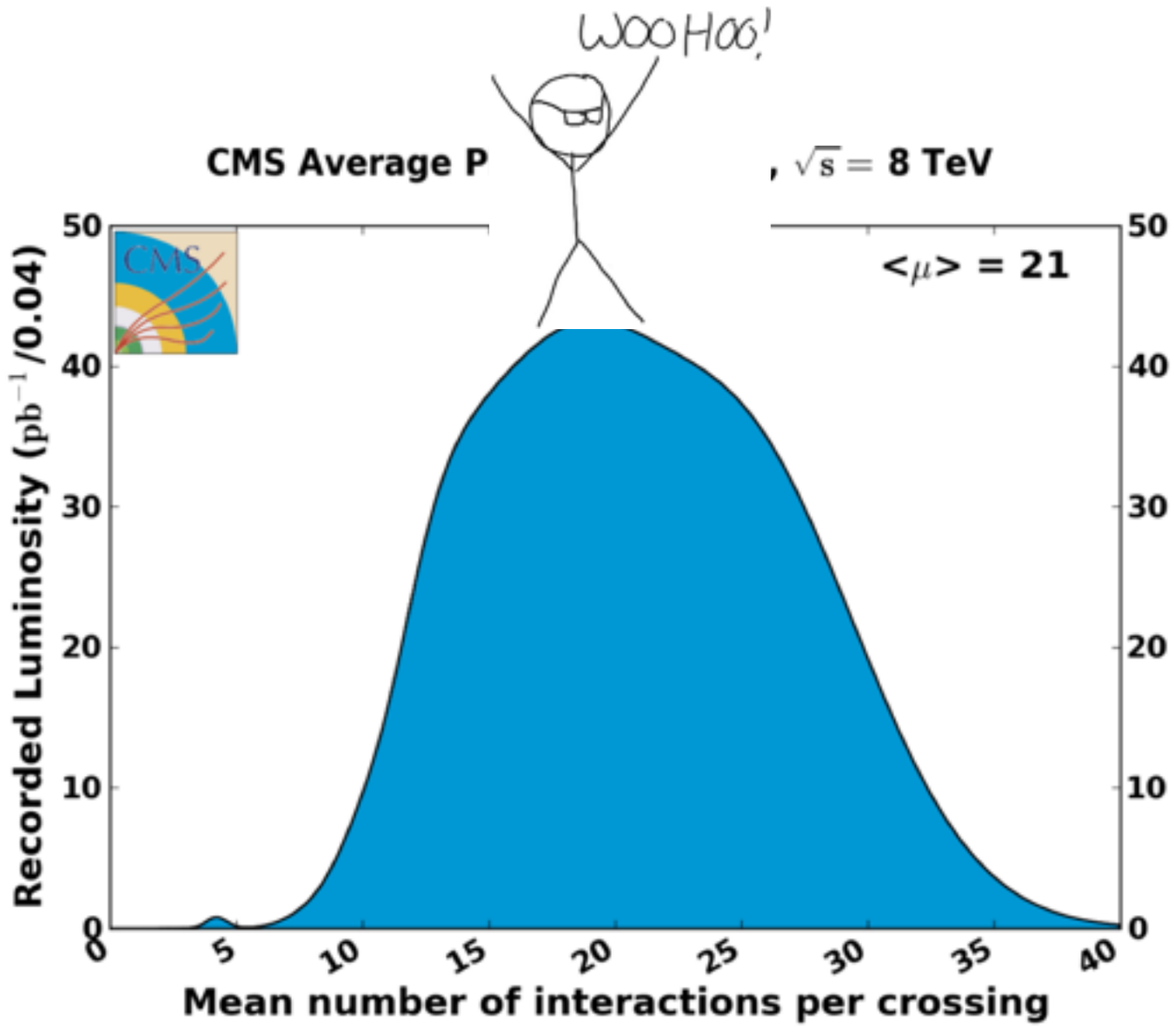


- Challenge for Run 1 : mitigate 20 interactions per crossing

Overall picture : Success!



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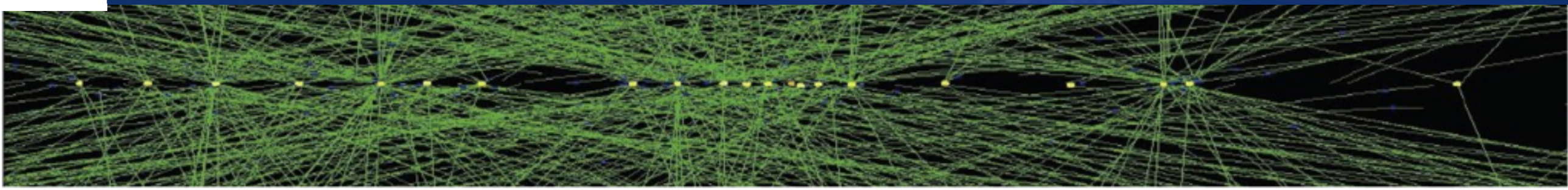

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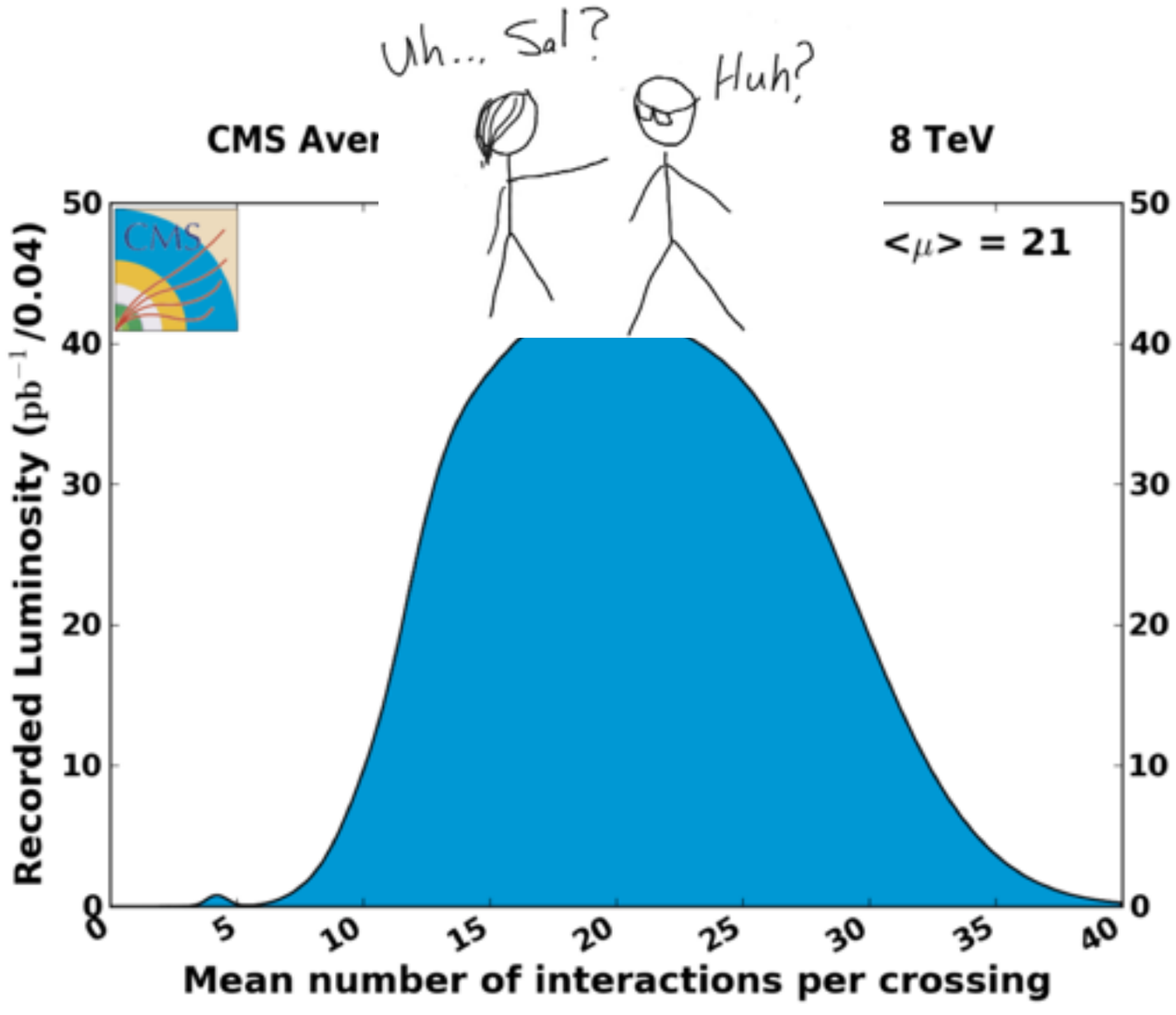
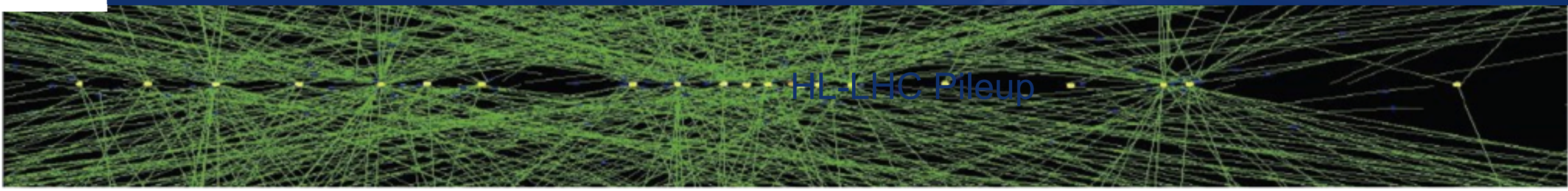
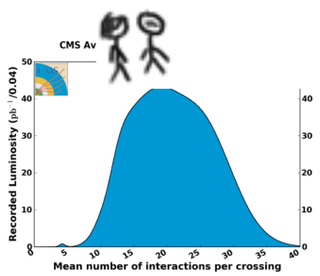


LHC : Luminosity and Pileup



Run 1 Lumi profile.

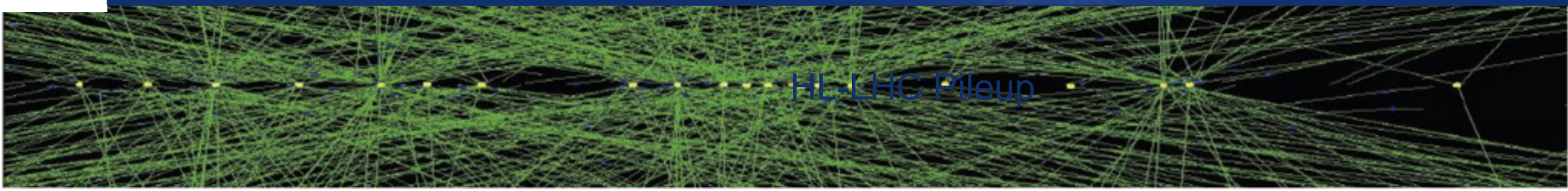
Oh my.



Run 2 Lumi profile.

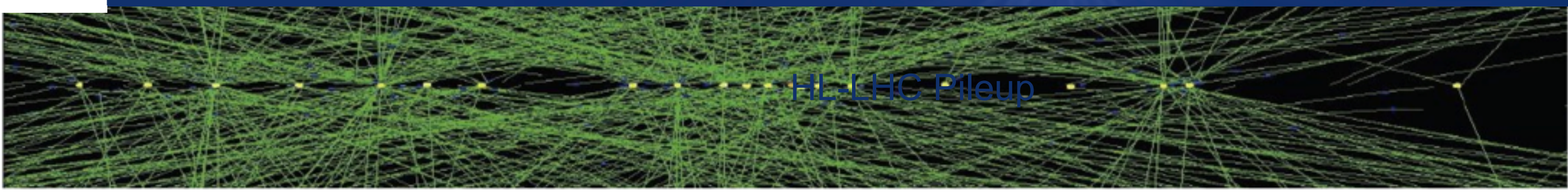
6 June 2014

LHC : Luminosity and Pileup



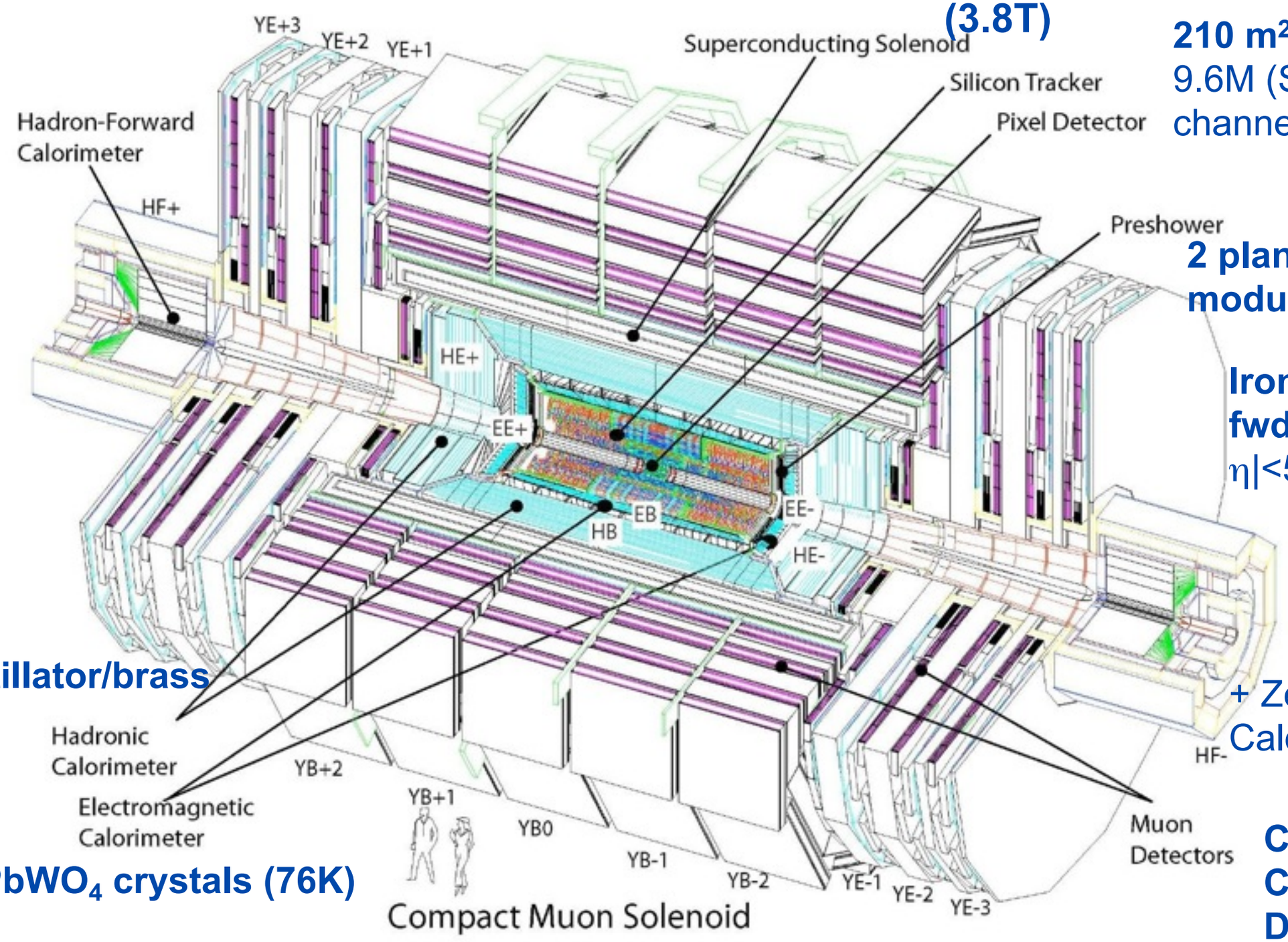
Should we turn back?

LHC : Luminosity and Pileup



Should we turn back?

The Compact Muon Solenoid



210 m² of silicon sensors: 9.6M (Str) & 66M (Pix) channels

2 planes of silicon modules for ECAL

Iron / Quartz fiber fwd calorimeter, 3<|η|<5;

+ Castor, 5<|η|<6.55

+ Zero Degree Calorimeter

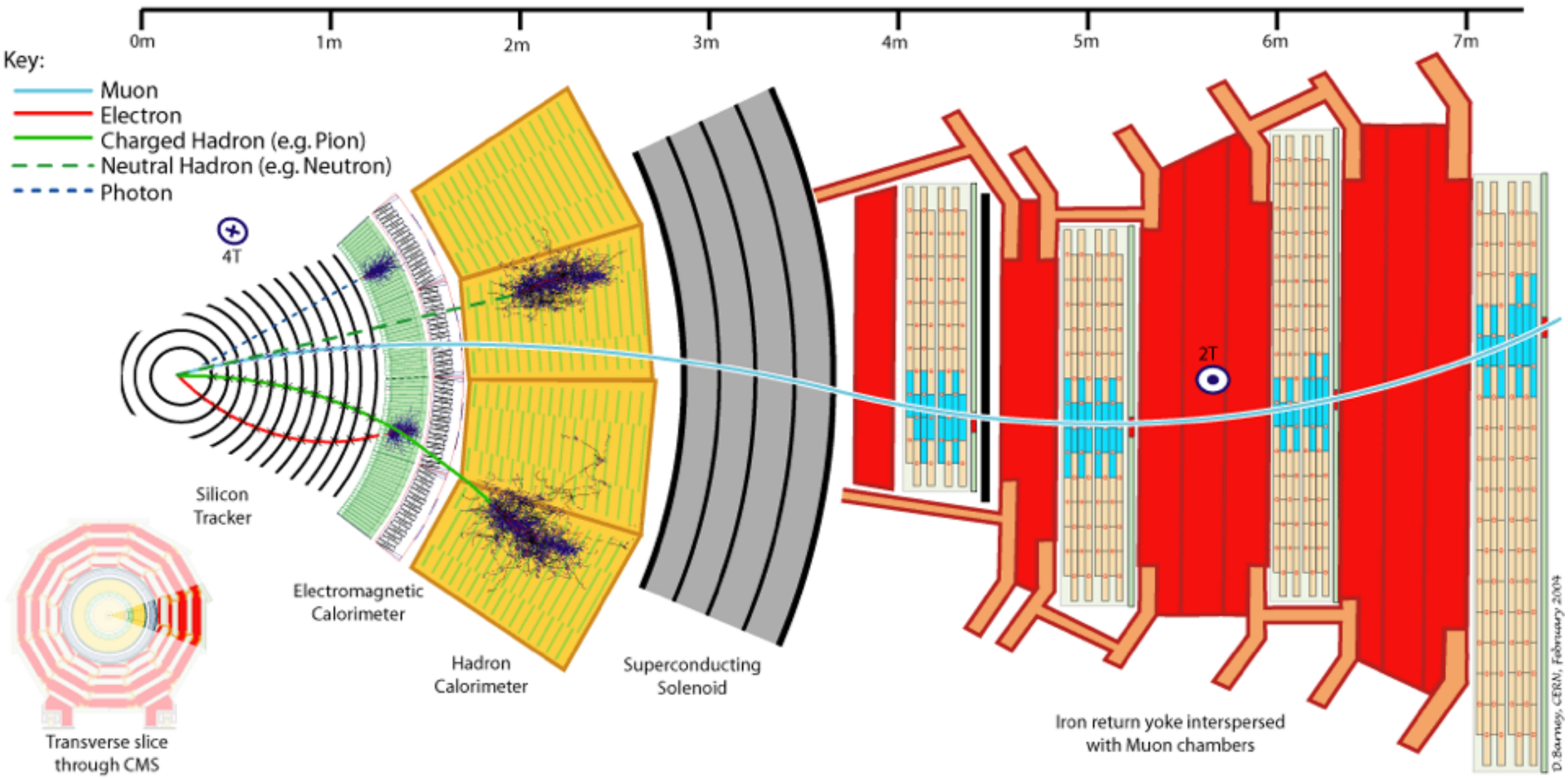
Scintillator/brass

$PbWO_4$ crystals (76K)

Cathode Strip Chambers, Drift Tubes, Resistive Plates

Physics Objects

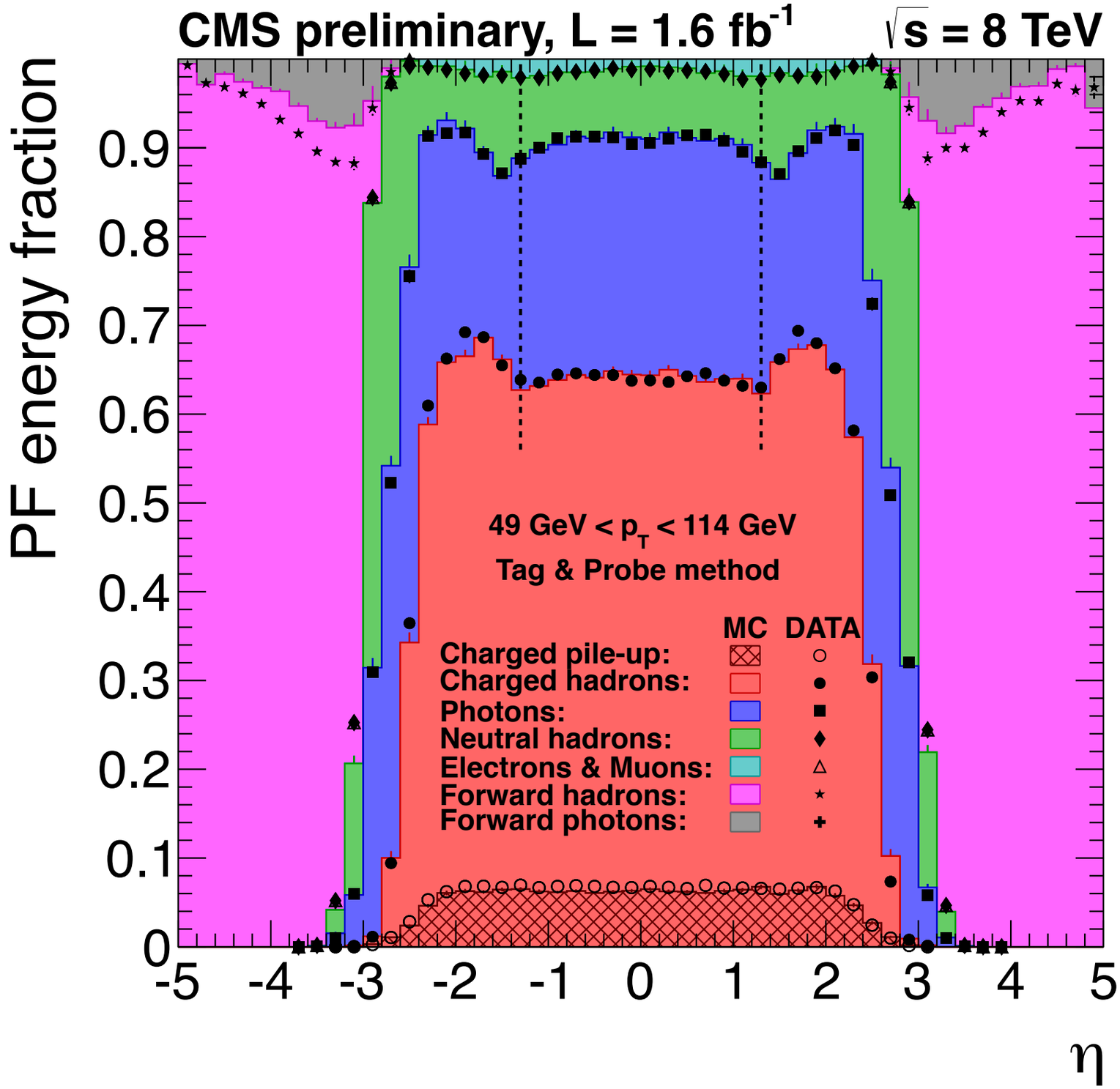
Classify objects into 5 categories



“Holistic” approach to reconstruction at CMS: Particle flow!

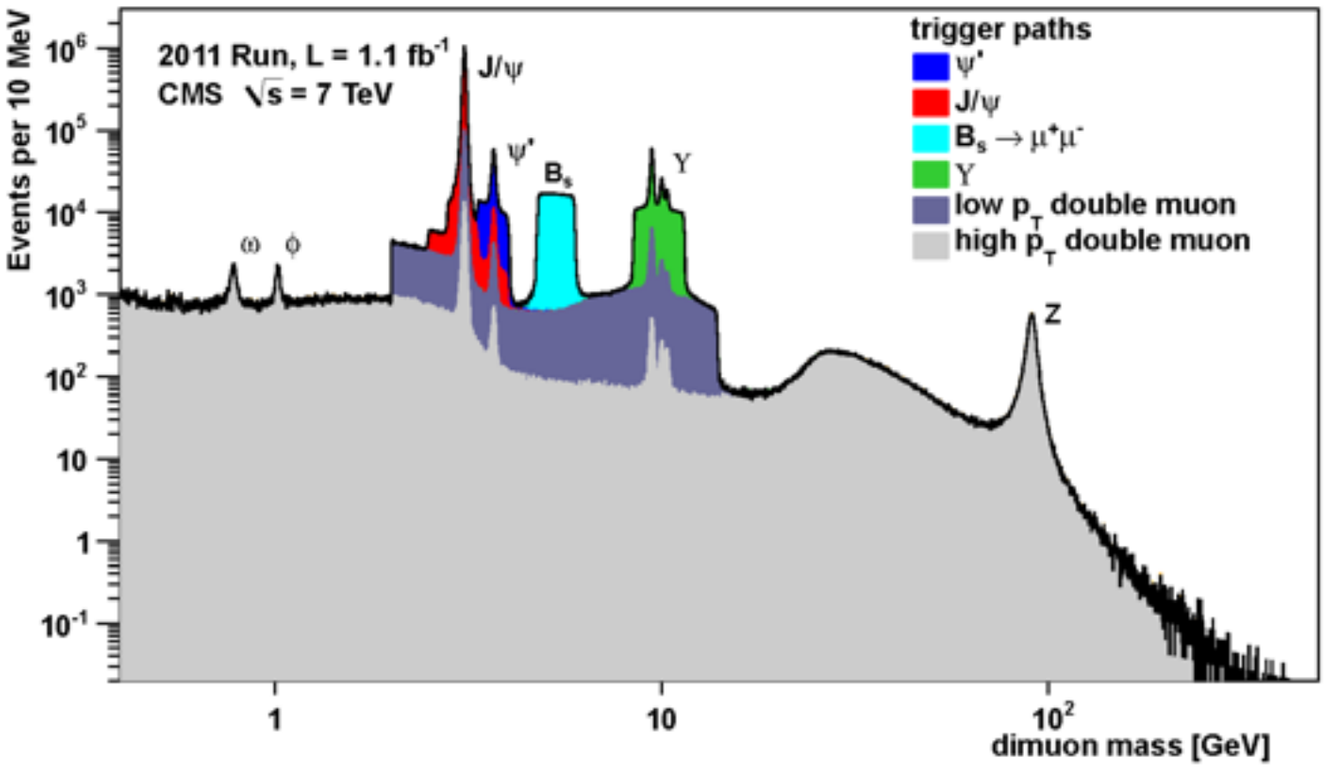
Physics Objects

- Performance of particle flow is spectacular!

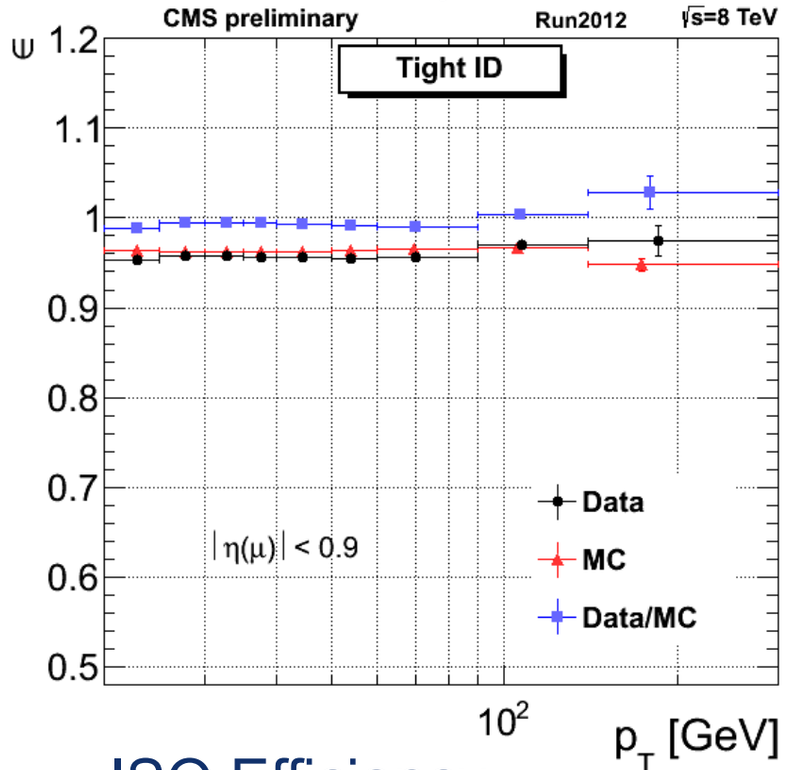


Physics Objects

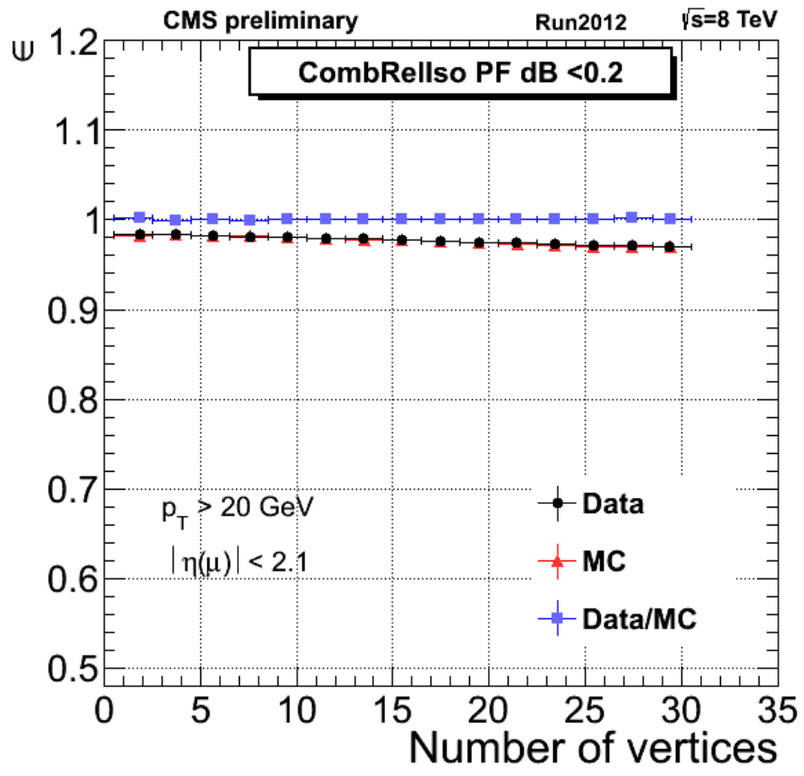
- Compact MUON Solenoid



ID Efficiency

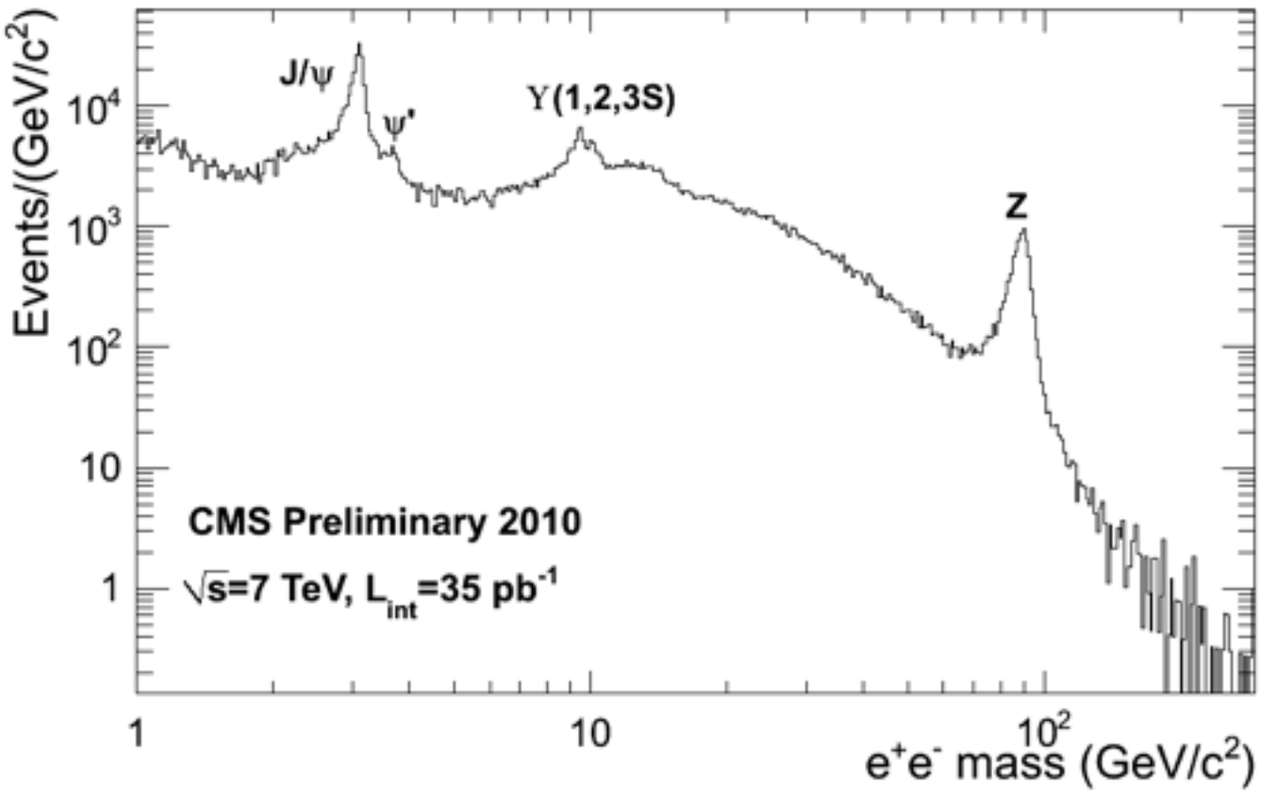


ISO Efficiency

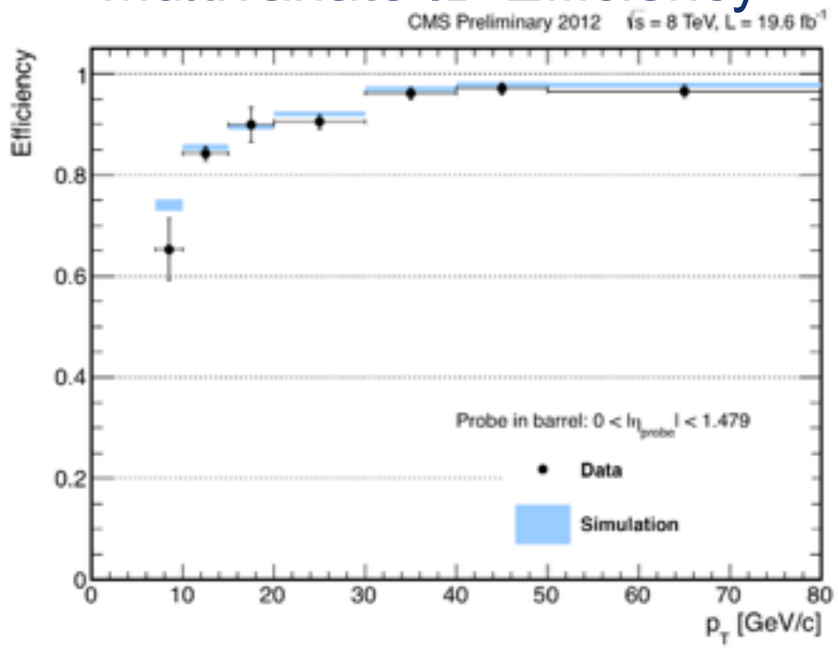


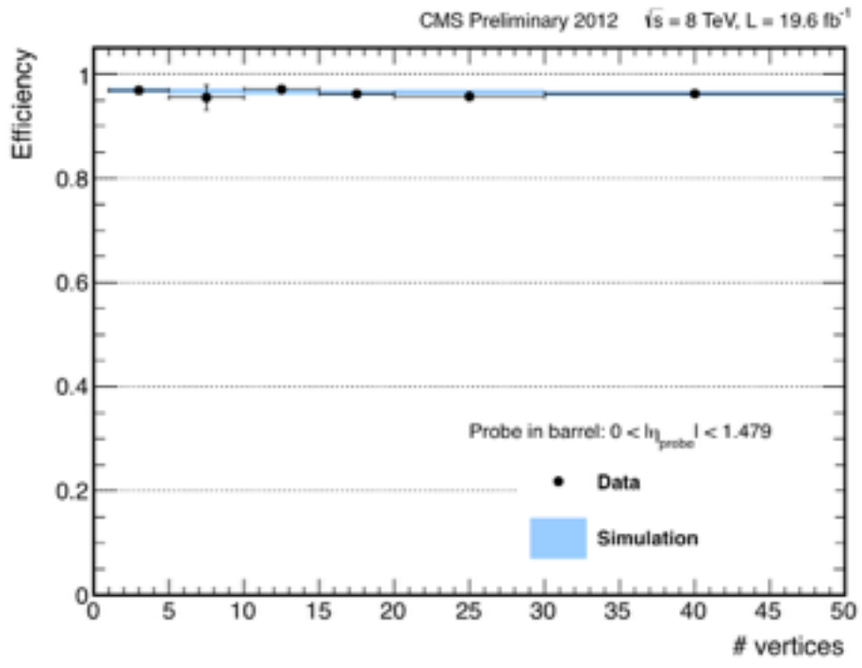
Physics Objects

- Electrons



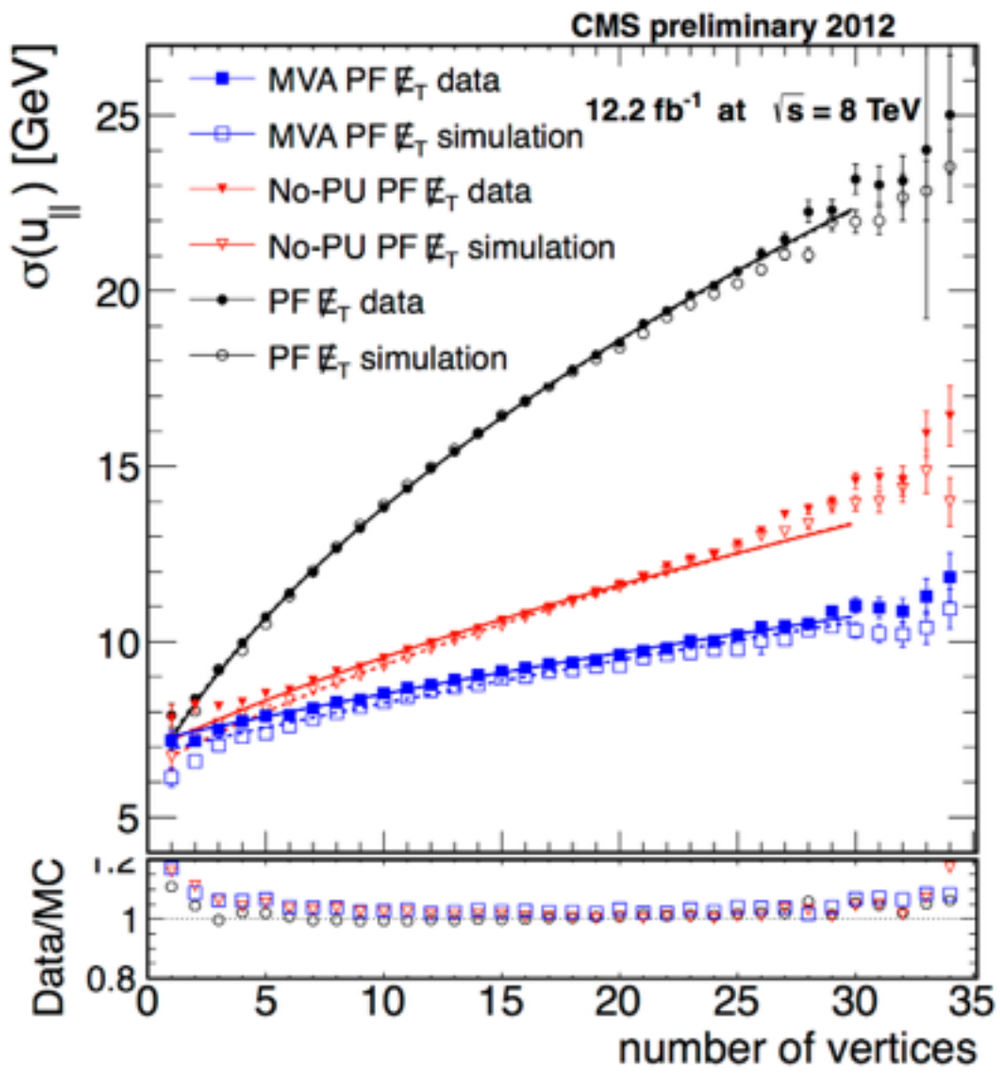
Multivariate ID Efficiency

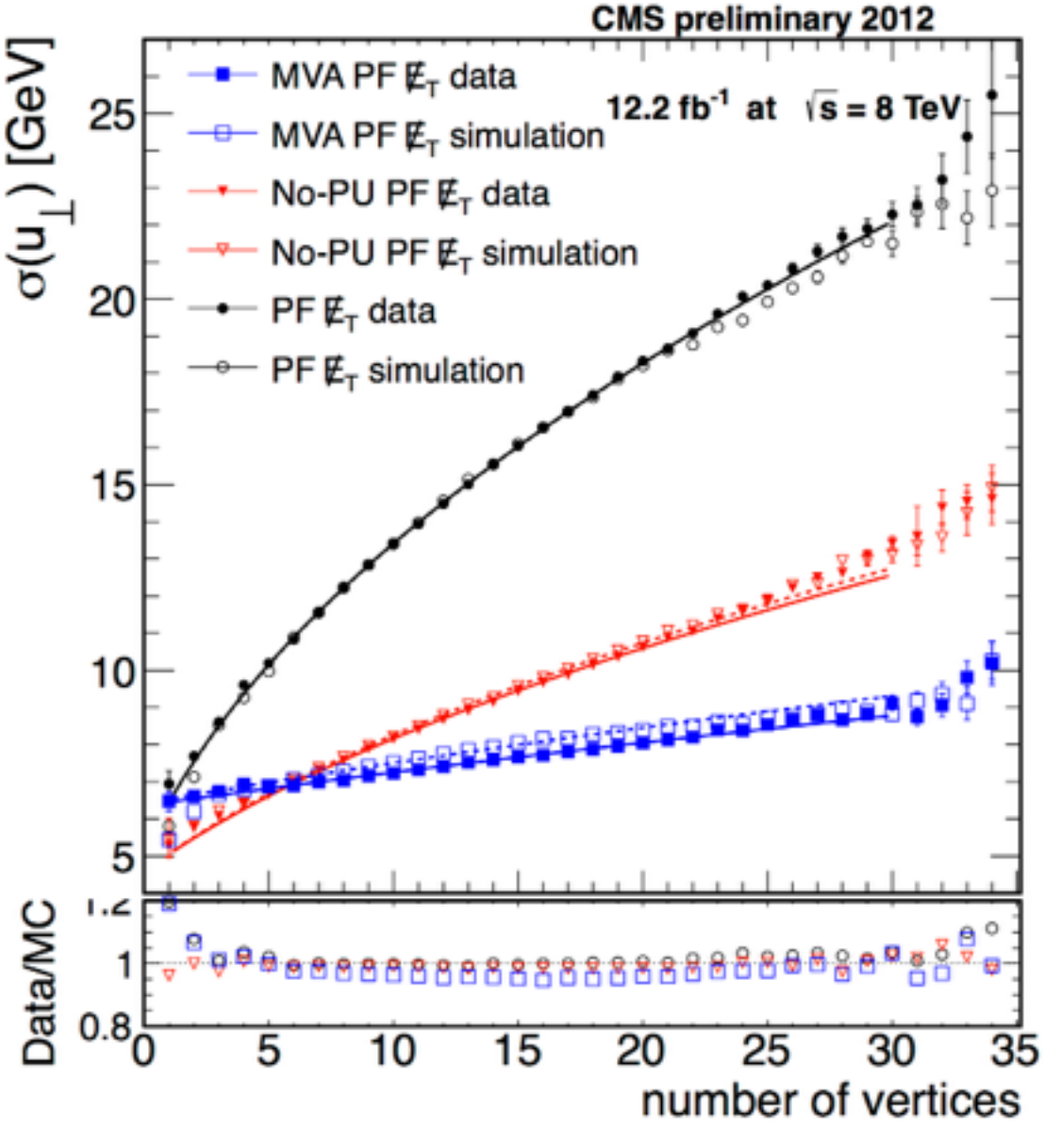




Physics Objects

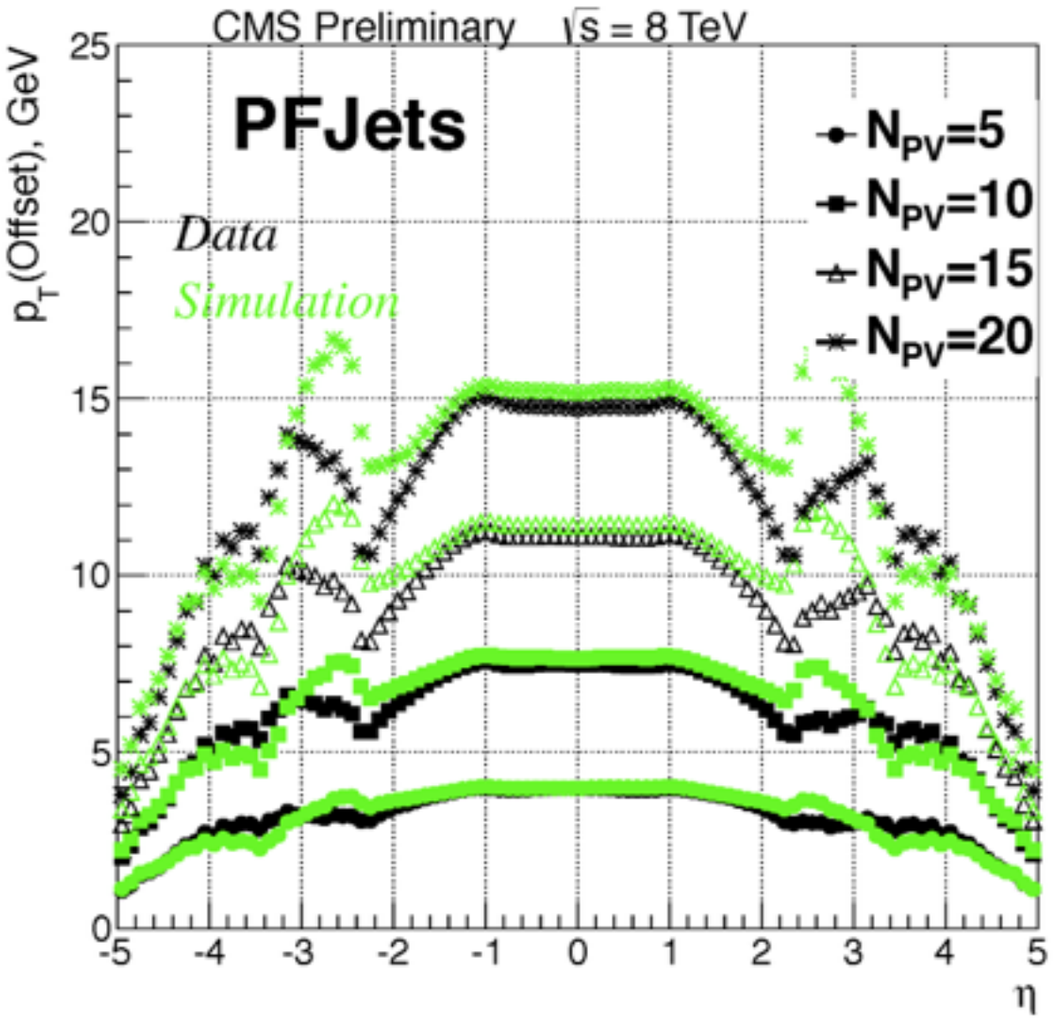
- MET
  - PF helps out here a lot!
  - Extensive work done on multivariate techniques to reduce the MET resolution

