Physics @ 100 fb^{-1} x 13 TeV: JetMET Focus

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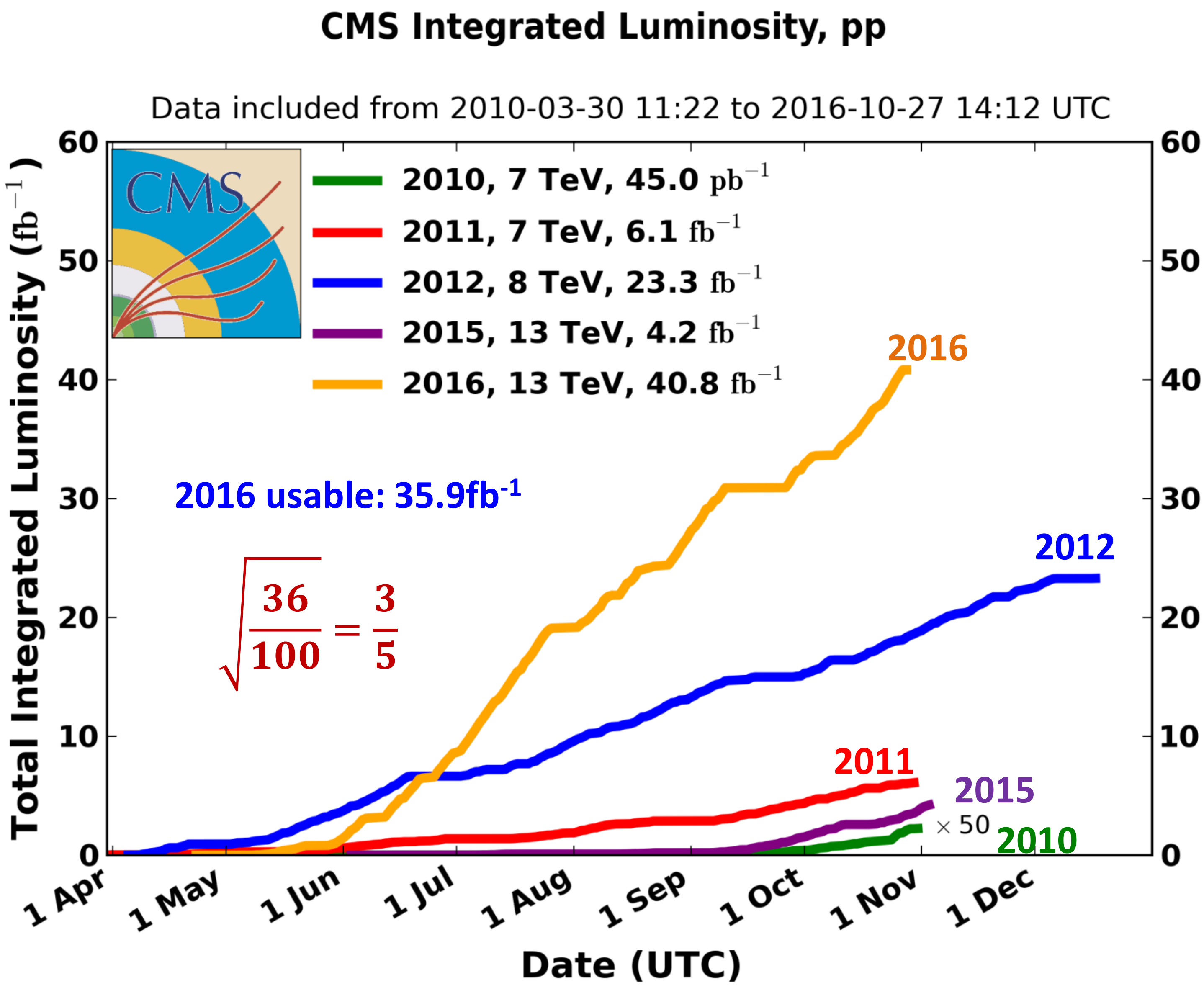
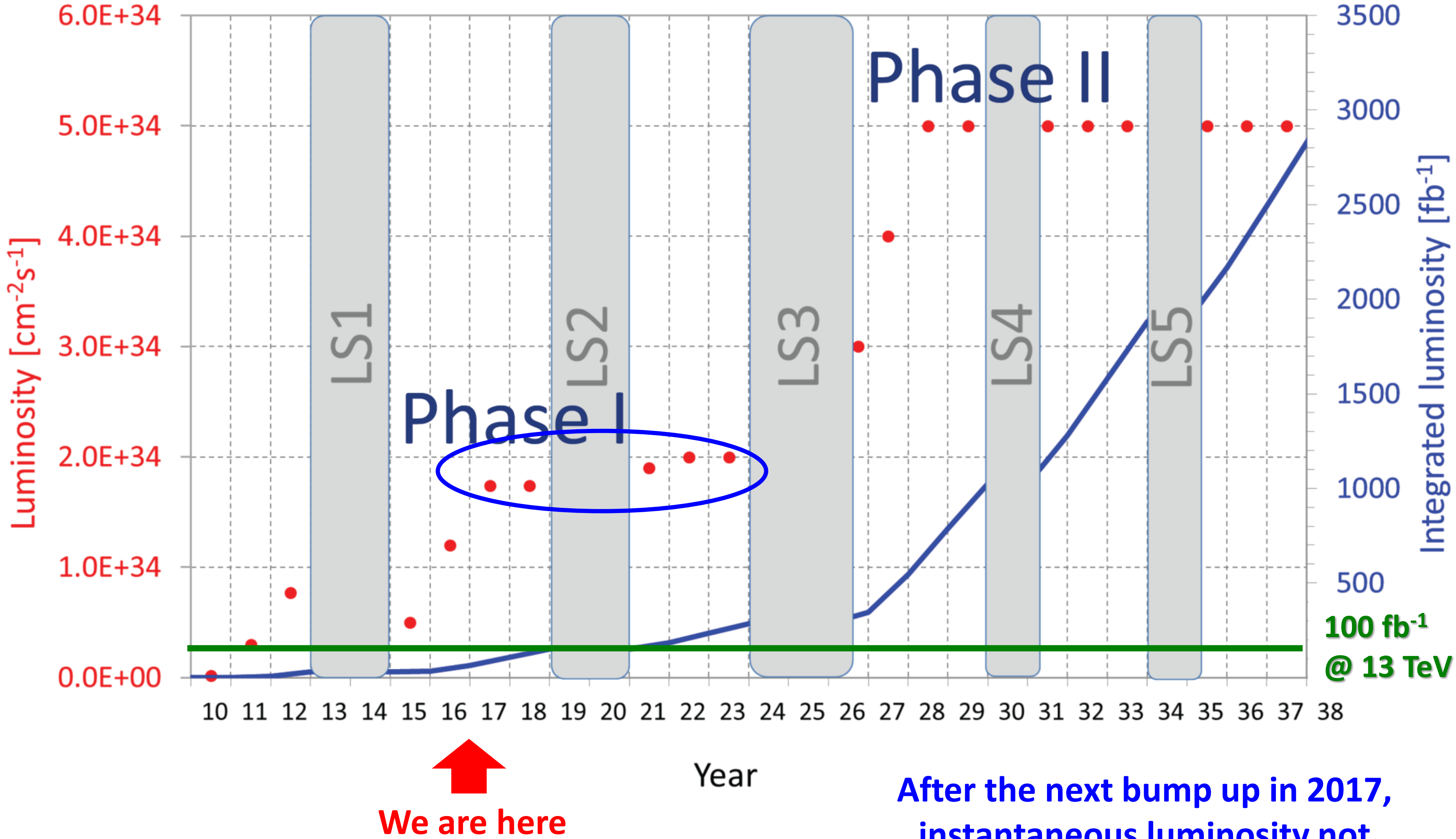
JME Workshop, Helsinki
May 10, 2017

Kick-off Talk!

2016 CMS Luminosity



Perspective



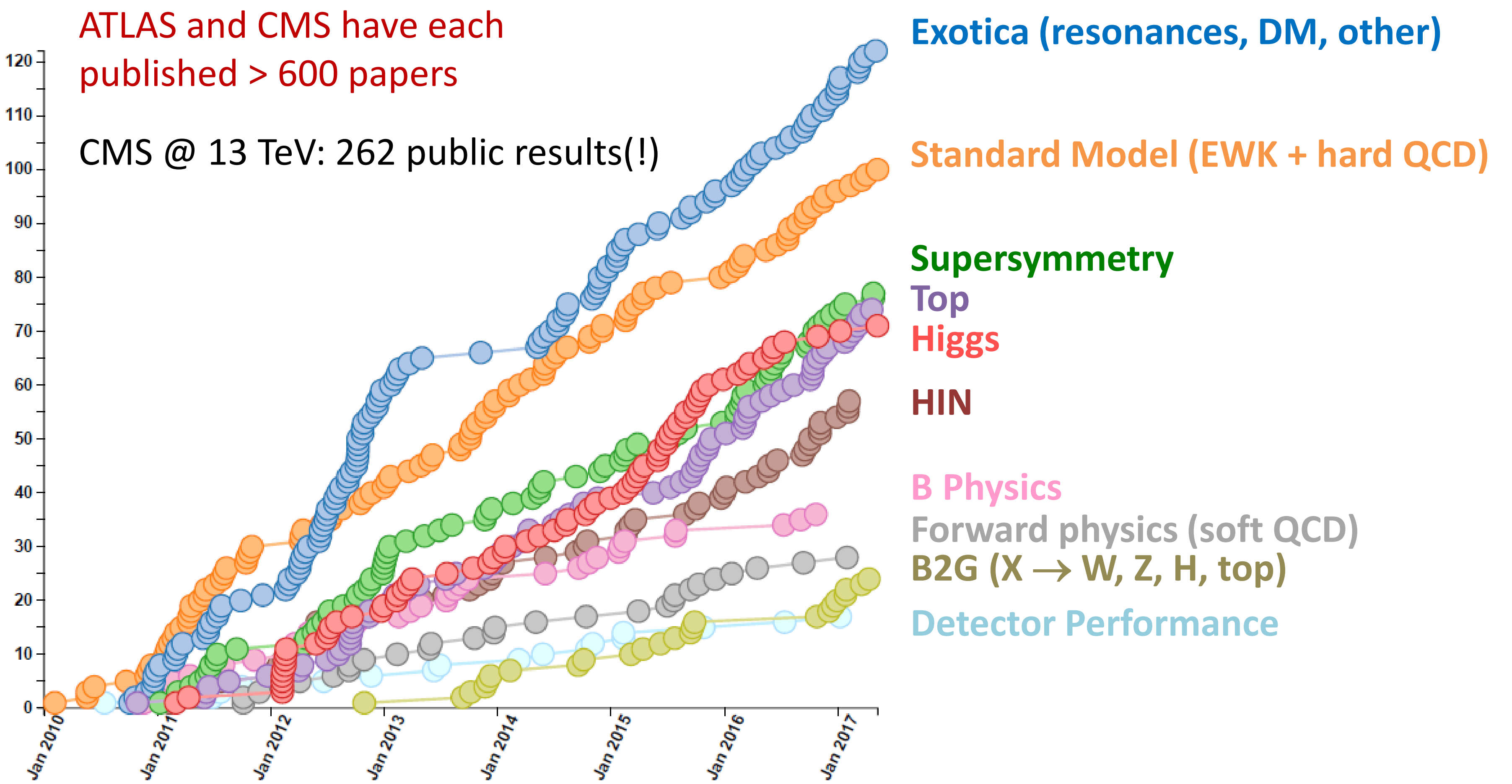
After the next bump up in 2017, instantaneous luminosity not changing much until HL-LHC

Caveats

- This is not a "Physics Overview" talk, for that you can see for example (if you are in CMS) S. Rahatlou at the Mumbai CMS Week (Nov., 2016)
  - https://indico.cern.ch/event/512834/contributions/2367393/attachments/1370694/2078730/rahatlou-20161114.pdf
- Instead, I decided to cover a few selected topics that are impacted directly by JetMET calibrations, uncertainties, new ideas, etc., for which some (hopefully) interesting conclusions can be drawn
  - Just a sampling, nowhere near a complete list!
  - Emphasis on questions to you, rather than answers from me; focused on recent Moriond 2017 results
- **Apologies to ATLAS:**
  - Plots are taken from CMS

What we Publish

Roughly **1/3 BSM** searches, **2/3 SM (+HIN)** measurements



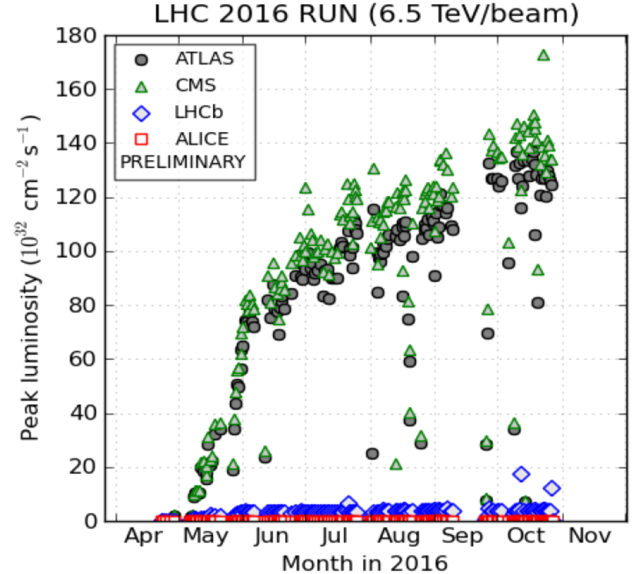
These proportions are not going to change for 100 fb^{-1}

