

ATLAS & CMS Run 1 Highlights

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Portorož 2015

Particle Phenomenology From the Early Universe to High Energy Colliders



**UNIVERSITÉ
DE GENÈVE**

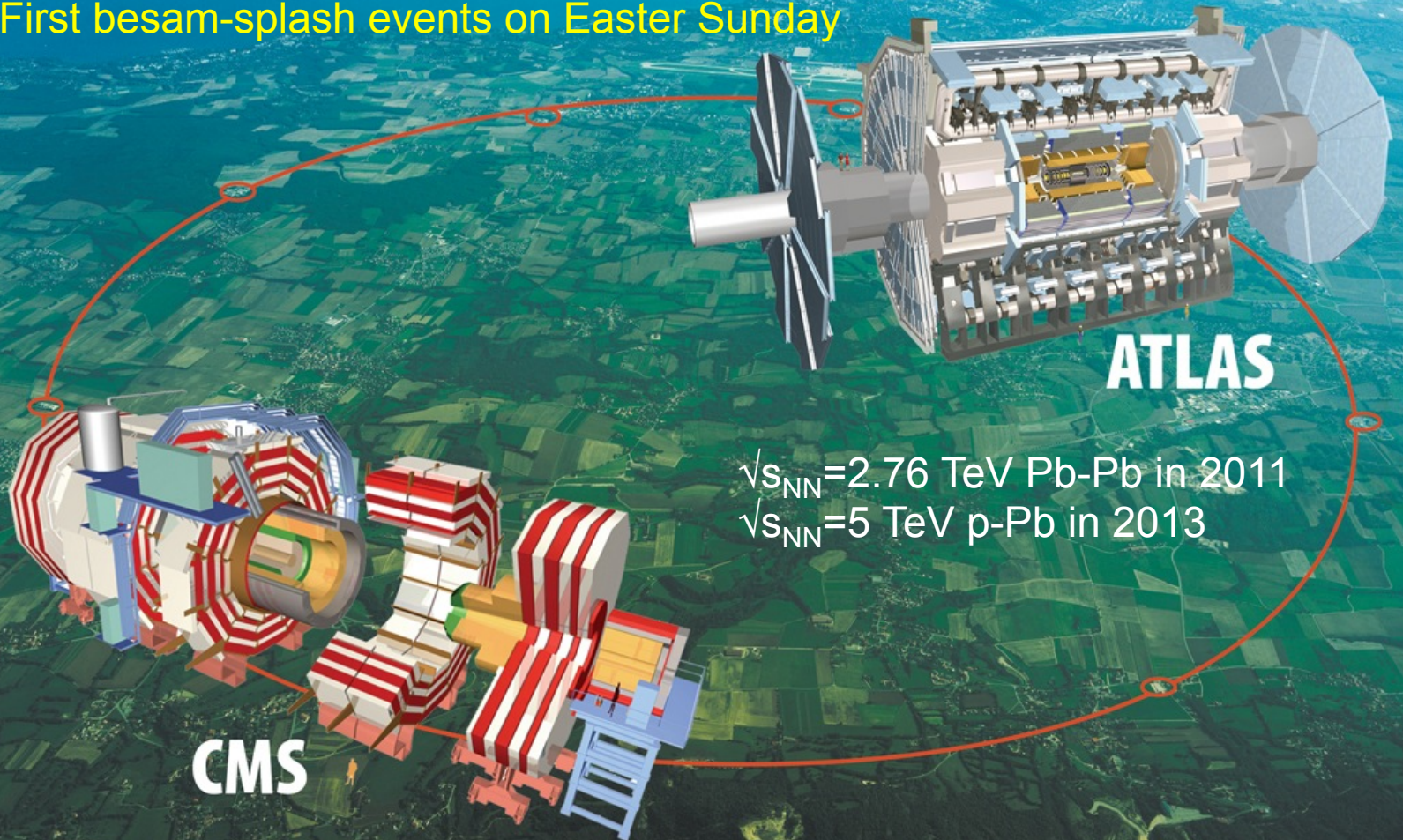
Disclaimer and Overview

- Personal selection of LHC results
- Impossible to do justice to the wealth of ATLAS and CMS results in 25 minutes
- Extensive program of precision measurements
 - Higgs now part of this family of precision objects
- Searches for new phenomena

The LHC

$\sqrt{s(pp)}$: (main physics runs)