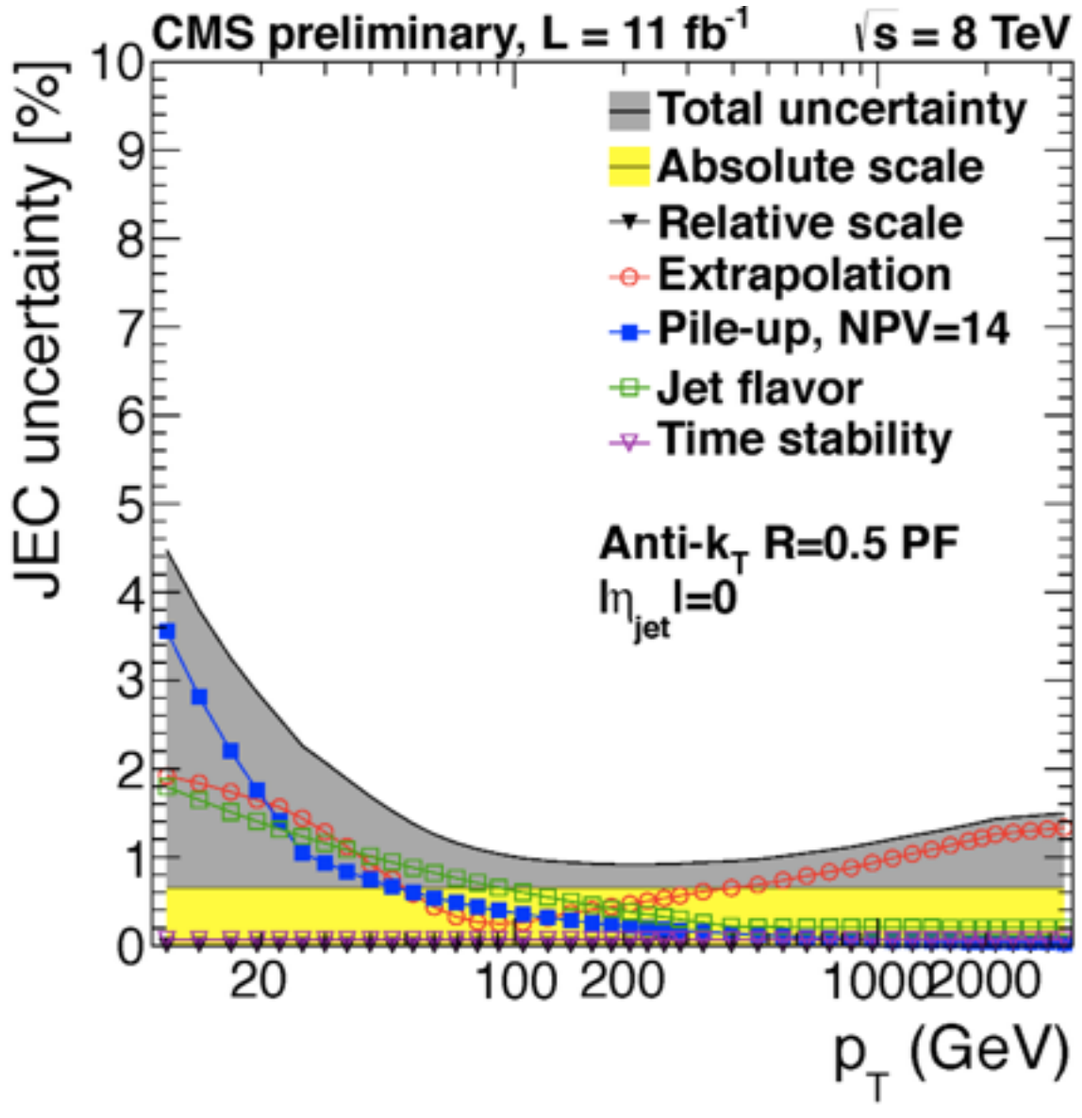




Physics Objects

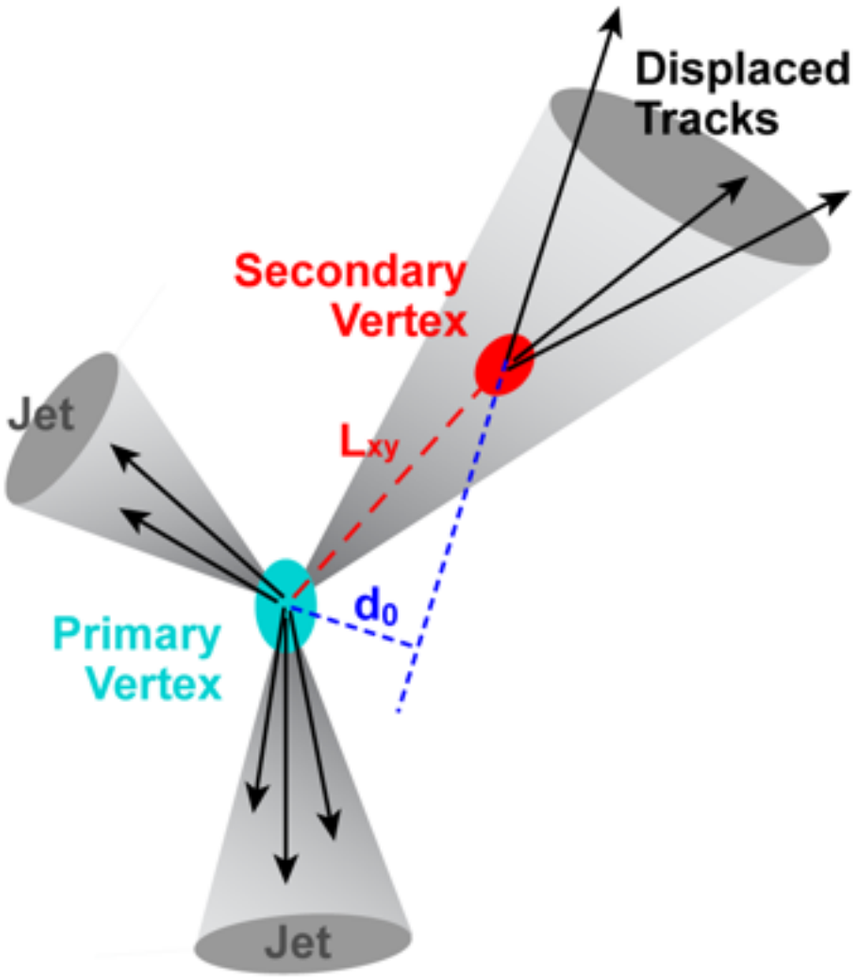
- Jets
  - PF allows CMS to excel in jet physics areas
  - Extremely good performance, uncertainties < 1% for pt > 100 GeV

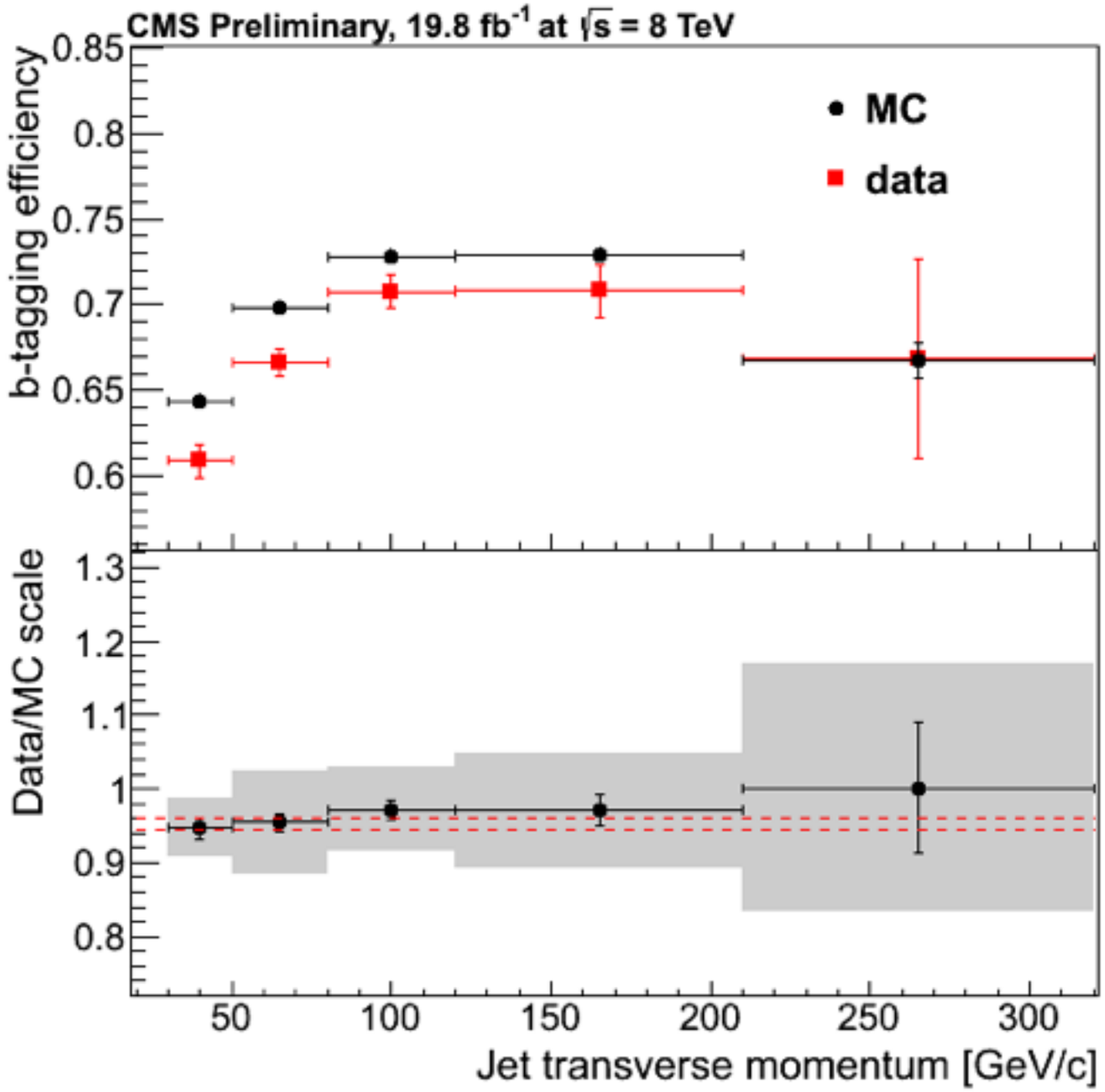




Physics Objects

- Bottom Jets :
  - BTV-13-001
  - Combines information from displaced tracks and vertices
  - “CSV” algorithm





Physics Objects

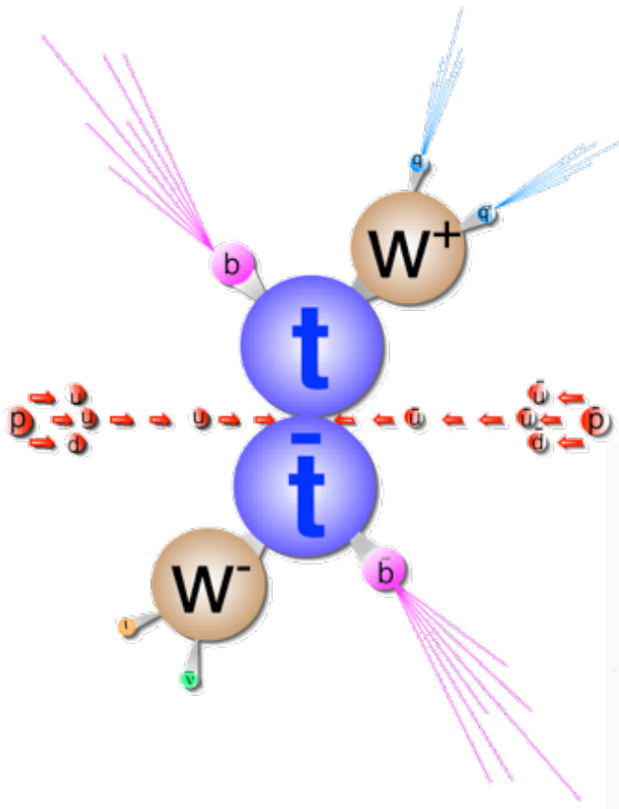
- Top Jets :

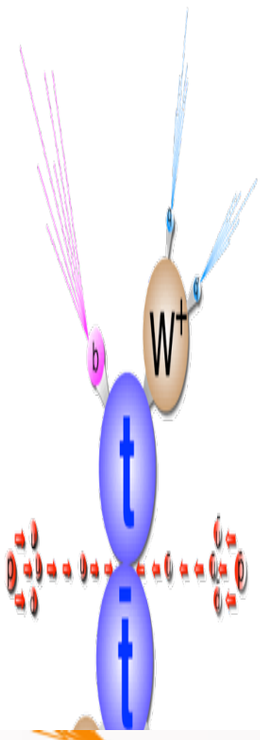
Physics Objects

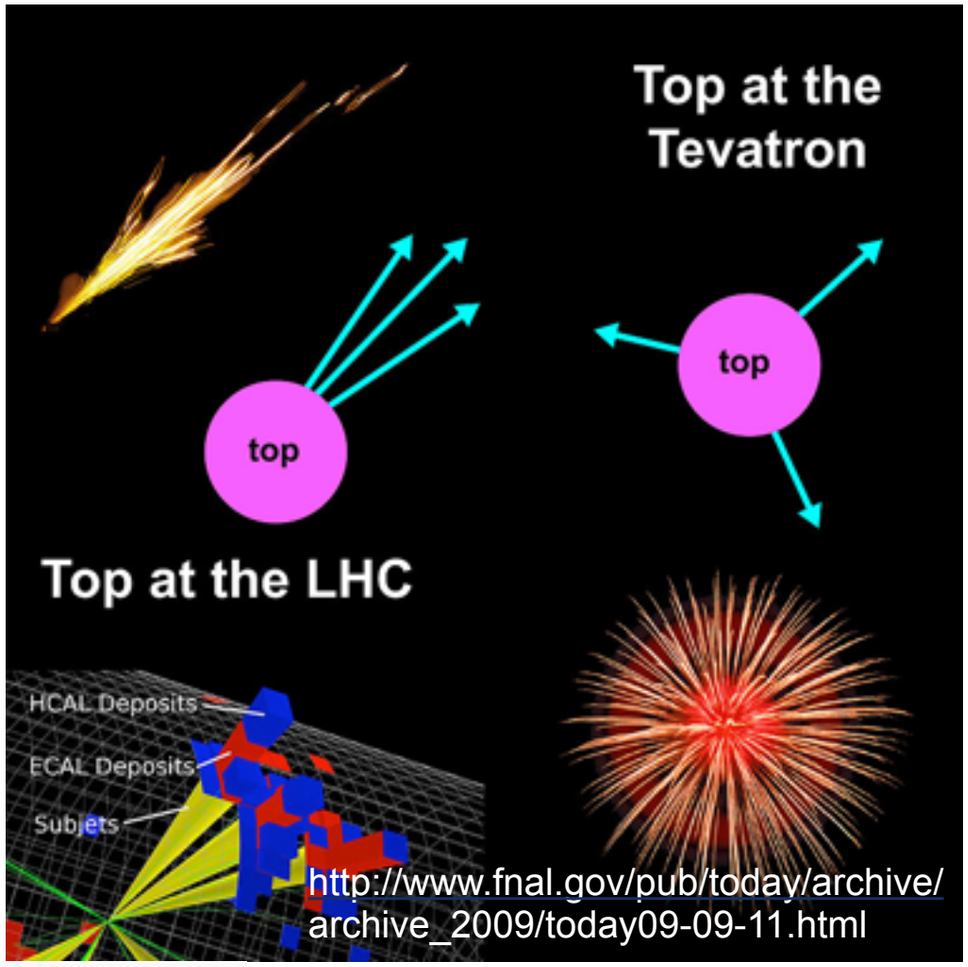
- Top Jets :
  - Wait, what?

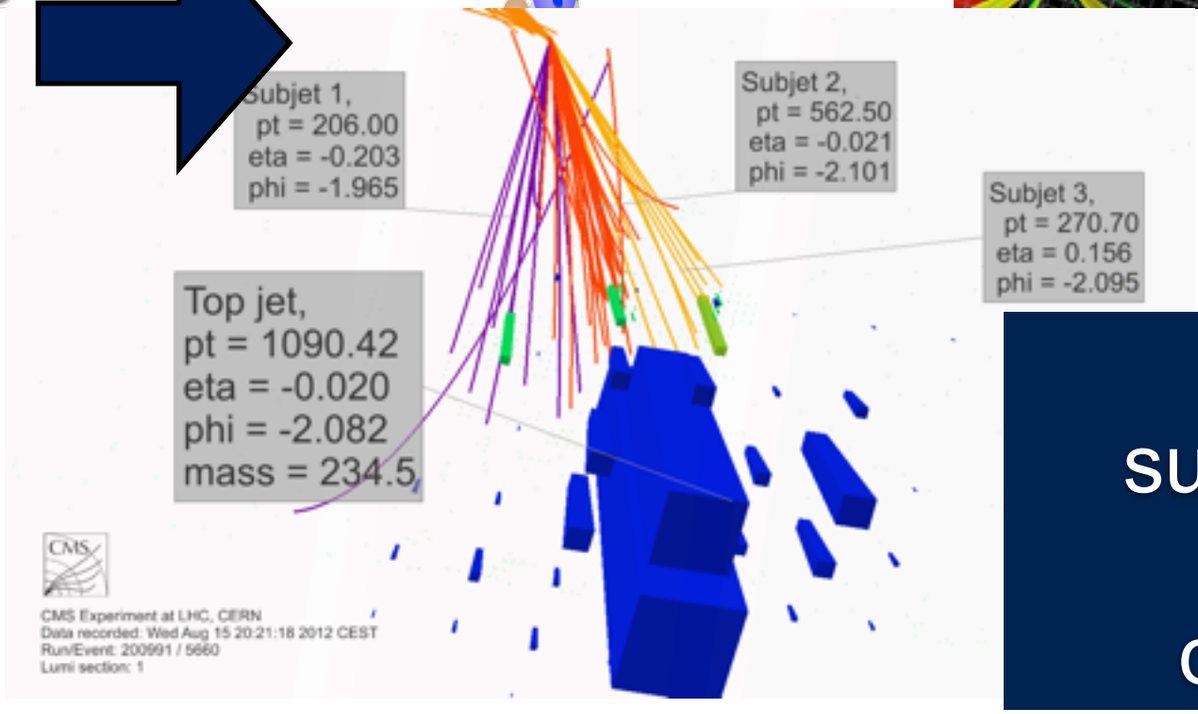
Physics Objects

- Top Jets :
  - Wait, what?



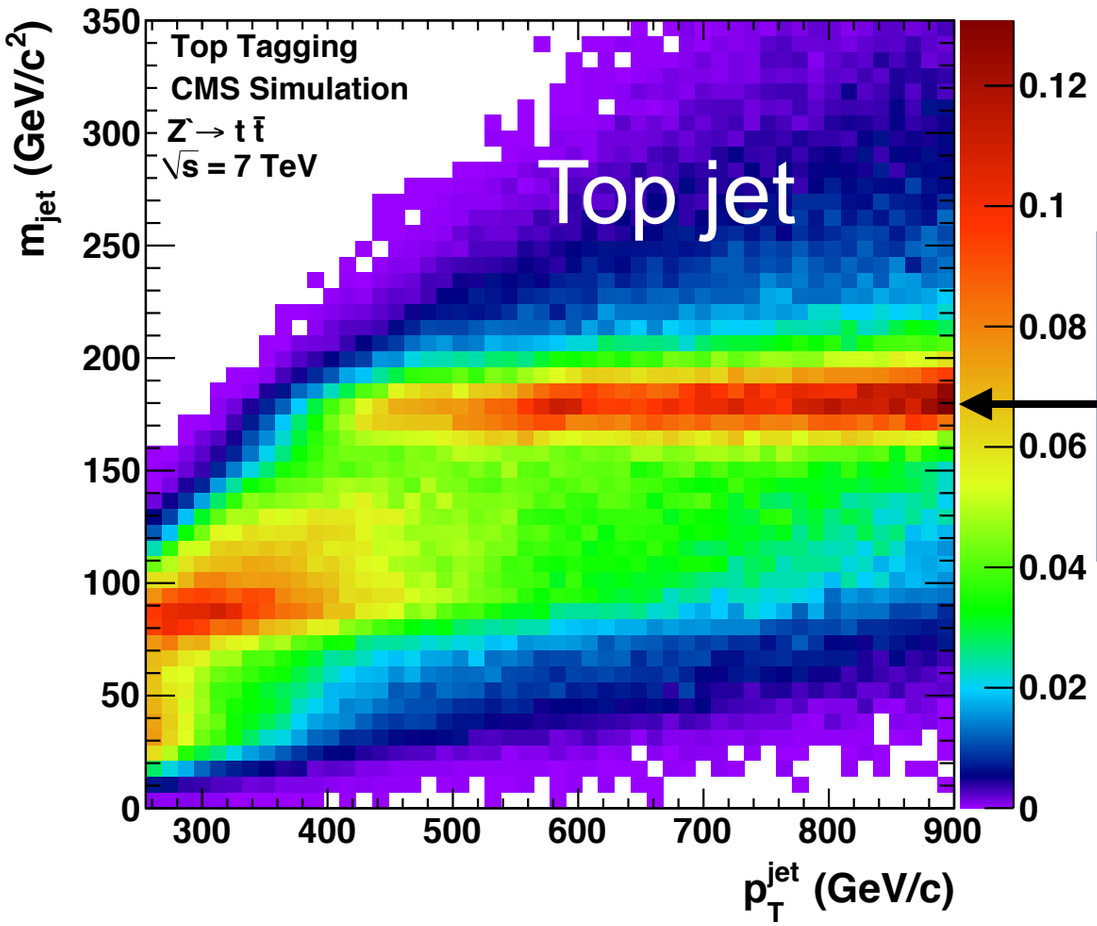


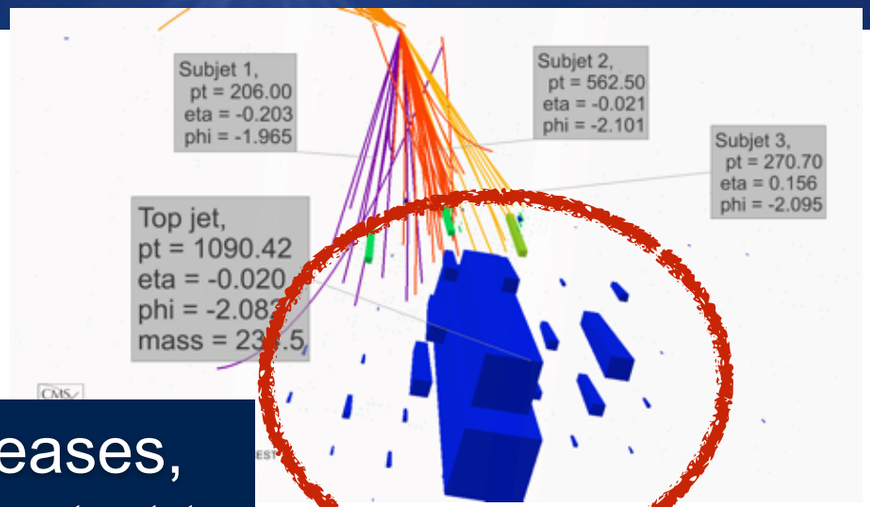




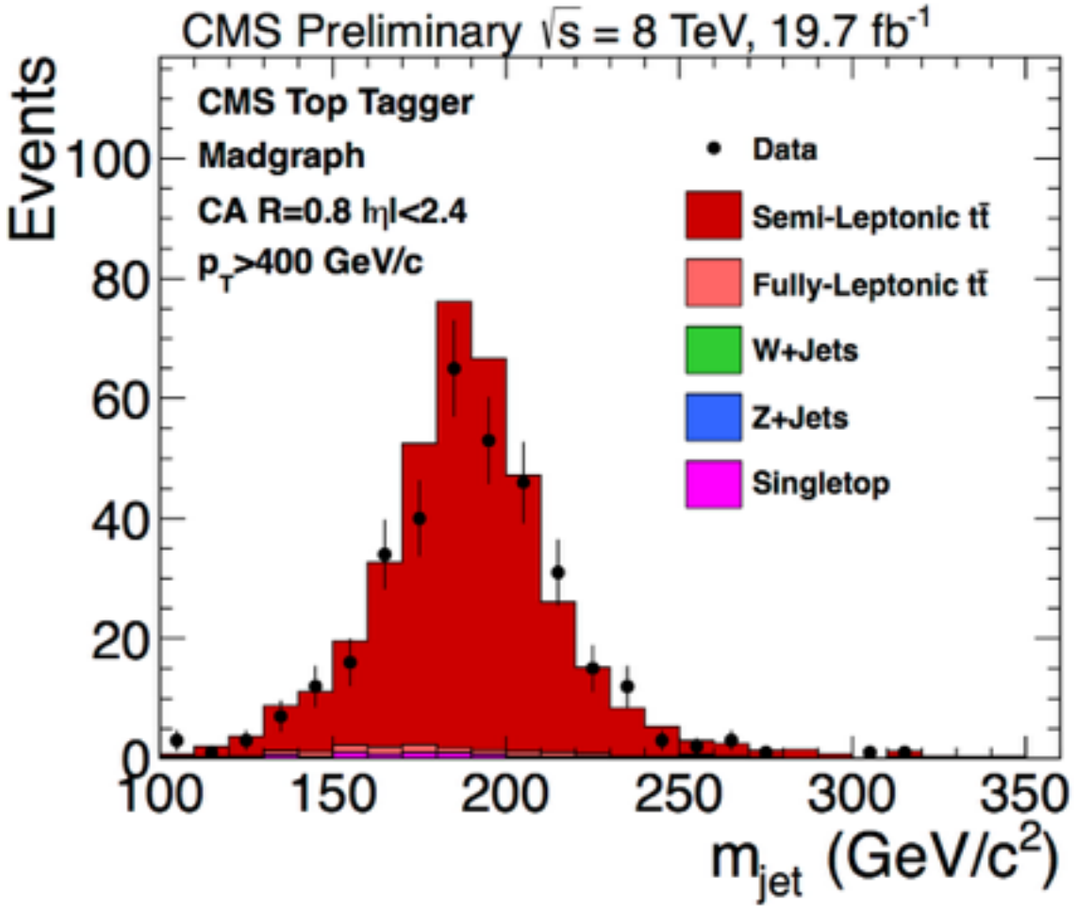
Rely on jet substructure and mass for discrimination

Boosted Tops





As pt increases, constituents start to merge, converge to top mass



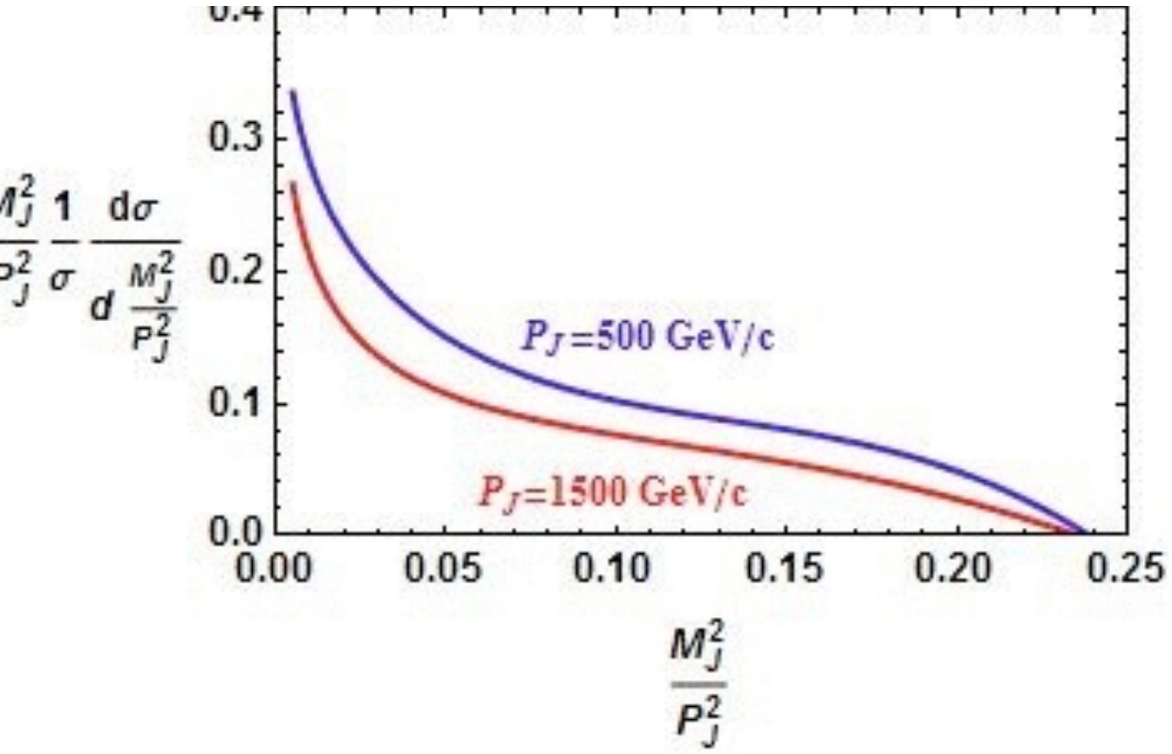
Boosted Tops

Finite-size effects from cutoff

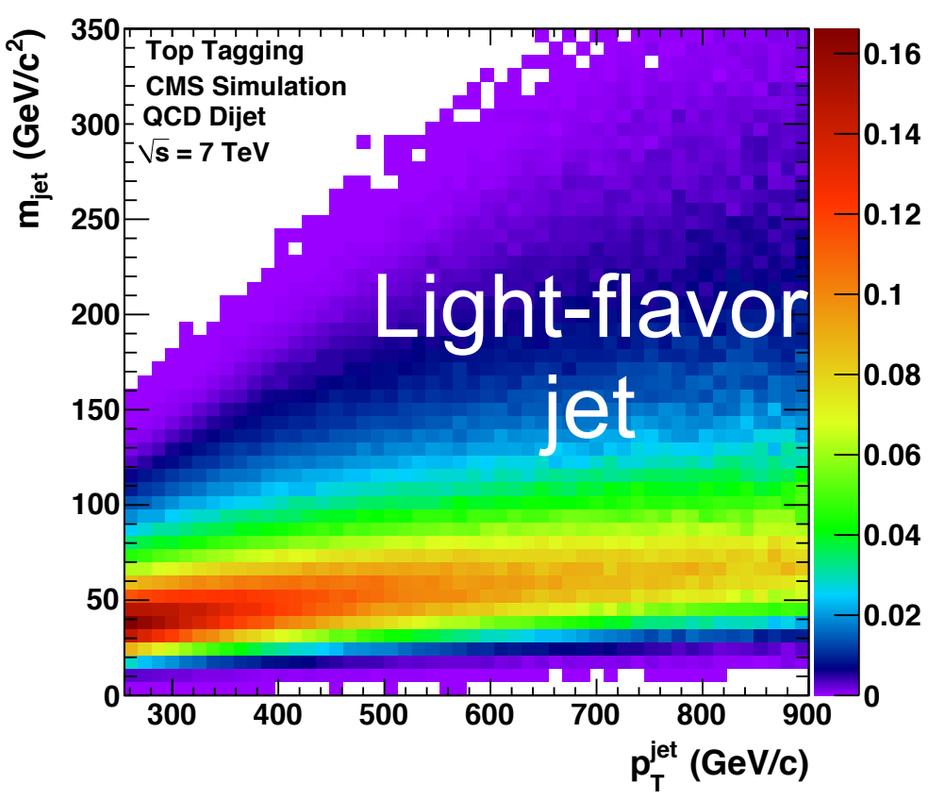
Scales ~linearly with momentum

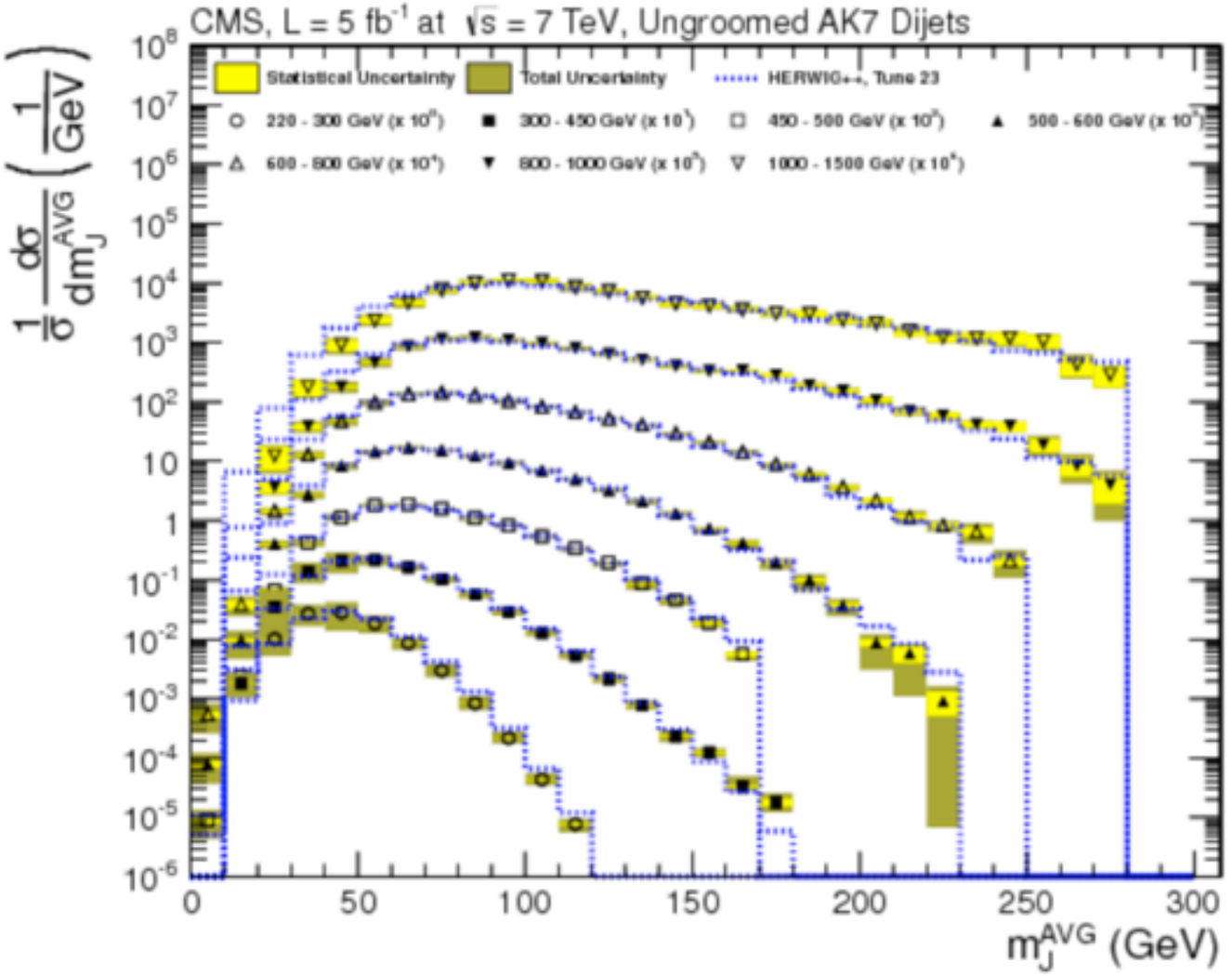
Log. divergence at low mass

$$\left\langle M_J^2 \right\rangle_{NLO} \simeq \overline{C} \left(\frac{p_J}{\sqrt{s}} \right) \alpha_s \left(\frac{p_J}{2} \right) p_J^2 R^2,$$