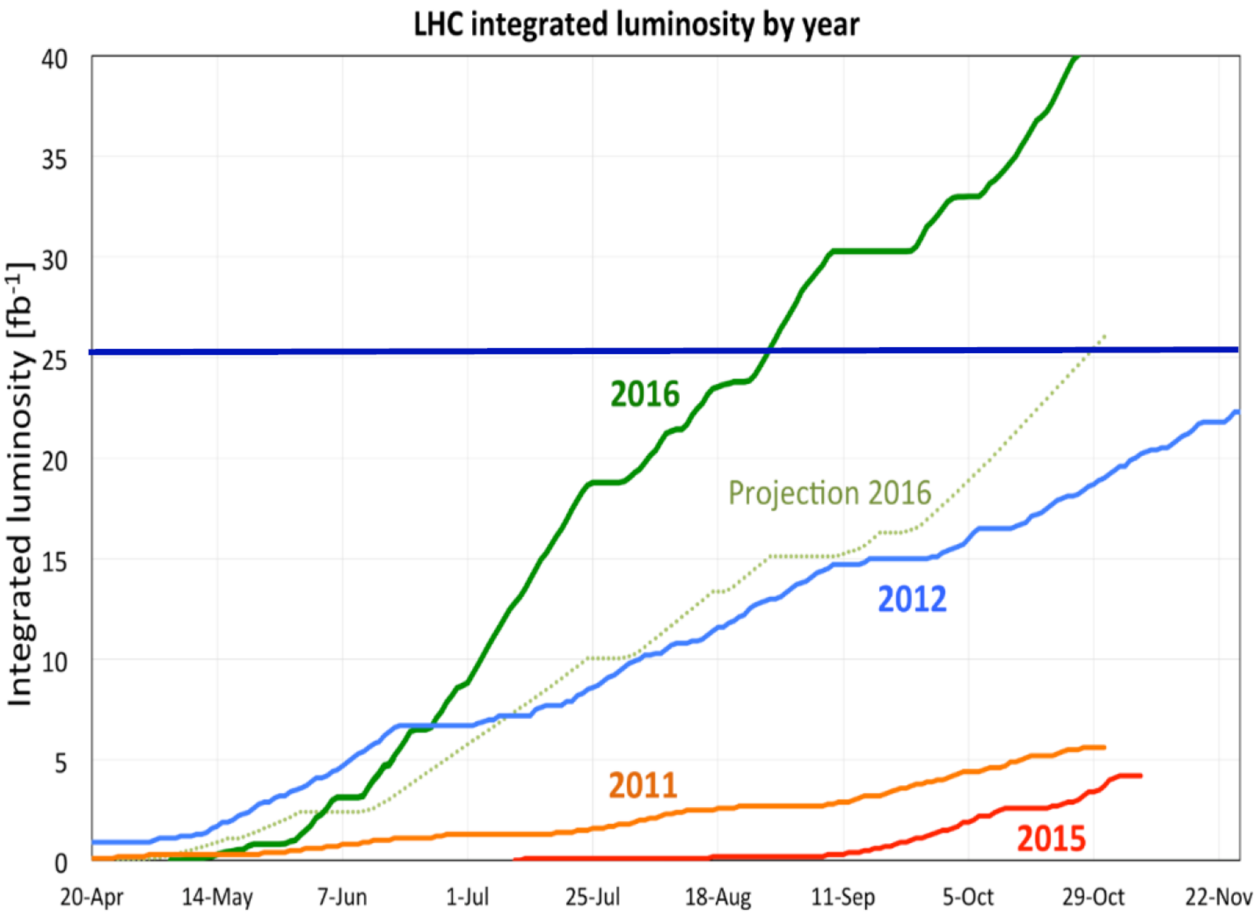
LHC News

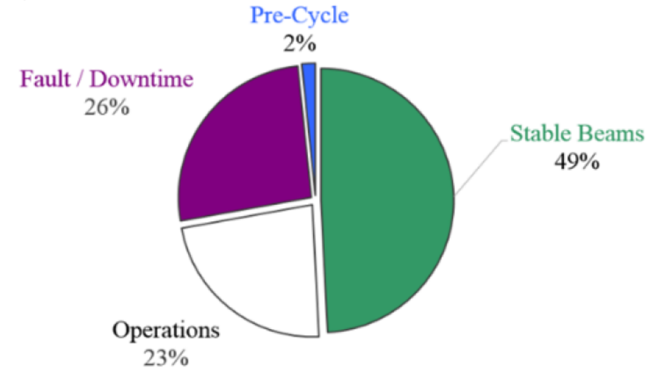
2016 LHC : Production year

Peak luminosity > 1.4 x 10^{34} $cm^{-2}s^{-1}$

OVER 25 fb^{-1} in both ATLAS and CMS







≈153 days physics ≈3738.7 hours

	Duration [h]
Stable Beams	1839.5
Fault / Downtime	980.0
Operations	857.9
Pre-Cycle	61.3

TS1 - TS2 : stable beams 58 %

TS2 - TS3 : stable beams 54 %

Beam Wizards

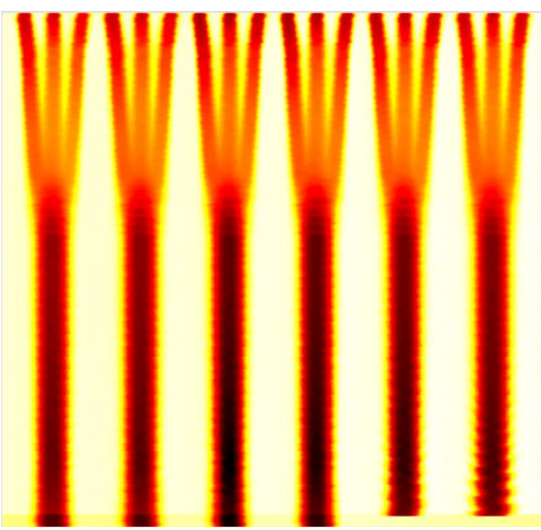
Doubling the luminosity with a trick: Beam Compression Multiple Splitting (BCMS)

$$L = \frac{n_{bb} f_{rev} N^2 \gamma}{4 \pi \varepsilon_n \beta^*} F$$

Emittance ε is easy to increase but difficult to decrease (constrained by magnets)

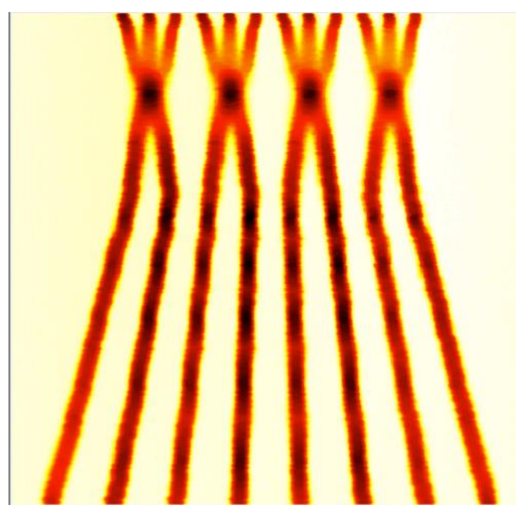
Bottleneck comes at the beginning of the LHC injector chain (space-charge effects)

Standard Injection (6 → 72)



Higher intensity / bunch

BCMS Injection (8 → 48)



Lower intensity / bunch

Required bunch intensity is halved in the BCMS scheme, less total current in machine, but…

Luminosity doubled overnight!

Downside: increased pile-up for ATLAS and CMS

2017 scenarios

LHC Goal: 45 fb^{-1} delivered

Parameter	Standard 25 ns	BCMS 25 ns	BCMS 25 ns Pushed	Comments
Energy [TeV]	6.5	6.5	6.5	
β* (1/2/5/8) [m]	0.4 / 10 / 0.4 / 3	0.4 / 10 / 0.4 / 3	0.33/ 10 / 0.33 / 3	Either 40 cm as 2016 or further squeeze to 33cm
Long-range separation [sigma] - assumed emittance	10 sigma - 3.5 um	10 sigma - 2.5 um	10 sigma - 2.5 um	
Half X-angle (1/2/5/8) [μrad]	-185 / 120 / 185 / -150	-155 / 120 / 155 / -150	-170 / 120 / 170 / -150	Went to 140 with lower intensities in 2016
Number of colliding bunches (1/5)	2736	2448	2448	BCMS - 144 bunches/injection from SPS
Bunch population	1.25e11	1.25e11	1.25e11	around 1.3e11 injected for both Standard and BCMS
Emittance into Stable Beams [μm]	3.2	2.3	2.3	Nominal 2.6 for Standard, 1.4 for BCMS at injection
Bunch length [ns] - 4 sigma	1.05	1.05	1.05	As 2016
Peak Luminosity (L0)	1.4e34	1.7e34	1.9e34	
Peak mean pile-up (*inel xsection 80 mb*)	37	51	56	Fast decay at start of fill
Average mean pile-up	27	33	36	**NB** Have to assume average fill length and lumi lifetime. Assume average fill length of 13 hours (June-July 2016 - optimistic)
Average luminosity lifetime (tau)	21 hours	15 hours	14 hours	Approx. - assuming burn only

Pause and Reflect

- **Machine performance in 2017 similar to worst of 2016**
  - Sustained peak lumi > 1.4 x 10^{34} cm^{-2} s^{-1}, reaching up to 1.9e34
  - Peak PU > 50 (but average PU ~35)
  - If we can deal with the worst of 2016, we should survive this year(?)
    - 2018 is unknown at the moment
- **Physics goals for pp running remain unchanged at 100 fb^{-1}**
  - Searches searches searches
    - High-mass resonances decaying to boosted objects
    - High-mass resonances decaying partially to nothing
    - SUSY particles decaying with or without large MET
    - Dark Matter produced in association with everything
    - Increasing interest in rare processes (rare decays, flavor violating, etc)
  - Increasing precision of SM measurements
    - V + jets, VV, Higgs, top, QCD
    - Differential distributions becoming more precise, theory test intensifies
- **Question to you: if we are OK @ 36 fb^{-1}, are we OK @ 100 fb^{-1}?**
  - My (pre-workshop) answer at the end

Climbing the Fruit Tree

1000 fb^{-1}

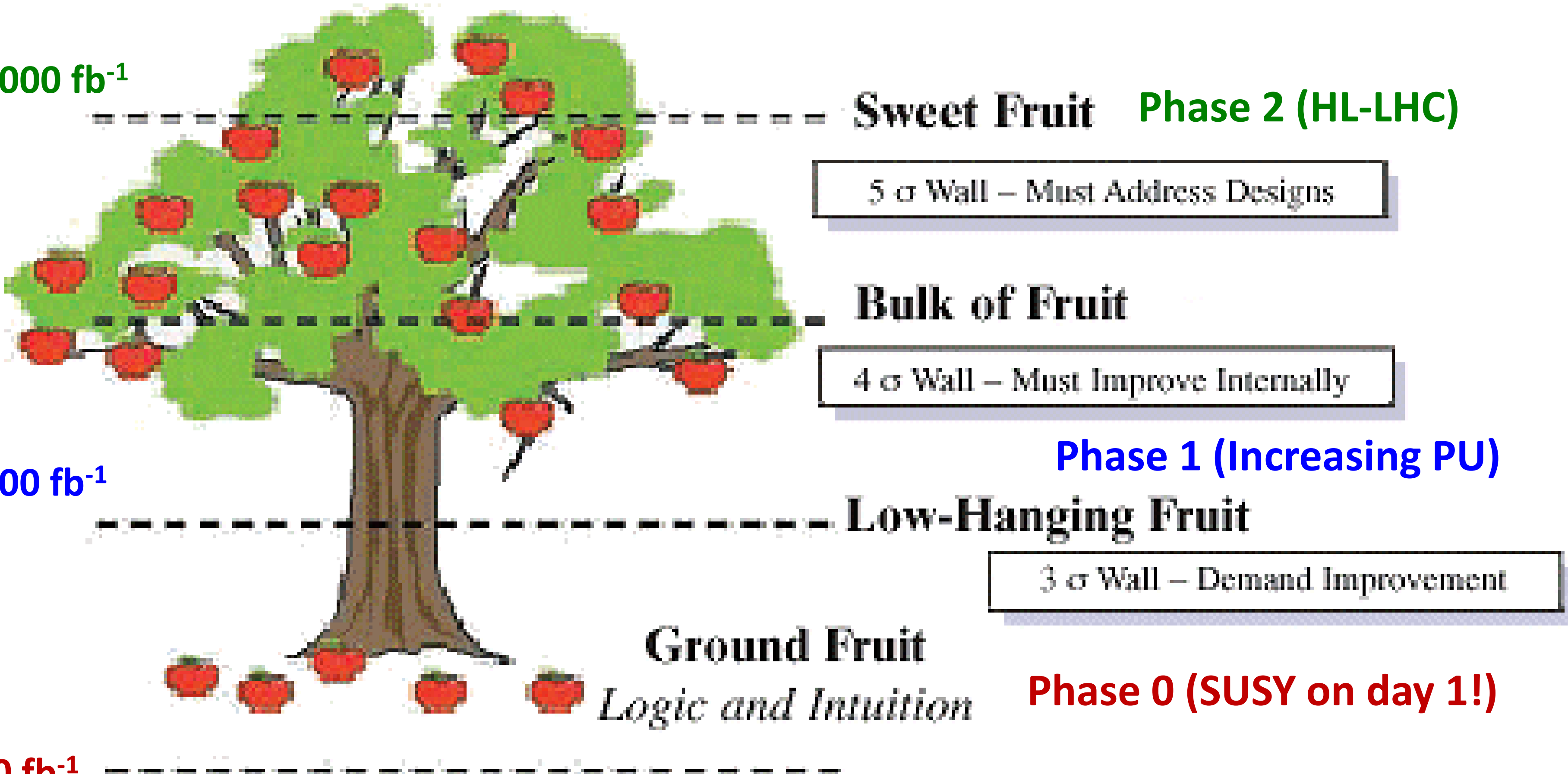
Phase 2 (HL-LHC)

Phase 1 (Increasing PU)

100 fb^{-1}

Phase 0 (SUSY on day 1!)