QCD has smoother behavior

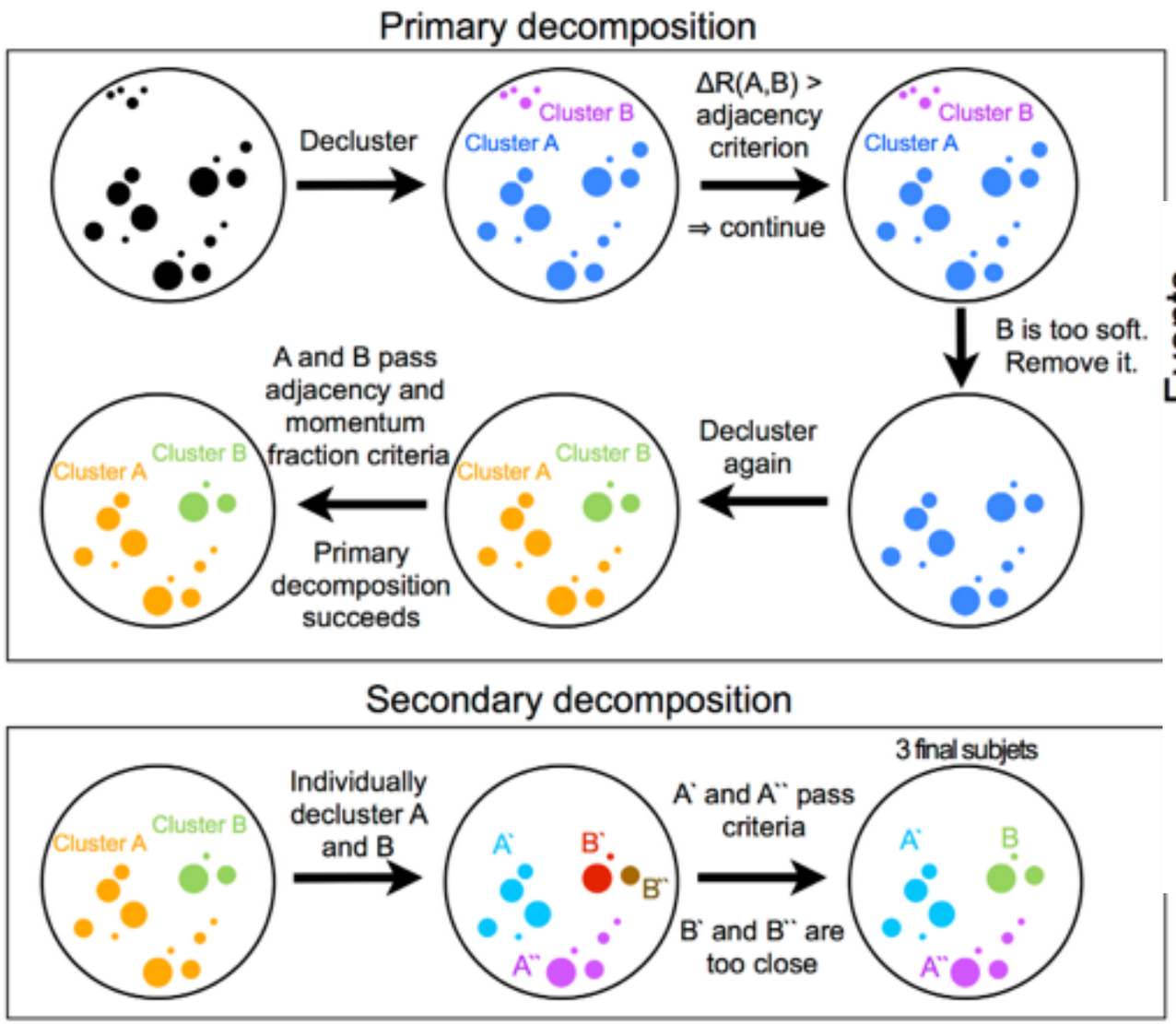


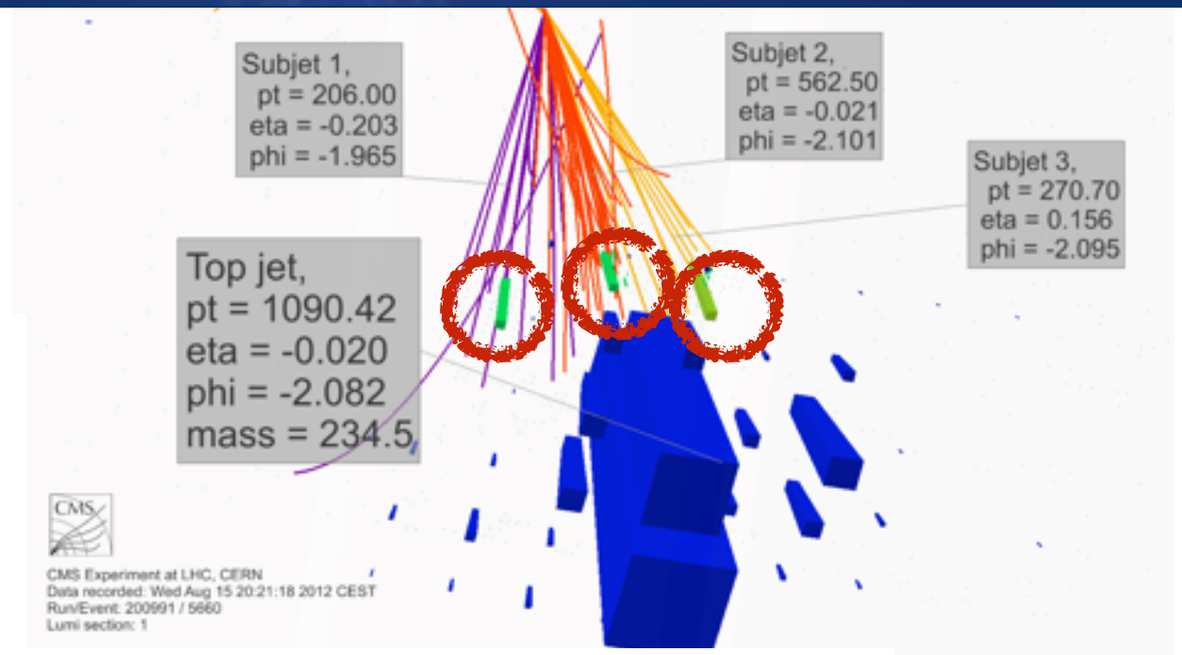


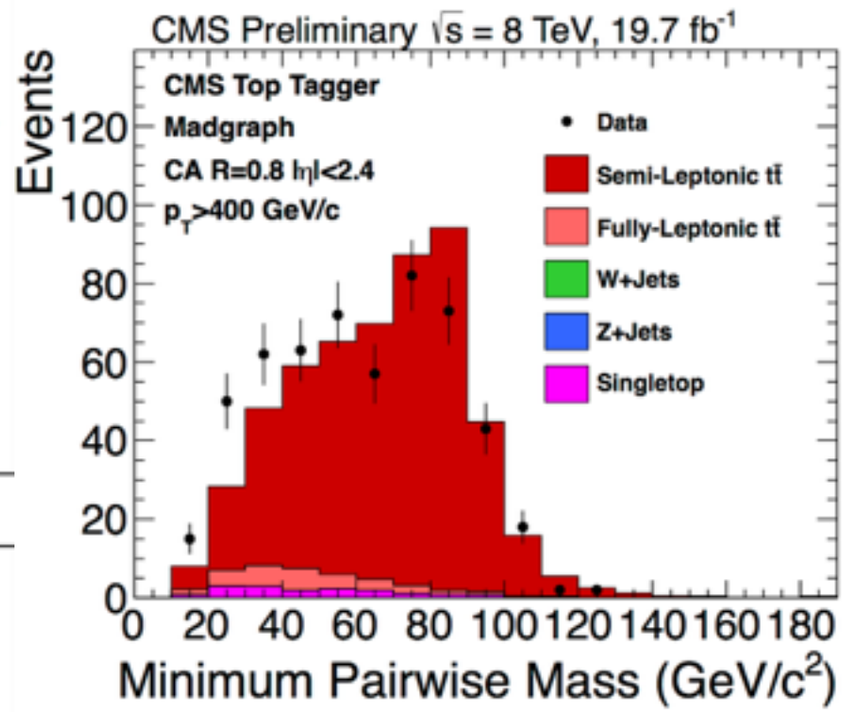
Boosted Tops

Decompose jet to reveal internal substructure

Example: CMS Top Tagger decomposition

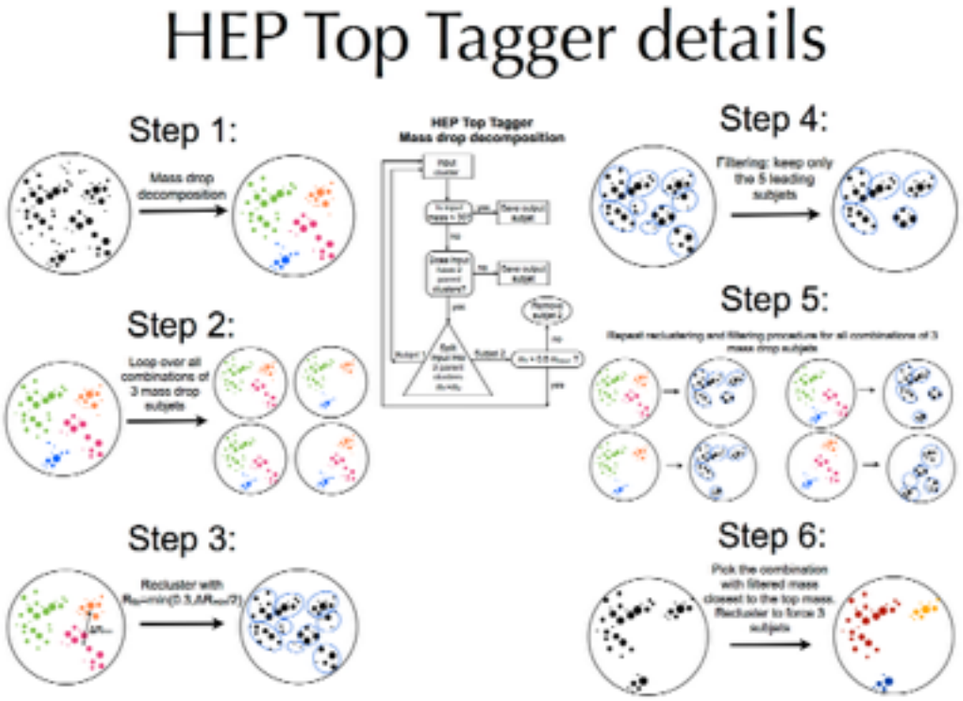


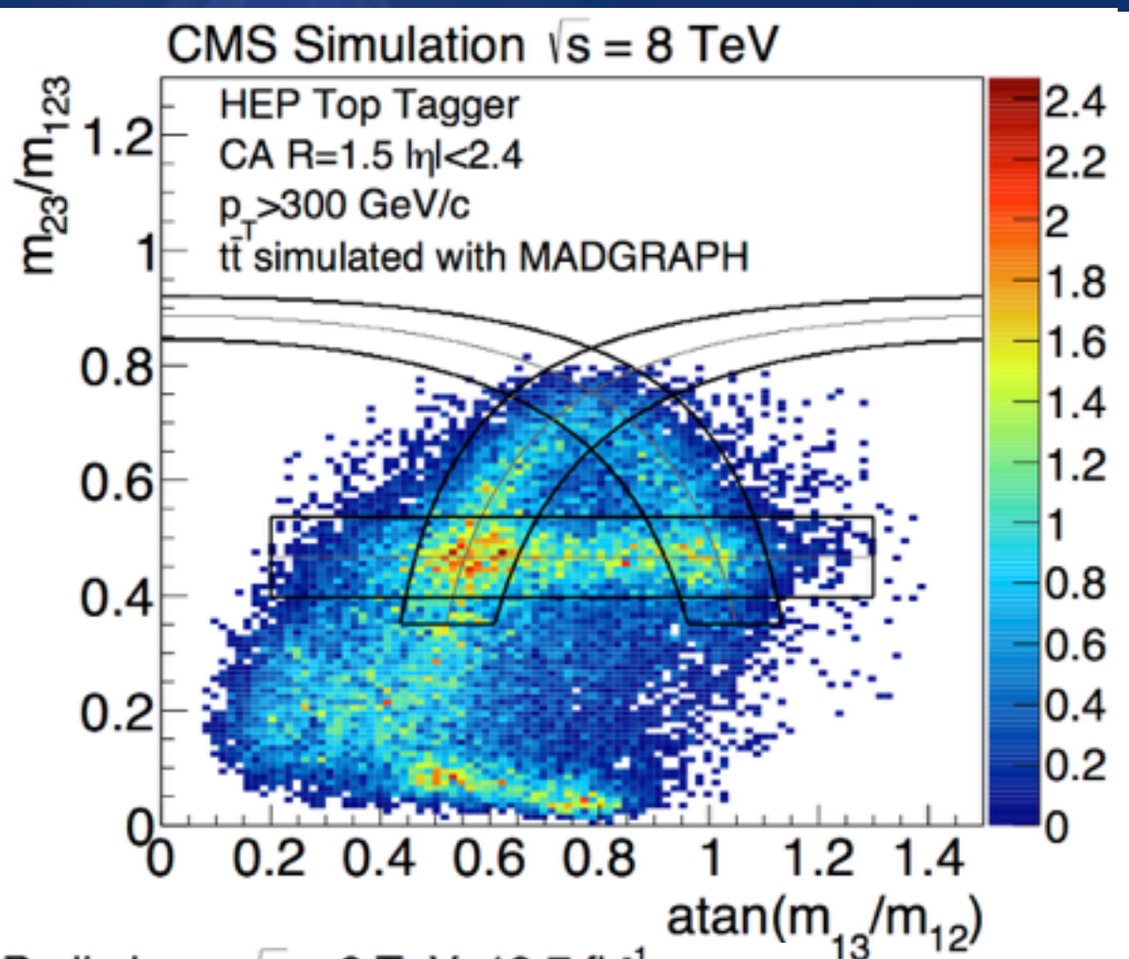


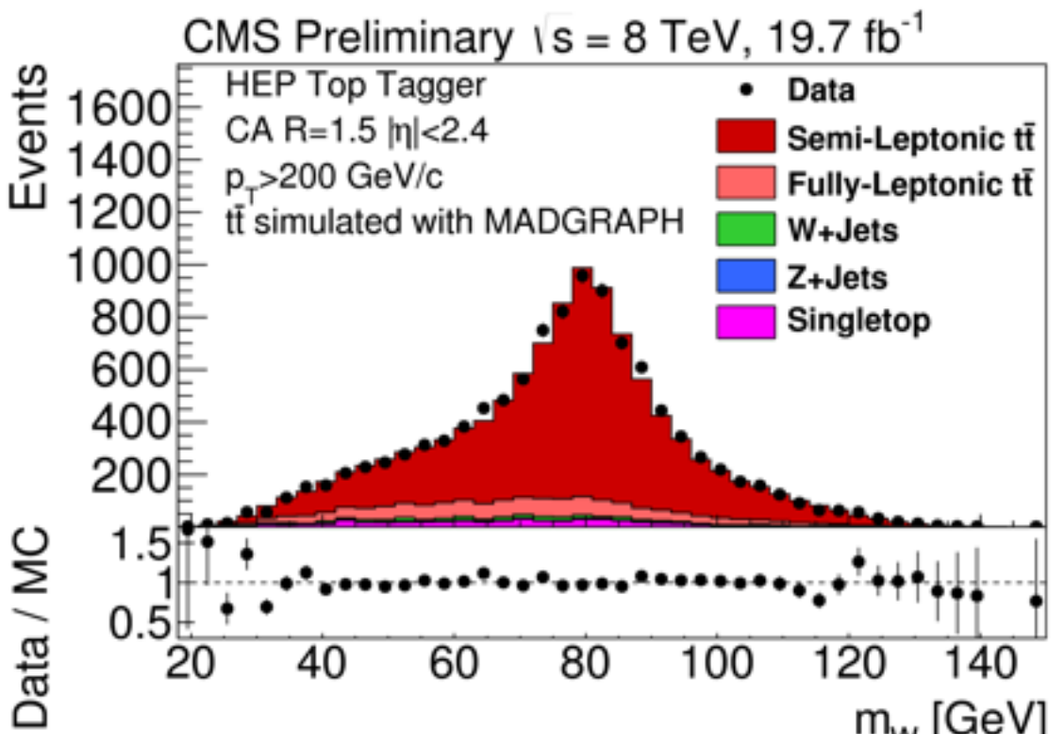


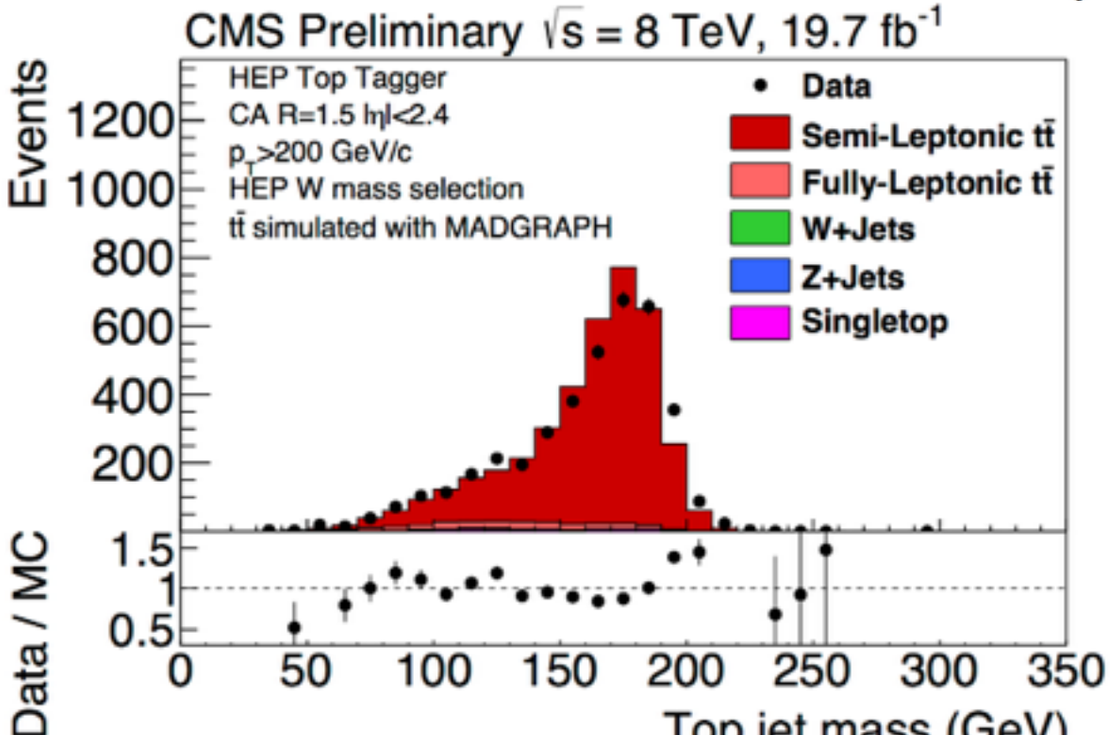
Boosted Tops

New!!! HEP TopTagger!

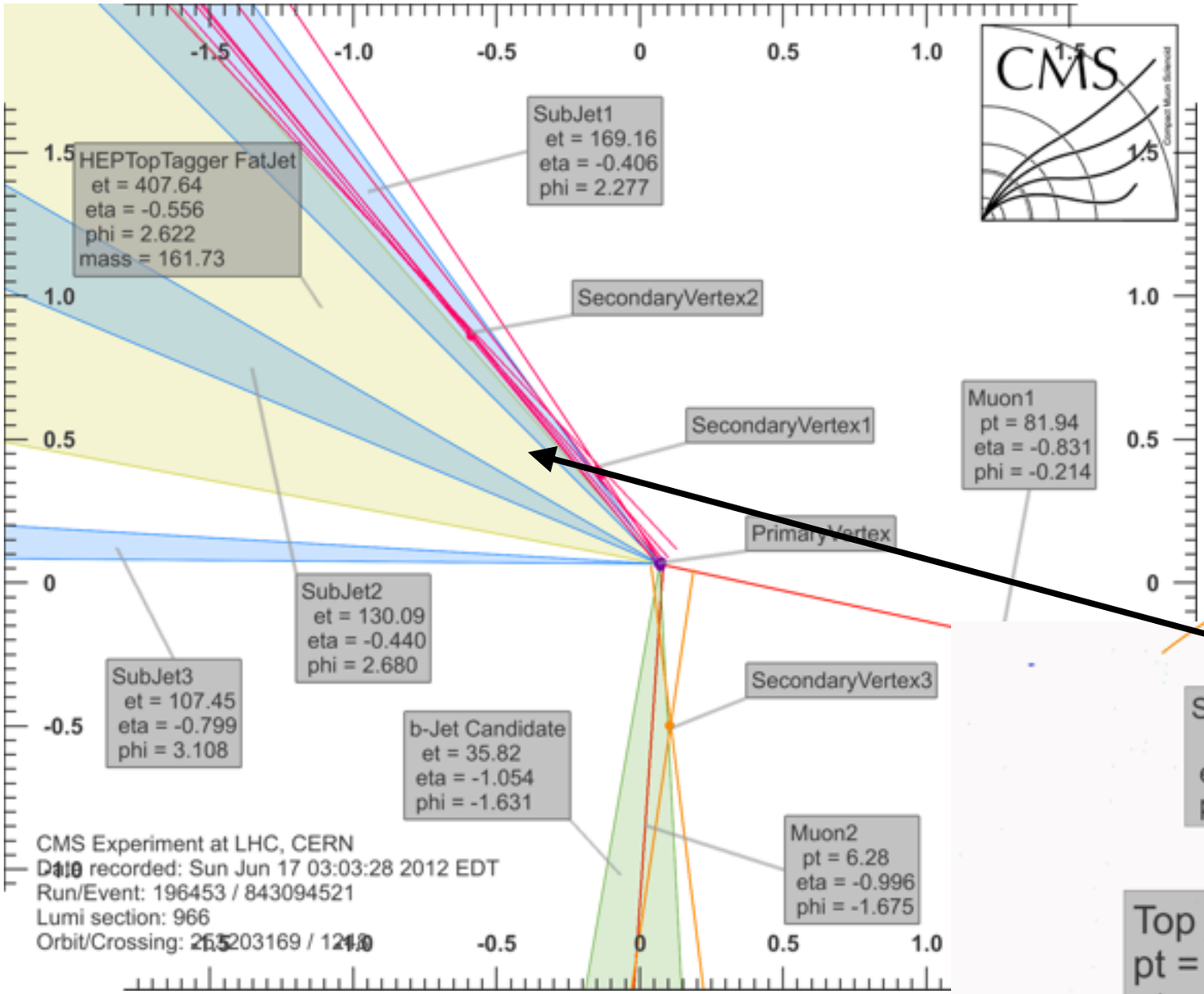




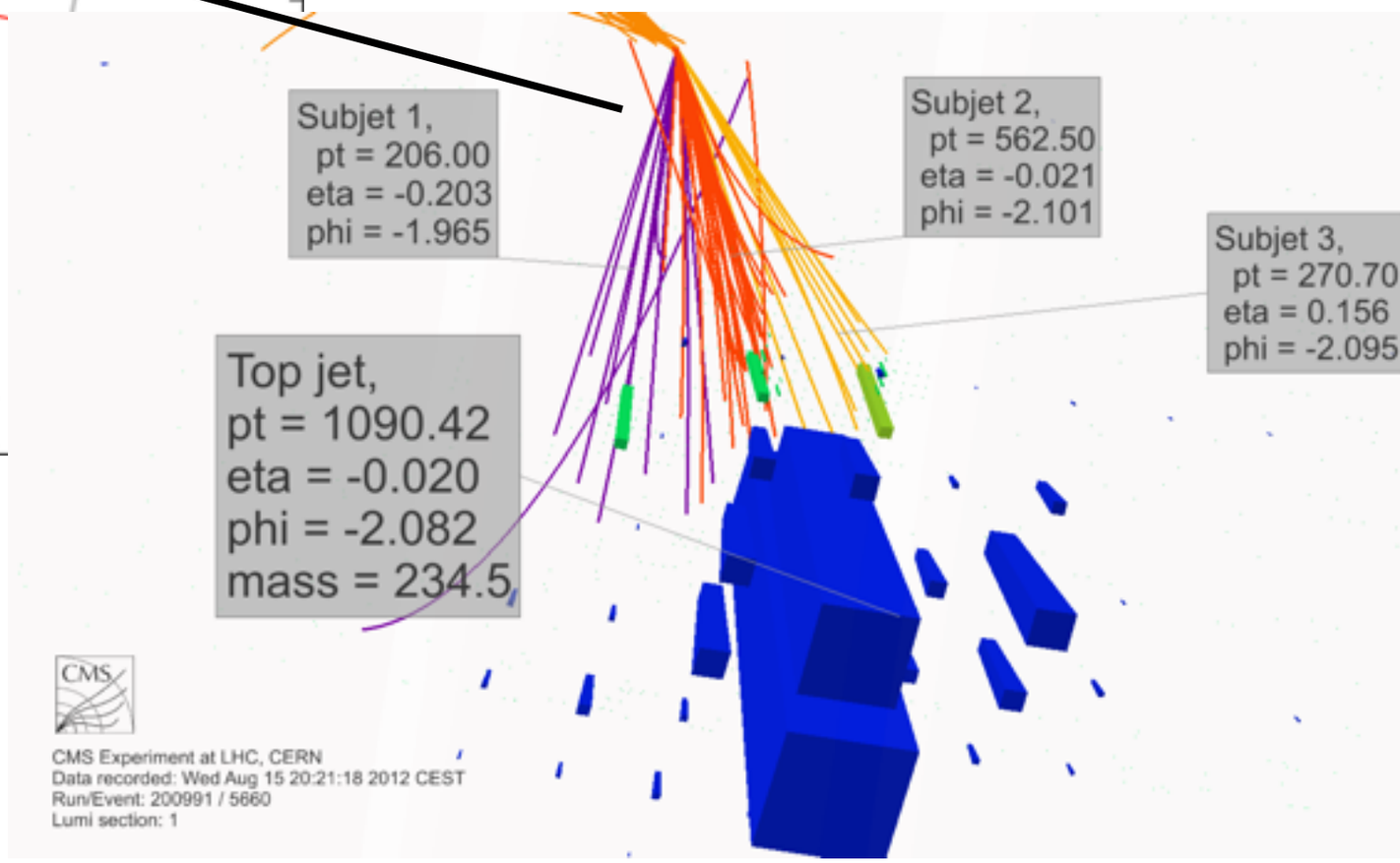




Boosted Tops and Bottoms

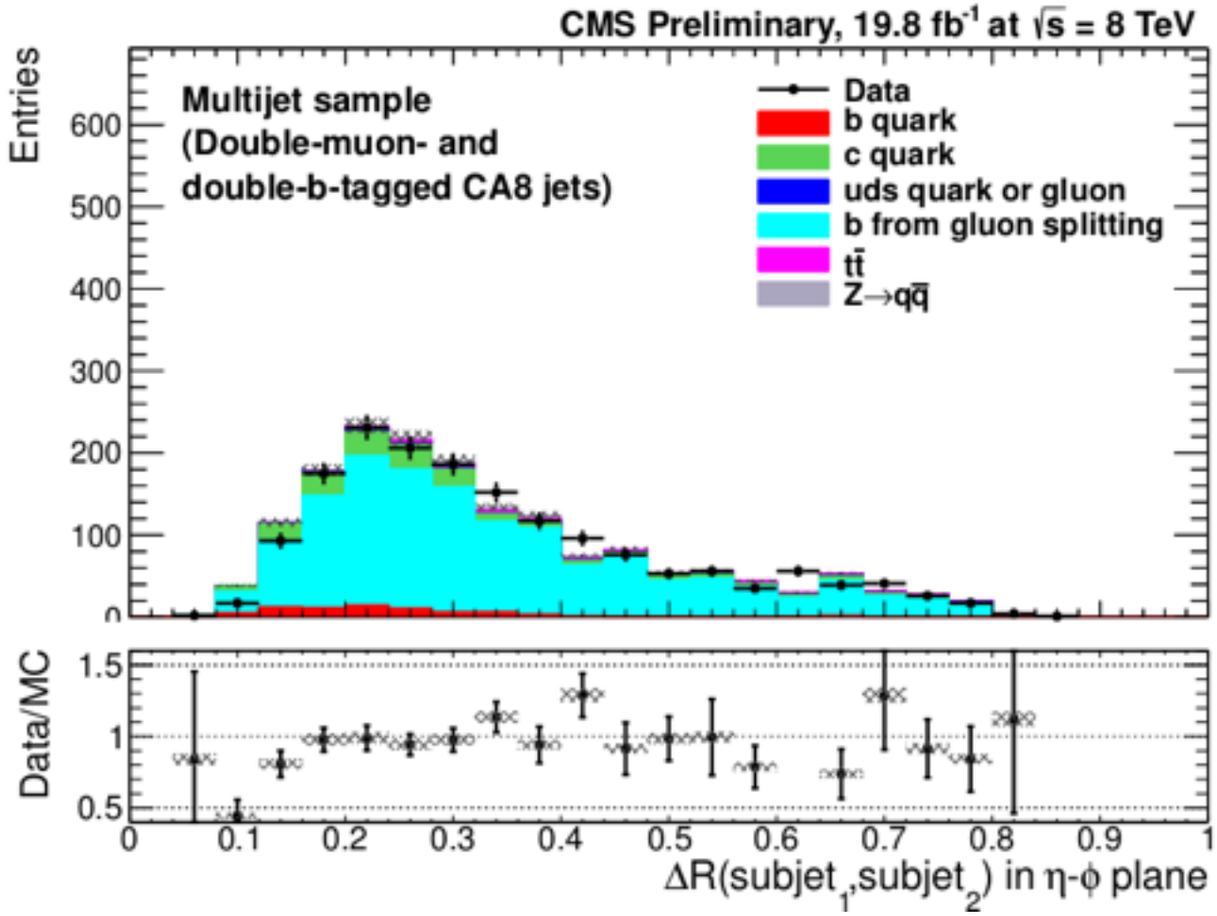


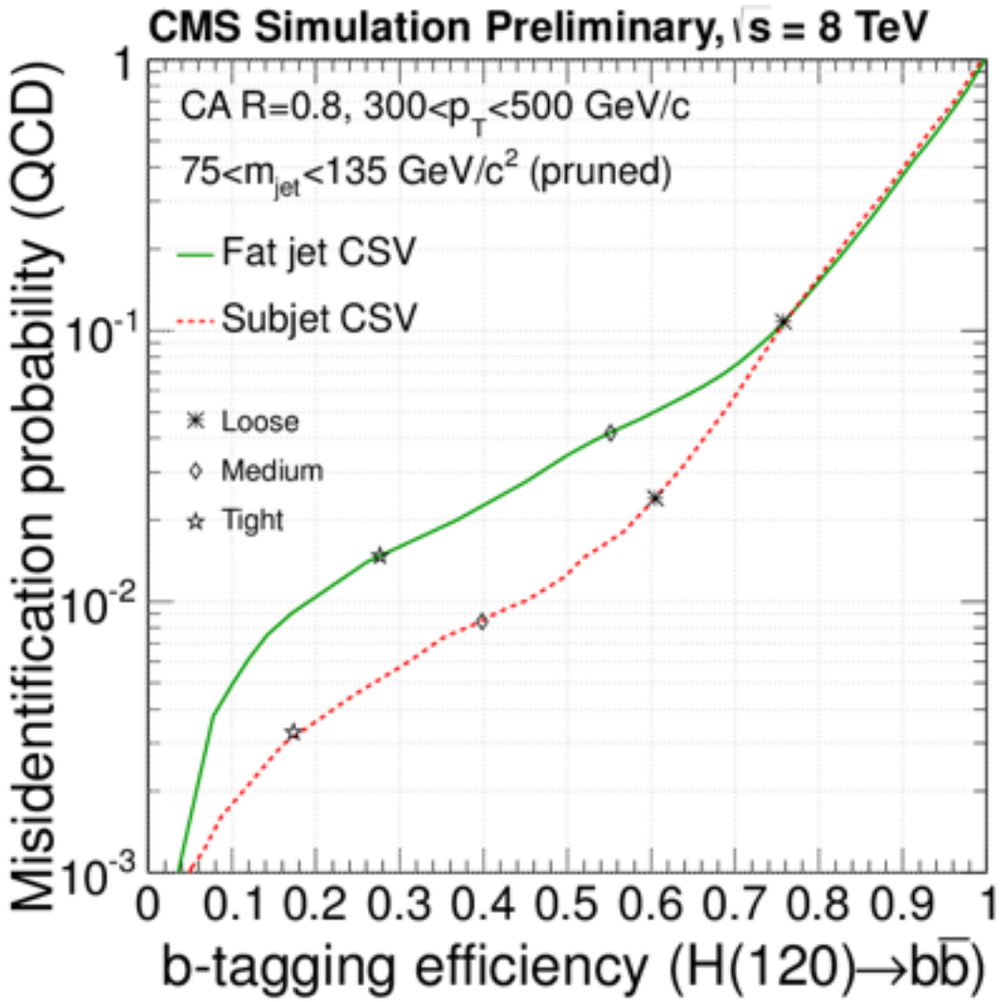
NEW!!!
Look at b-tags WITHIN the boosted jets
(“subjet b-tagging”)



Boosted Tops and Bottoms

- Calibrate with gluon splitting to b-bbar
- Excellent performance by b-tagging subjets!

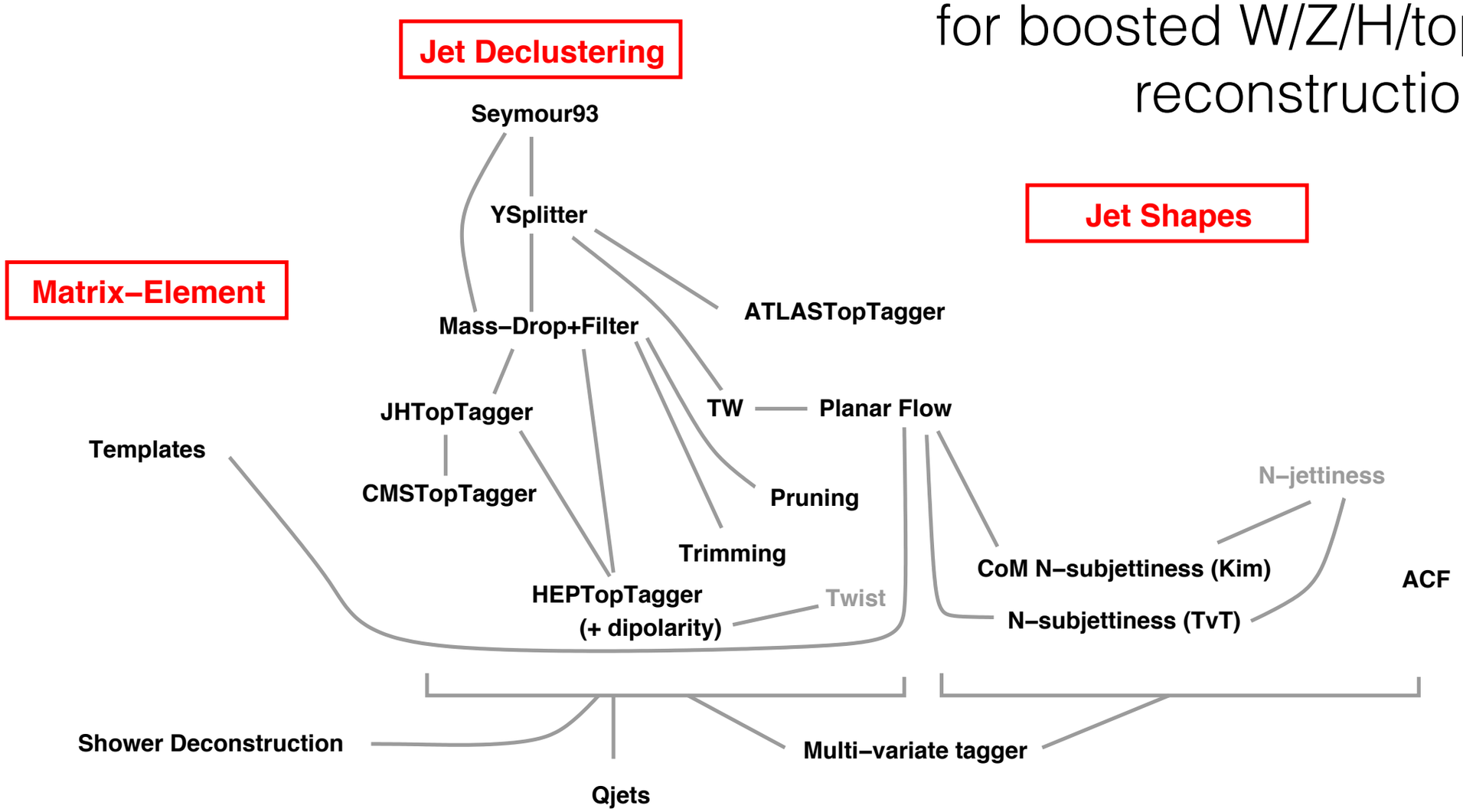




Boosted Jets

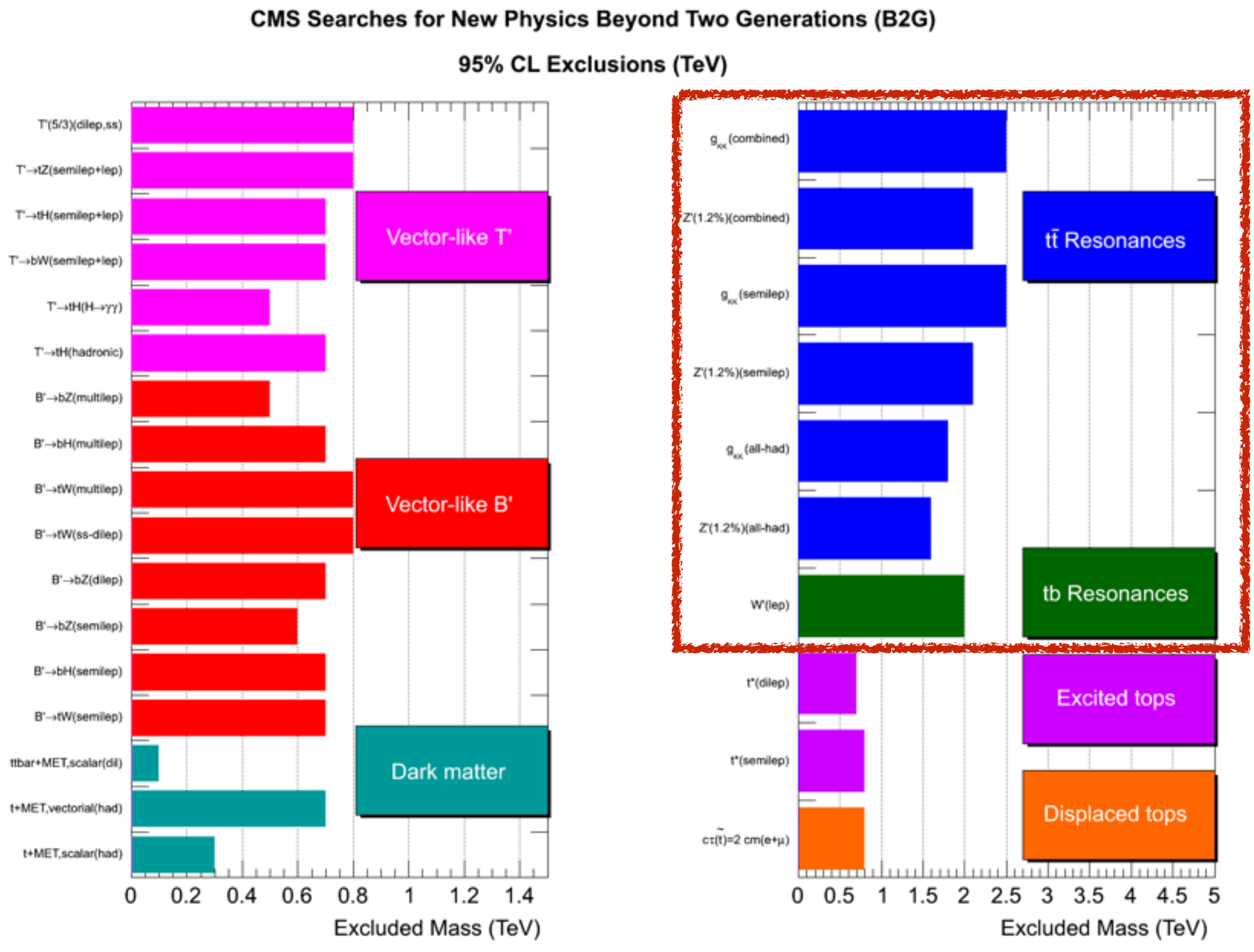
Very active research field

Some of the tools developed for boosted W/Z/H/top reconstruction



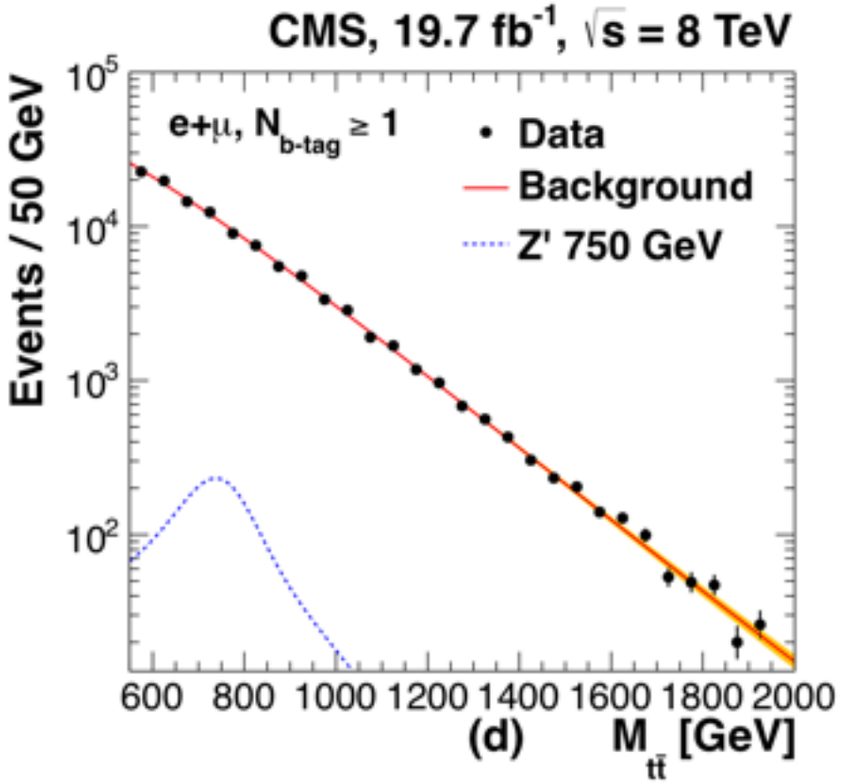
apologies for omitted taggers, arguable links, etc.