0 fb^{-1}

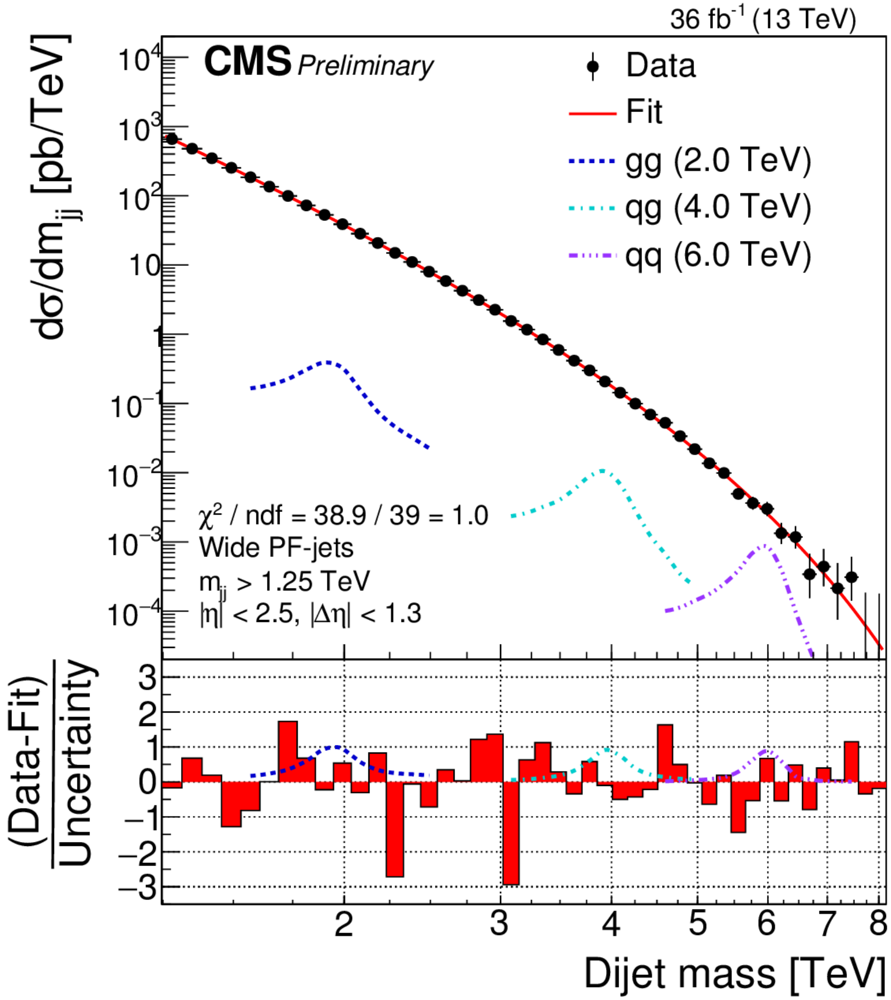


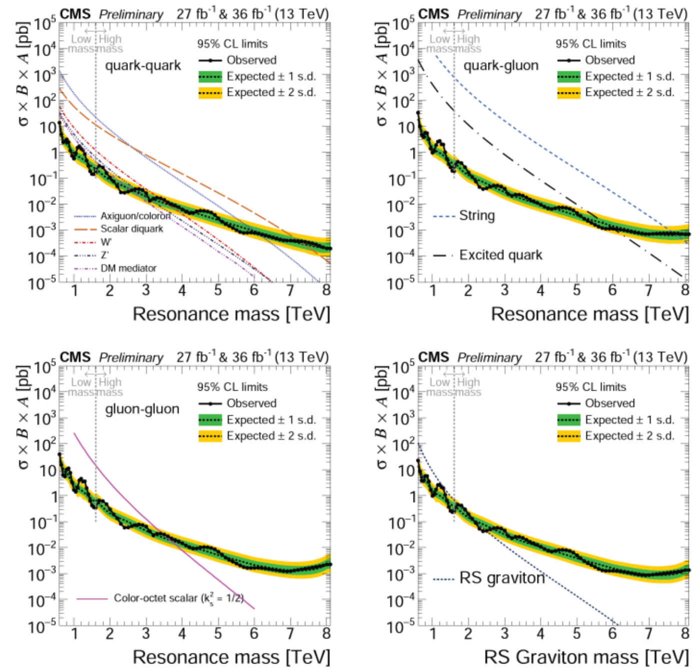
As we climb the tree, improved methods are needed!

For original topic, see https://www.isixsigma.com/industries/healthcare/what-do-when-low-hanging-fruit-gone/

Searches for BSM Signals

Dijet Search





Model	Final State	Observed (expected) mass limit [TeV] 36 fb^{-1} 13 TeV	12.9 fb^{-1} 13 TeV	2.4 fb^{-1} 13 TeV	20 fb^{-1} 8 TeV
String	qg	7.7 (7.7)	7.4 (7.4)	7.0 (6.9)	5.0 (4.9)
Scalar diquark	qq	7.2 (7.4)	6.9 (6.8)	6.0 (6.1)	4.7 (4.4)
Axigluon/coloron	$q\bar{q}$	6.1 (6.0)	5.5 (5.6)	5.1 (5.1)	3.7 (3.9)
Excited quark	qg	6.0 (5.8)	5.4 (5.4)	5.0 (4.8)	3.5 (3.7)
Color-octet scalar ($k_s^2 = 1/2$)	gg	3.4 (3.6)	3.0 (3.3)	—	—
W′	$q\bar{q}$	3.3 (3.6)	2.7 (3.1)	2.6 (2.3)	2.2 (2.2)
Z′	$q\bar{q}$	2.7 (2.9)	2.1 (2.3)	—	1.7 (1.8)
RS Graviton ($k/M_{PL} = 0.1$)	$q\bar{q}$, gg	1.7 (2.1)	1.9 (1.8)	—	1.6 (1.3)
DM Mediator ($m_{DM} = 1$ GeV)	$q\bar{q}$	2.6 (2.5)	2.0 (2.0)	—	—

Dominant systematic is effect of jet resolution on signal mass shape.

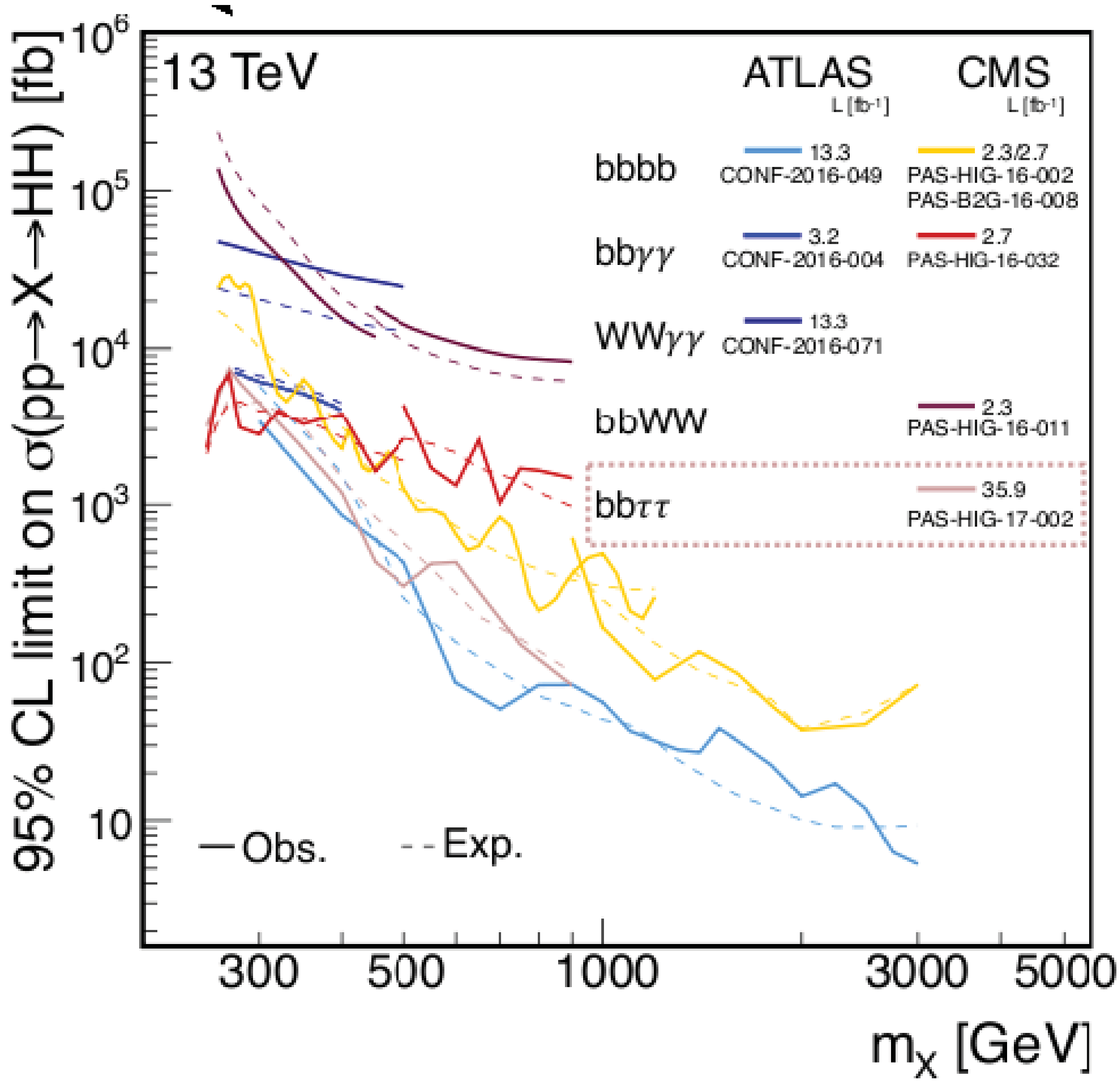
Can new ideas help us ‘beat the curve’?

Diboson (HH) Searches

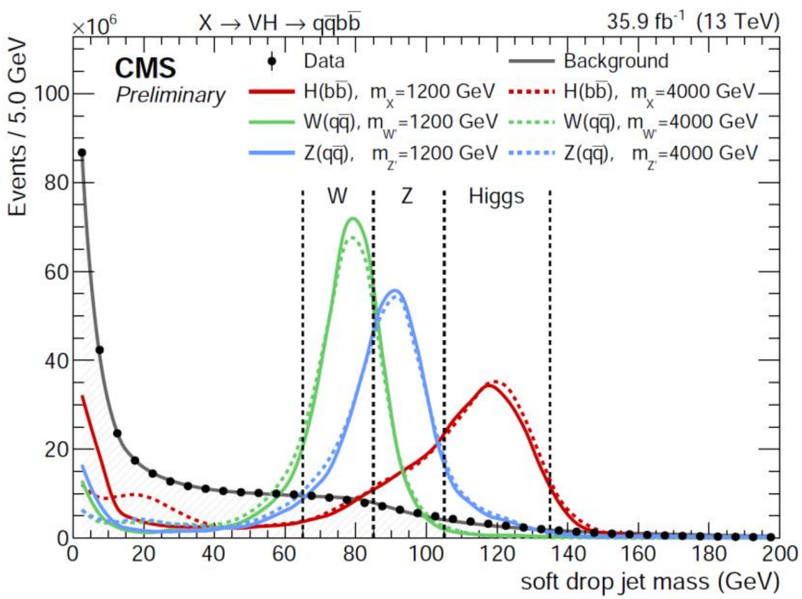
Use H decays to:

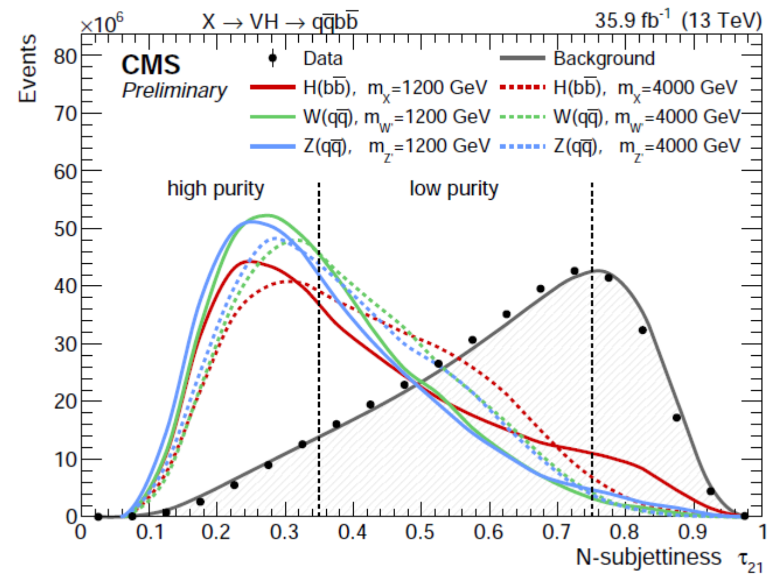
- Bottom quarks
- Photons
- W bosons
- Z bosons
- Tau leptons

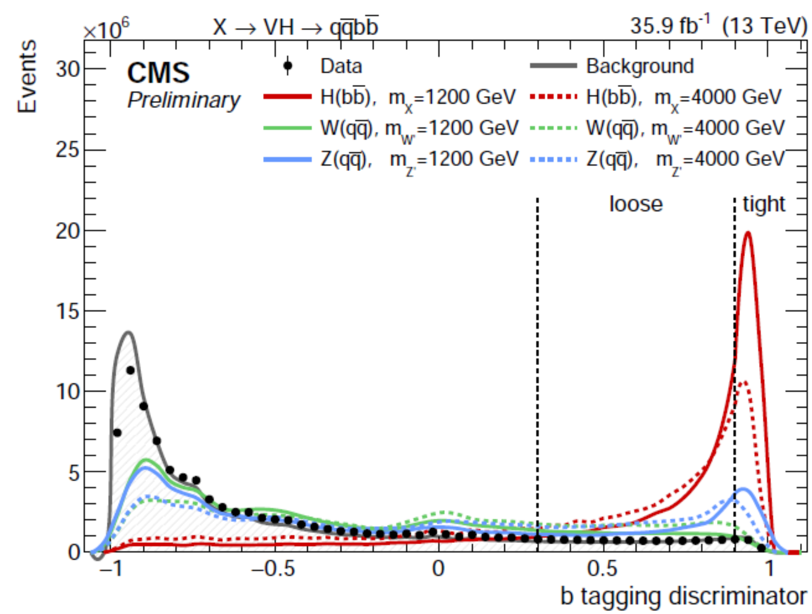
Are there limitations on Hbb (and Vbb) tagging as PU increases?



V(bb,qq) Tagging with 36 fb^{-1}







Excellent agreement with data

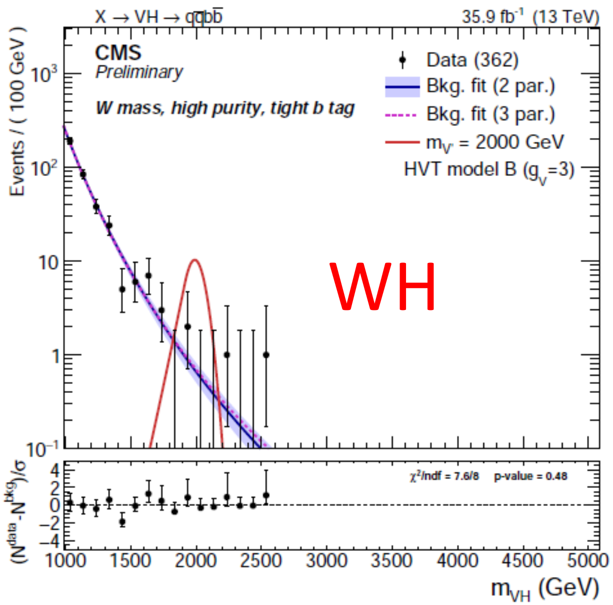
Shapes are ~mostly independent of pT

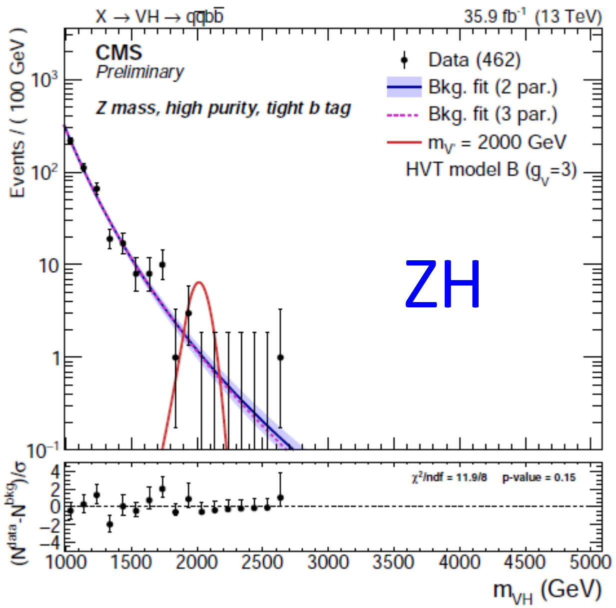
Is PUPPI all we need?

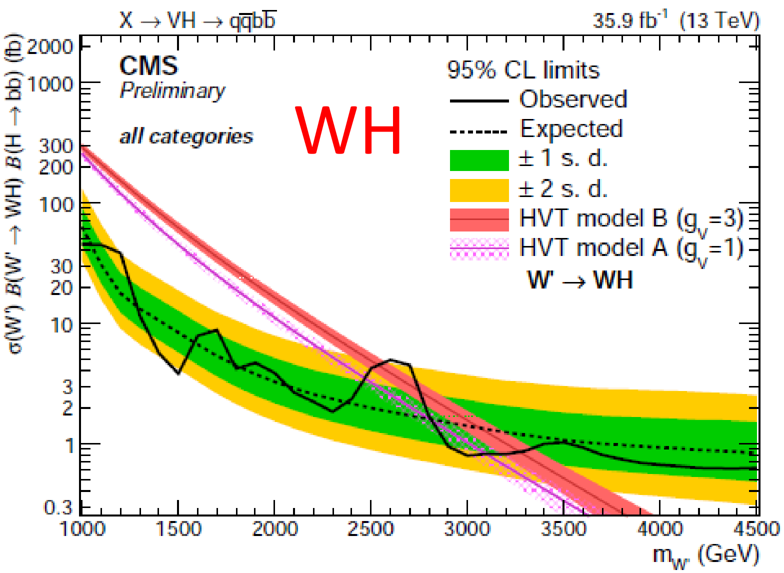
Do we hit a wall?

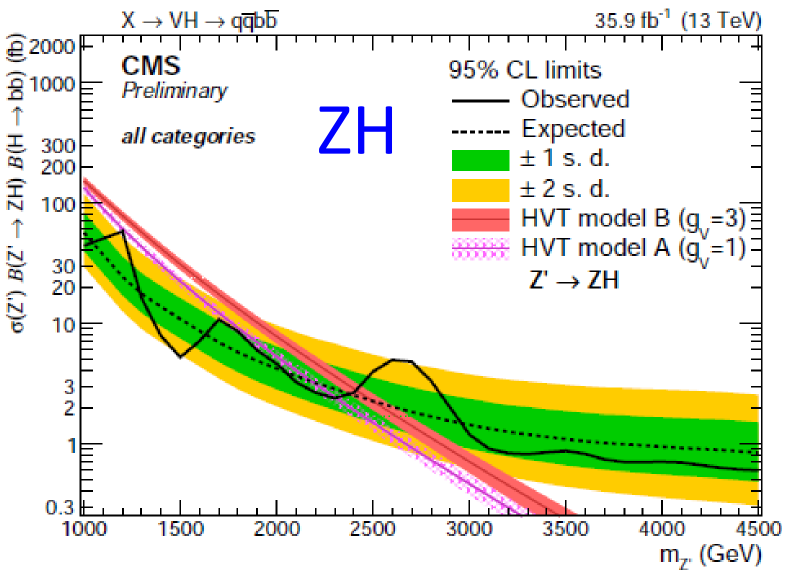
Talks this afternoon by P. Harris and M. Dasgupta

V(qq)H(bb) Resonance Search

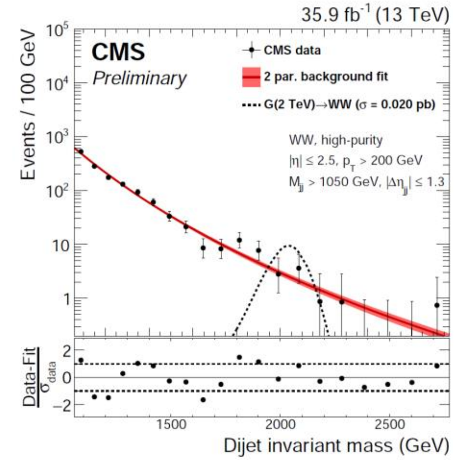






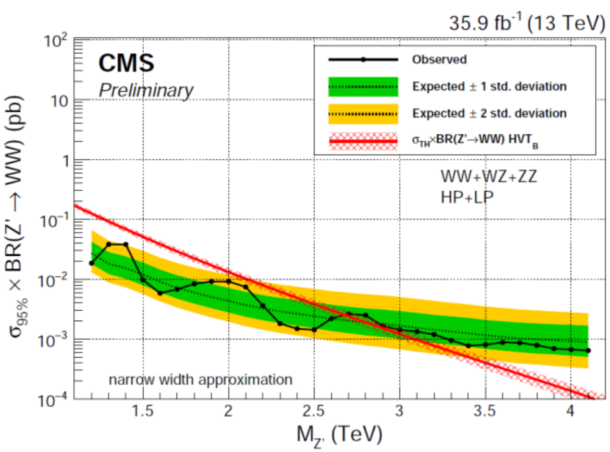


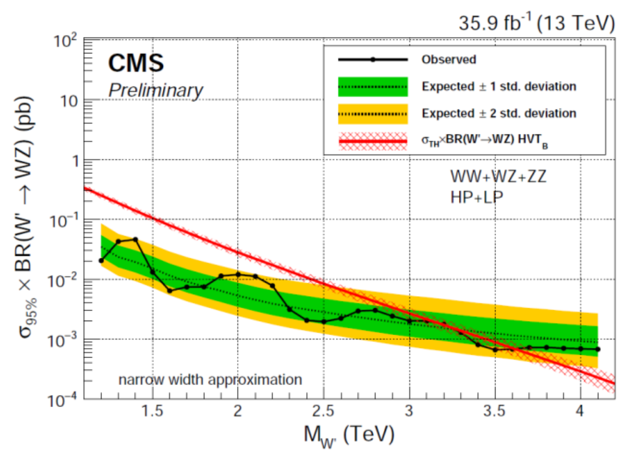
Diboson (VV) Searches

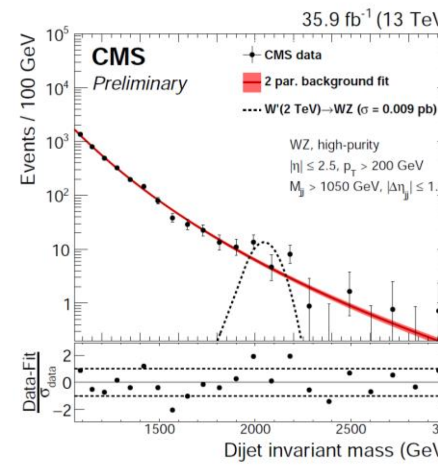


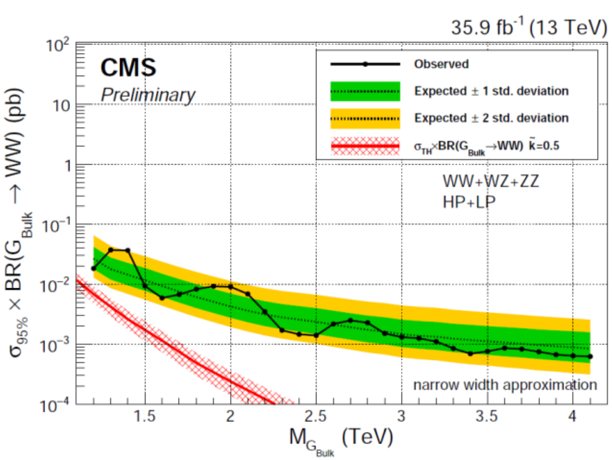
Reminder: for VV and VH, background comes from fit

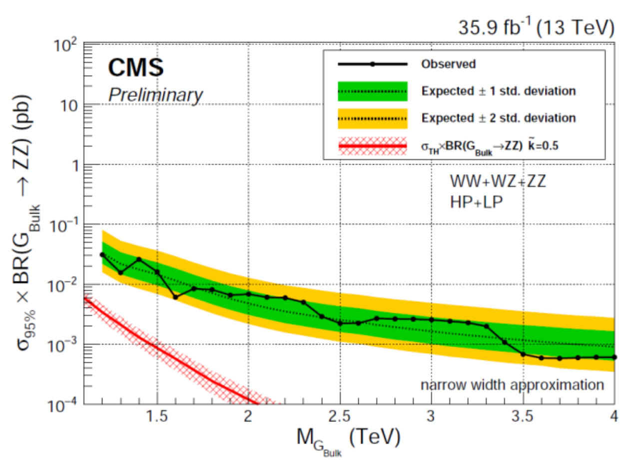
Dominant effect from jet energy scale and resolution is on signal shape, and associated efficiency for V(H)-tagger cut