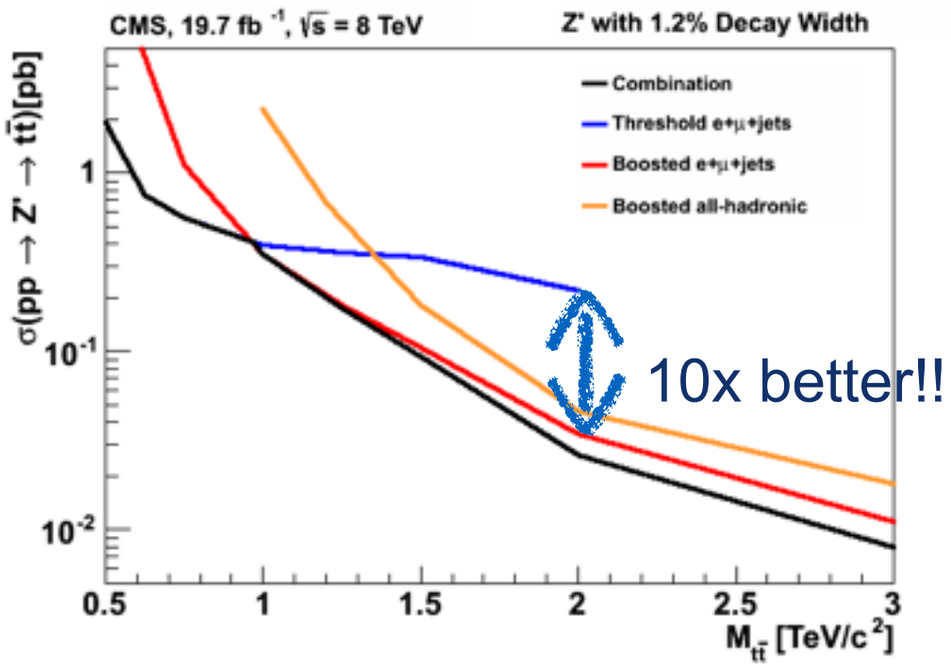
Resonances from Extra Dimensions



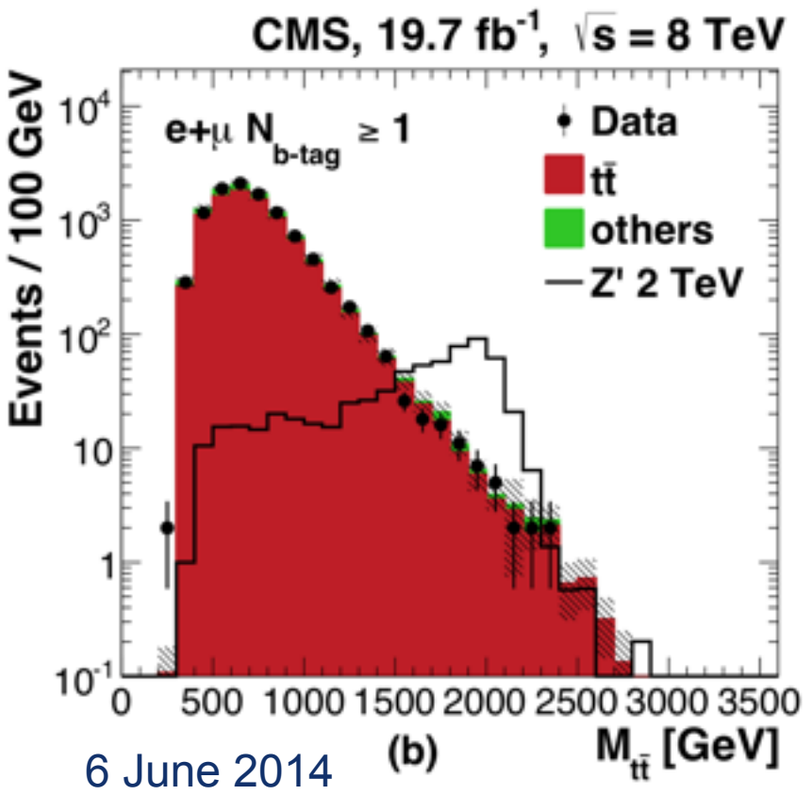
ttbar Resonances

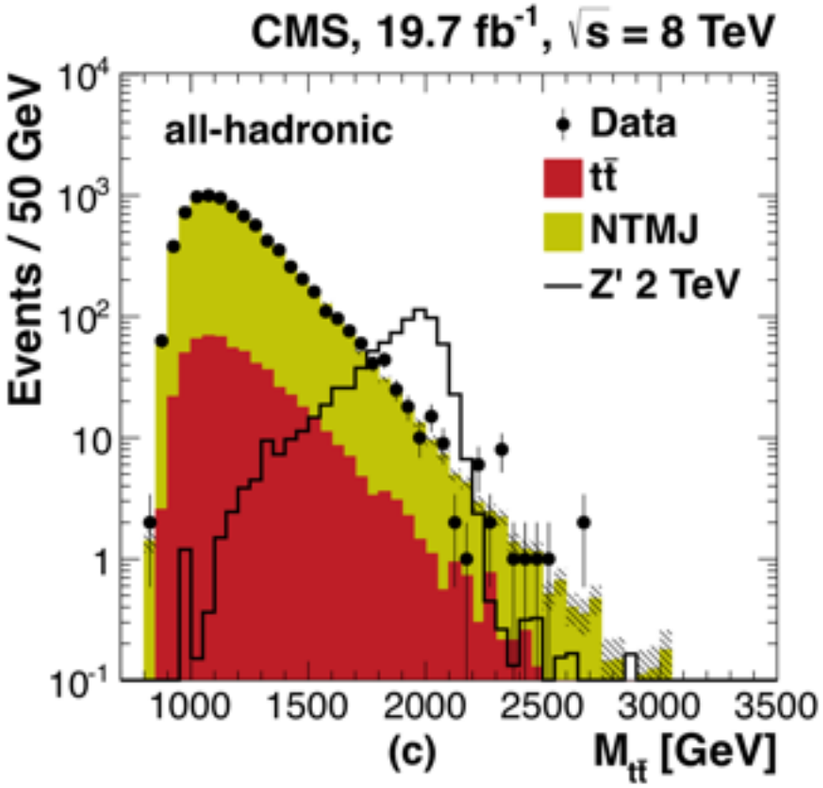
Phys. Rev. Lett. 111 (2013) 211804

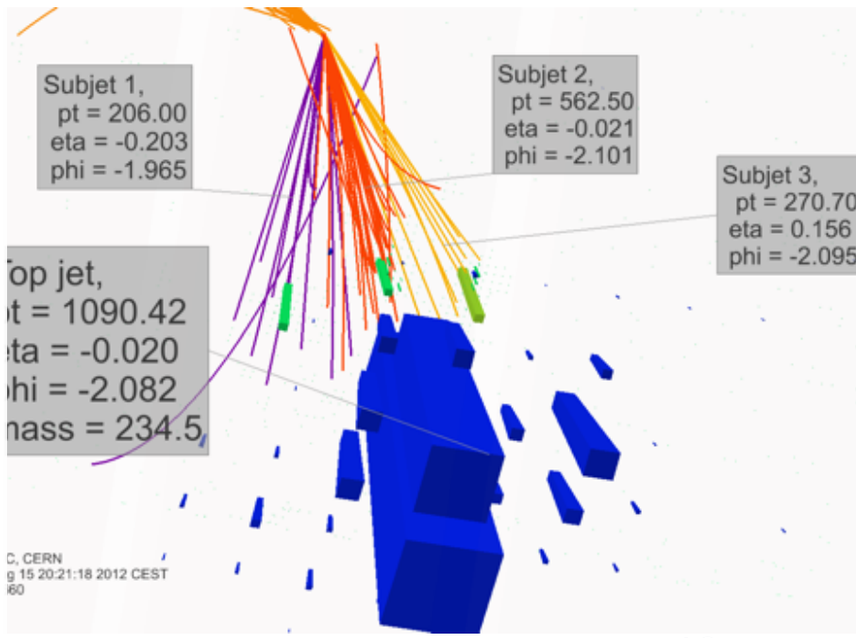




Classic application of boosted top methods :
- Substructure
- Boost-safe isolation

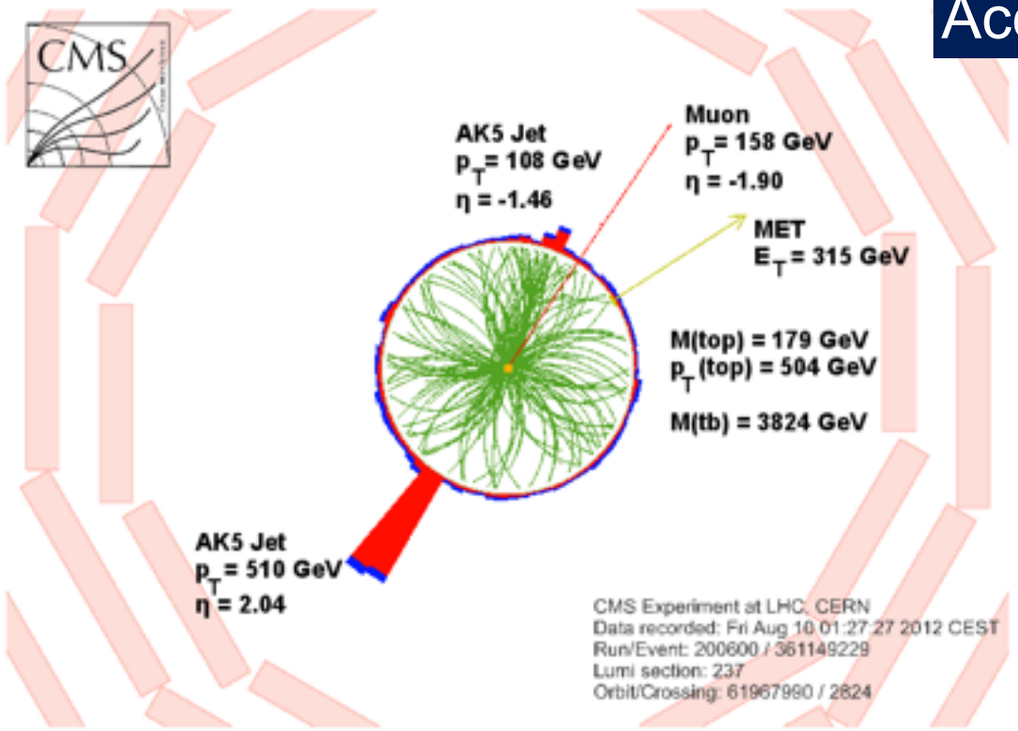


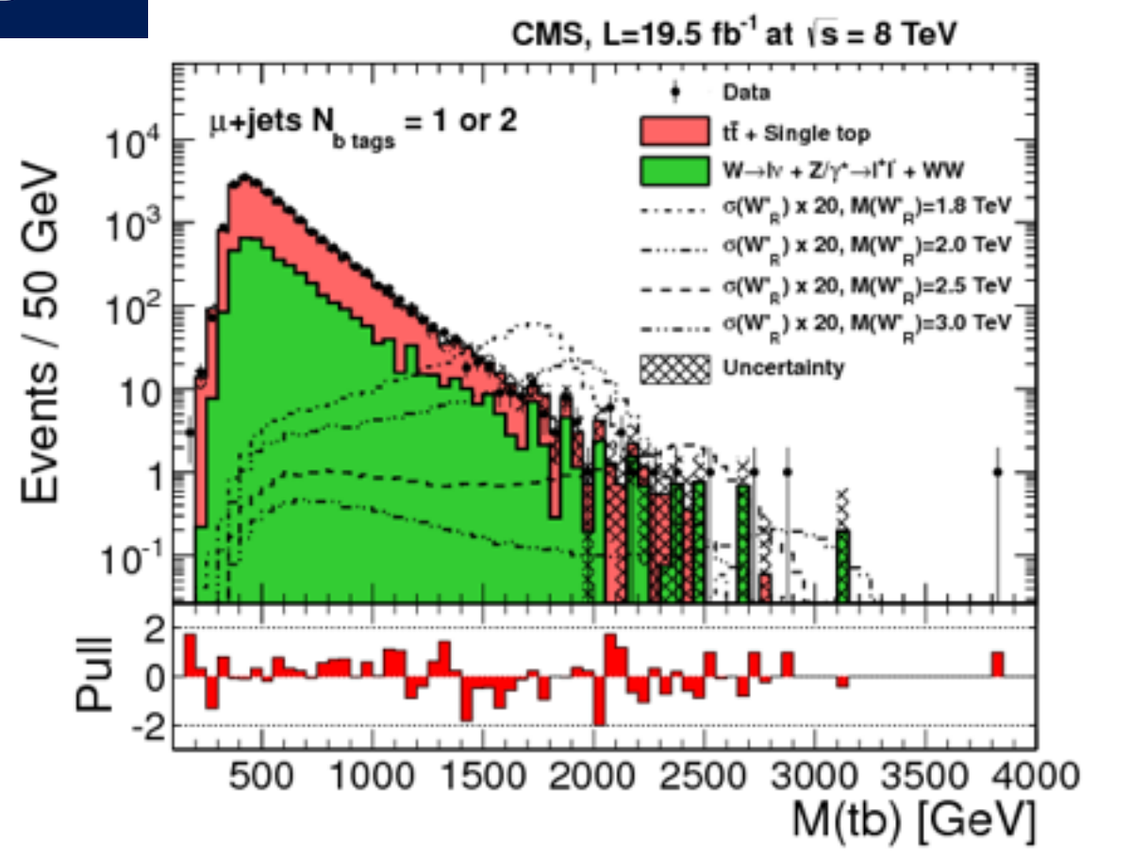


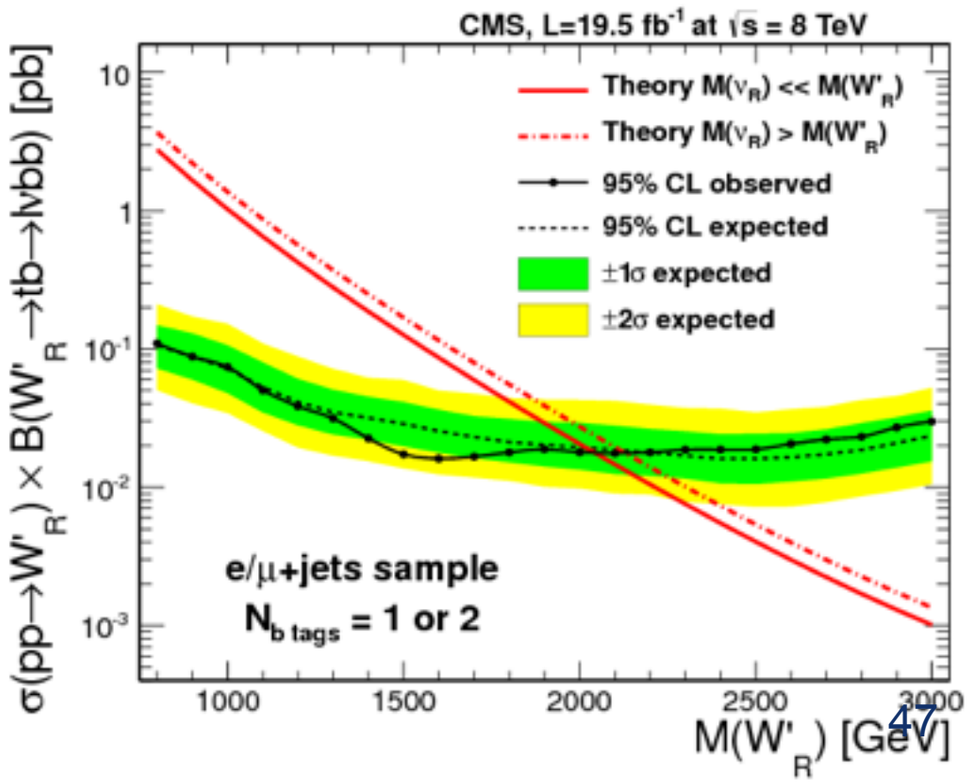


tb Resonances

Accepted by JHEP

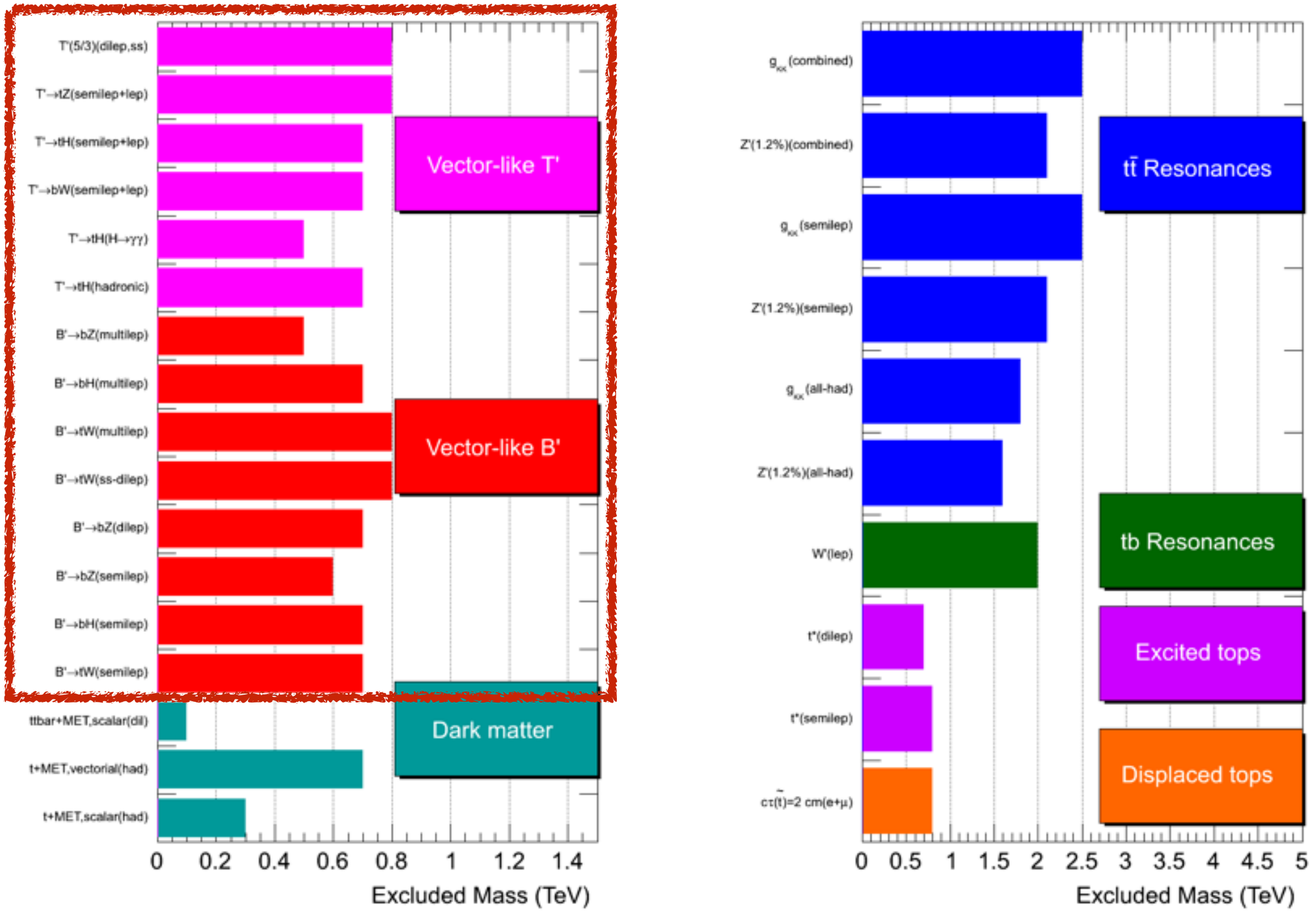






- Coming soon : all-hadronic channel and combination!

Vector-like Quarks



Vector-like Quarks : T5/3

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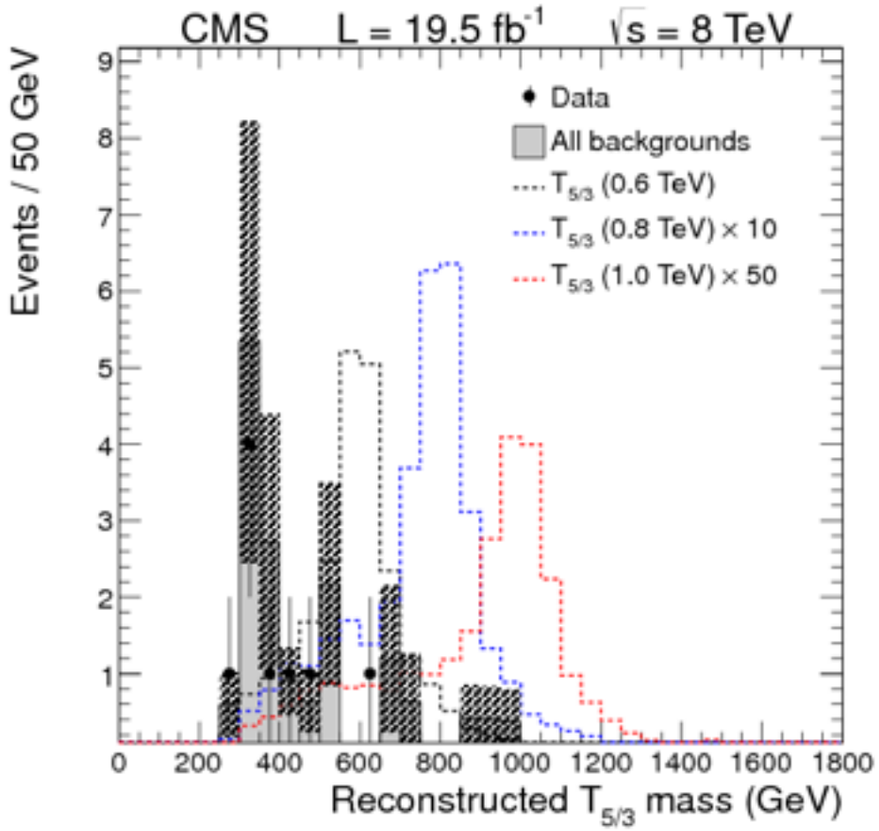
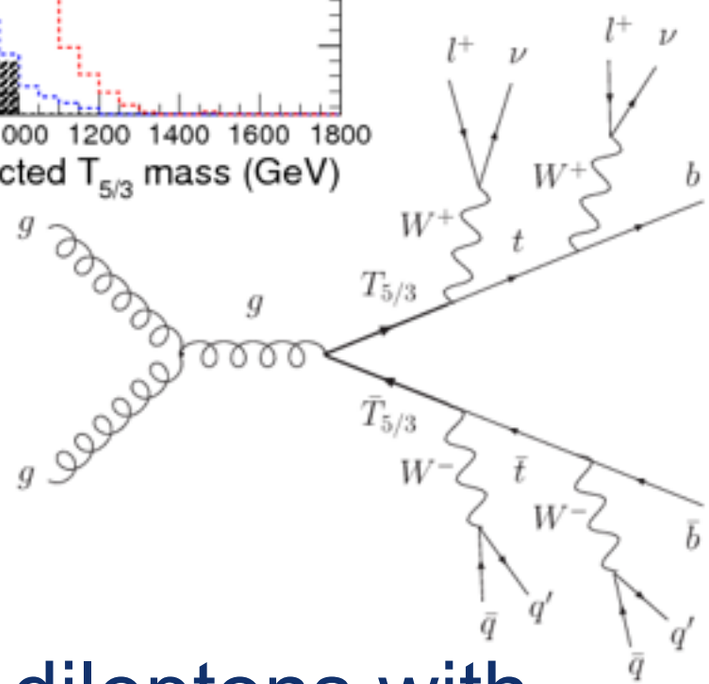
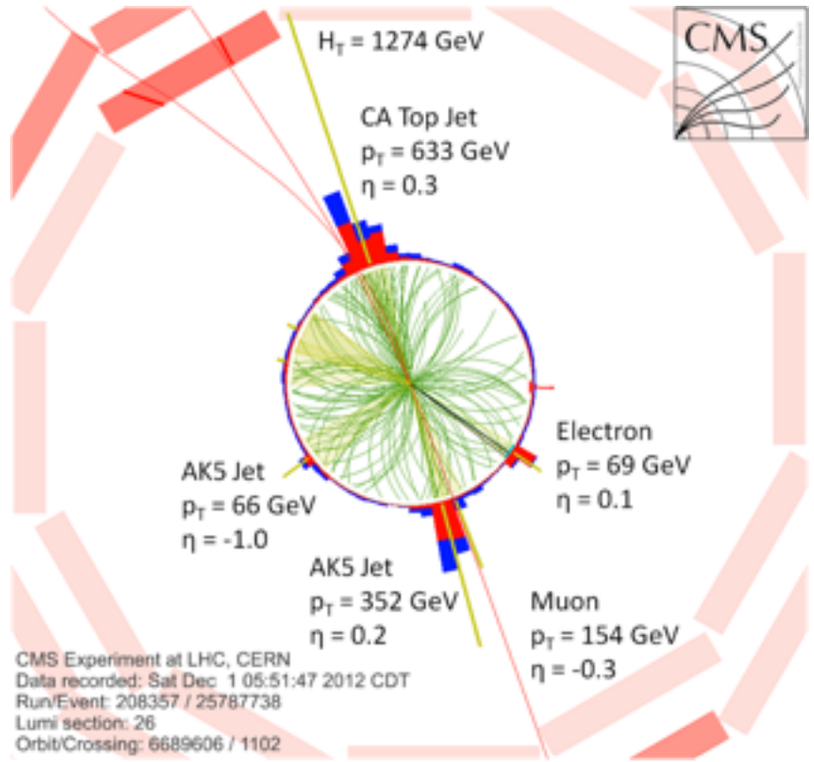
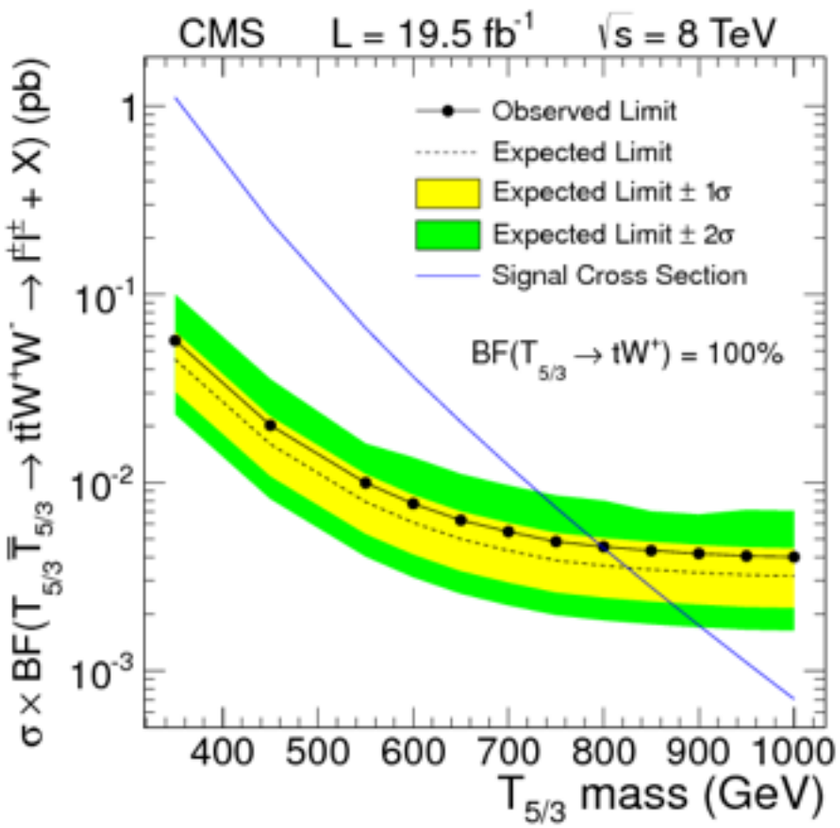


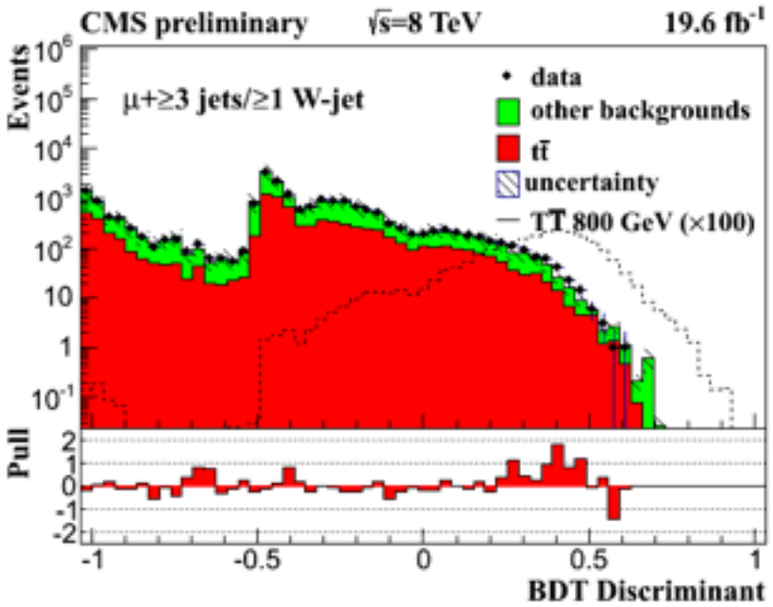


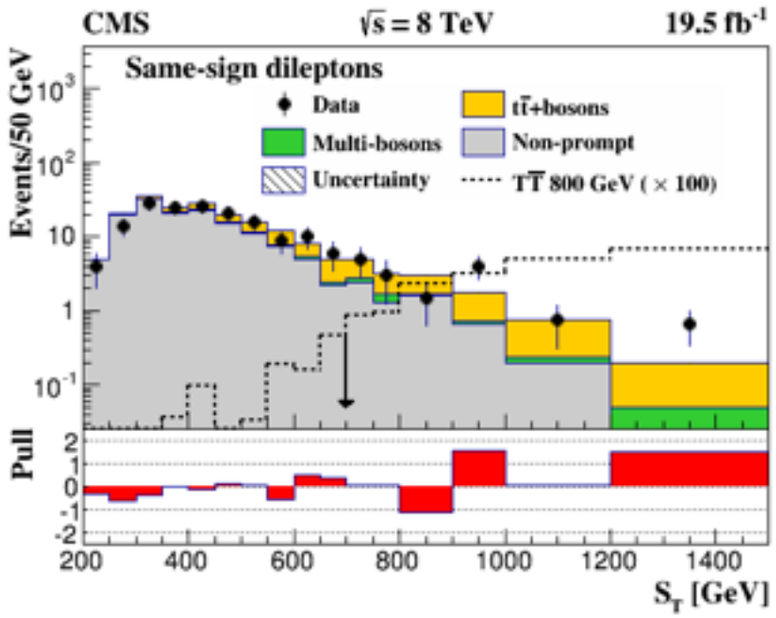


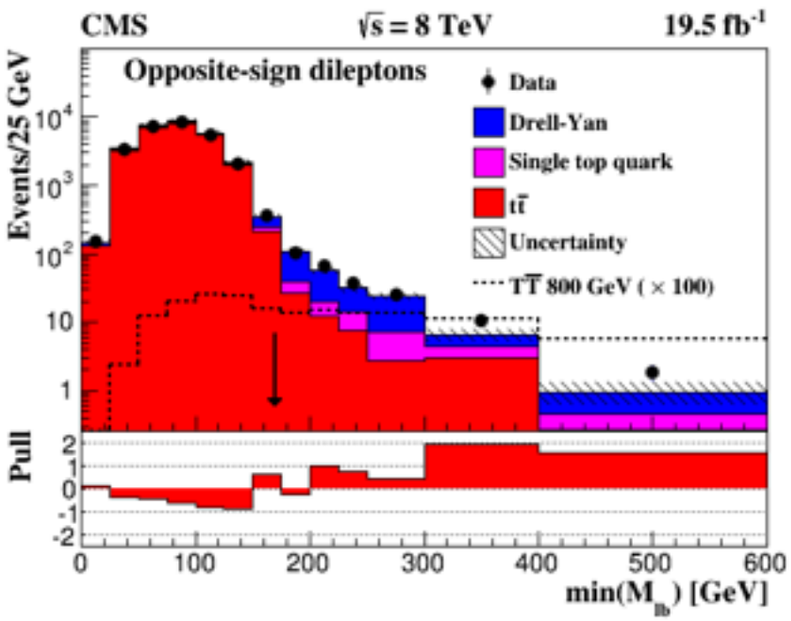


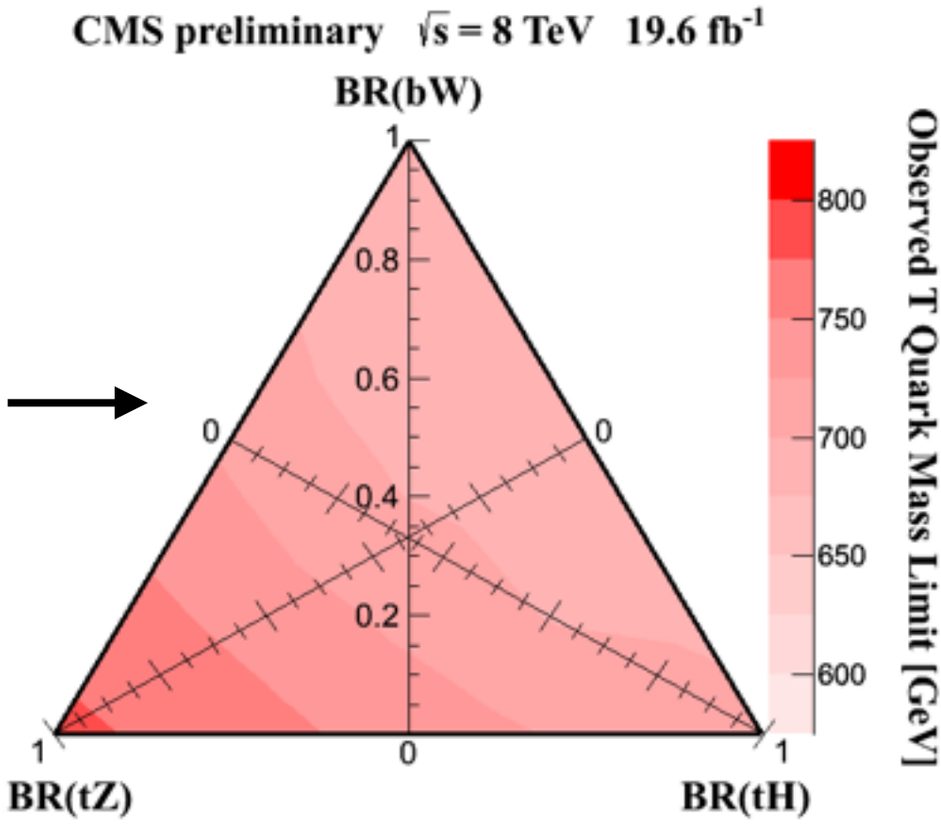
- Same-sign dileptons with boosted top and W categories

Vector-like Quarks : T2/3









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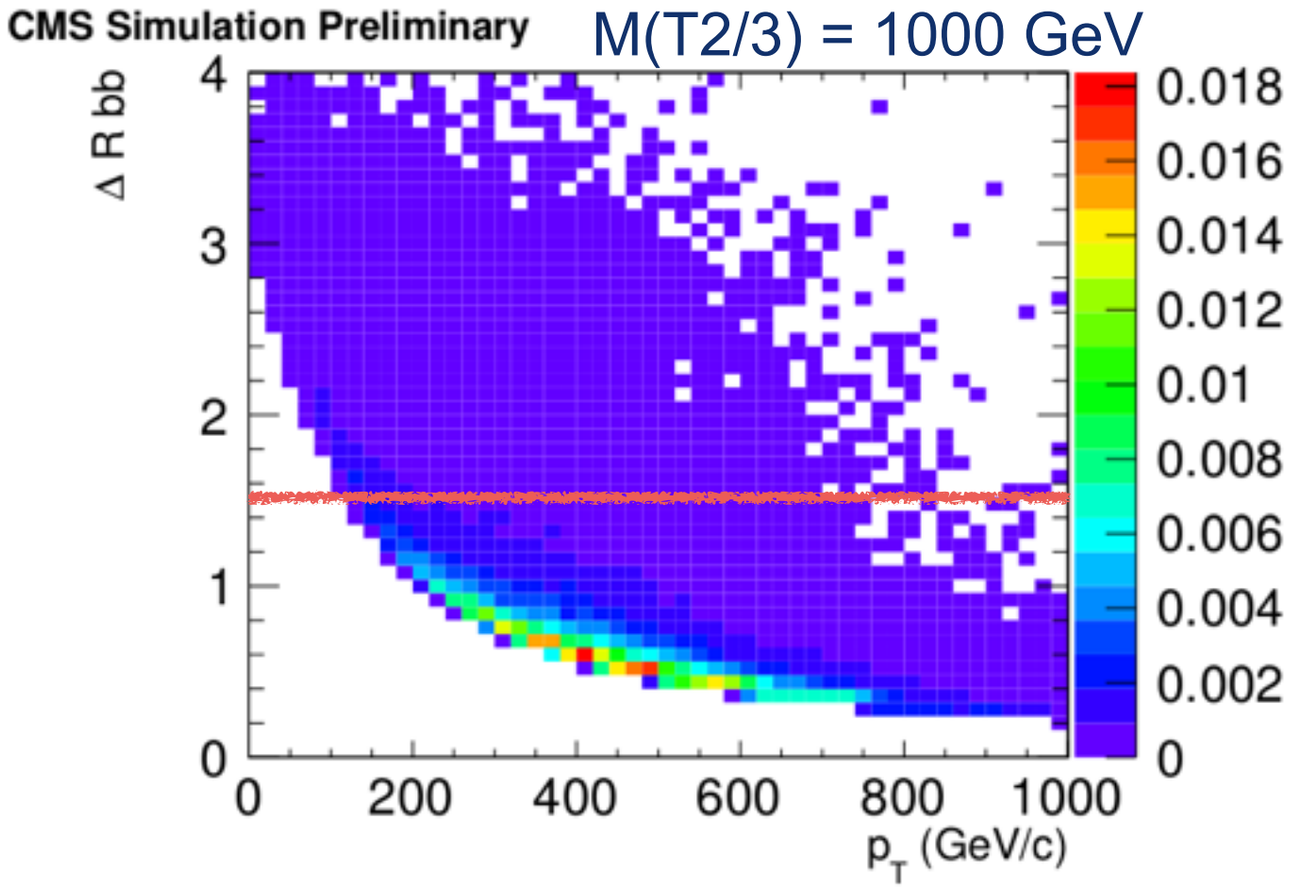
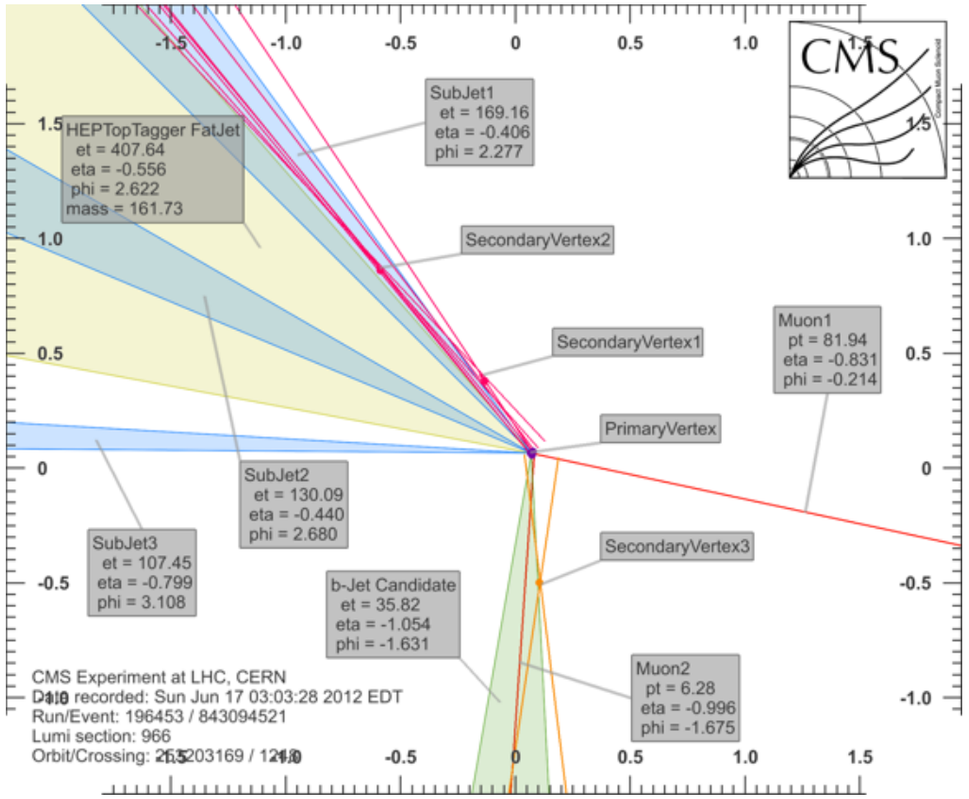
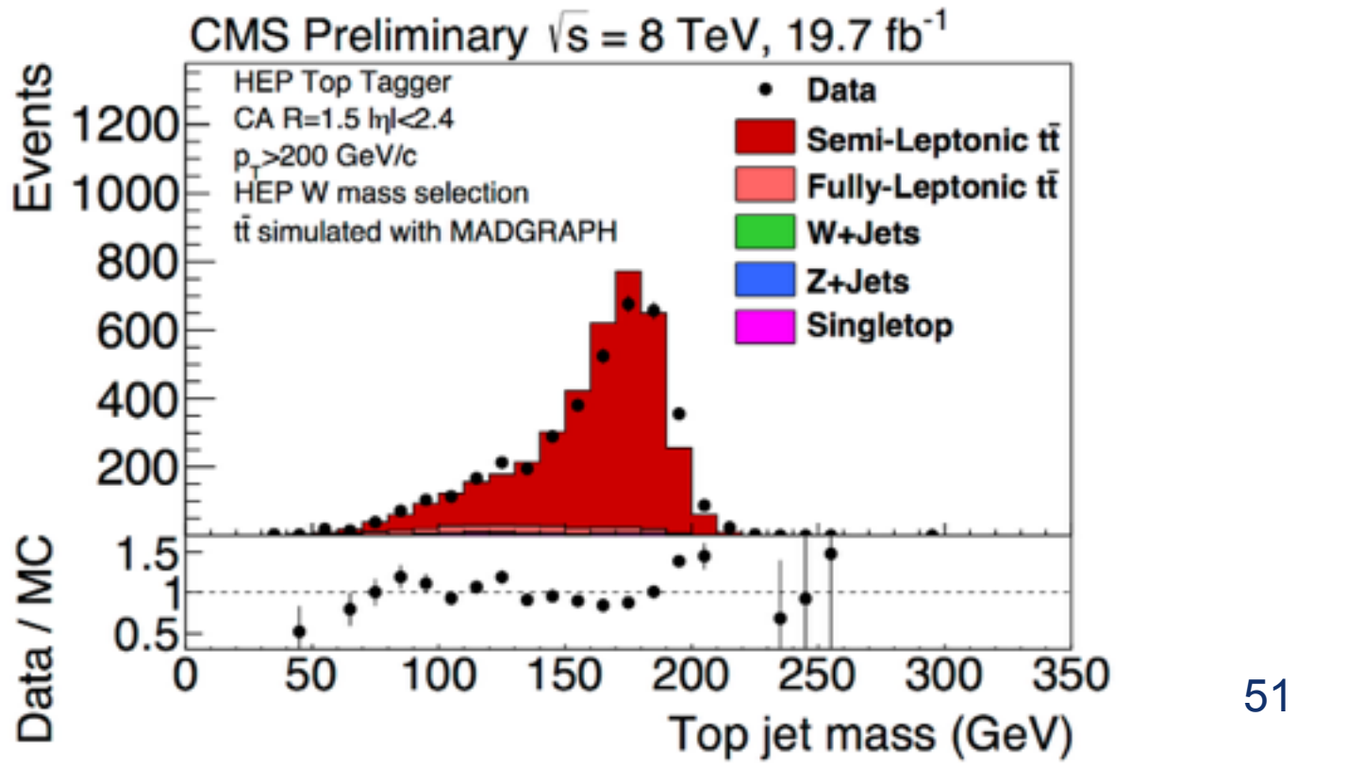
- T2/3 -> tH, tZ, bW
- OS, SS dileptons and semileptonic analysis combined
- W-tagged categories for the semileptonic analysis

Vector-like Quarks : T2/3

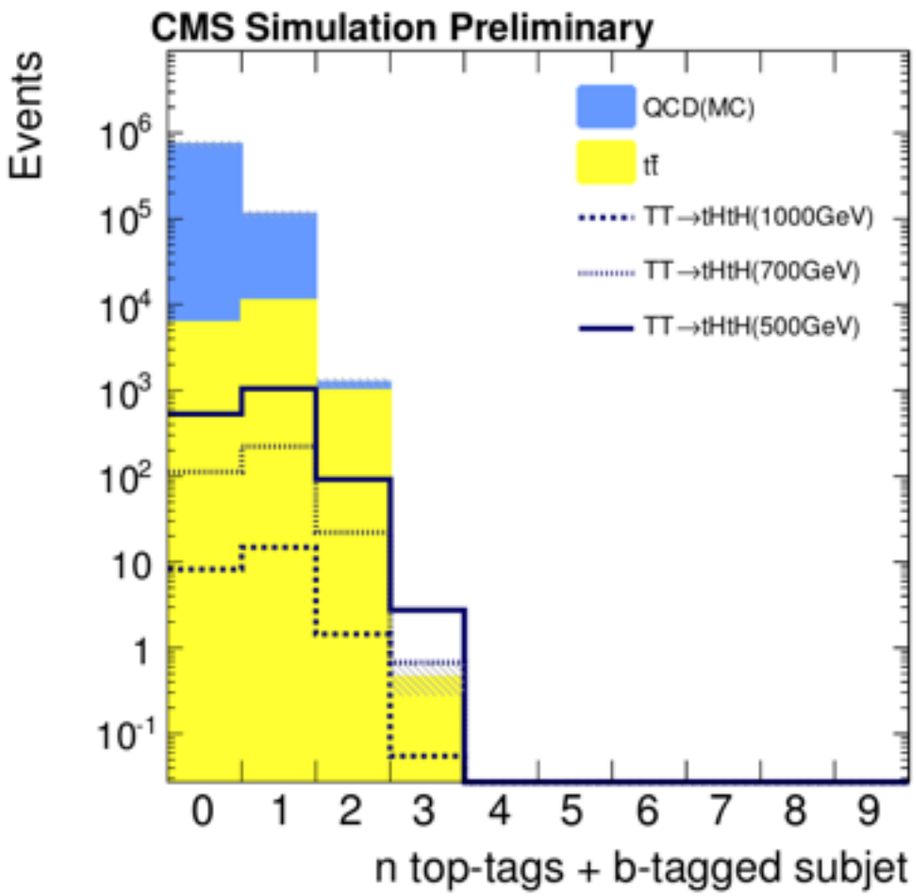
- B2G-14-002 :
  - T2/3 -> tH exclusively
  - All new! All firsts for CMS!
  - Higgs tagger :
    - Filtered CA15 jets with subjet b-tagging
  - HEP top tagger
    - Also using subjet b-tagging



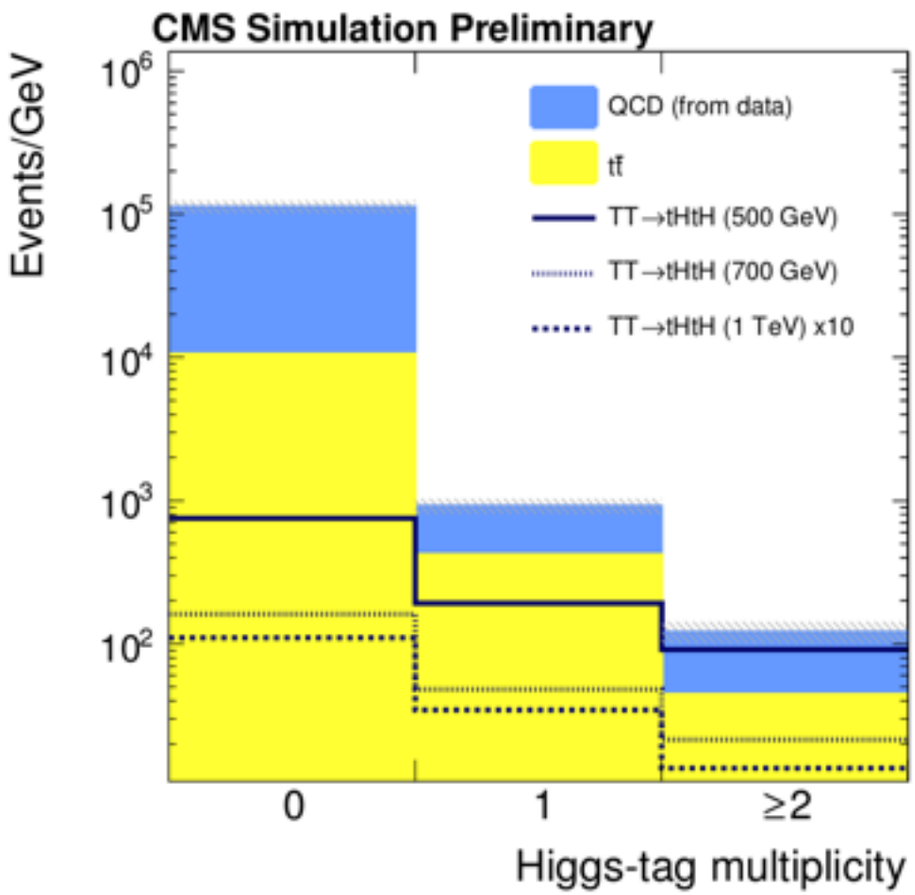




Vector-like Quarks : T2/3

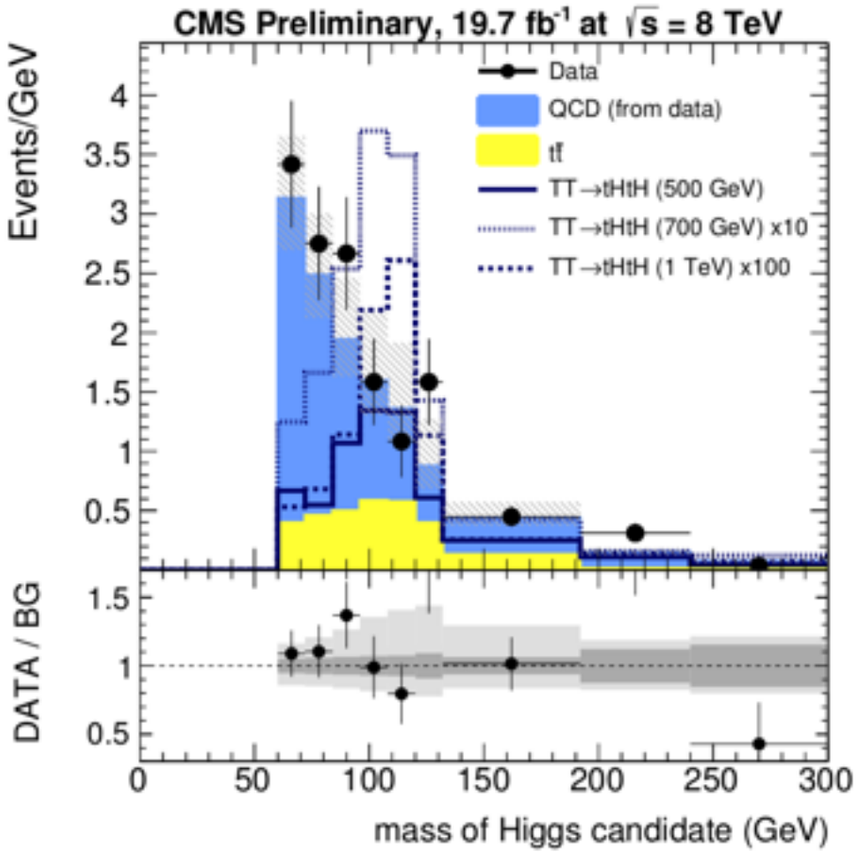


“top tag” = HEP + subjet b-tag

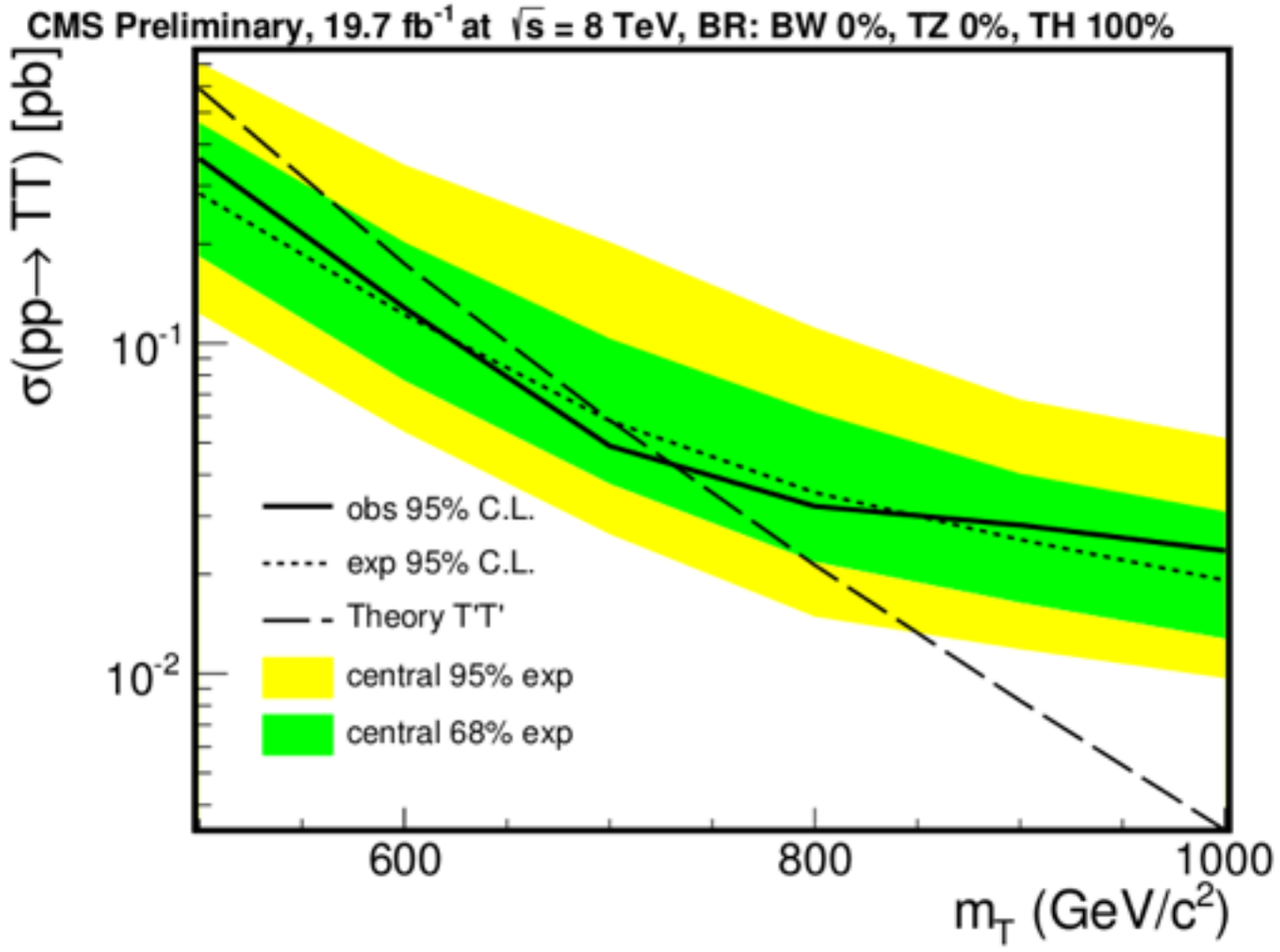


“Higgs tag” = CA15 + 2 subjet b-tags
(plot after 1 top tag)

Vector-like Quarks : T2/3



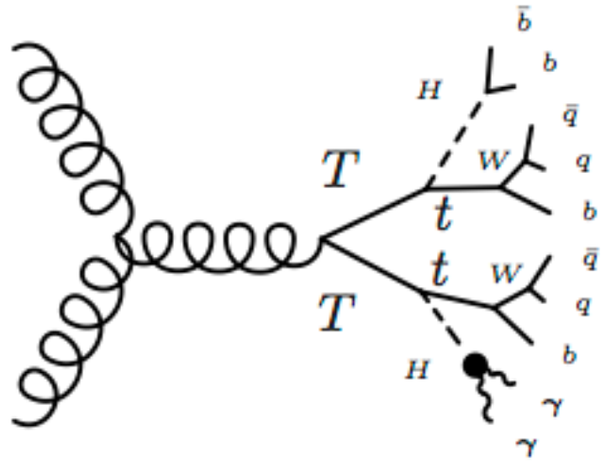
2 Higgs tags + 1 top tag

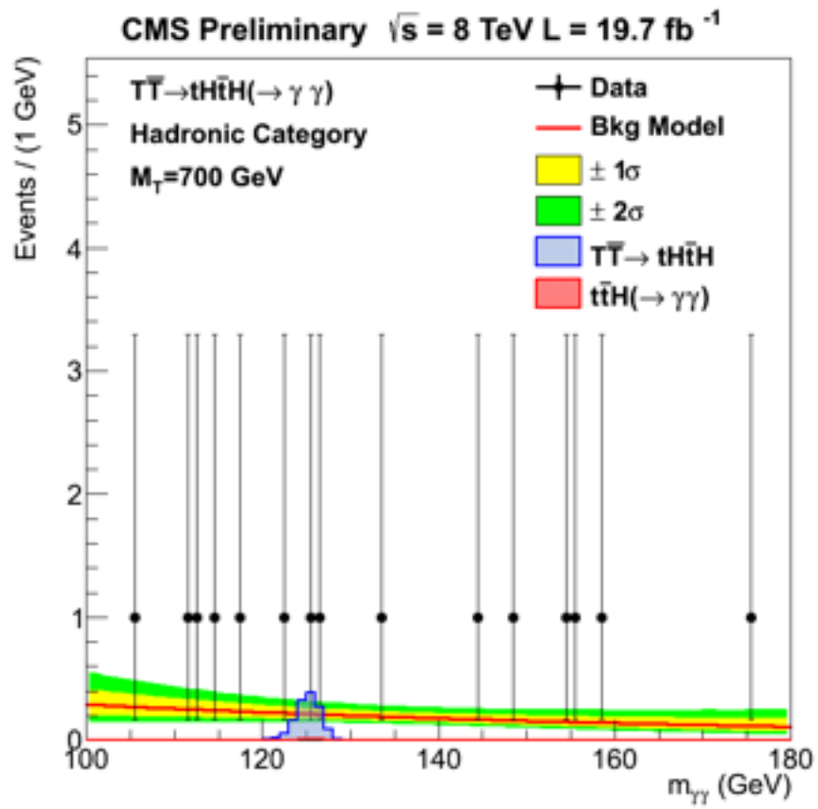


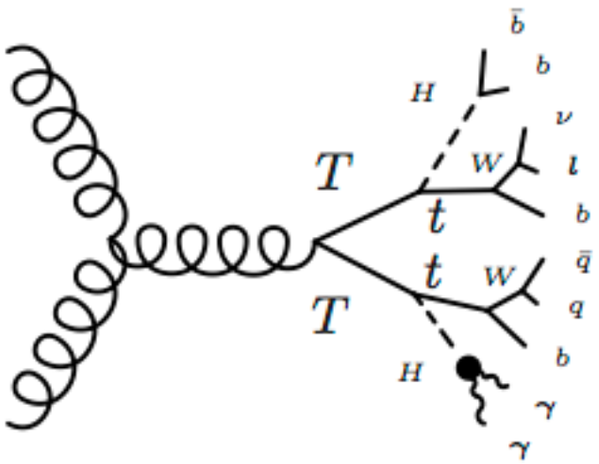
- Combine 1 Htag and 2 Htag categories
- Limit ~0.7 TeV, comparable to (l+jets + dil) combined ~0.7 TeV

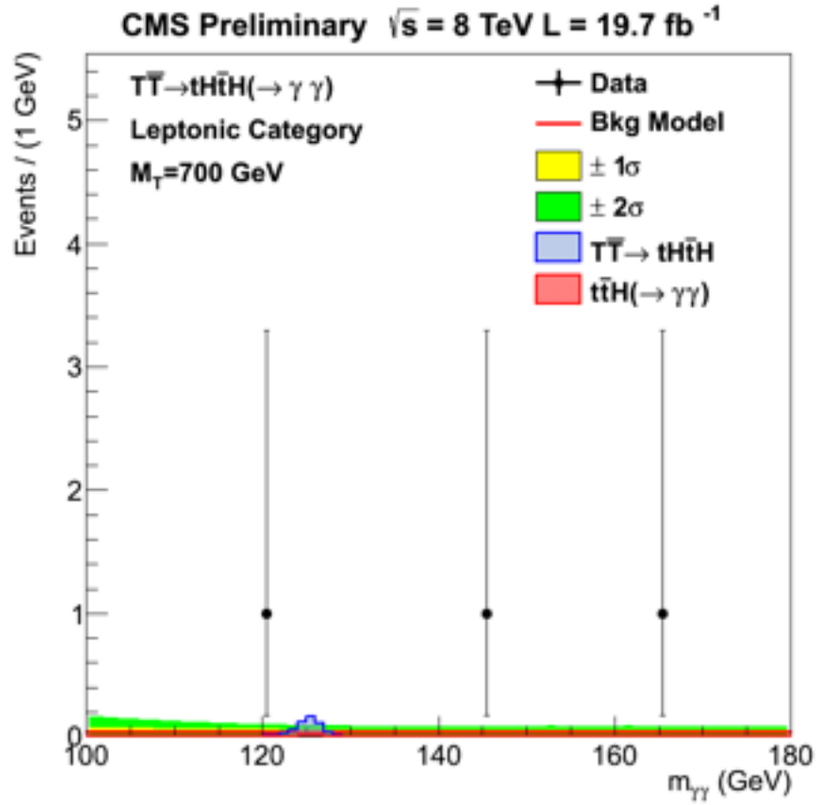
Vector-like Quarks : T2/3

- B2G-14-003 :
  - T2/3 -> t + H
  - All new! H->gamma gamma channel!
- Lower statistics than others, but critical to confirm discovery
- Use gamma gamma mass spectrum to constrain BSM production
- Combines leptonic and hadronic channels for th tops

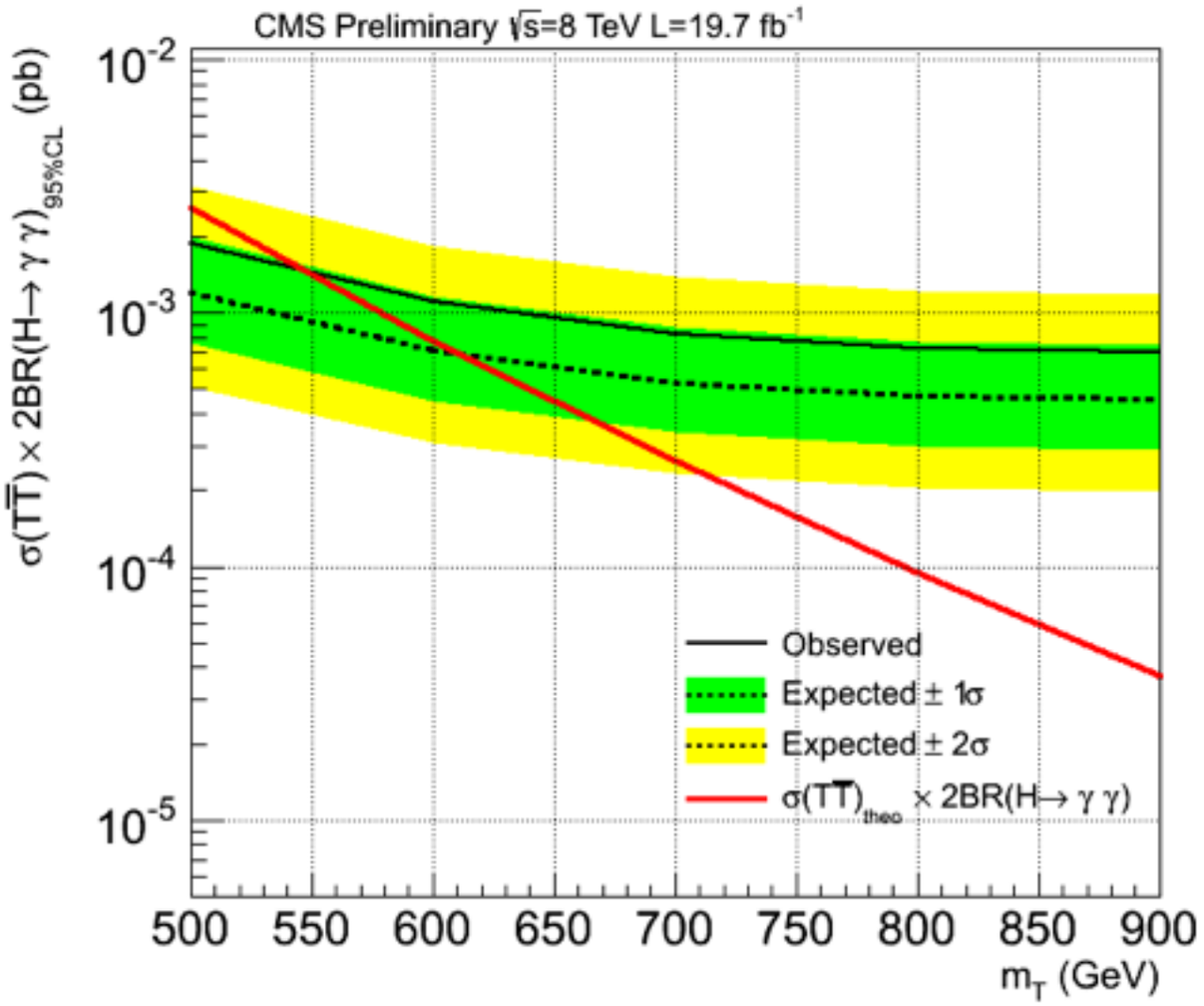








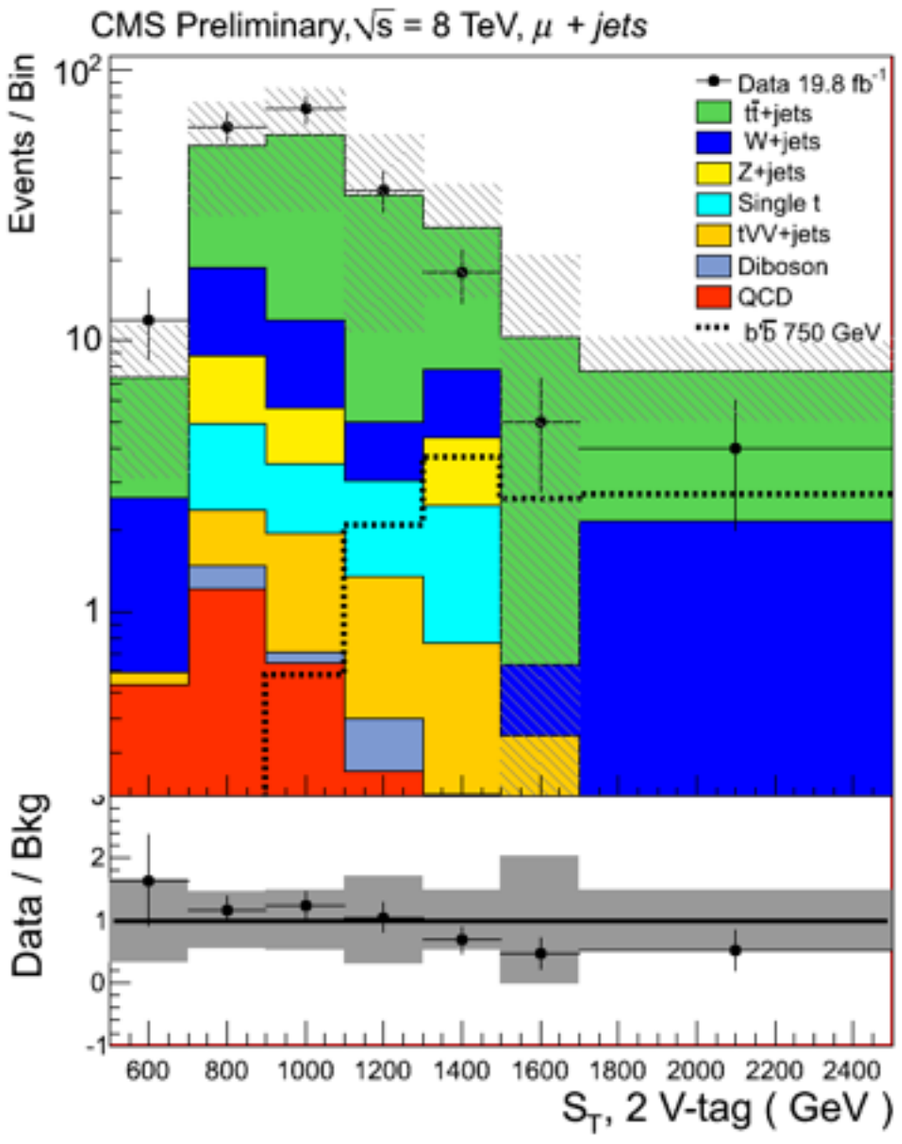
Vector-like Quarks : T2/3

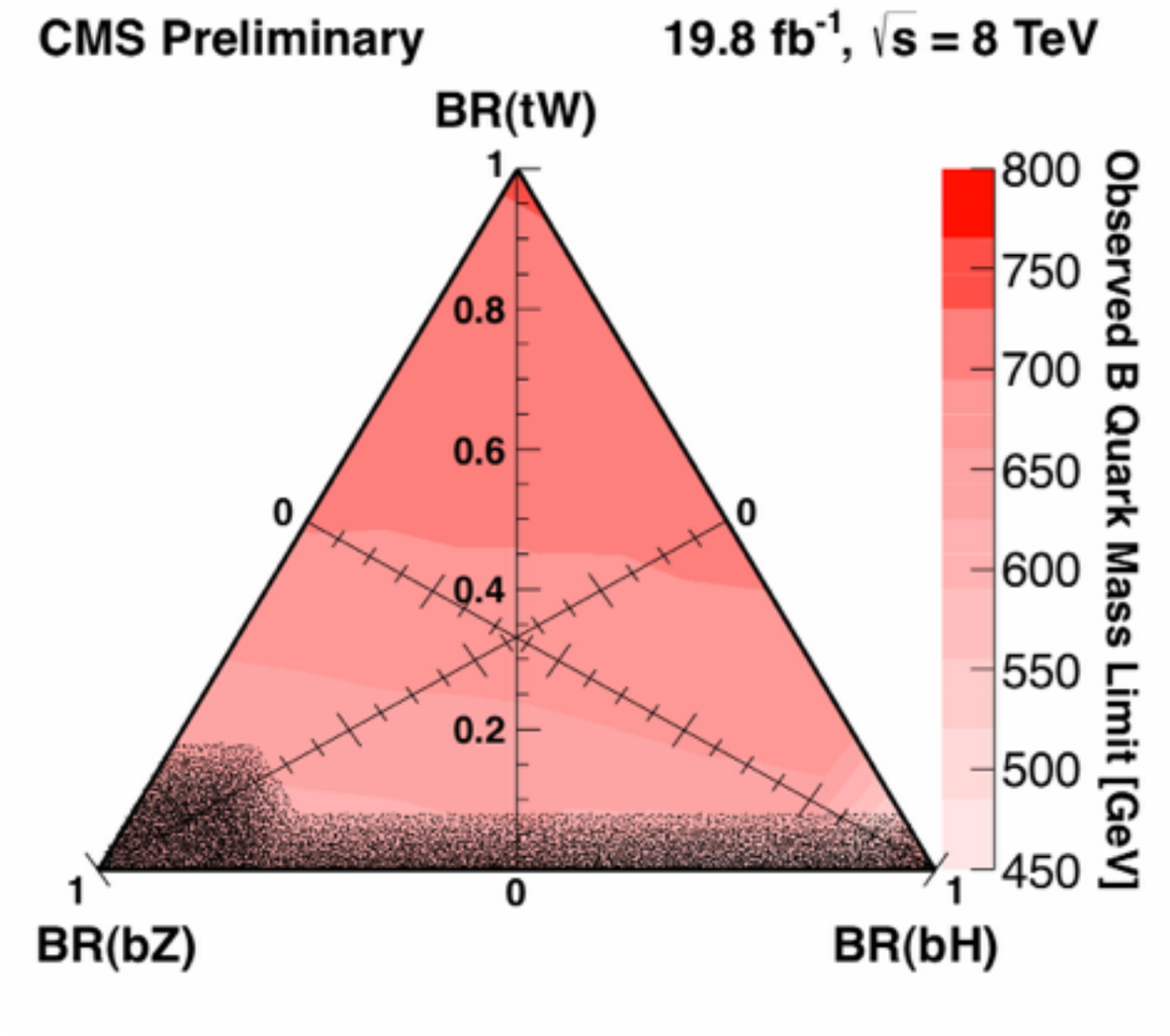


- Orthogonal sample, can be used for combination
- Coming soon :
  - T2/3 -> bW with kinematic reconstruction
  - T2/3 grand combination

Vector-like Quarks : B1/3

- B2G-12-019
  - B1/3 -> tW, bH, bZ
  - New!! (Well… since Freya's W+C talk anyway!)
  - Uses W/Z tags in the semileptonic channel

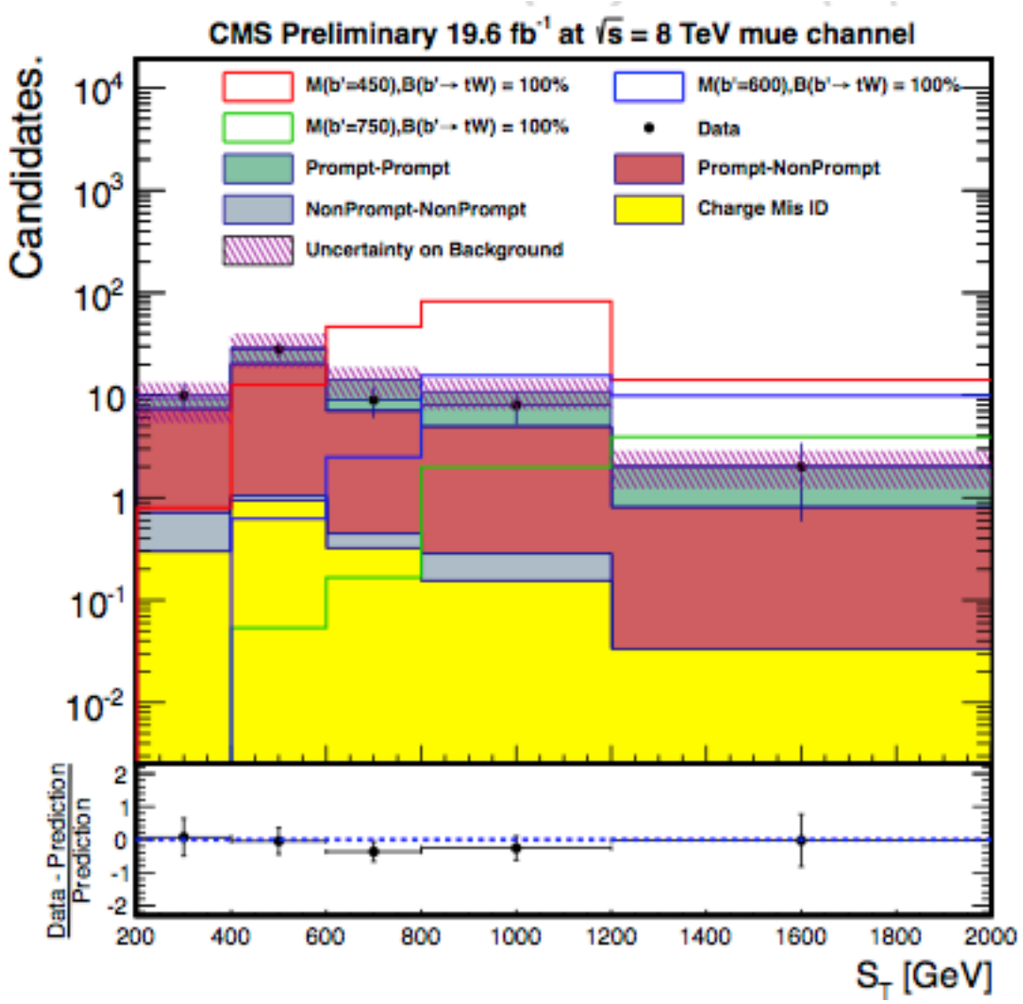


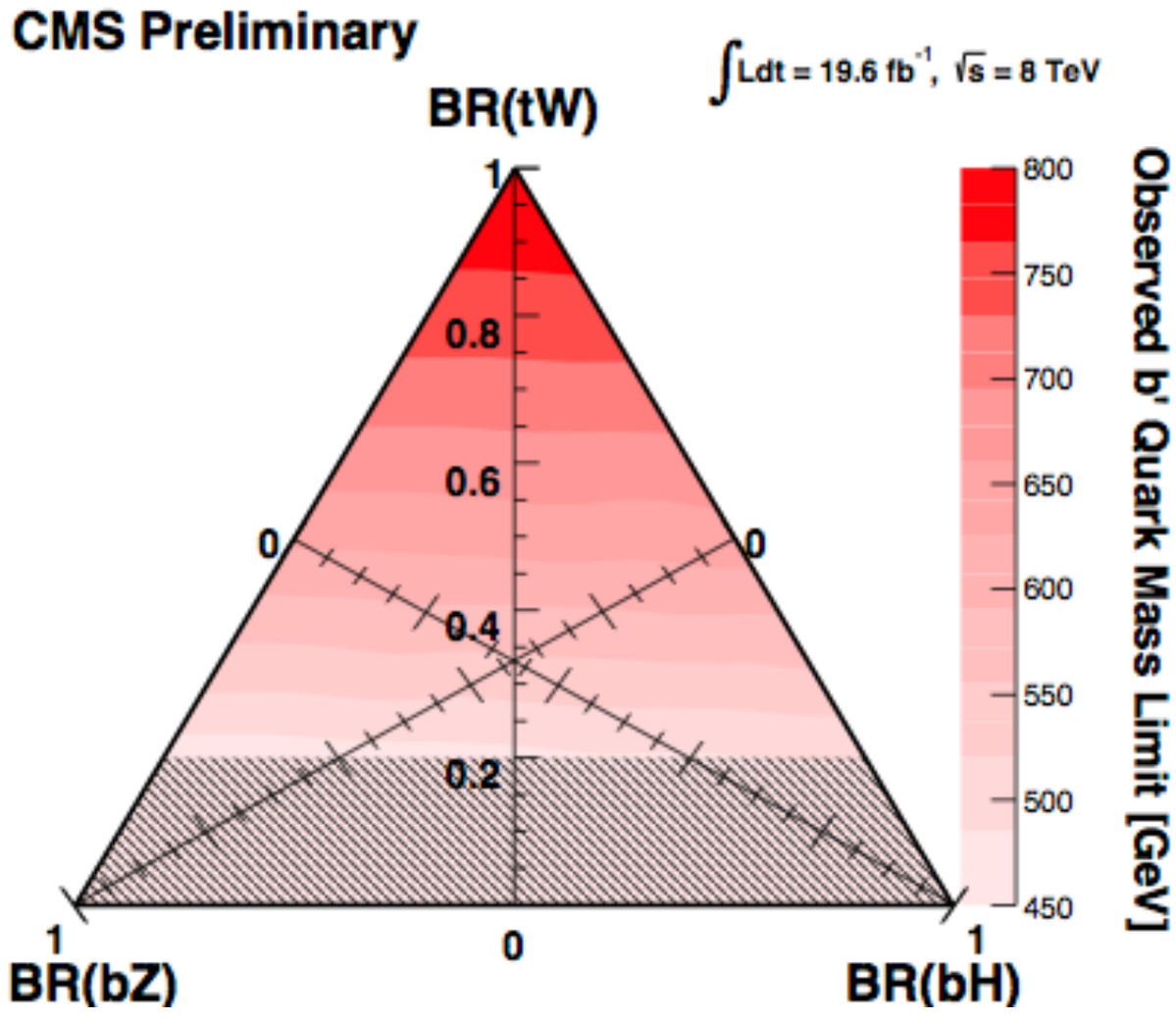


Vector-like Quarks : B1/3

- B2G-12-020
  - New!! B1/3 -> tW
  - Same-sign dileptons plus categories in ST

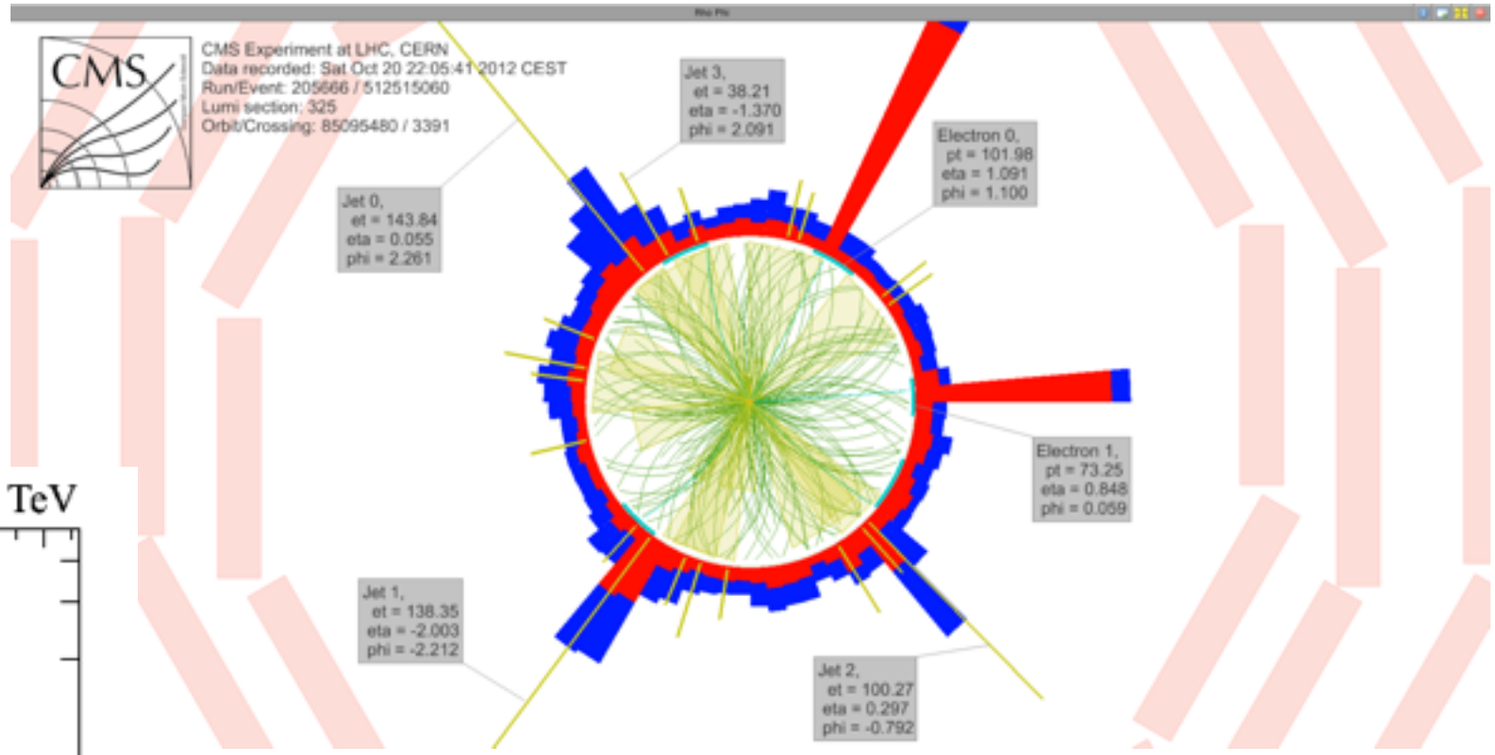
$$S_T = \sum p_T(\text{jets}) + \sum p_T(\text{leptons}) + \text{MET}$$