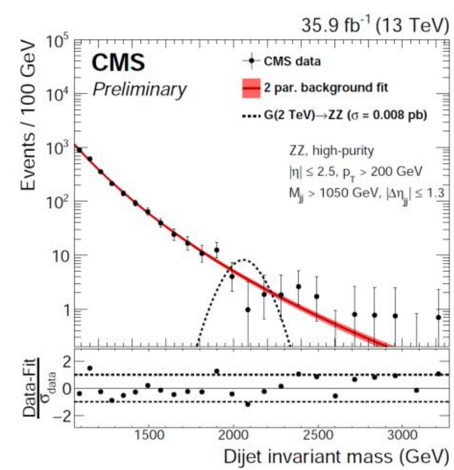




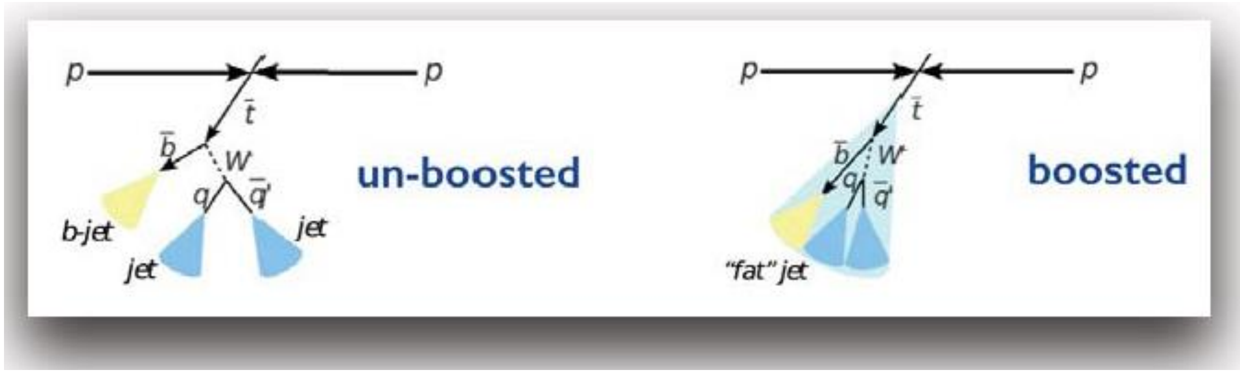




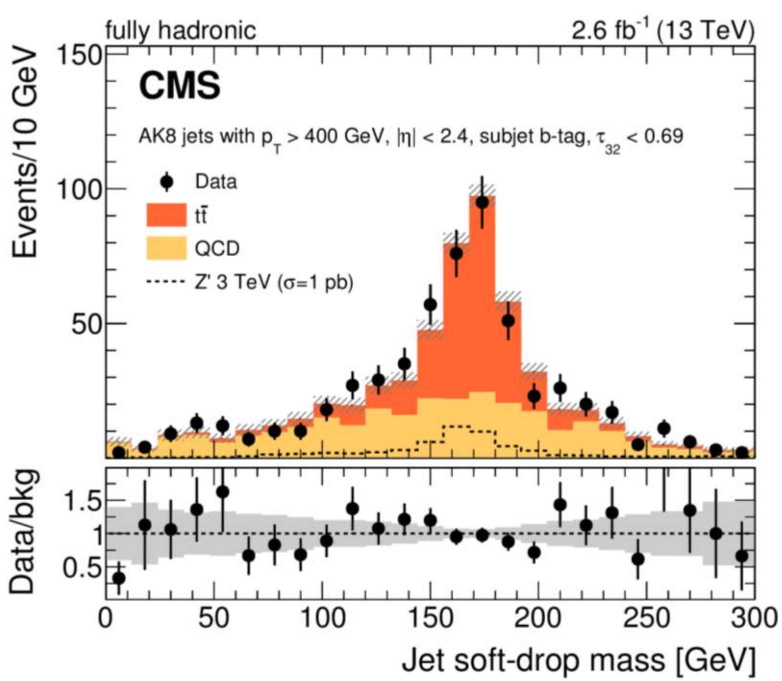


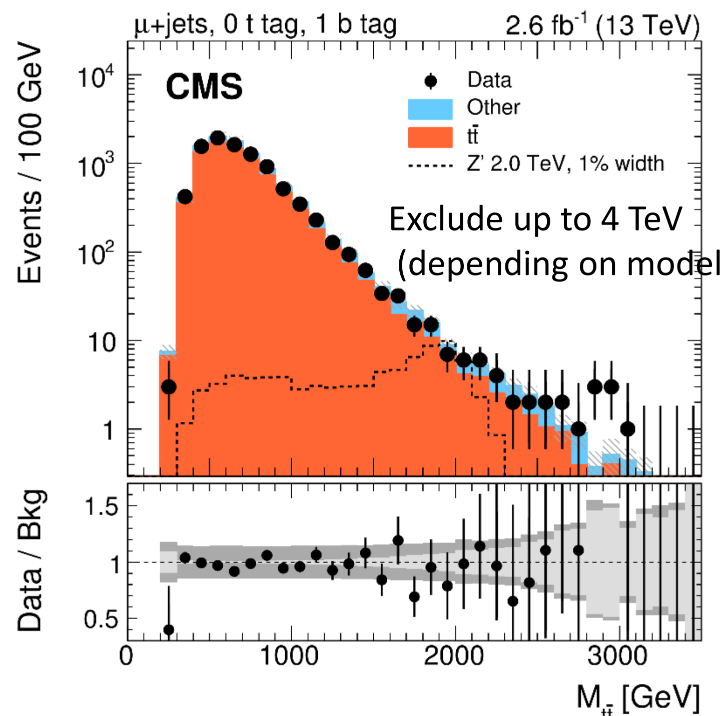


Highly Boosted Top Quarks



Same questions here: do we run into issues with top tagging at high PU? (Here only 2.6fb^{-1} used)



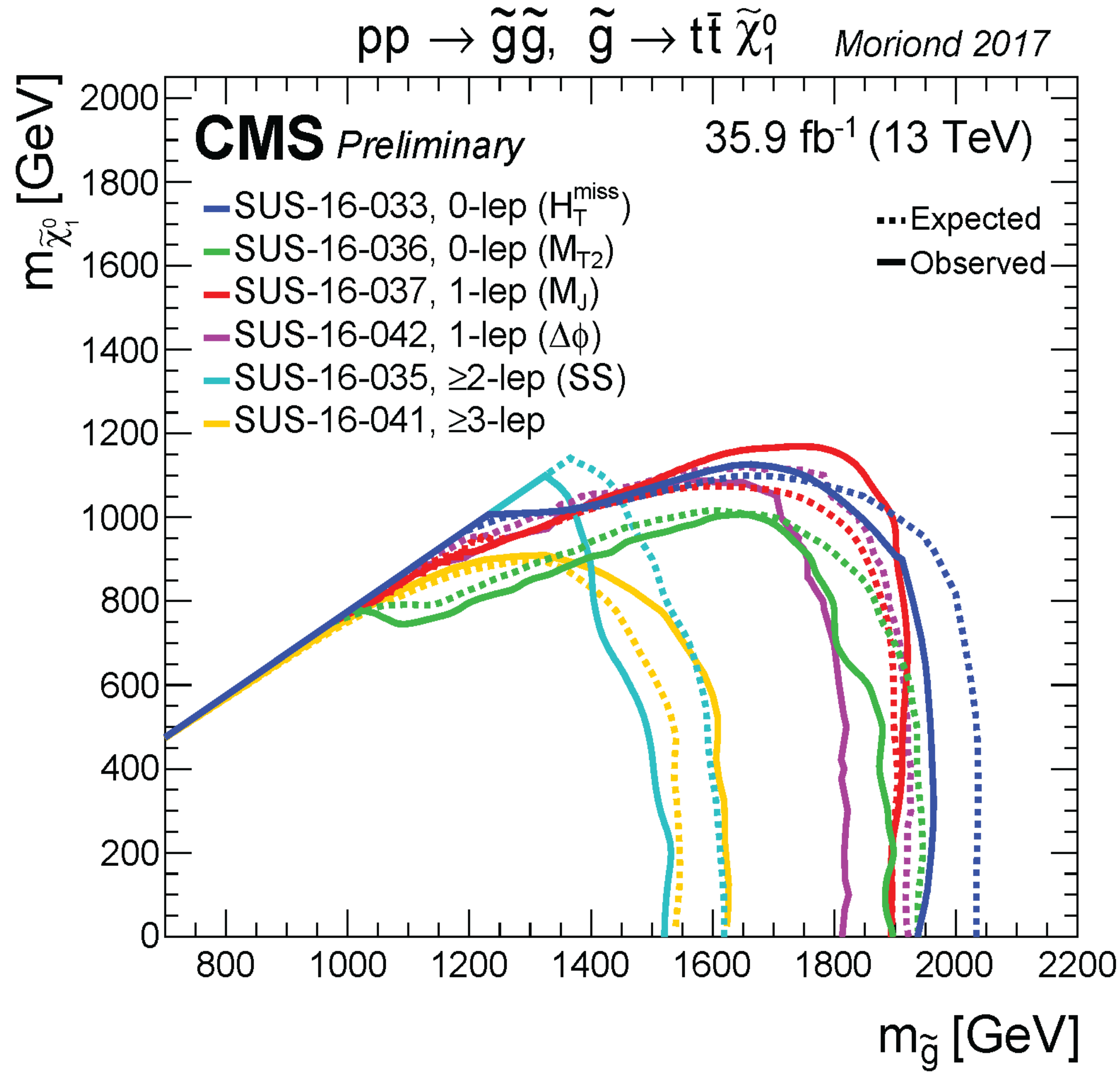


Hadronic SUSY Searches

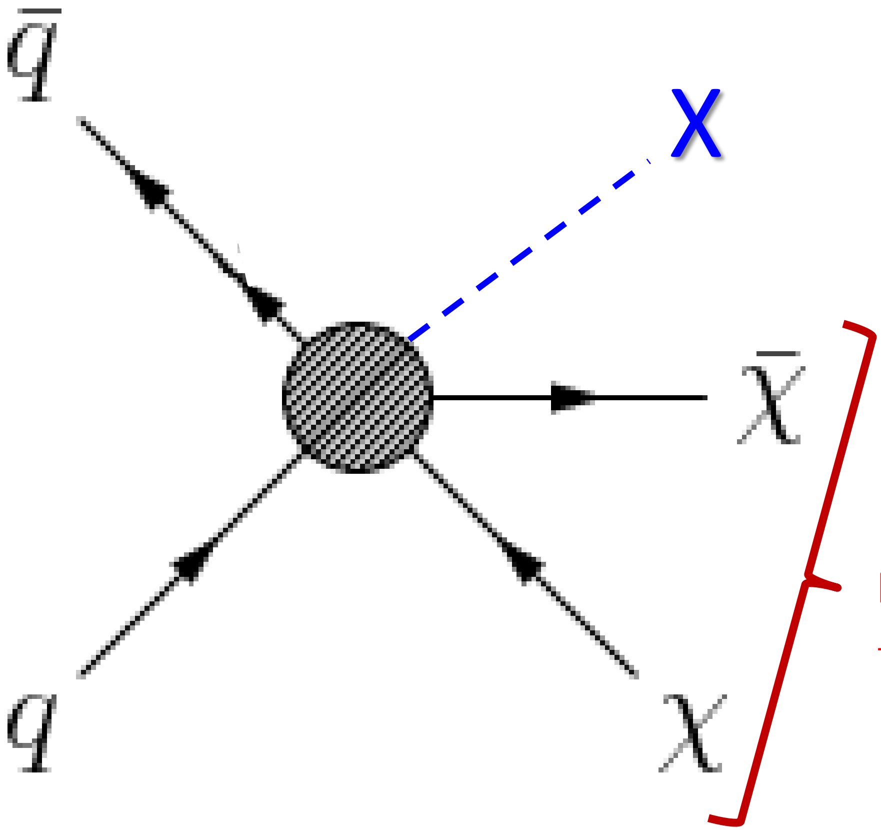
Full suite of SUSY searches updated with 36 fb^{-1} for Moriond

Effect of JES/JER in hadronic SUSY analyses are typically at the ~5% level

Scaling to 100 fb^{-1} should not present any problems



Dark Matter at the LHC



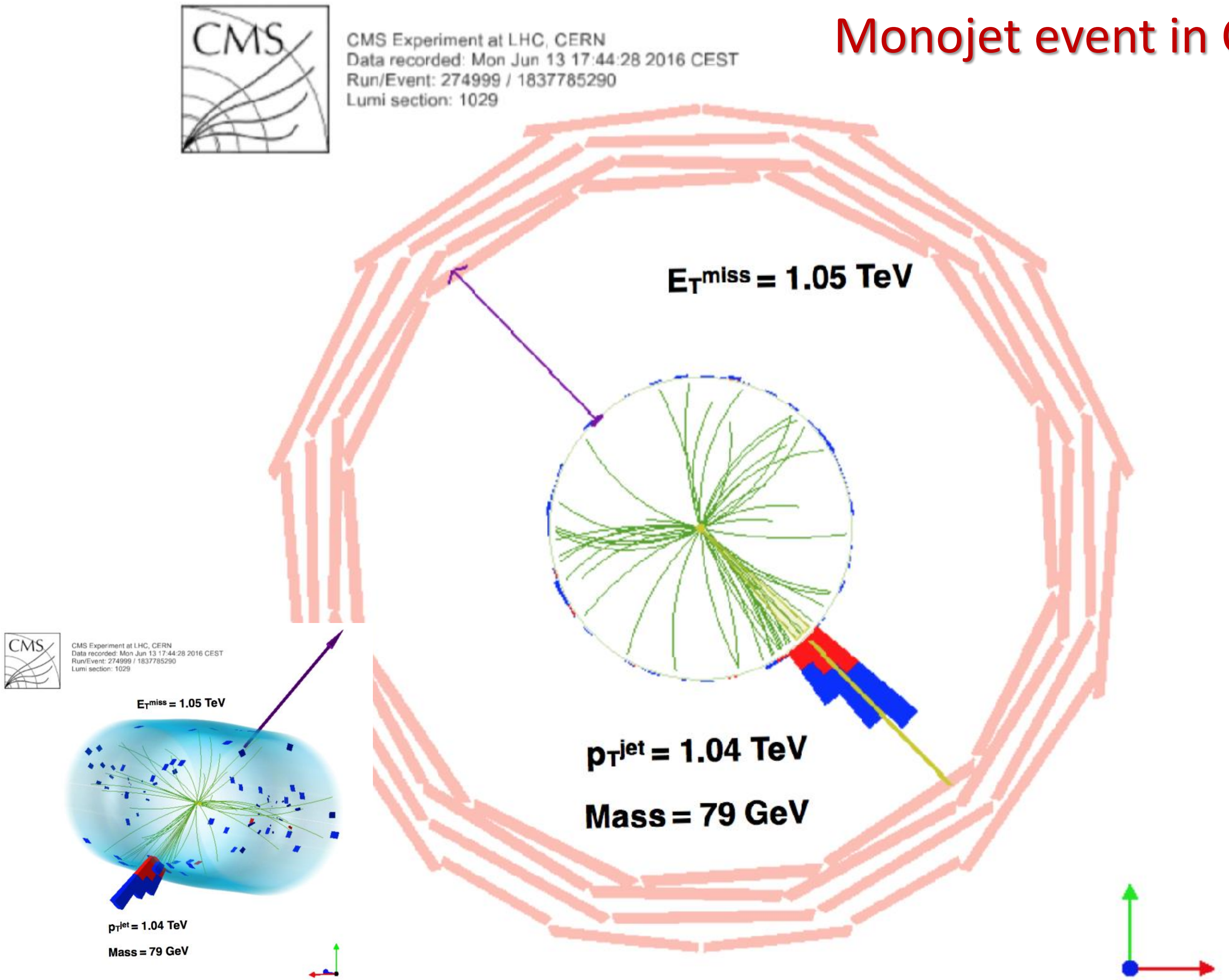
X can be any SM particle:

- Jet (quark or gluon)
- Photon
- W or Z
- Top quark
- Higgs boson

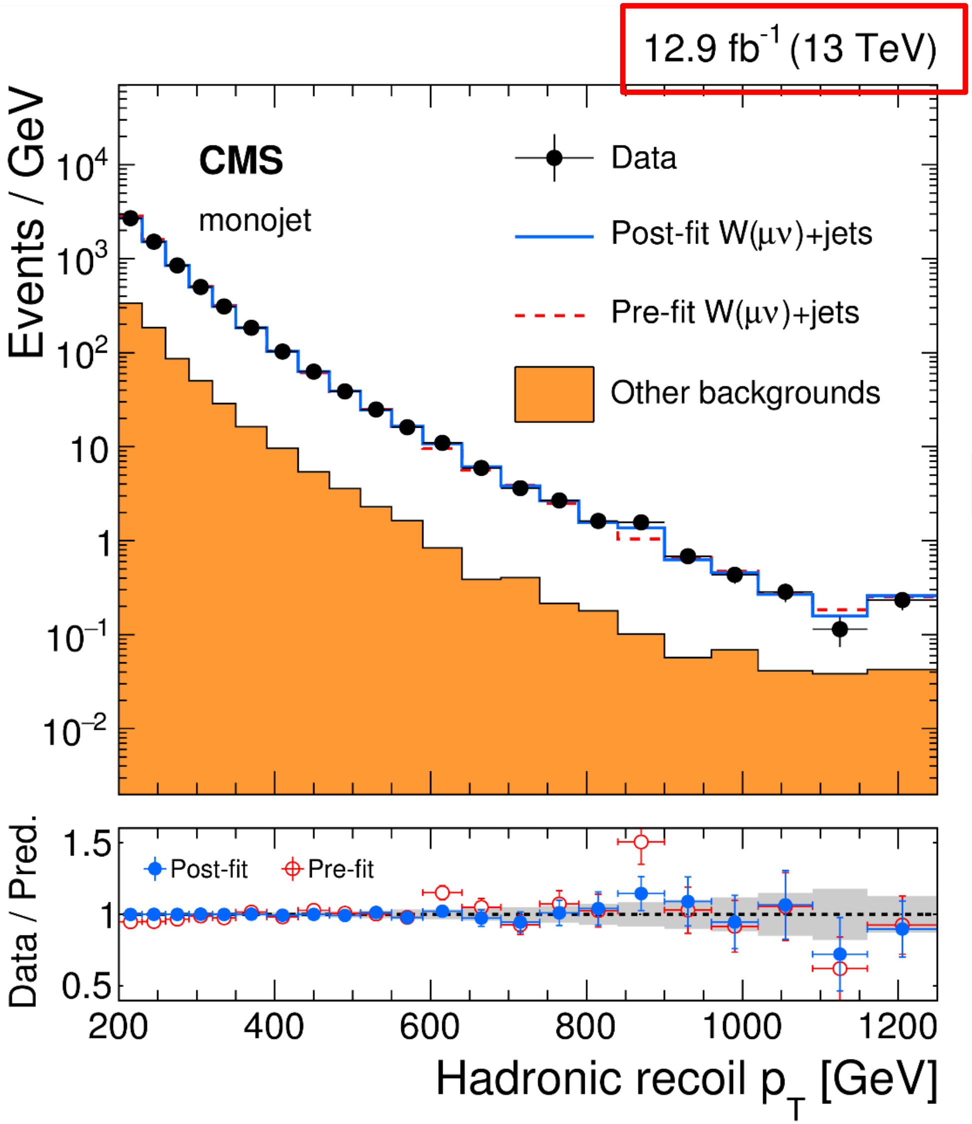
“Mono-mania”

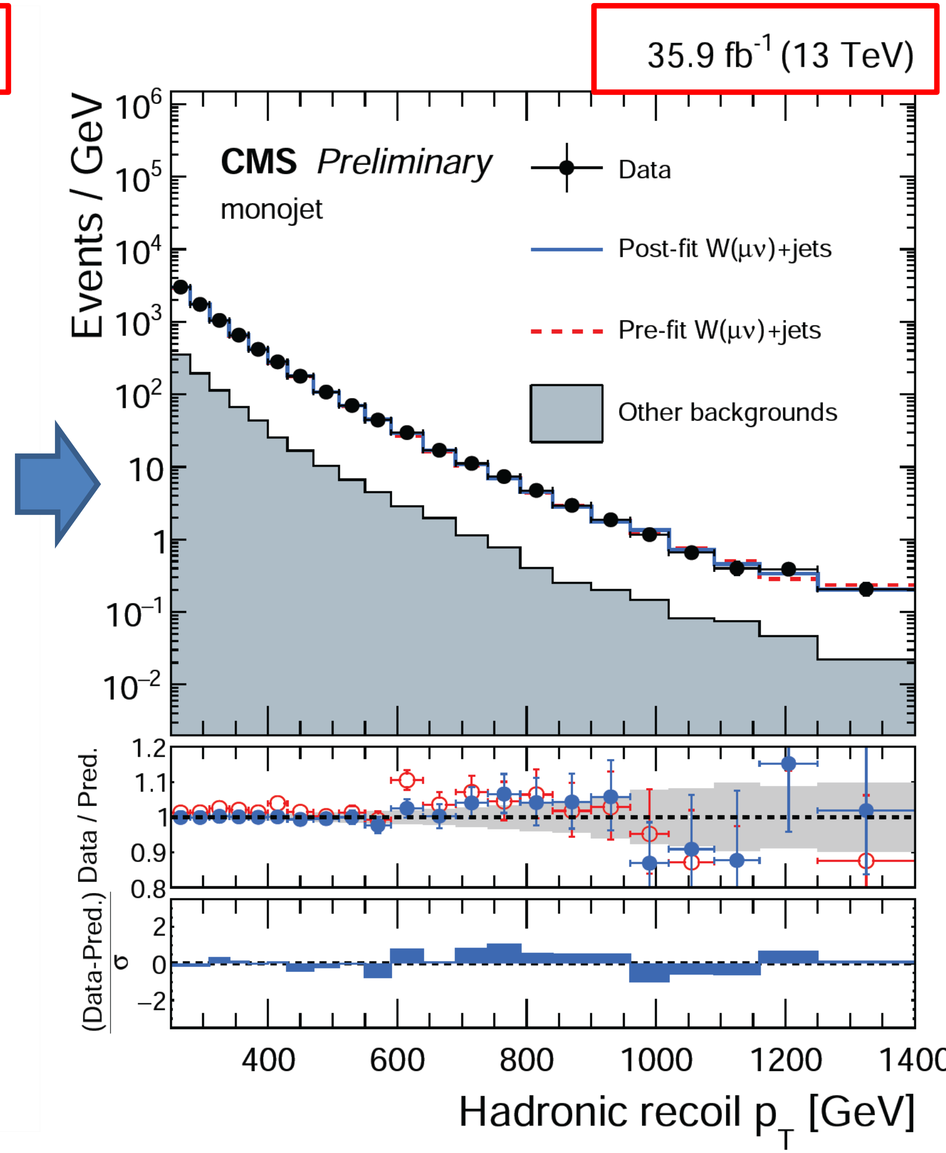
Not detected (WIMPs)
$\rightarrow$ “missing momentum”

Monojet event in CMS

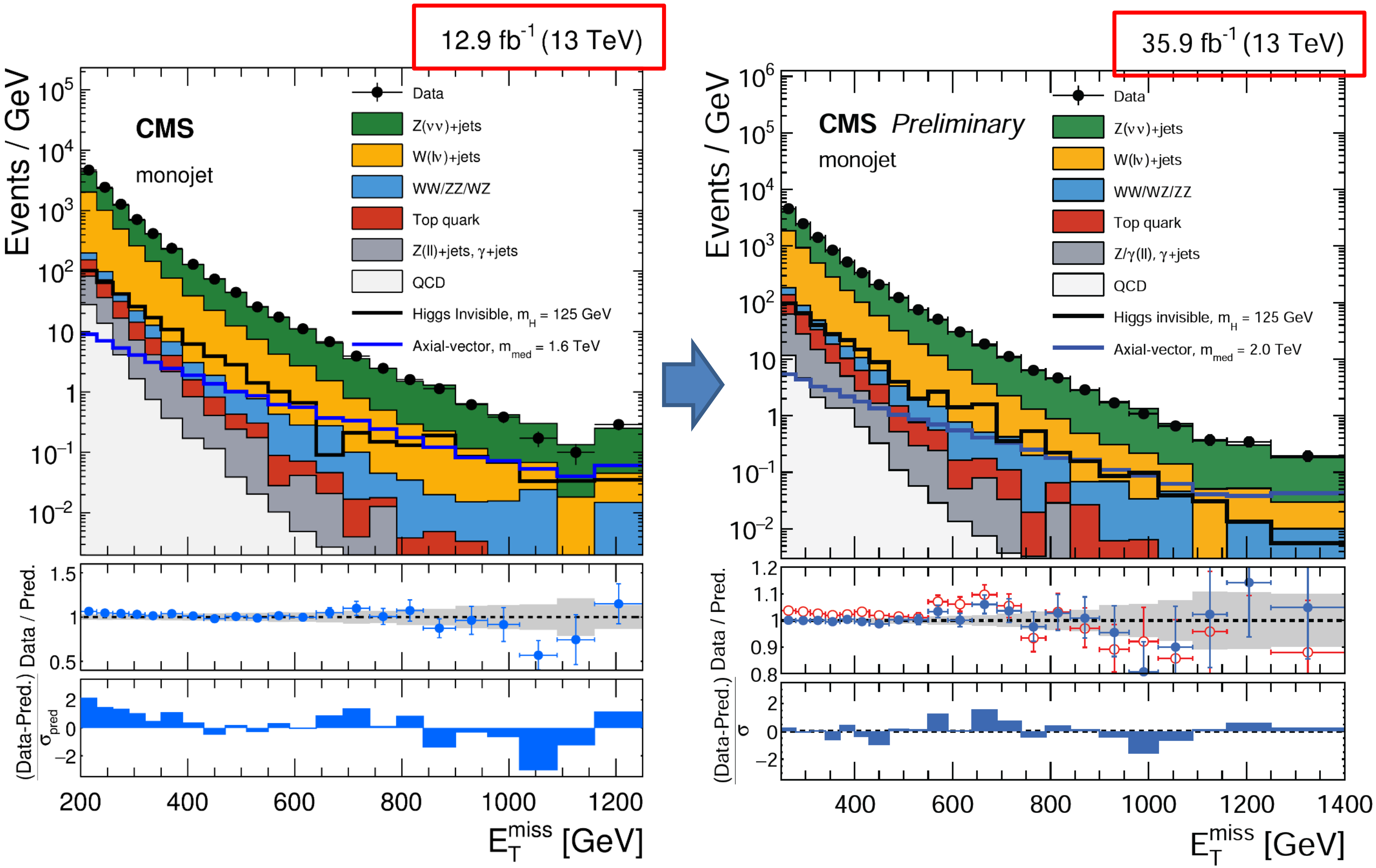


Check jet calibration using recoil in V+jet events





Look for signal in the MET tail

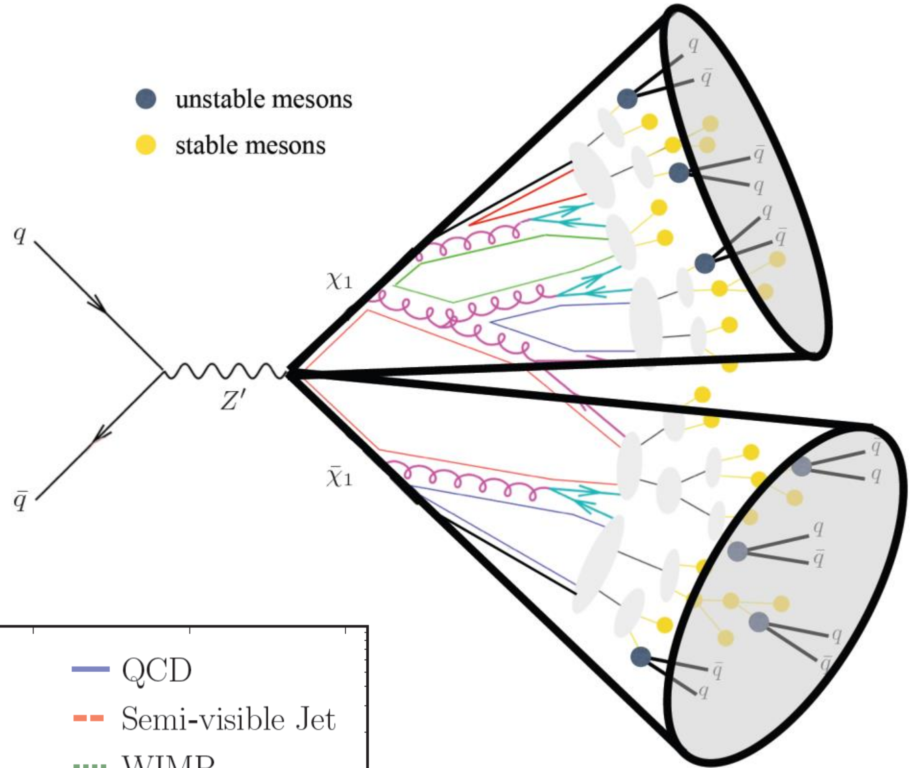


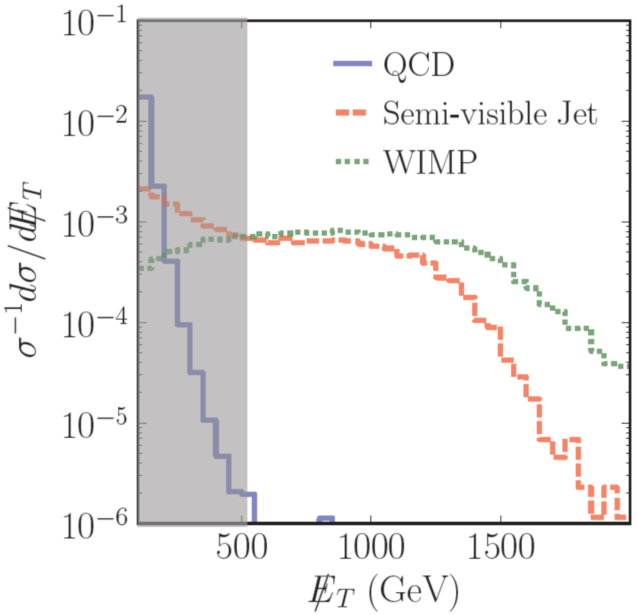
High-hanging Fruit: DM in Jets?