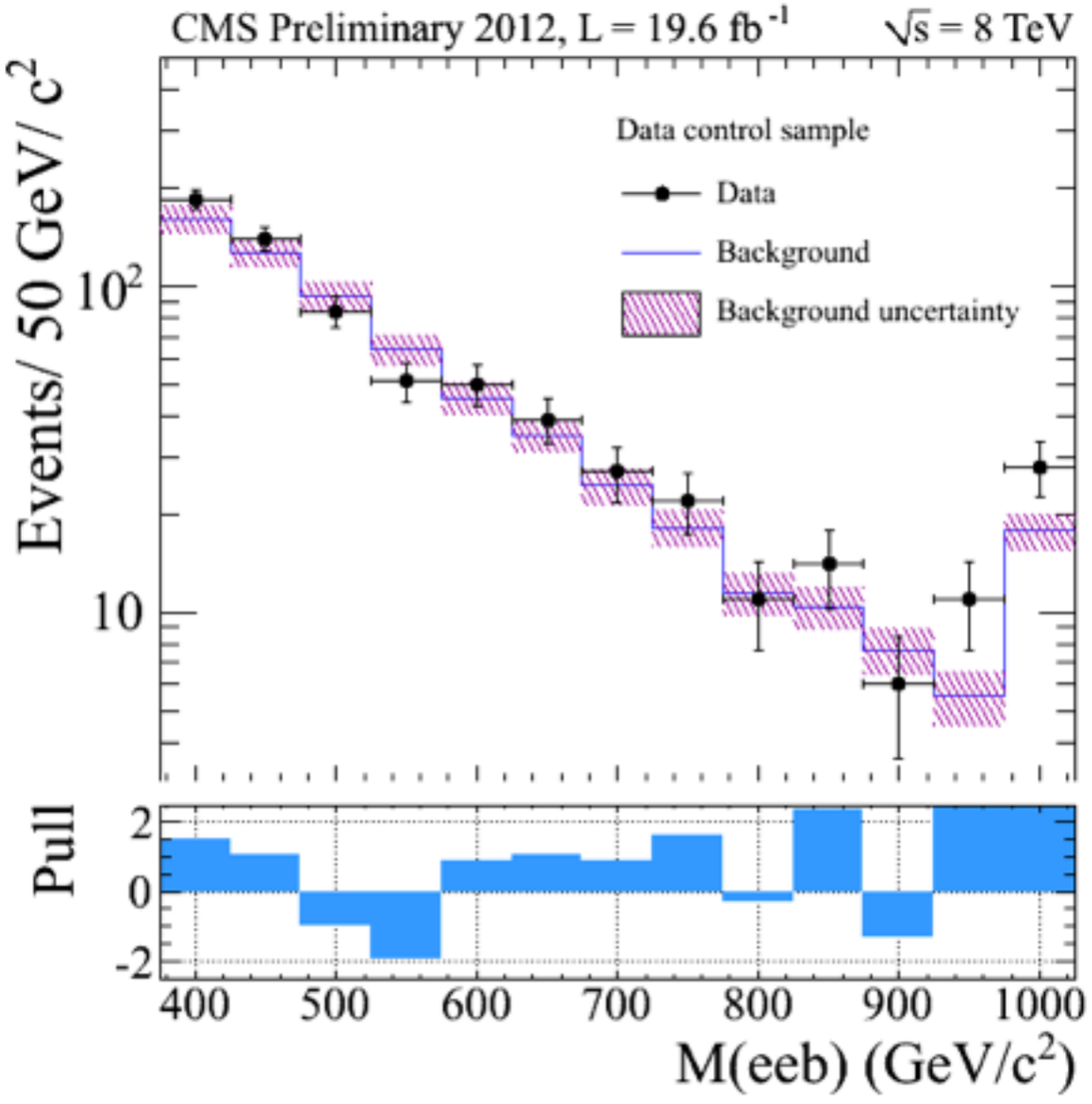


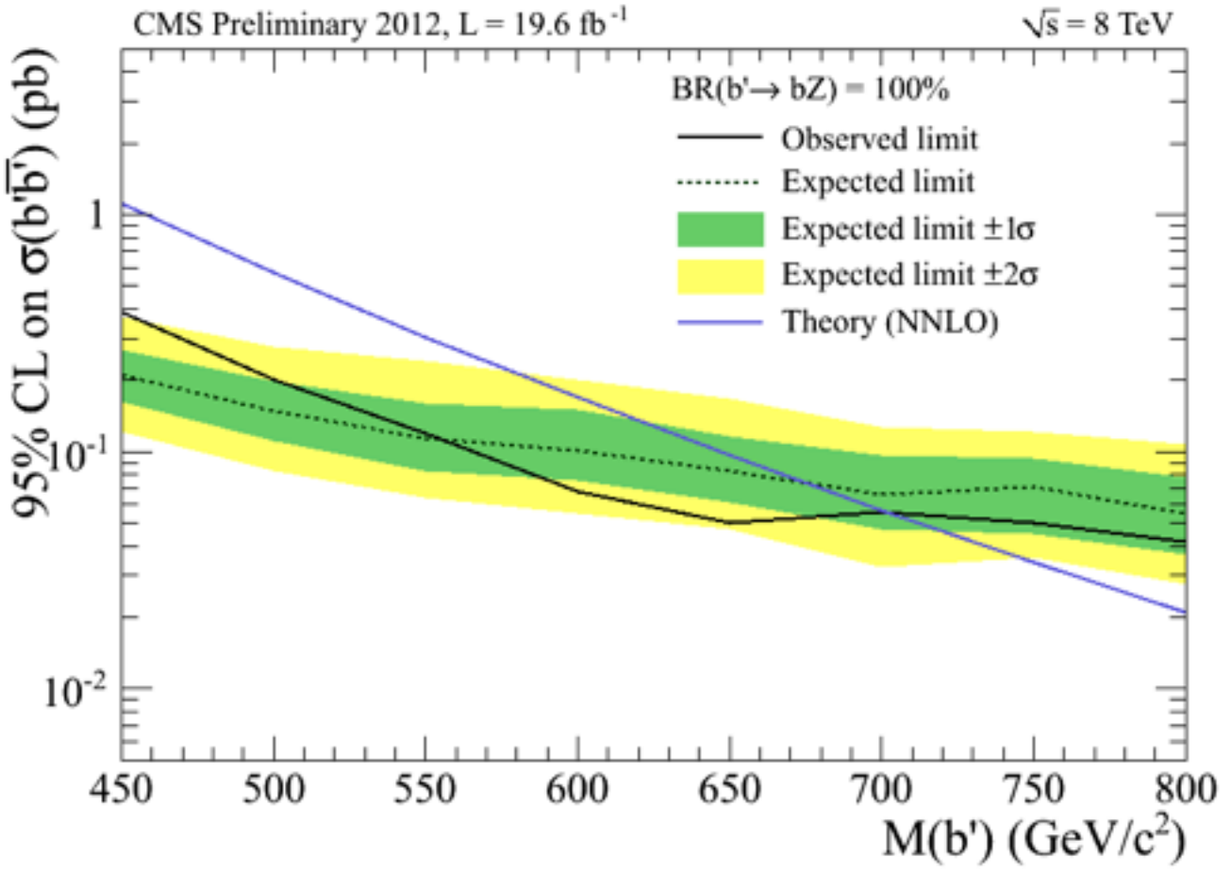


Vector-like Quarks : B1/3

- B2G-12-021
  - New since Freya's talk
  - B1/3 -> bZ exclusive reconstruction



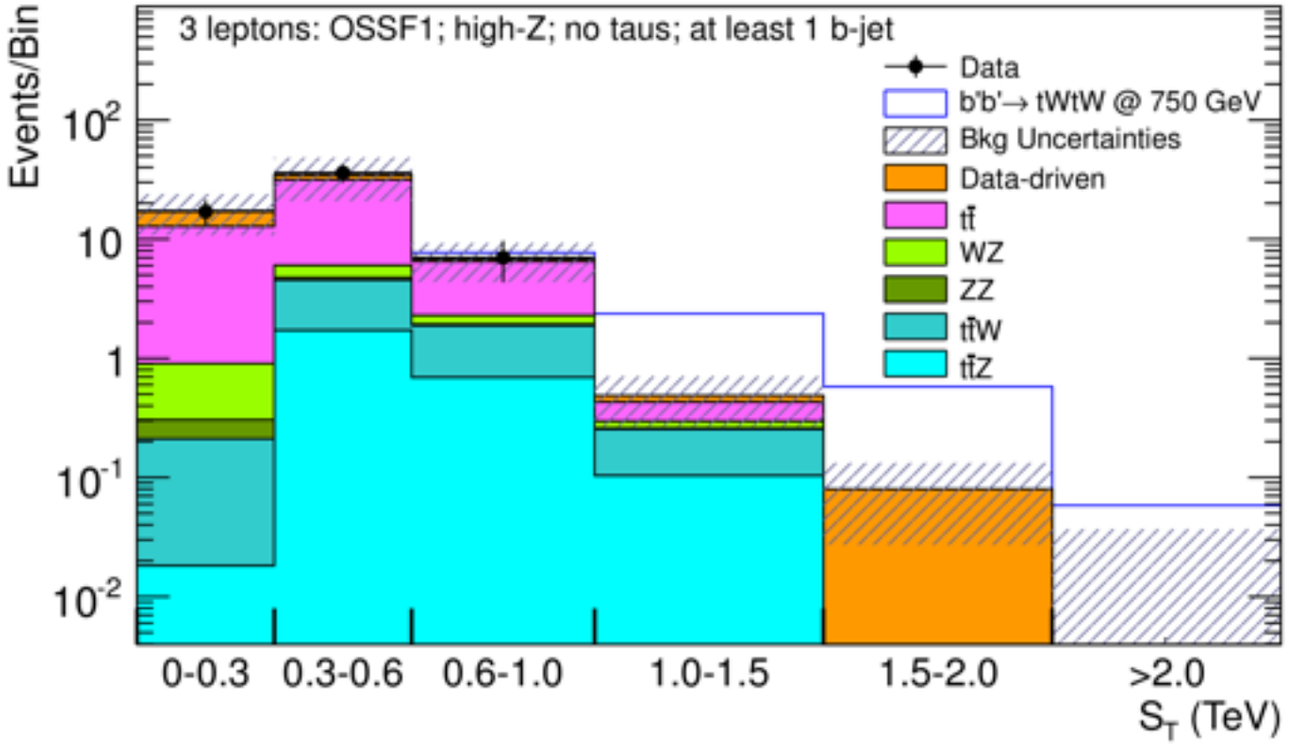


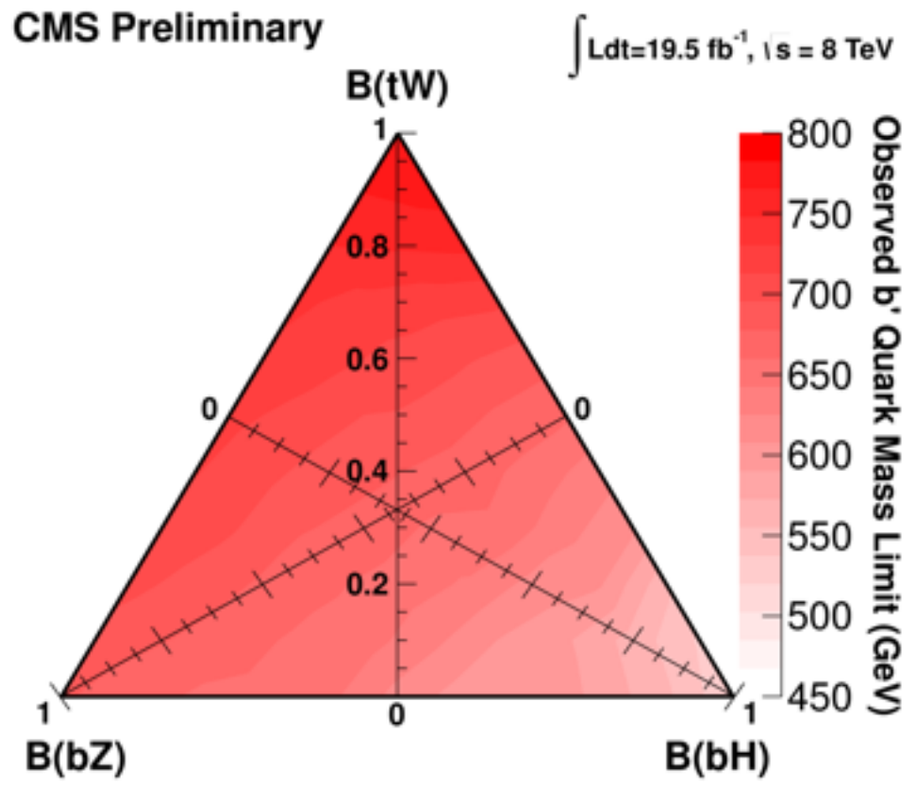


Vector-like Quarks : B1/3

- B2G-13-003
  - New since Freya's talk
  - B1/3 -> bH, bZ, tW
  - >=3 leptons combined, many categories!
  - Consider also tau categories

N_{OSSF}	on- or off-Z	S_T (TeV)	$N_{\tau_h}=0, N_{b\text{-jets}}=0$ obs	exp	$N_{\tau_h}\geq 1, N_{b\text{-jets}}=0$ obs	exp	$N_{\tau_h}=0, N_{b\text{-jets}}\geq 1$ obs	exp	$N_{\tau_h}\geq 1, N_{b\text{-jets}}\geq 1$ obs	exp
0	-	> 2.0	0	< 0.02	0	0 ± 0.02	0	0 ± 0.02	0	0 ± 0.02
0	-	1.5 – 2.0	0	< 0.02	0	0 ± 0.02	0	0 ± 0.02	0	0 ± 0.02
0	-	1.0 – 1.5	0	< 0.02	0	0 ± 0.02	0	0 ± 0.02	0	0.007 ± 0.02
0	-	0.6 – 1.0	0	< 0.02	0	0.12 ± 0.11	0	0.05 ± 0.05	†0	0.12 ± 0.1
0	-	0.3 – 0.6	0	0.09 ± 0.06	1	0.5 ± 0.19	0	0.001 ± 0.02	0	0.28 ± 0.12
0	-	0 – 0.3	0	0.05 ± 0.05	2	1.1 ± 0.45	0	0.0003 ± 0.02	0	0.25 ± 0.16
1	offZ	> 2.0	0	< 0.02	0	0 ± 0.02	0	0 ± 0.02	0	0 ± 0.02
1	onZ	> 2.0	0	< 0.02	0	0 ± 0.02	0	0 ± 0.02	0	0 ± 0.02
1	offZ	1.5 – 2.0	0	< 0.02	0	0.007 ± 0.02	0	0 ± 0.02	0	0 ± 0.02
1	onZ	1.5 – 2.0	0	< 0.02	0	0.02 ± 0.03	0	0.01 ± 0.03	0	0.007 ± 0.02
1	offZ	1.0 – 1.5	0	0.002 ± 0.02	0	0.12 ± 0.07	†0	0.03 ± 0.04	0	0.02 ± 0.02
1	onZ	1.0 – 1.5	1	0.06 ± 0.06	0	0.1 ± 0.07	0	0.11 ± 0.08	0	0.04 ± 0.04
1	offZ	0.6 – 1.0	0	0.06 ± 0.04	2	0.48 ± 0.17	0	0.06 ± 0.07	†0	0.3 ± 0.13
1	onZ	0.6 – 1.0	0	0.43 ± 0.15	0	1.7 ± 0.6	0	0.5 ± 0.29	†0	0.7 ± 0.33
1	offZ	0.3 – 0.6	0	0.27 ± 0.11	4	2.1 ± 0.5	0	0.33 ± 0.17	0	1.2 ± 0.43
1	onZ	0.3 – 0.6	5	1.8 ± 0.47	10	12 ± 3	2	1 ± 0.5	2	1.6 ± 0.5
1	offZ	0 – 0.3	2	0.48 ± 0.18	18	8.3 ± 2.1	0	0.04 ± 0.04	1	0.6 ± 0.3
1	onZ	0 – 0.3	2	3 ± 0.9	43	41 ± 10	2	0.07 ± 0.04	2	1 ± 0.4
2	offZ	> 2.0	0	$1e\text{-}05 \pm 0.02$	-	-	0	0 ± 0.02	-	-
2	onZ	> 2.0	0	0.002 ± 0.02	-	-	0	0.02 ± 0.03	-	-
2	offZ	1.5 – 2.0	0	0.0002 ± 0.02	-	-	0	0 ± 0.02	-	-
2	onZ	1.5 – 2.0	0	0.05 ± 0.03	-	-	0	0.01 ± 0.02	-	-
2	offZ	1.0 – 1.5	0	0.01 ± 0.02	-	-	0	0 ± 0.02	-	-
2	onZ	1.0 – 1.5	1	0.6 ± 0.26	-	-	†0	0.1 ± 0.05	-	-
2	offZ	0.6 – 1.0	0	0.11 ± 0.04	-	-	0	0.14 ± 0.08	-	-
2	onZ	0.6 – 1.0	4	5.9 ± 2.0	-	-	1	1 ± 0.39	-	-
2	offZ	0.3 – 0.6	3	1 ± 0.3	-	-	1	0.22 ± 0.1	-	-
2	onZ	0.3 – 0.6	26	42 ± 10	-	-	4	3.2 ± 1	-	-
2	offZ	0 – 0.3	7	8.2 ± 2.3	-	-	0	0.18 ± 0.07	-	-
2	onZ	0 – 0.3	*135	122 ± 29	-	-	1	1 ± 0.26	-	-
Total4	All	All	186	187 ± 39	80	68 ± 15	11	8.3 ± 2.7	5	6.3 ± 1.6

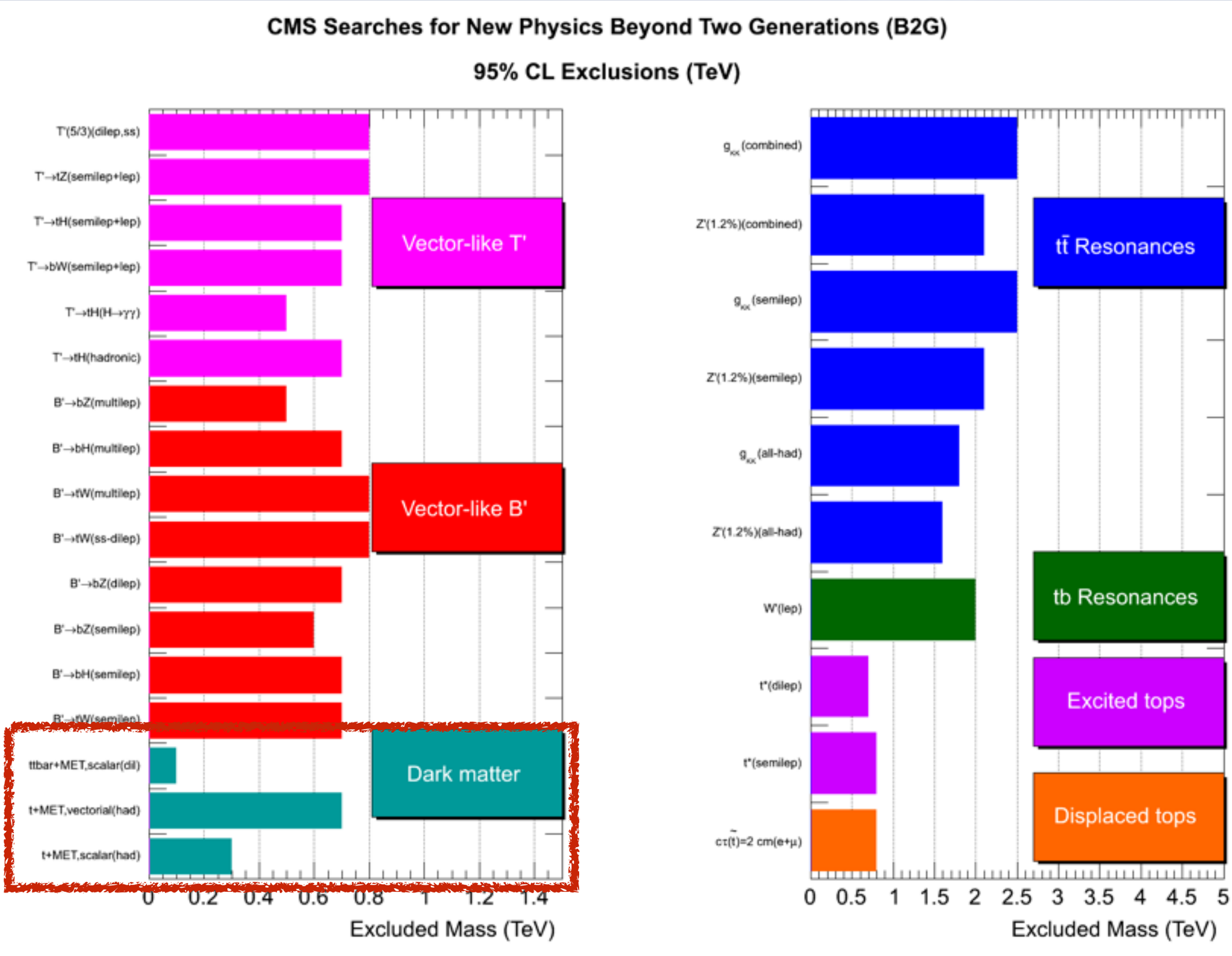




Vector-like Quarks : B1/3

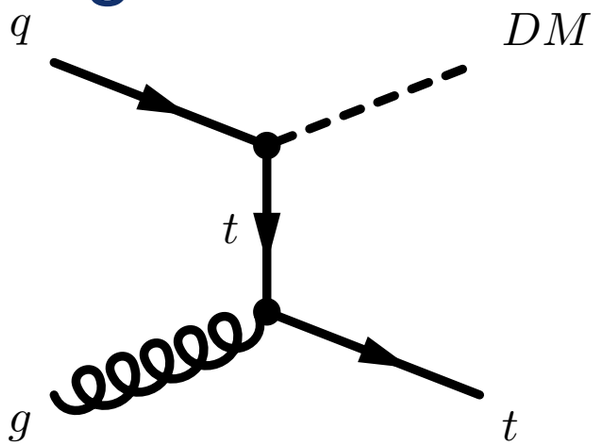
- Coming soon :
  - B1/3 -> bH with Higgs tagging
  - Legacy combination of all B1/3 analyses

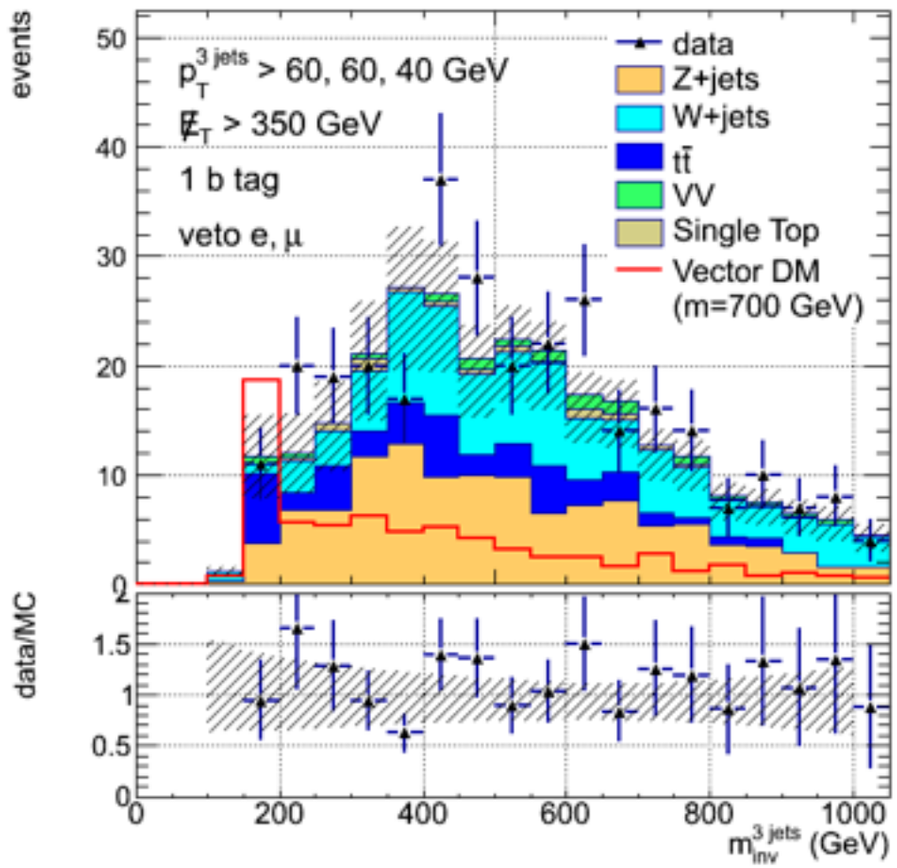
Top(s) and Dark Matter

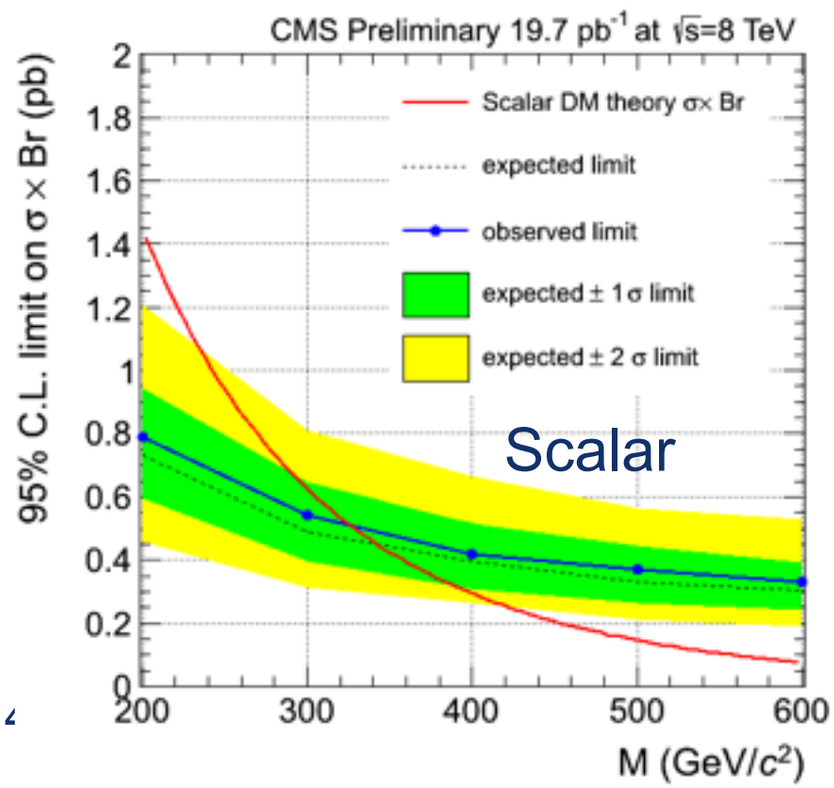


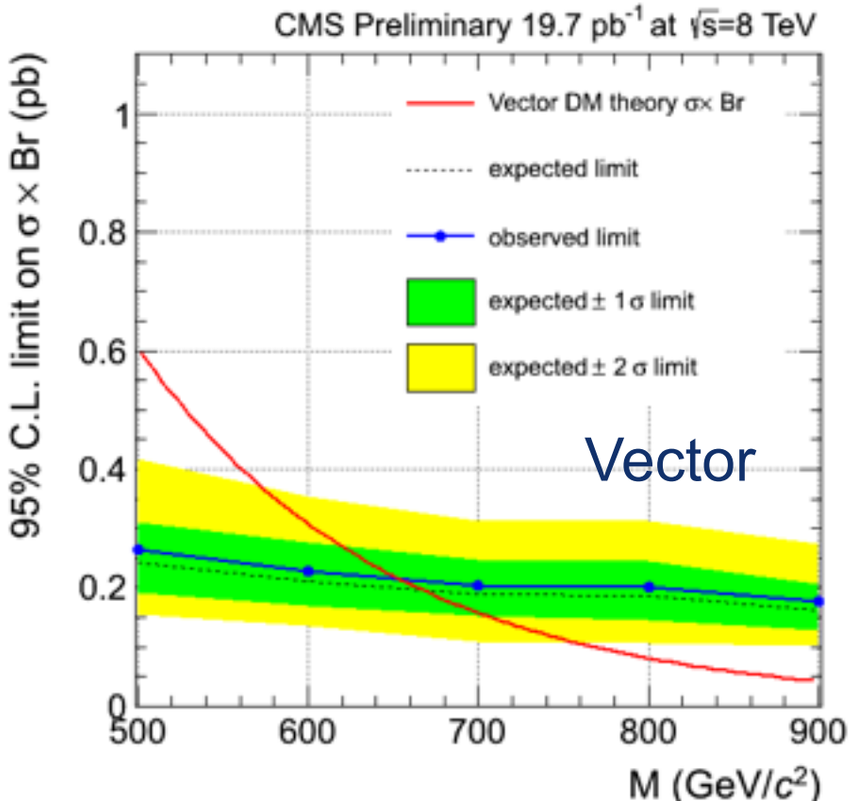
Top(s) and Dark Matter

- B2G-12-022
  - NEW!!!
- Looking for mono-top signature with FCNC



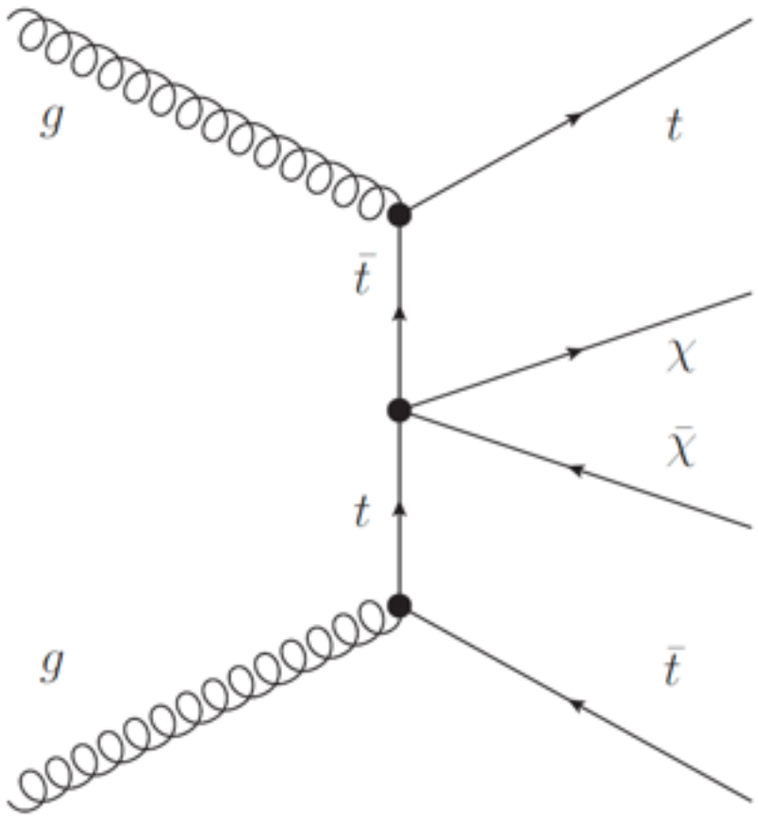


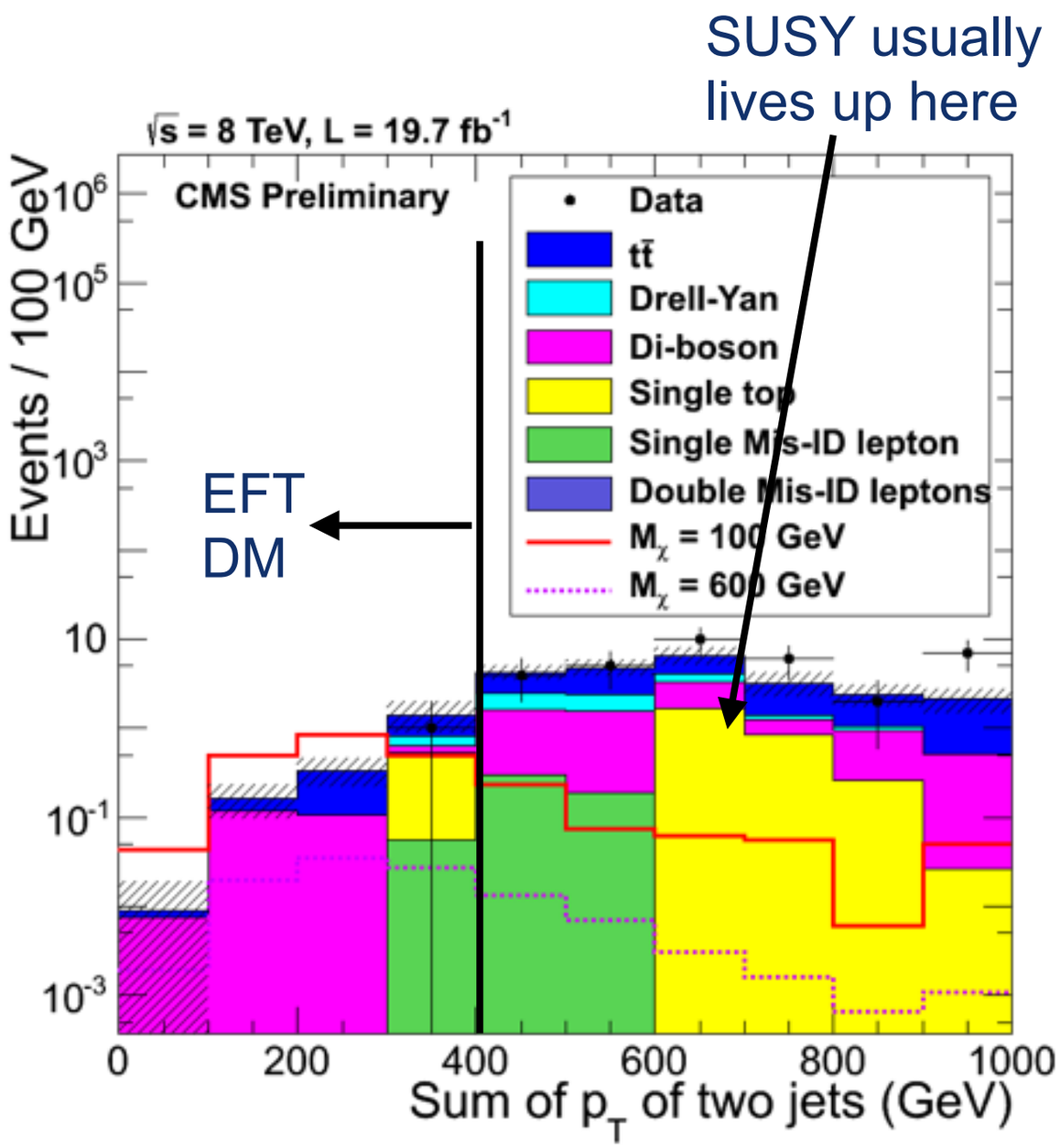




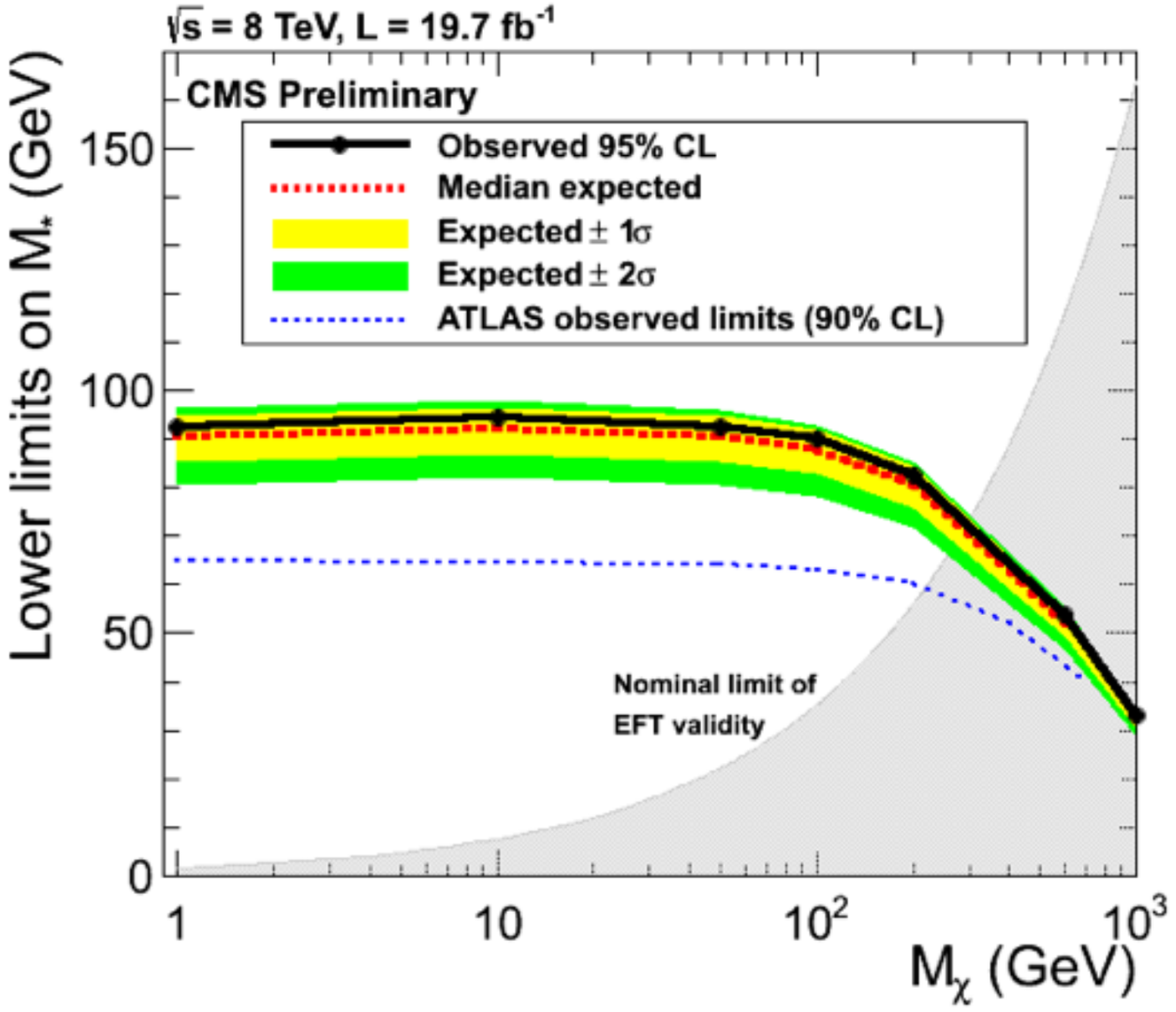
Top(s) and Dark Matter

- B2G-13-004
  – NEW!
- EFT approach
- ttbar (dilepton) + MET search
- Sounds like SUSY, but has low HT of the jets



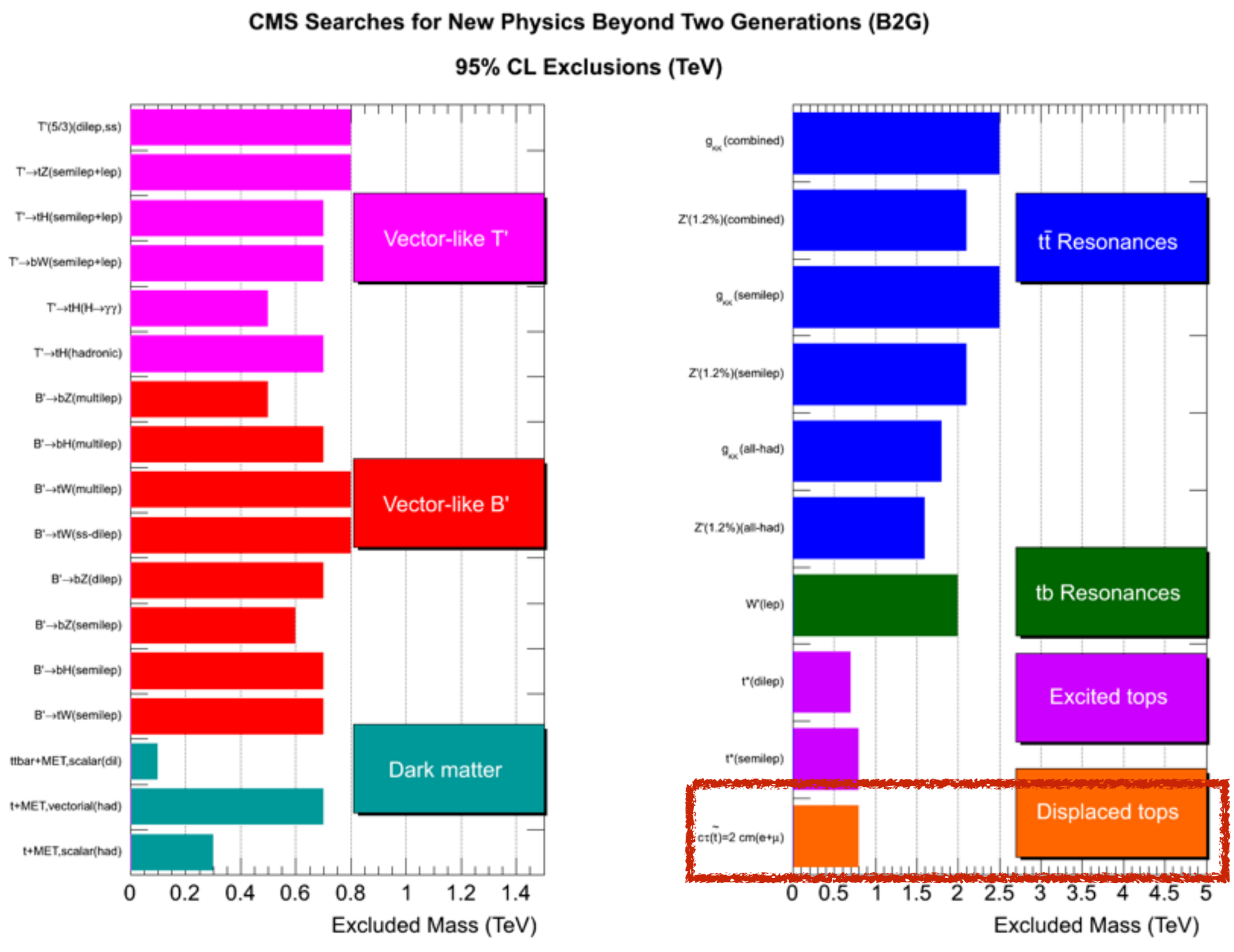


Top(s) and Dark Matter



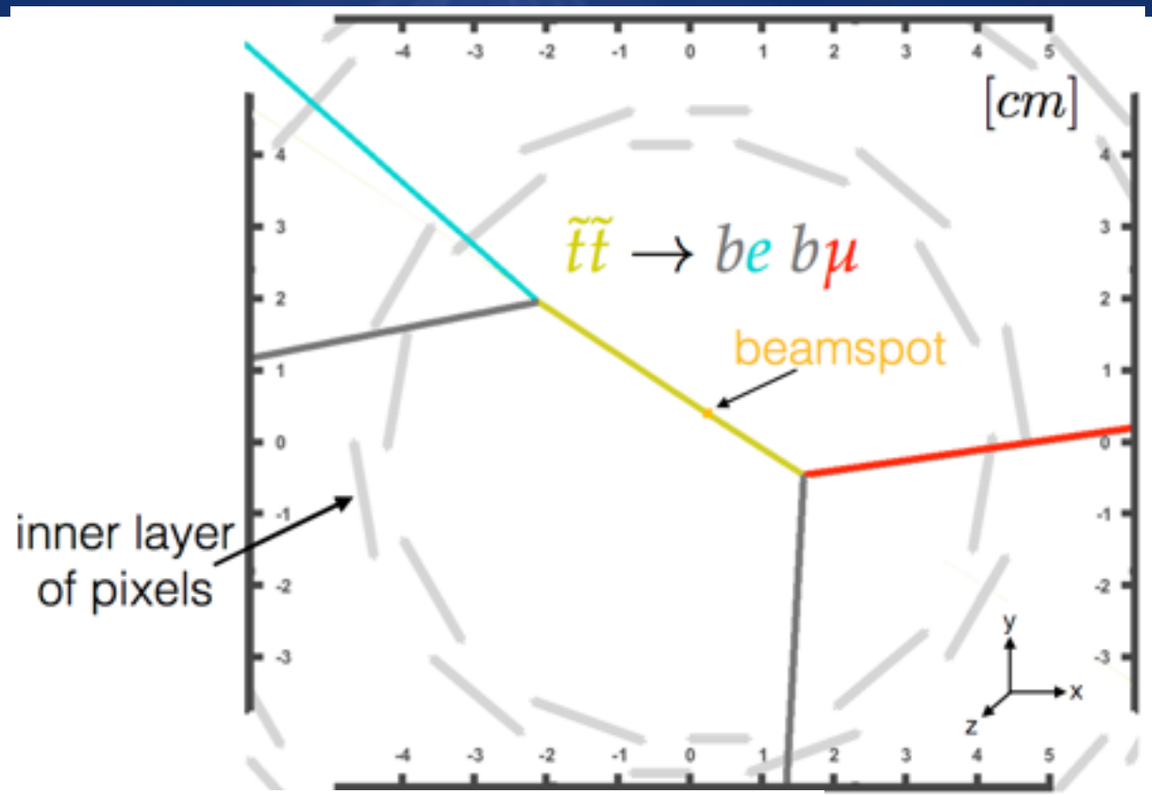
- Coming soon : semileptonic channel and combination!