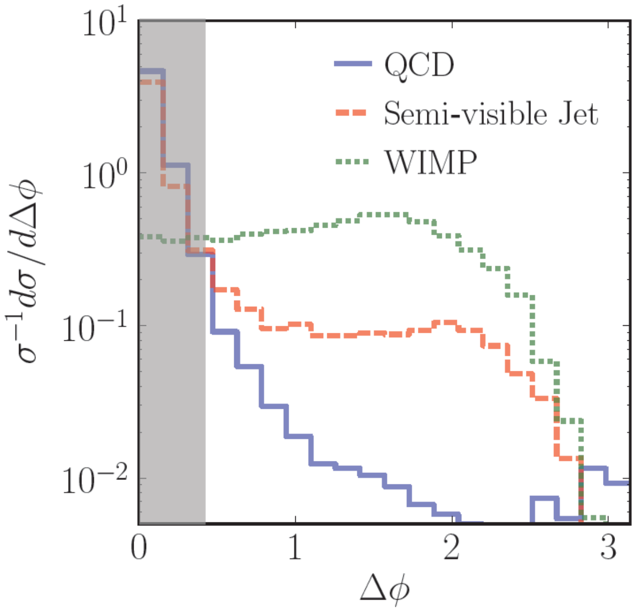
Dark Sector stable mesons produced inside jets along with unstable SM hadrons

Consequence: MET aligned with jets!

Can we find DM in jets with 100 fb^{-1} ?







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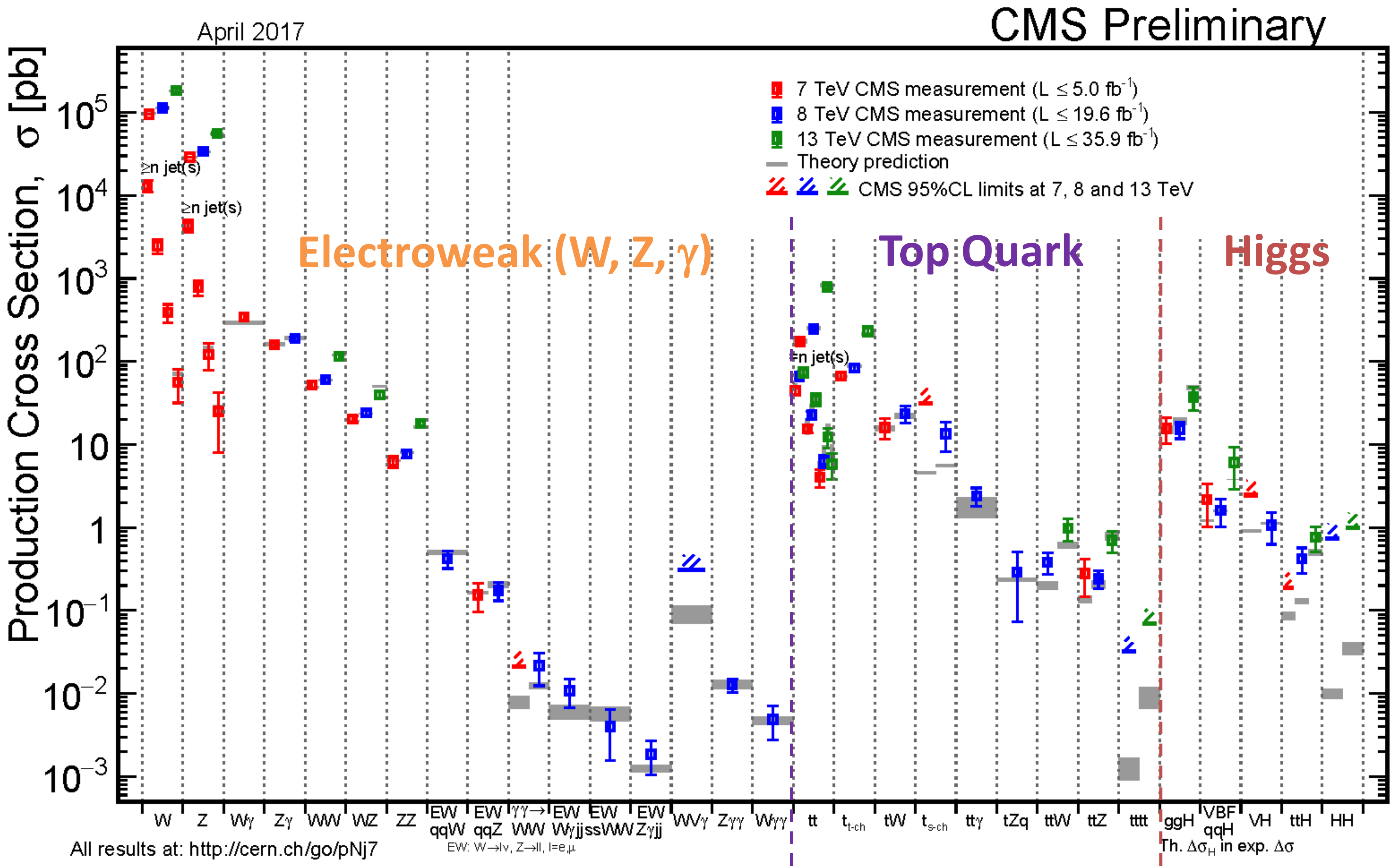
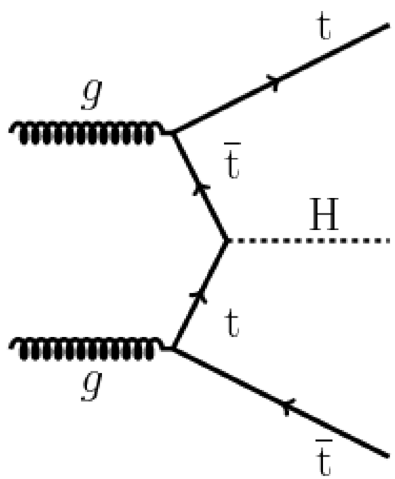
Standard Model Measurements

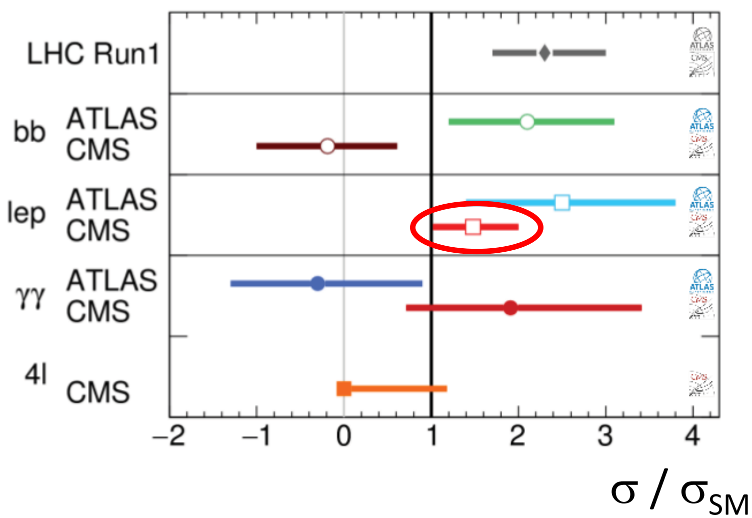


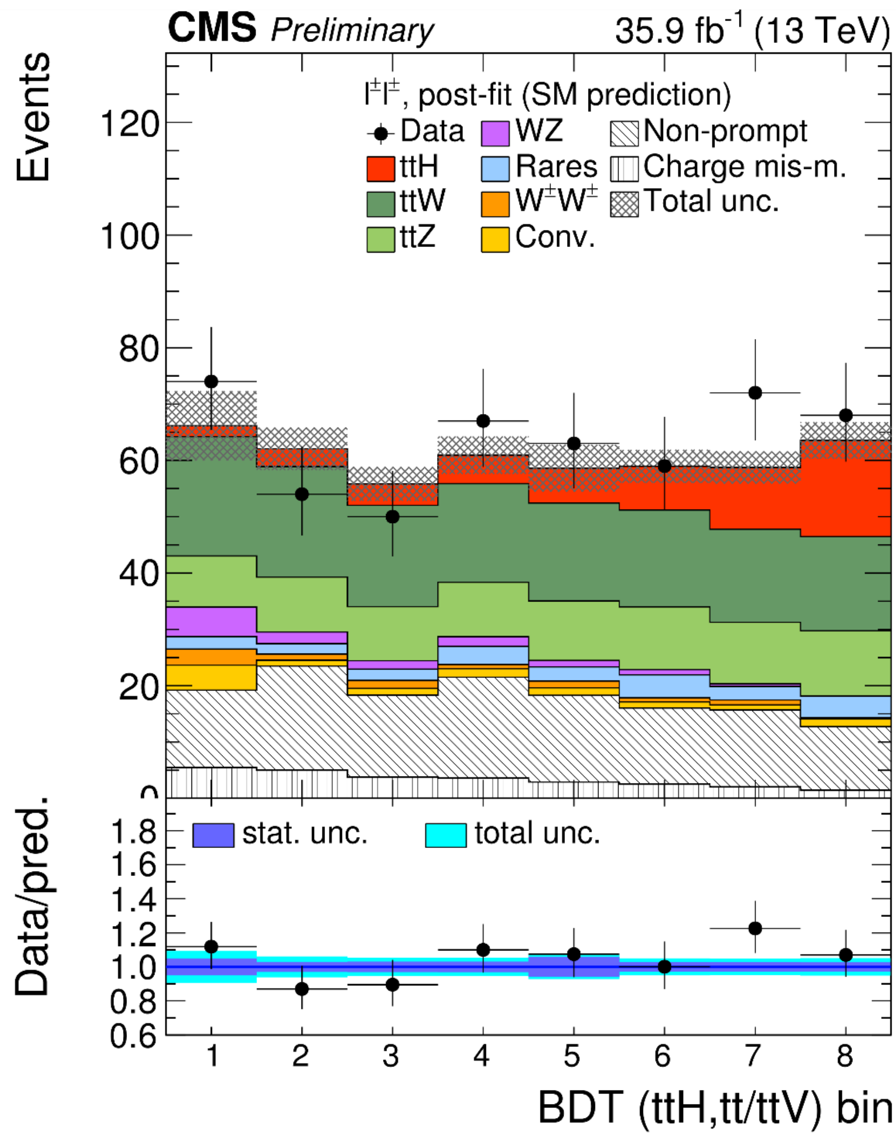
Just getting started at 13 TeV, how far can we dig at 100 fb^{-1}?

Is there a floor to some measurements from jet energy/resolution?

Anomalous Top-Higgs Coupling?







More events than expected, not yet significant

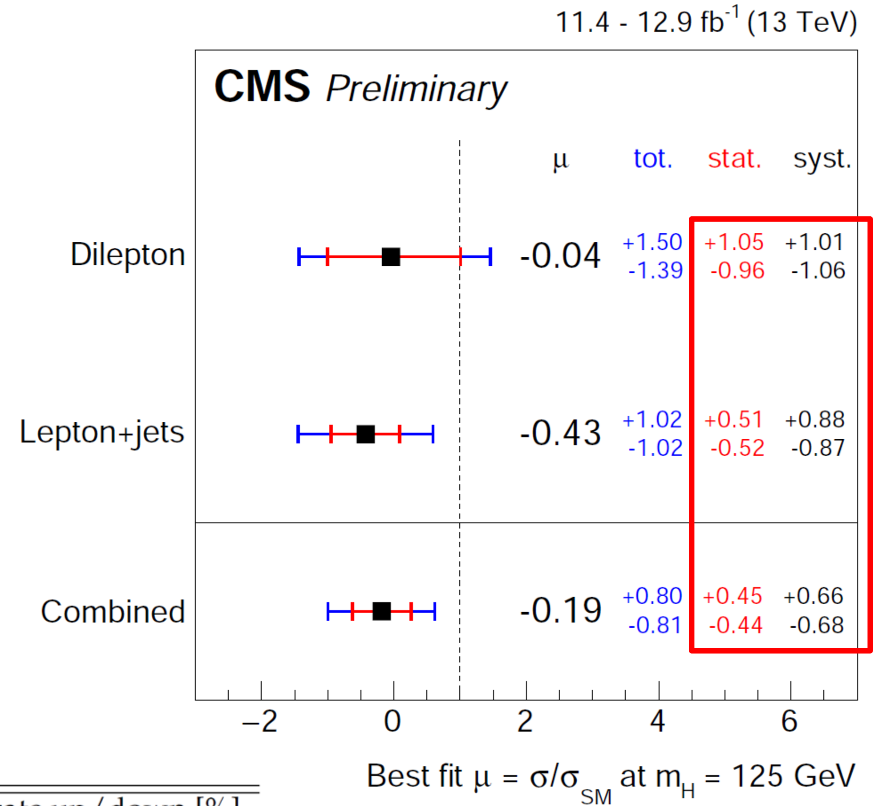
Lepton final state is most sensitive, what about bb?

ttH(bb)

Complicated final state with up to 8 jets and 4 b jets!