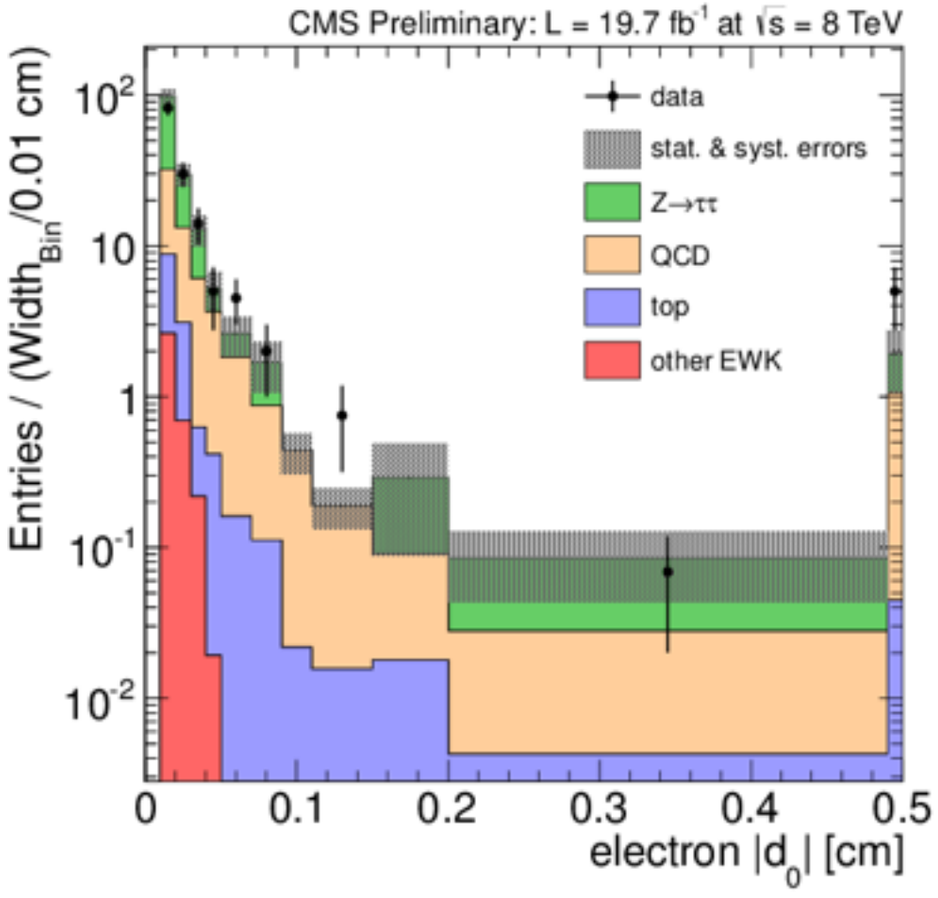
Displaced Tops

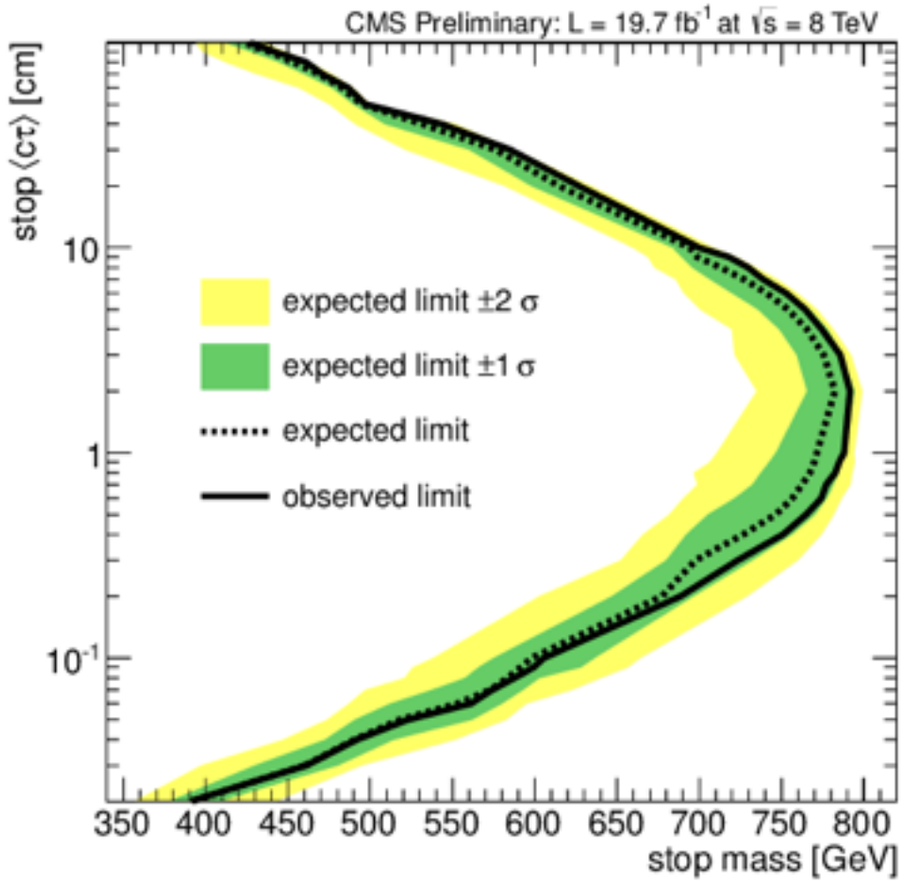


Displaced Tops

- B2G-12-024
  - NEW!!
- Signature-driven search
- Look for moderately-displaced tracks
- e-mu channel

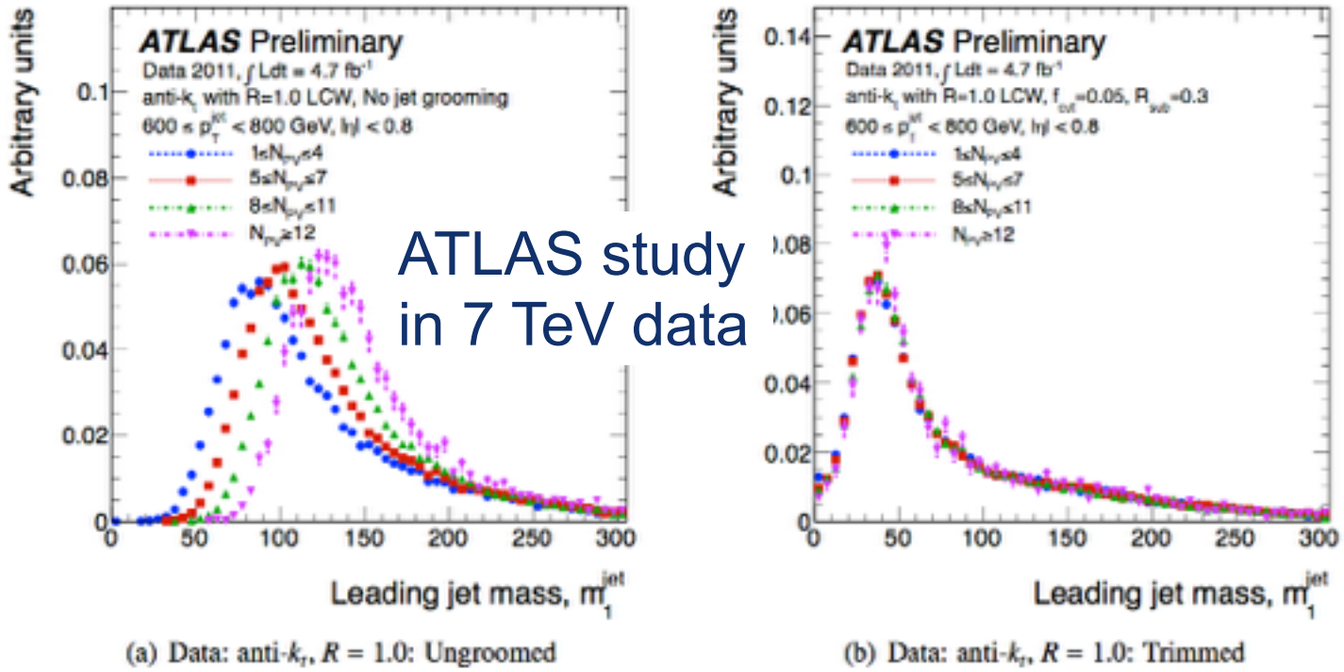






The Future?

- For high-lumi jet grooming becomes absolutely critical!

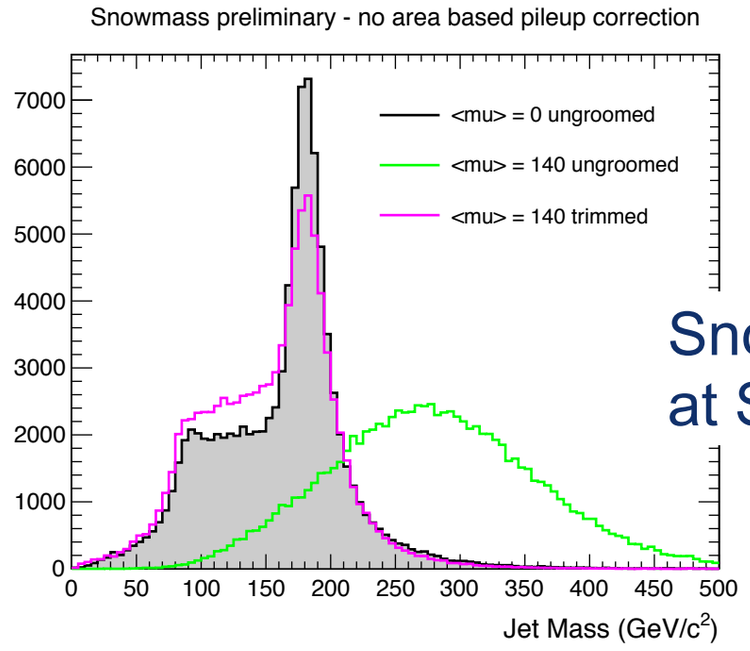


ATLAS study in 7 TeV data

(a) Data: anti-k_t, $R = 1.0$: Ungroomed

(b) Data: anti-k_t, $R = 1.0$: Trimmed

- In fact, may be the ONLY way to do jet physics at all

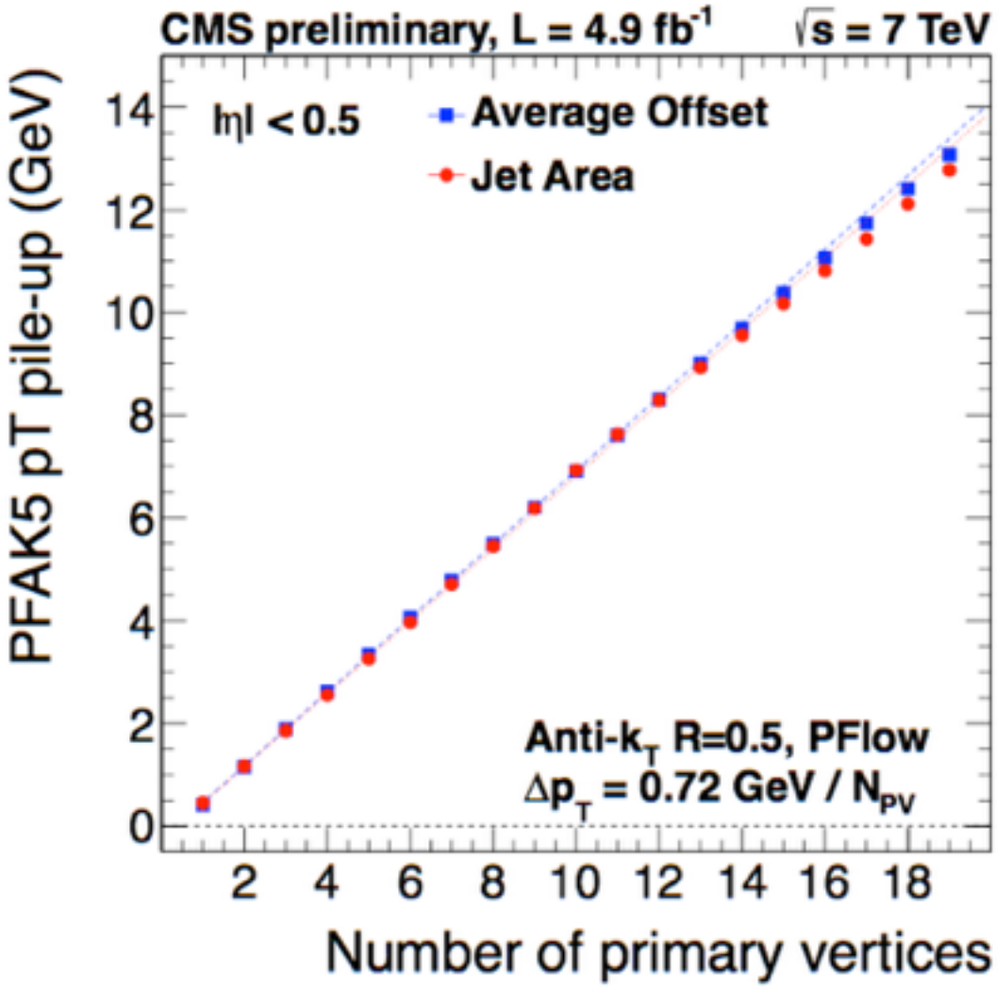


SnowMass study at SLHC lumi's

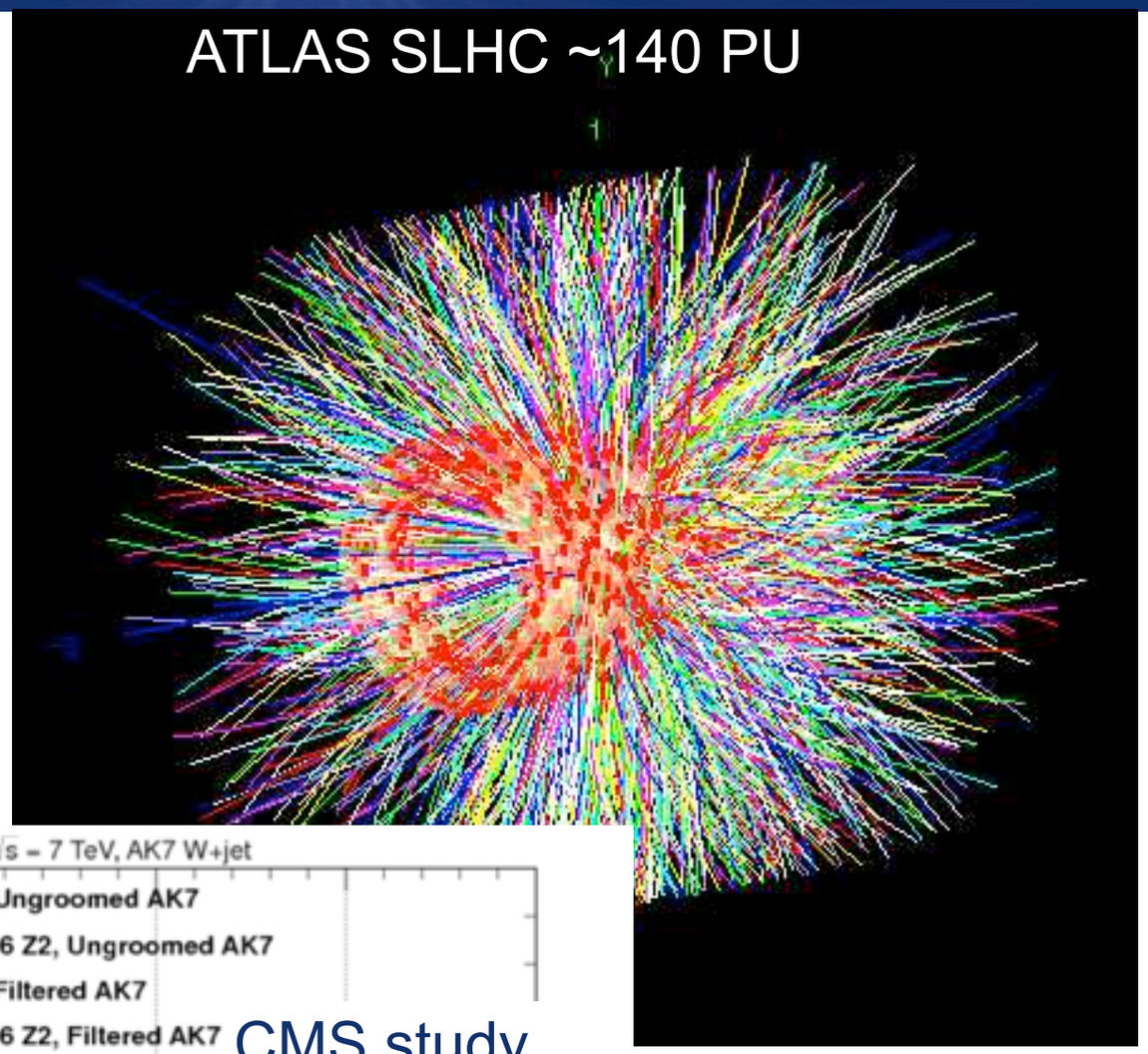
Becomes necessary with 140 pileup

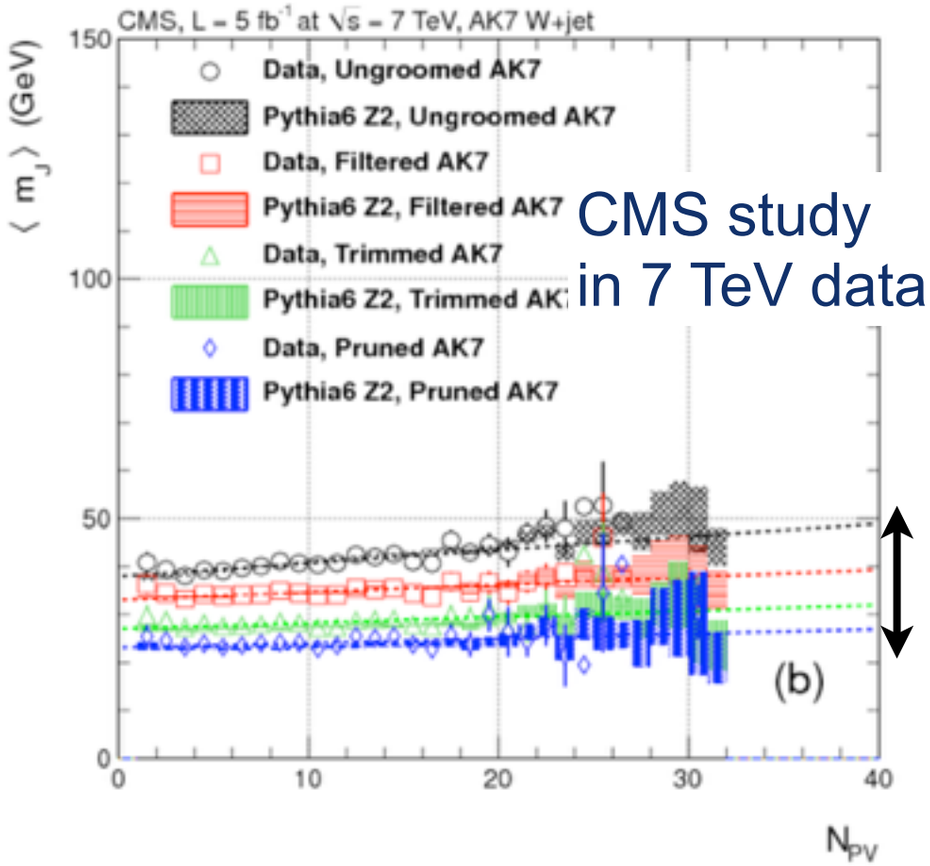
The Future?

- We know that the amount of jet activity scales with pileup (linearly)
- ~1 GeV / PU
- If PU = 140, 100 GeV of each jet is from pileup!



ATLAS SLHC ~140 PU



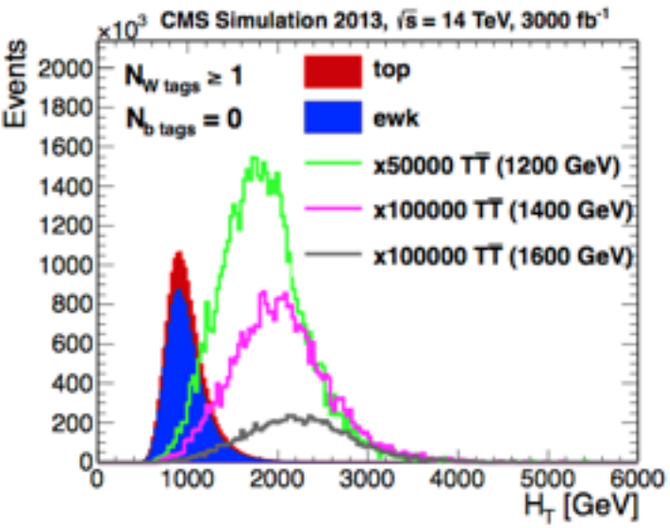


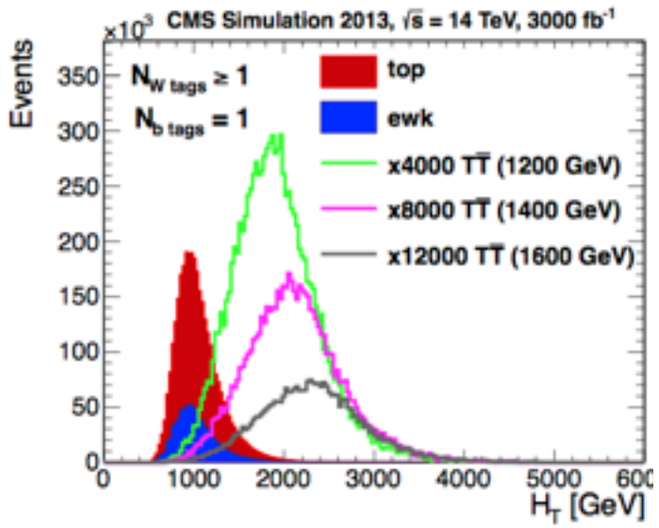
CMS study in 7 TeV data

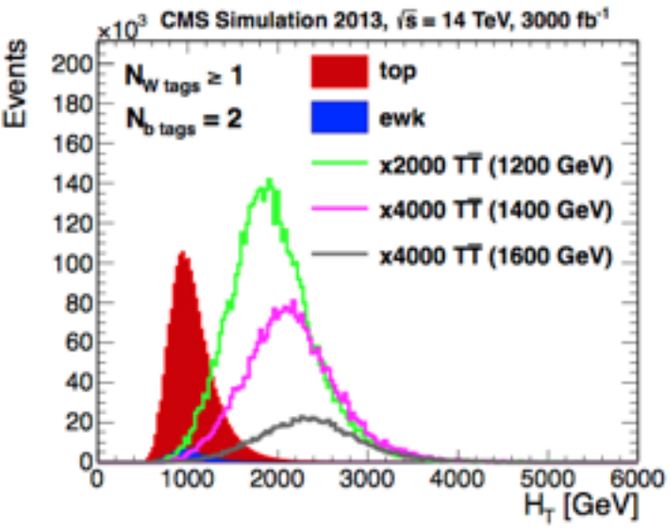
Grooming reduces PU dependence!

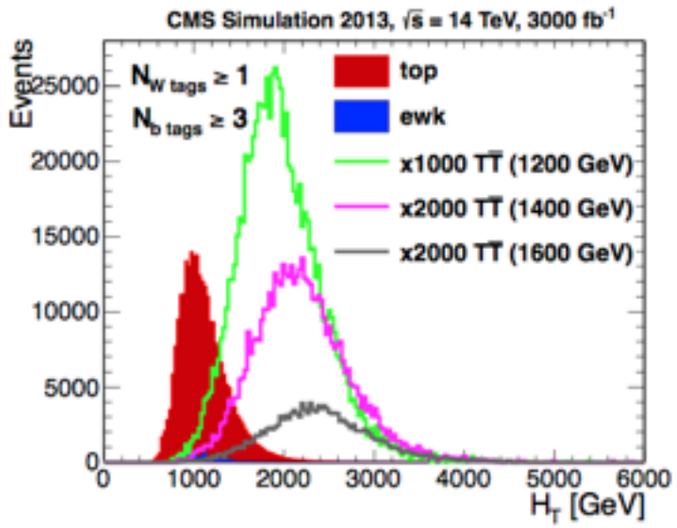
The Future

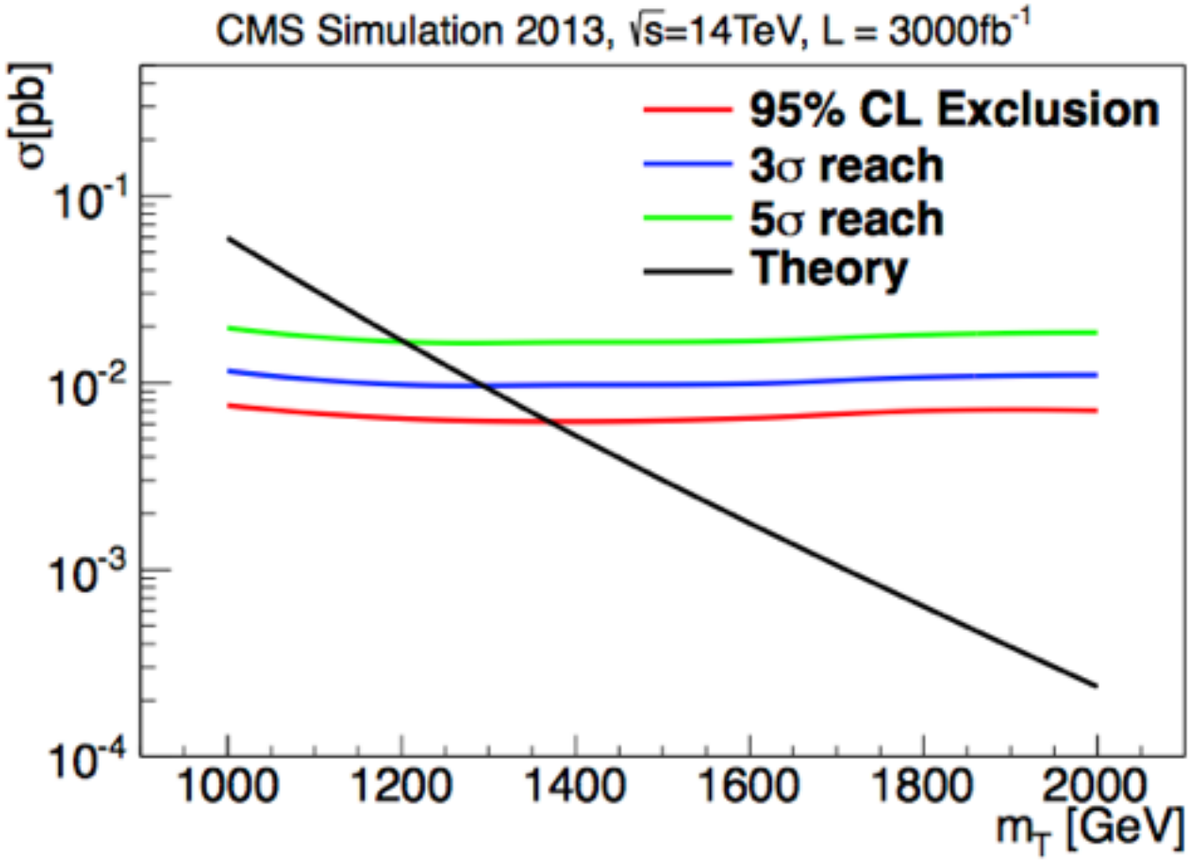
- Vector-like T2/3
  - FTR-13-026
  - Investigate T2/3 semilep selection in SLHC era





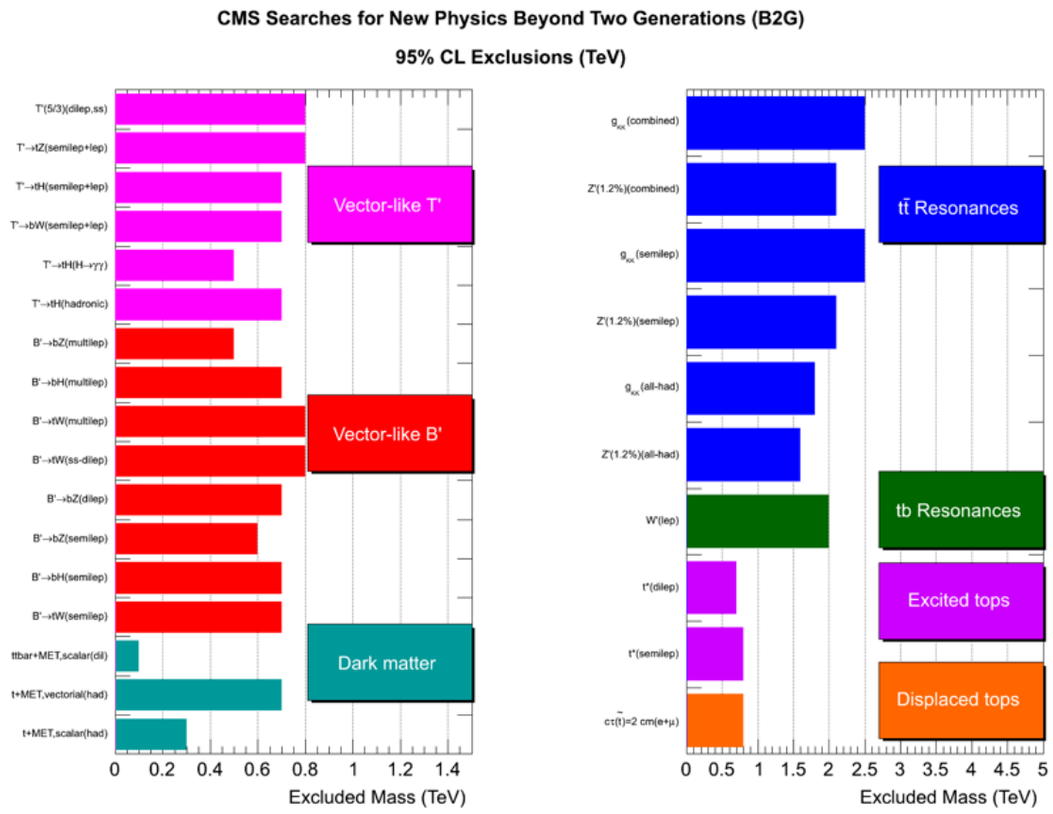






Conclusion

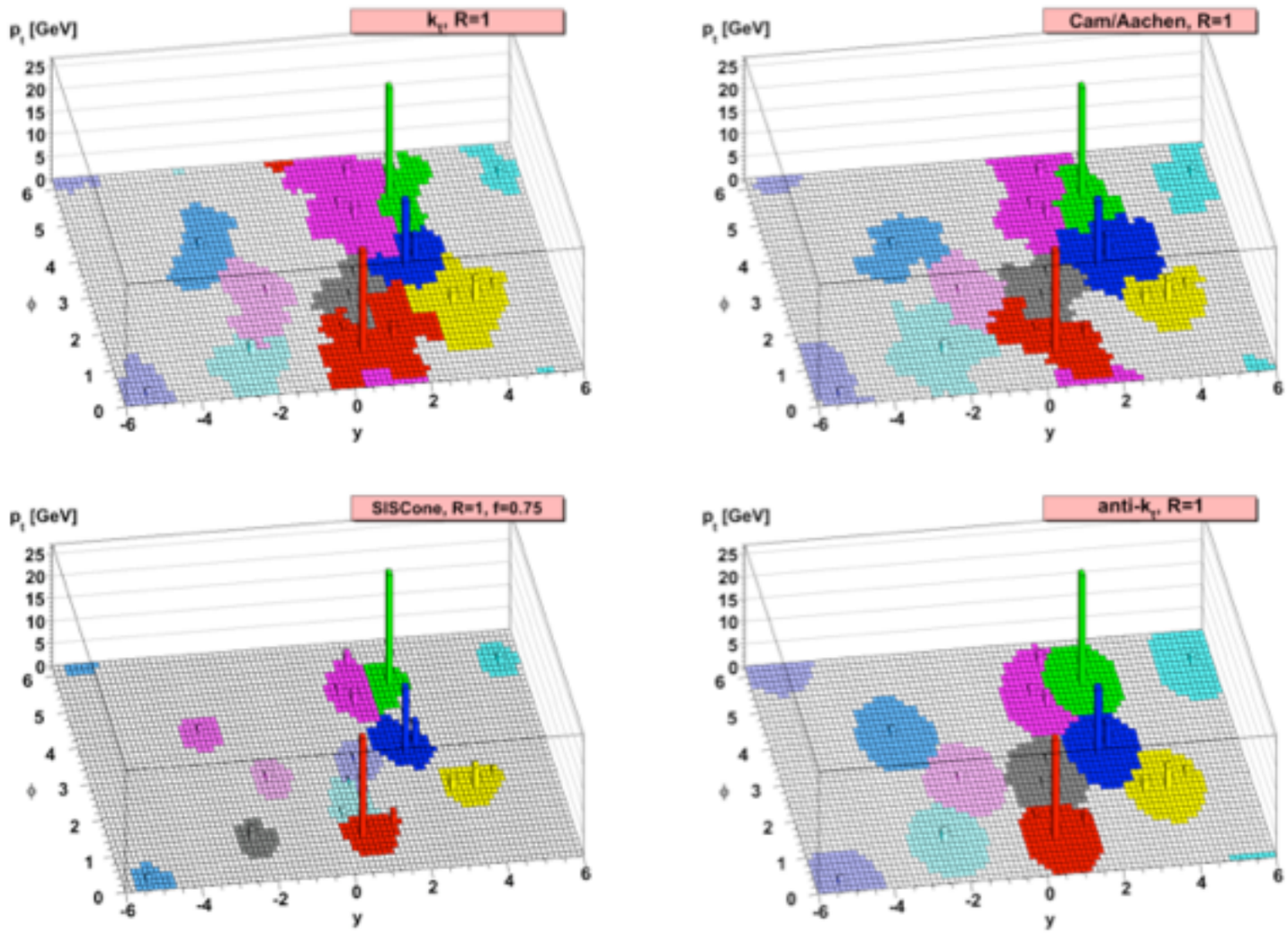
- Lots of exciting Run 1 results from the Beyond Two Generations (B2G) group at CMS!
- We are a major driver for new technology to deal with boosted and merged jets on CMS
- Run 2 is looking very rosy for us, please come join the fun!



Backups

Jets

- Different types
  - N = 2: “kT”
    - QCD in reverse
  - N = 0 : “Cambridge-Aachen” (CA)
    - Angular-only
  - N = -2: “anti-kT”
    - “Idealized” cone algorithm



arXiv:0802.1189v2 [hep-ph]
Cacciari, Salam, Soyez

Boosted Jets

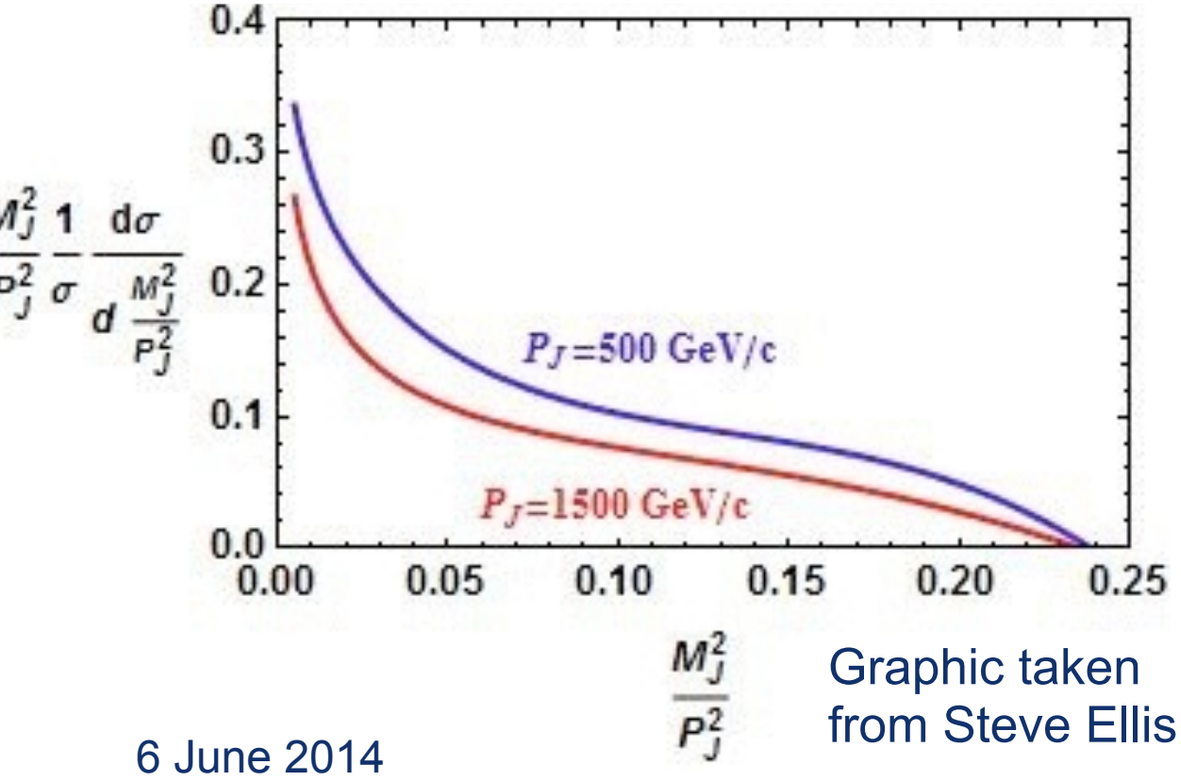
- First look at jet mass
  - See e.g. Ellis et al (arXiv:0712.2447v1)

Finite-size effects from cutoff

Scales ~linearly with momentum

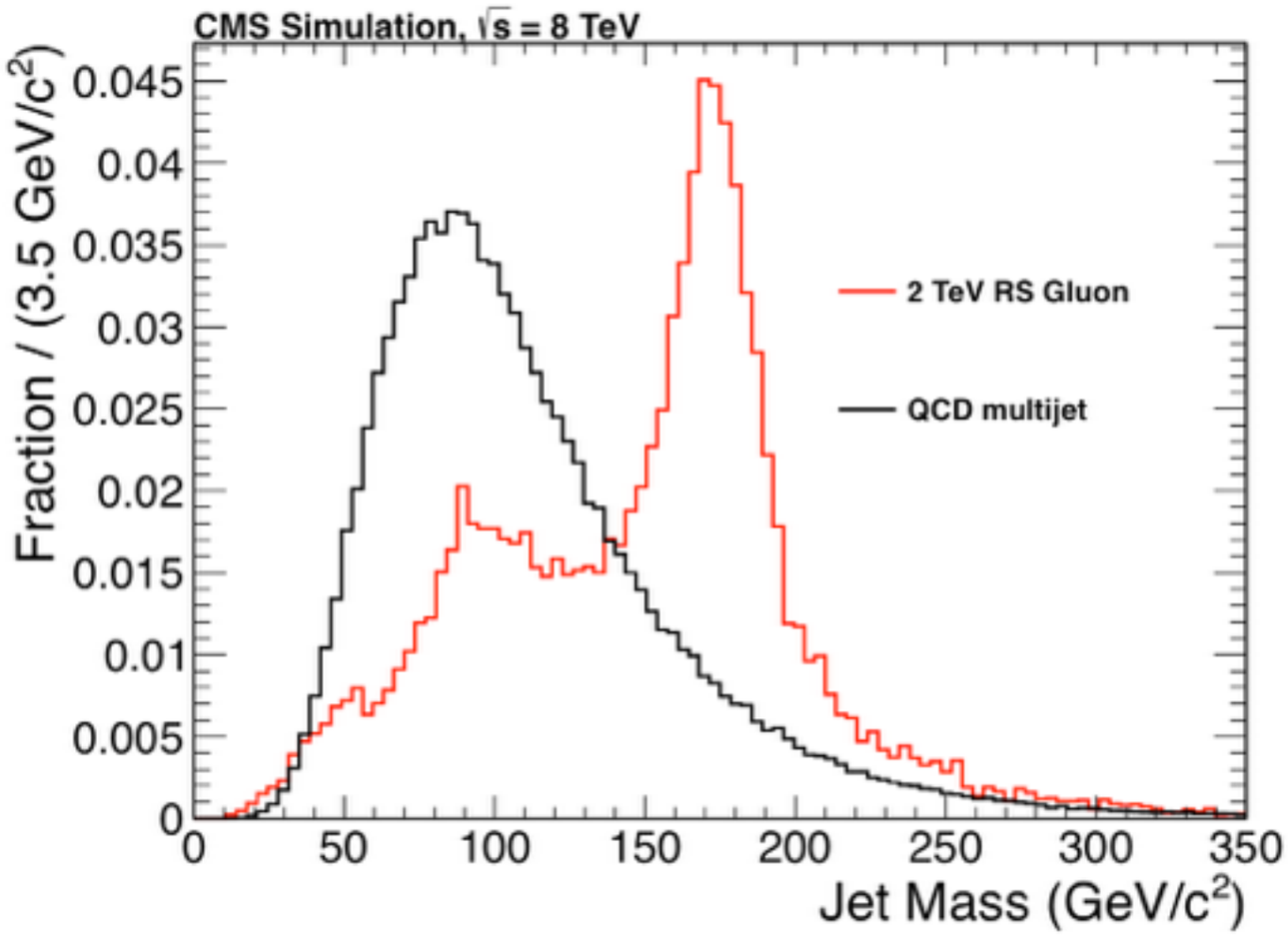
Log. divergence at low mass

$$\langle M_J^2 \rangle_{NLO} \simeq \overline{C} \left(\frac{p_J}{\sqrt{s}} \right) \alpha_s \left(\frac{p_J}{2} \right) p_J^2 R^2,$$



Graphic taken from Steve Ellis

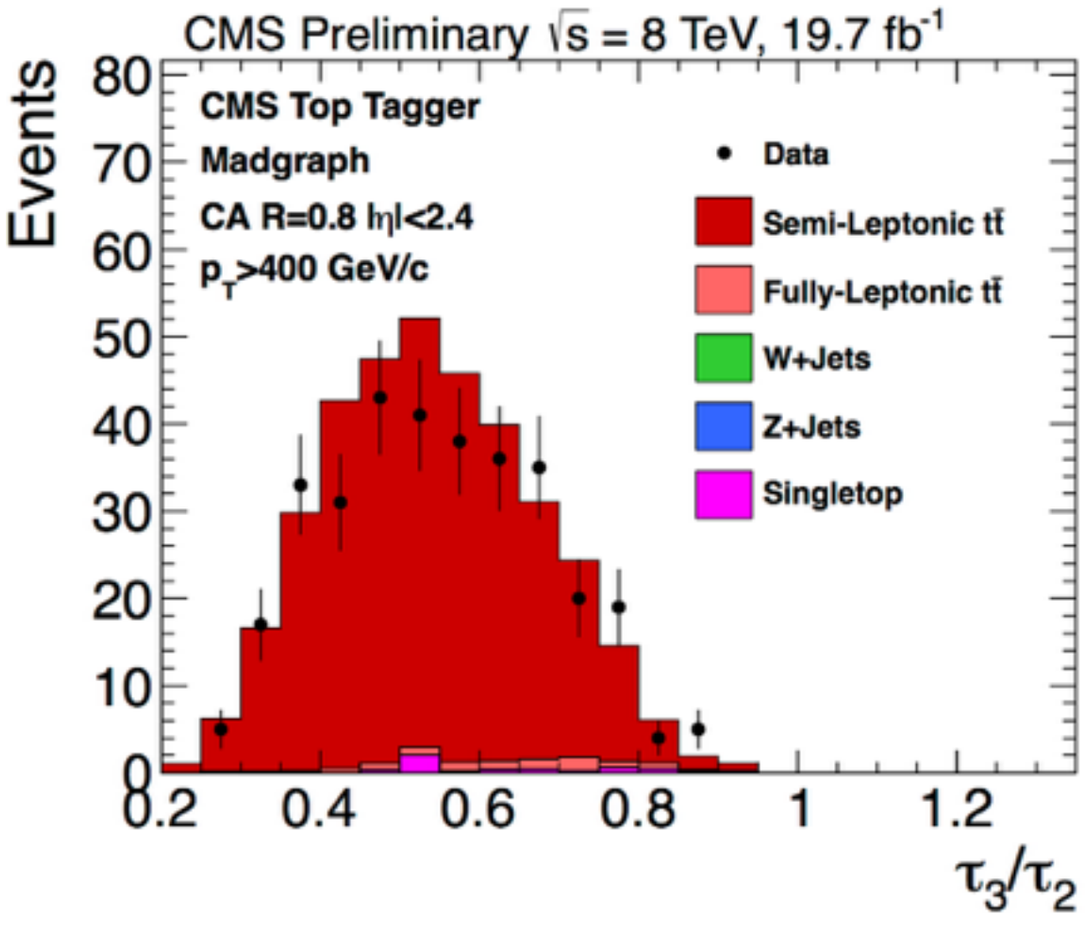
Expect something looking like this :



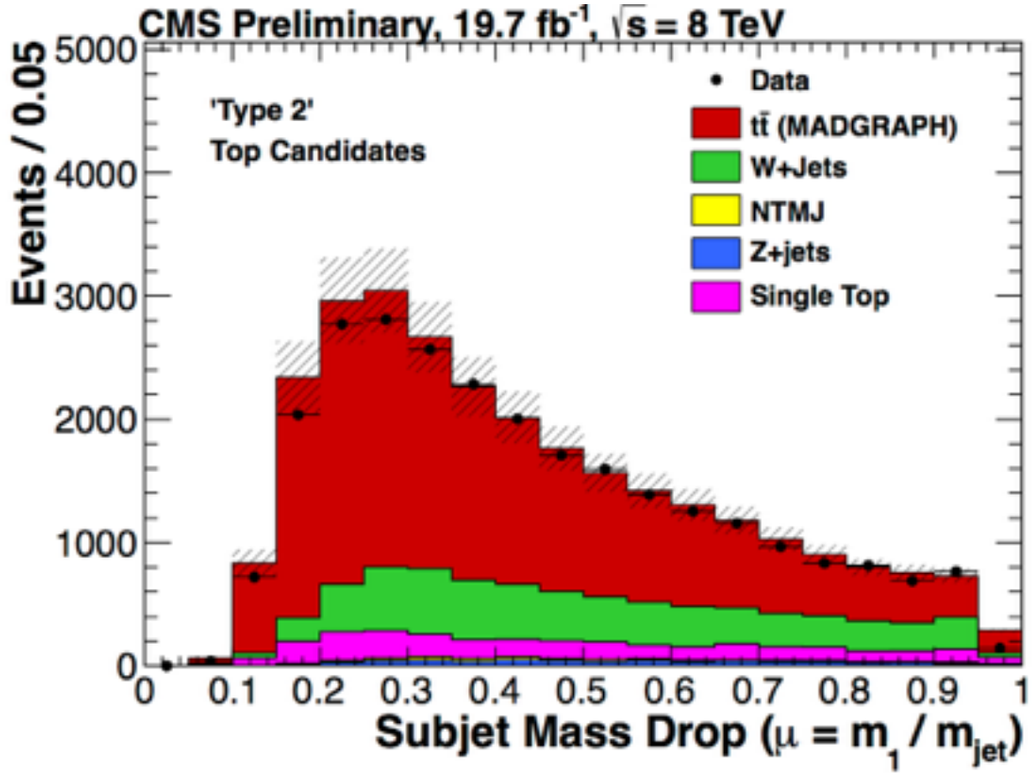
Boosted Tops

- Can also look at jet shapes

N-subjettiness

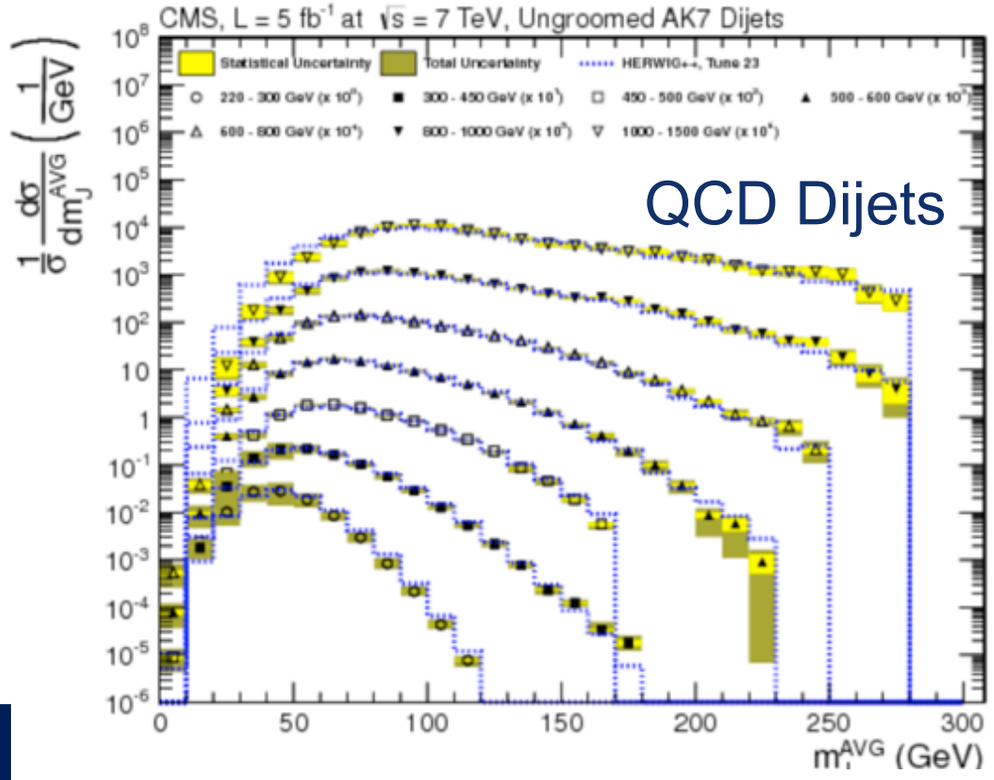


Mass drop



Boosted Jets

- Jet mass has been measured at ATLAS, CMS, and Tevatron



Overall good agreement with MC!

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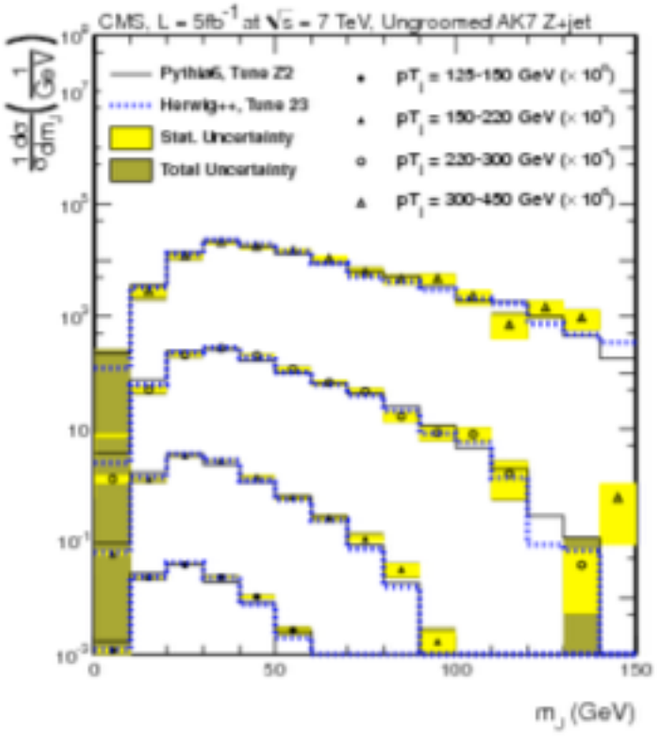
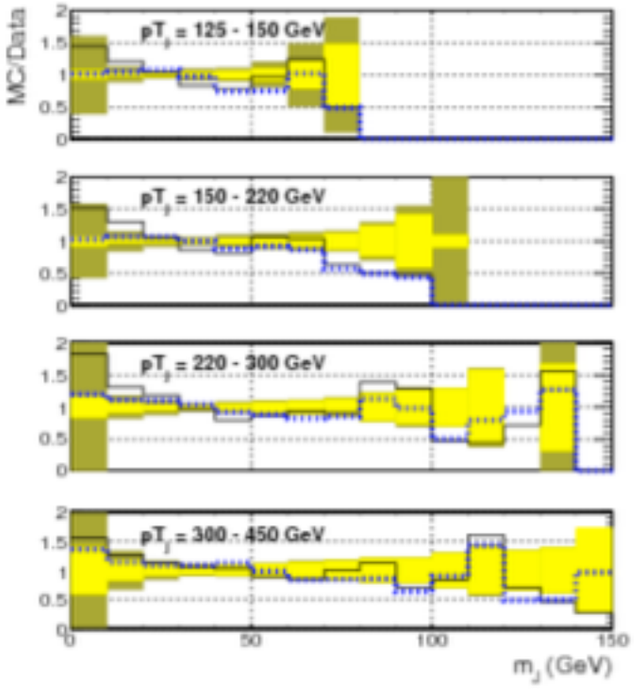
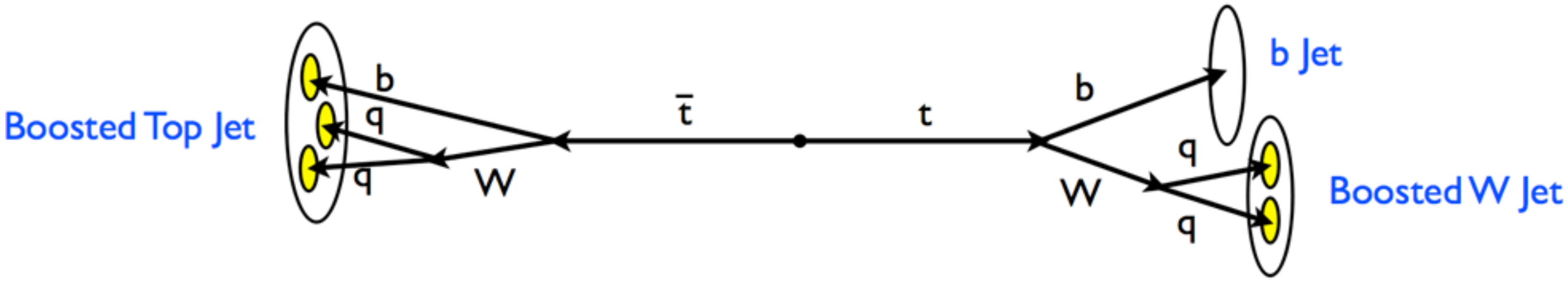


Z + jets



Boosted Jets

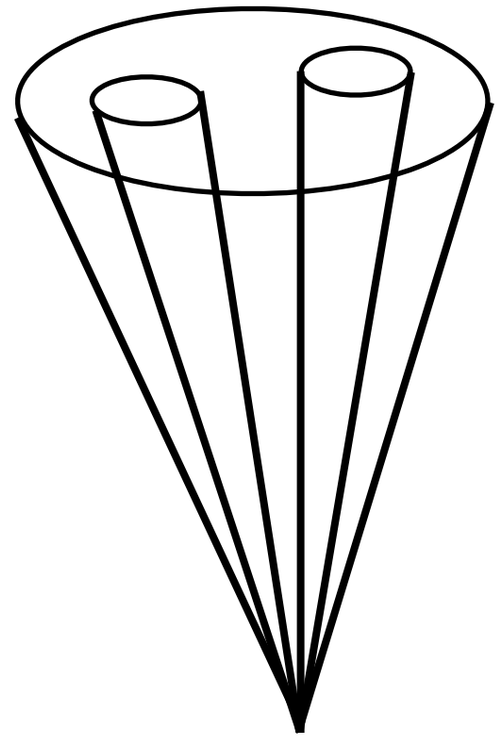


- For boosted tops : look for “three-prong” jets
  - Impose W and top mass hypothesis

- For boosted H/W/Z : look for “two-prong” jets
  - Impose W/Z/H mass hypothesis

Boosted Jets

- Other tools :
  - N-subjettiness
    - How “n-subjetty” the jet looks like
  - Energy correlation function
    - Axis-less version of n-subjettiness
  - Q-jets (“quantum” jets)
    - Cluster the jet many times with different parameters, look at the properties as an ensemble
  - Jet Charge
  - Jet width, etc

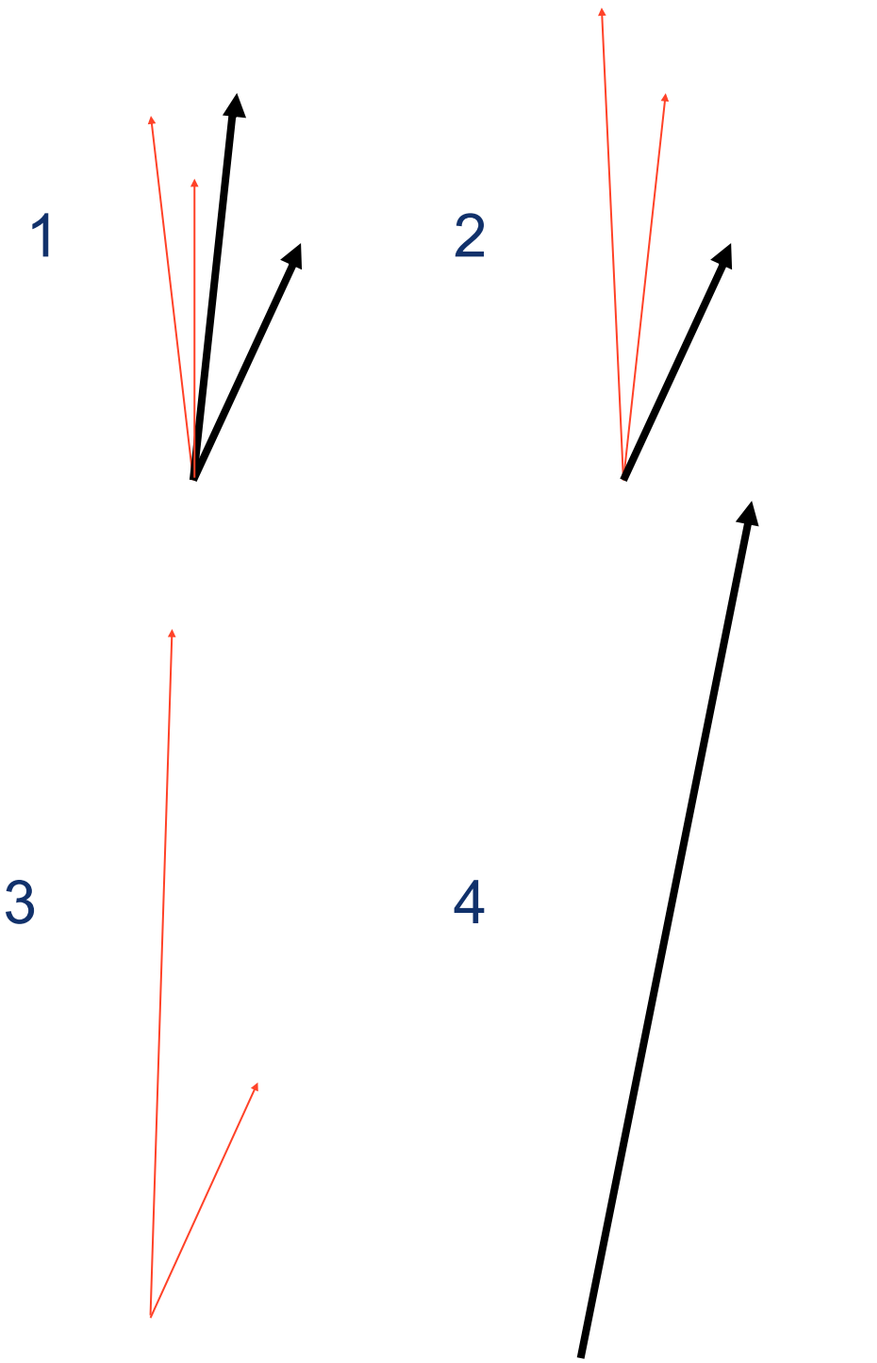


[1] Thaler, Van Tilburg, JHEP 1103:015,2011
[2] Larkoski, Salam, Thaler, arXiv:1305.0007
[3] Ellis et al., PRL 108, 182003 (2012)
[4] Krohn et al., Phys. Rev. Lett. 110 (2013) 21200

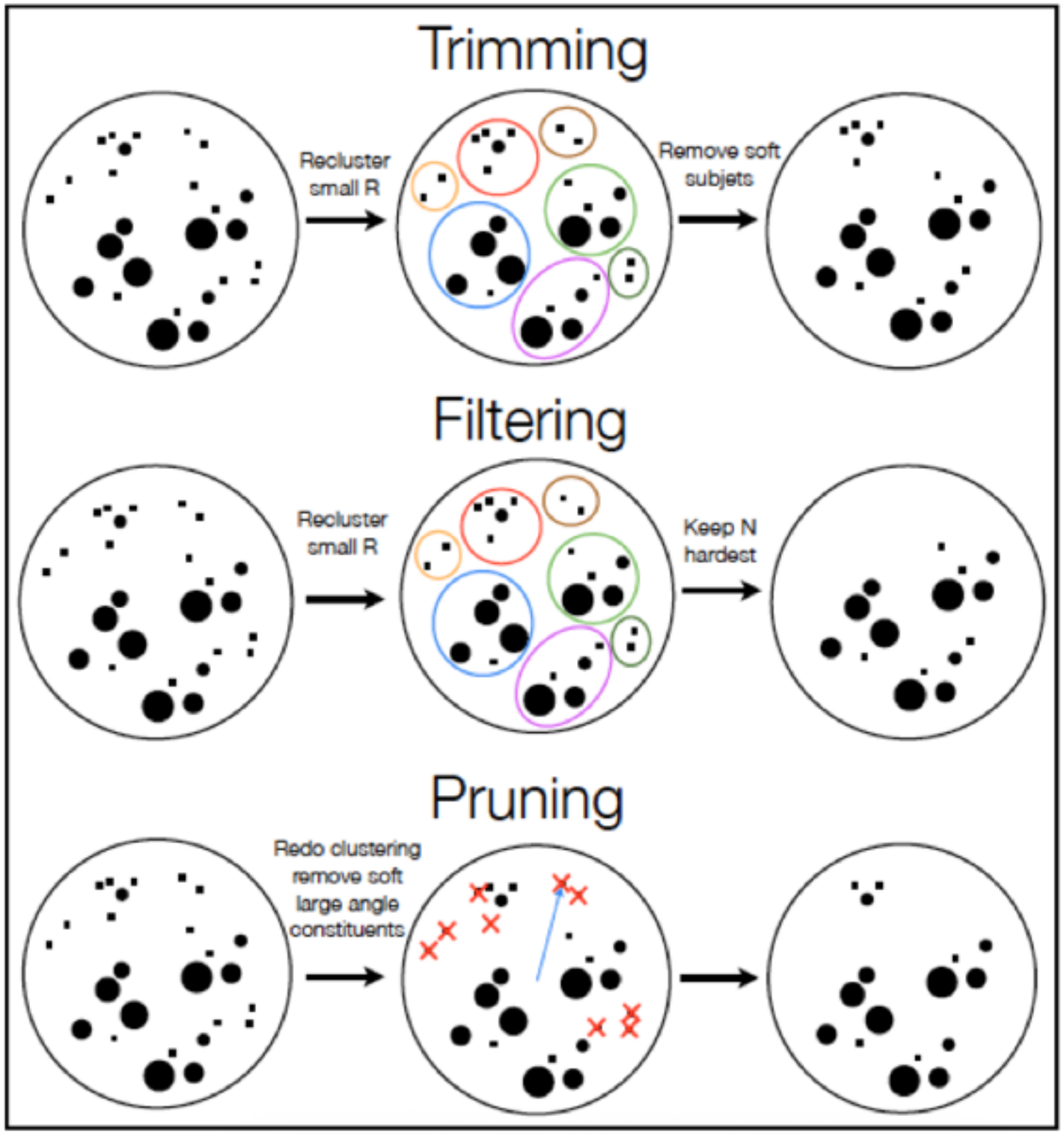
“All of the above” used at CMS!

Jet Grooming

- Examine the cluster sequence
  - Gives you information about how QCD would have behaved
- Remove unwanted bits
  - A lot of QCD is low-pt and uninteresting
  - Also don't want pileup
- You're left with the interesting parts



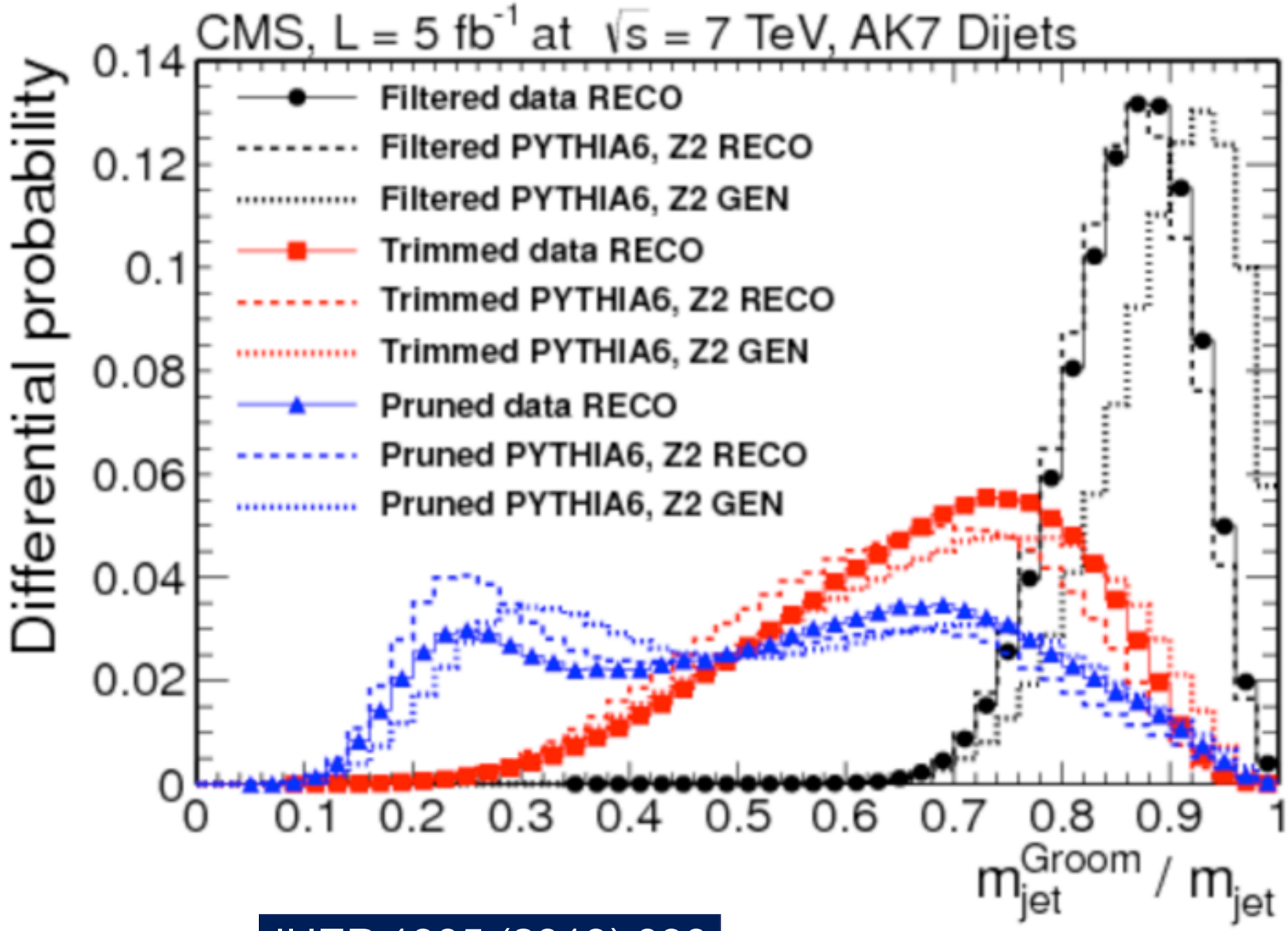
That's jet grooming in a nutshell!


Trimming
Recluster
small R
Remove soft
subjets
Filtering
Recluster
small R
Keep N
hardest
Pruning
Redo clustering
remove soft
large angle
constituents

Jet Grooming

- Comparing the three :

arXiv:1303.4811



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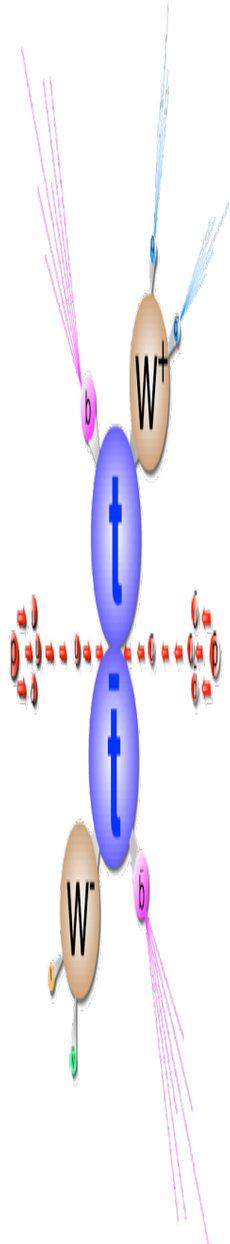
Boosted b-tagging

- Another problem with merged jets :
  - Overlapping tracks!
  - Problematic for b-tagging
  - Misidentification rate grows with combinatorics



- Use jet tools to handle this case also!
  - B-tag subjets instead of the “fat” jet!

JHU / CMS Top Tagging Details

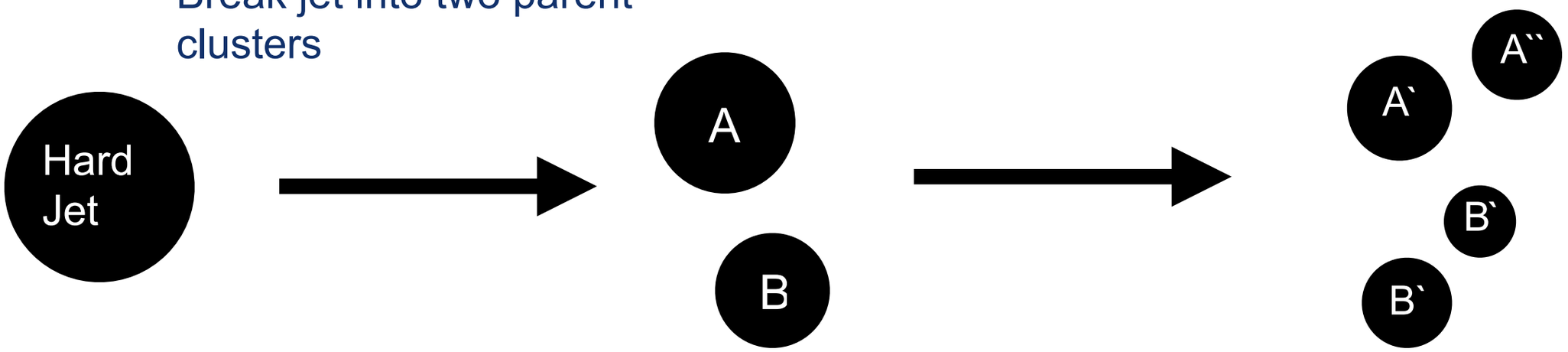
- Based on Kaplan et al. (arXiv:0806.0848)
- Cluster particle flow candidates using Cambridge Aachen
- Reverse the clustering sequence in order to find substructure
- Subjets must satisfy two requirements
  - Momentum fraction criterion: pTsubjet > 0.05×pThard jet
  - Adjacency criterion: ΔR(A, B) > 0.4 - 0.0004×pT
- Iterative process - throw out objects that fail momentum fraction cut and try to decluster again

Removes soft clusters

Removes wide angle clusters

<u>Primary Decomposition:</u>
Break jet into two parent clusters

<u>Secondary Decomposition</u>
Repeat on parent clusters



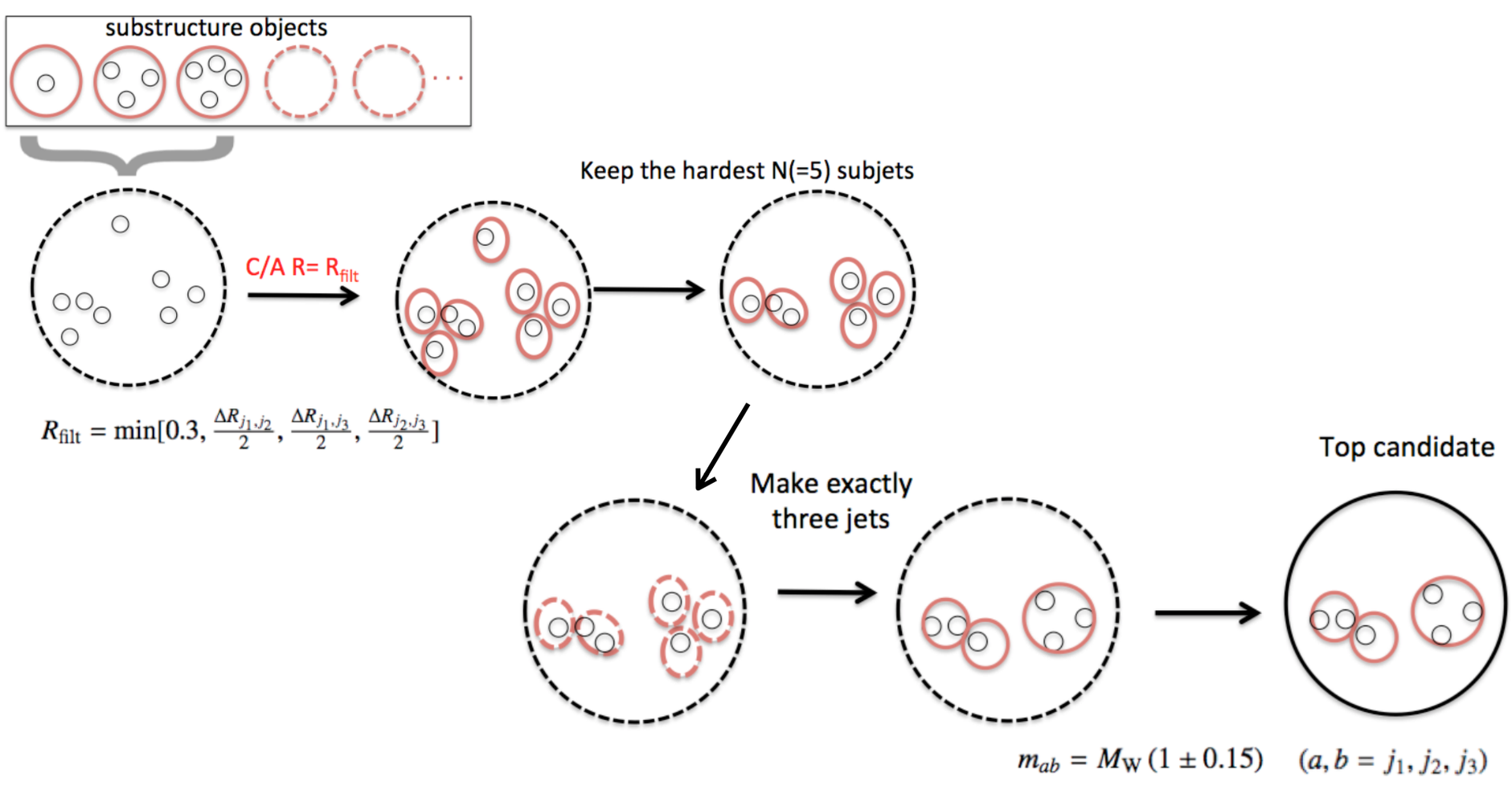
Require >= 3

HEP Top Tagging Details

HEP Top Tagger

ATLAS CONF-2012-065

- ATLAS has extensively studied and optimized the HEPTopTagger
- HEPTopTagger reclusters the large-R jet using a smaller distance parameter
- Removes soft, wide-angle radiation
- Left with 3 decay products of top quark reconstructed as subjets

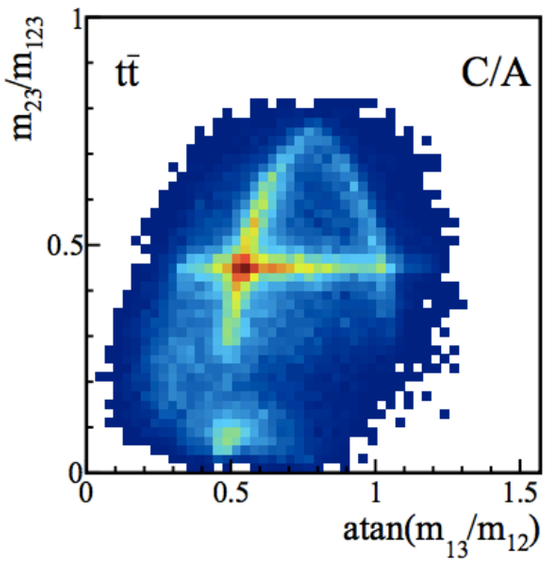


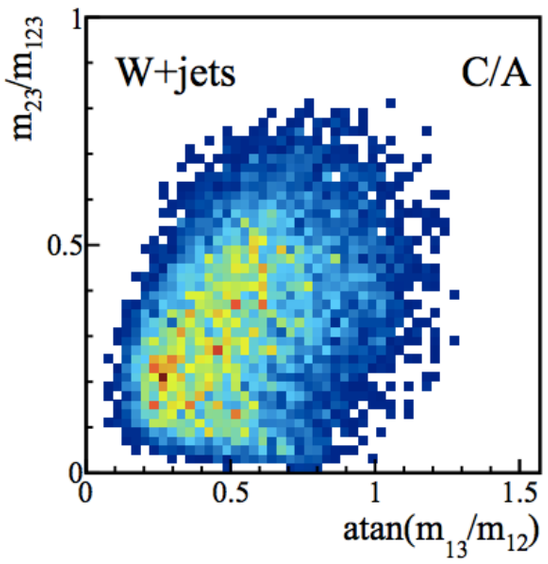
HEP Top Tagging Details

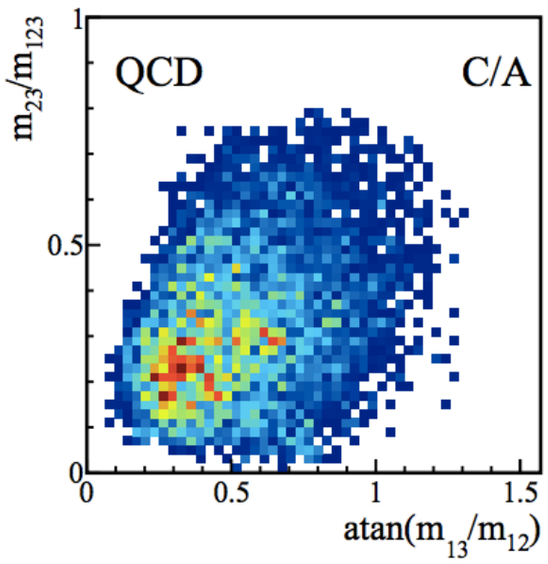
HEP Top Tagger

Plehn, Spannowsky, Takeuchi, arXiv:1111.5034

- Can then use the three subjets to impose criteria
- W mass, top quark mass
- Good discriminating power between top pair events and backgrounds

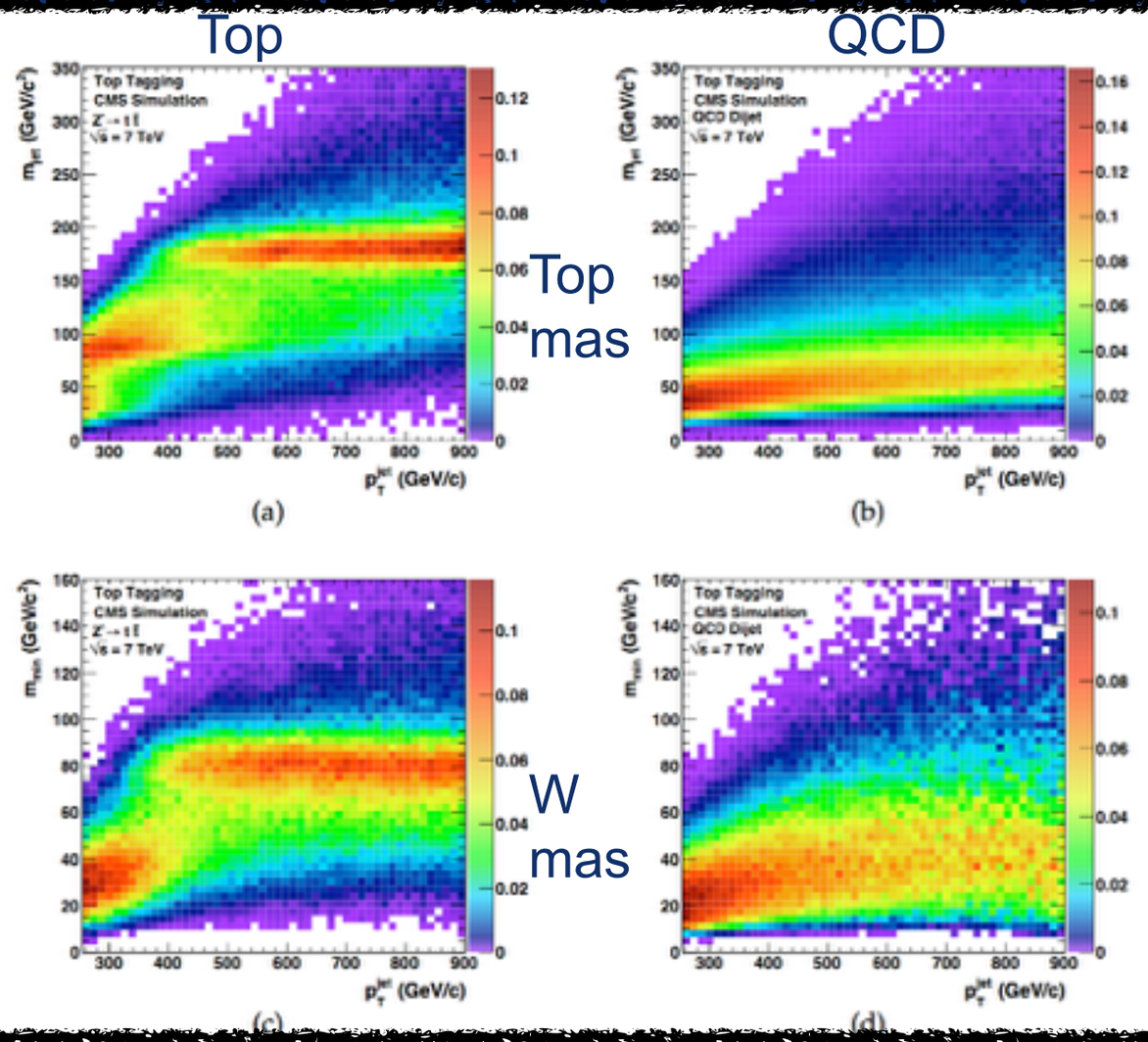






Jet Grooming

- JHU / CMS top tagger
  - Phys.Rev.Lett. 101 (2008) 142001
  - Break up cluster sequence to get three or four subjets
  - Impose top and W mass



- HEP top tagger
  - Break up cluster sequence to get three or four subjets
  - Impose “Dalitz-like” cuts