Dominant background contributions from tt + bb/cc

JES is largest source of systematic (@ 13 fb^{-1})

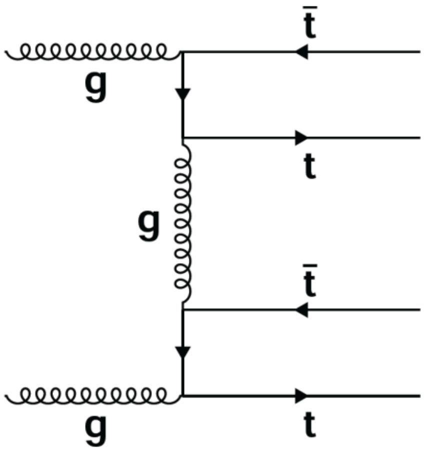


Process	$t\bar{t}$ rate up/down [%]	$t\bar{t}H$ rate up/down [%]
Jet energy scale	+12.6/ − 11.8	+8.4/ − 8.0
Jet energy resolution	+0.2/ − 0.3	−0.0/ − 0.1
Pile-up	+0.1/ − 0.1	−0.2/ + 0.1
Electron efficiency	+0.5/ − 0.5	+0.5/ − 0.5
Muon efficiency	+0.4/ − 0.4	+0.4/ − 0.4
Electron trigger efficiency	+1.2/ − 1.2	+1.3/ − 1.3
Muon trigger efficiency	+0.8/ − 0.8	+0.9/ − 0.9
b-Tag HF contamination	−9.4/ + 9.8	−2.6/ + 2.8
b-Tag HF stats (linear)	−3.1/ + 3.3	−2.5/ + 2.7
b-Tag HF stats (quadratic)	+2.6/ − 2.4	+2.4/ − 2.2
b-Tag LF contamination	+7.1/ − 5.2	+5.8/ − 4.5
b-Tag LF stats (linear)	−2.0/ + 4.4	+0.5/ + 1.5
b-Tag LF stats (quadratic)	+2.1/ + 0.2	+1.5/ + 0.5
b-Tag charm Uncertainty (linear)	−11.1/ + 14.9	−3.1/ + 4.1
b-Tag charm Uncertainty (quadratic)	+0.5/ − 0.5	−0.0/ + 0.0

Given in the excess in the leptonic channel, this is a critical analysis @ 100 fb^{-1}

Are there new ideas at the jet reco/calibration/ID level that mitigate PU effects in high-jet-multiplicity events?

Four Tops

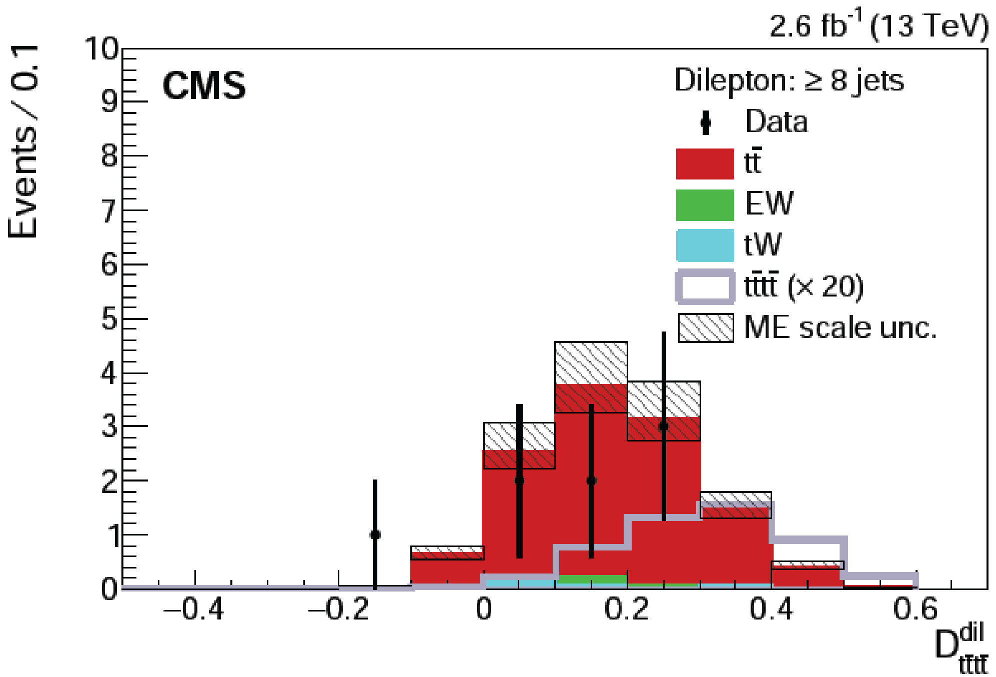


5 orders of magnitude smaller cross section than ttbar, sensitive to new physics decaying to top pairs

JES/JER not dominant here, but only 2.6 fb^{-1} used

Observed limit 69 fb @ 95% C.L. (SM = 9.1 fb)

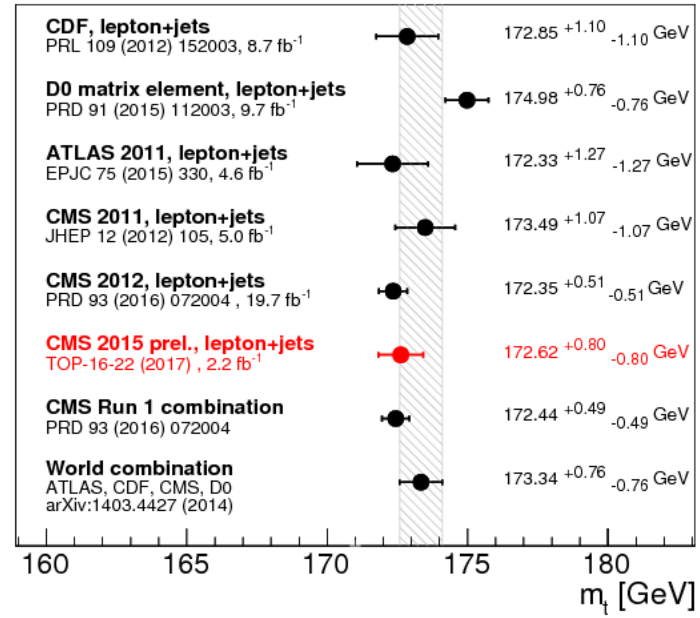
Assuming sqrt(L) scaling, this channel starts to approach the SM prediction with 100 fb^{-1}



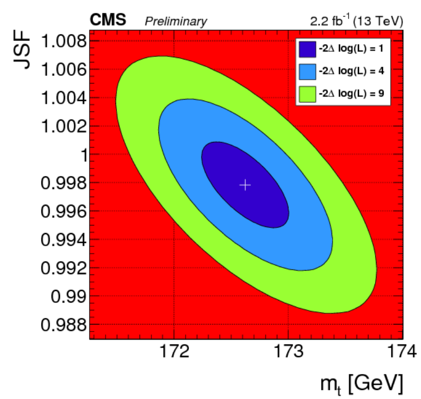
First Look at Top Mass (2.2 fb^{-1})

Critical parameter in the Standard Model, different methods with different systematic uncertainties

No escaping the jet energy scale (unless you don't use jets!) Fit one overall scale factor simultaneously with m_t



	δm_t	δJSF
Experimental uncertainties		
Method calibration	0.07	<0.001
Jet energy corrections (quad. sum)	(0.30)	(0.006)
– JEC: InterCalibration	0.03	<0.001
– JEC: MPFInSitu	0.12	0.001
– JEC: Uncorrelated non-pileup	0.26	0.004
– JEC: Uncorrelated pileup	0.11	0.004
Muon energy scale	0.03	<0.001
Jet energy resolution	0.04	0.001
b tagging	0.05	<0.001
Pileup	0.01	0.001
Non-$t\bar{t}$ background	0.19	0.001
Modeling of hadronization		
JEC: Flavor-dependent	0.41	0.001
b-jet modeling	0.18	<0.001
Modeling of perturbative QCD		
PDF	0.09	0.001
Ren. and fact. scale	0.01	<0.001
ME/PS matching	0.04	0.001
Parton shower scale	0.23	0.001
ME generator	0.12	0.001
Top quark transverse momentum	0.01	<0.001
Modeling of soft QCD		
Underlying event	0.18	0.007
Color reconnection modeling	0.22	0.001
Systematic	0.70	0.010
Statistical (expected)	0.38	0.003
Total (expected)	0.80	0.010



$$m_t = 172.62 \pm 0.38\,(\text{stat.+JSF}) \pm 0.70\,(\text{syst.})\ \text{GeV}\,,$$
$$\text{JSF} = 0.998 \pm 0.003\,(\text{stat.}) \pm 0.010\,(\text{syst.})\,.$$

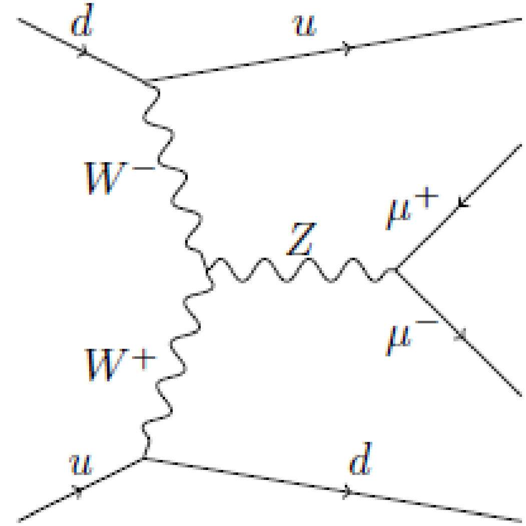
Relatively large systematic due to early JEC

Are flavor corrections under control?

What is the ultimate uncertainty achievable in 100 fb^{-1} ?

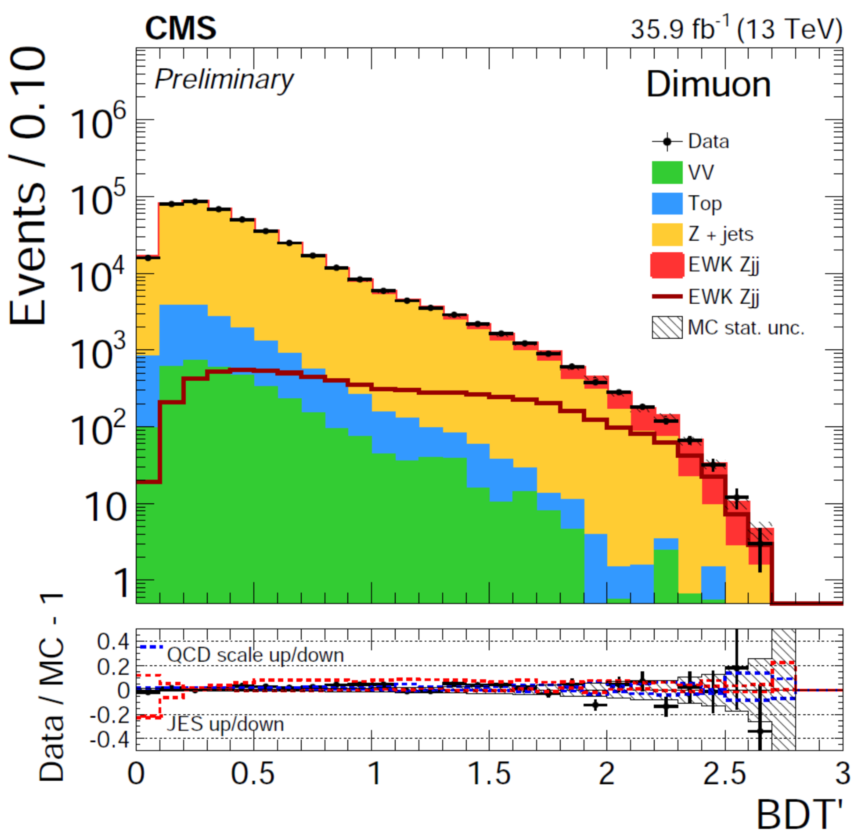
Talks this afternoon by M. Mulders and A. Hoang on top mass, and J. Kieseler on jet flavor corrections

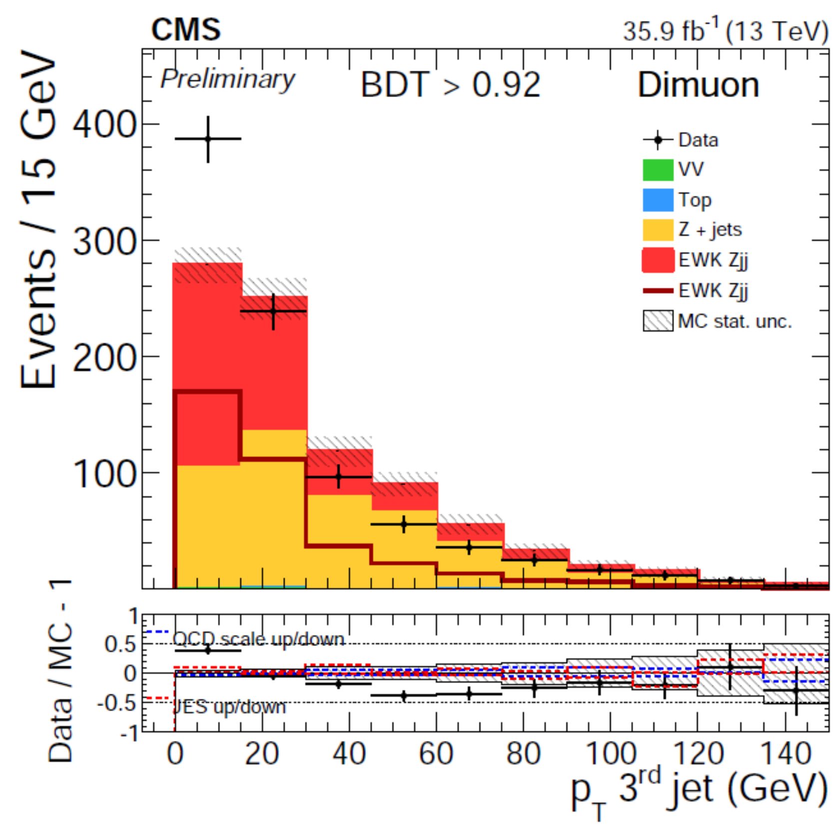
VBF with Z + jets (36 fb^{-1})



Pure EWK production of Z bosons, useful calibration for VBF processes (Higgs, etc)

Classic application of quark-gluon discrimination





Summary

- Physics goals @ 100 fb^{-1} and 13 TeV largely unchanged from 10 fb^{-1}
- LHC performance in 2017 should match the worst of 2016 (so far so good with 36 fb^{-1})
- Many new results using full 2016 dataset
  - Pile-up is not killing us yet!
  - Do we cross a threshold before 100 fb^{-1}?
    - I think not, at least in the bulk of analyses
    - Some analyses already systematics limited, there we will benefit from improved JetMET techniques