- 7 TeV in 2010-11
- 8 TeV in 2012
- 13 TeV+ collisions scheduled in less than 2 months!
 - First beam-splash events on Easter Sunday

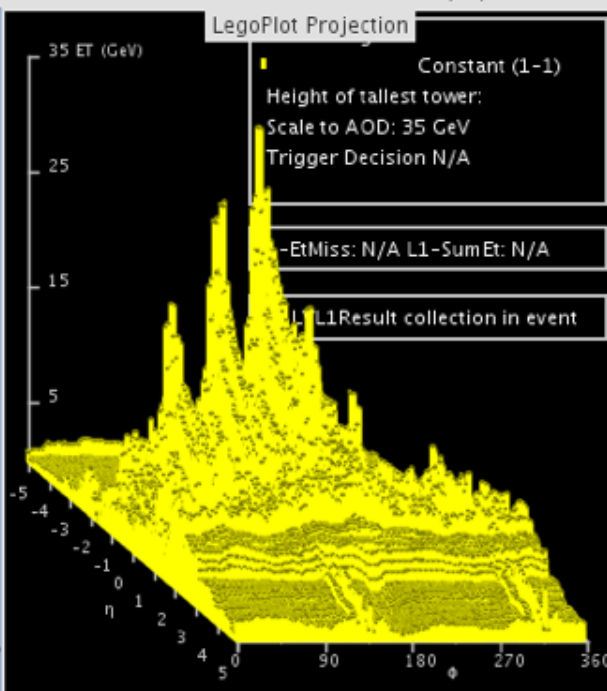
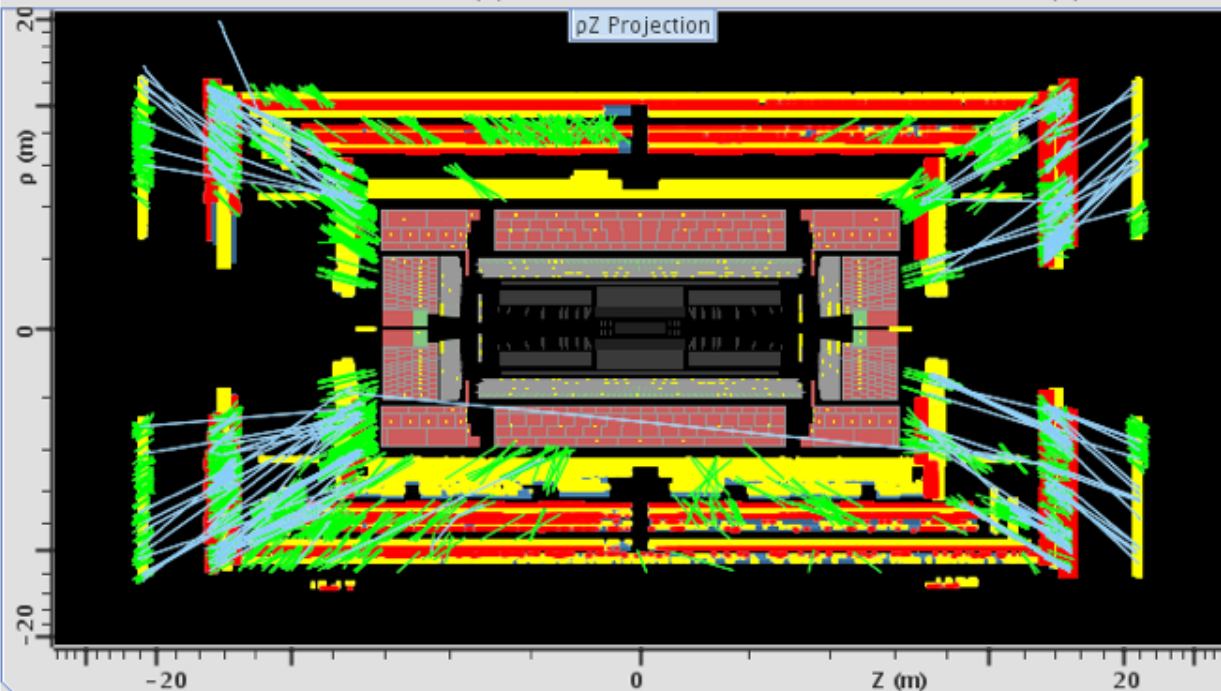
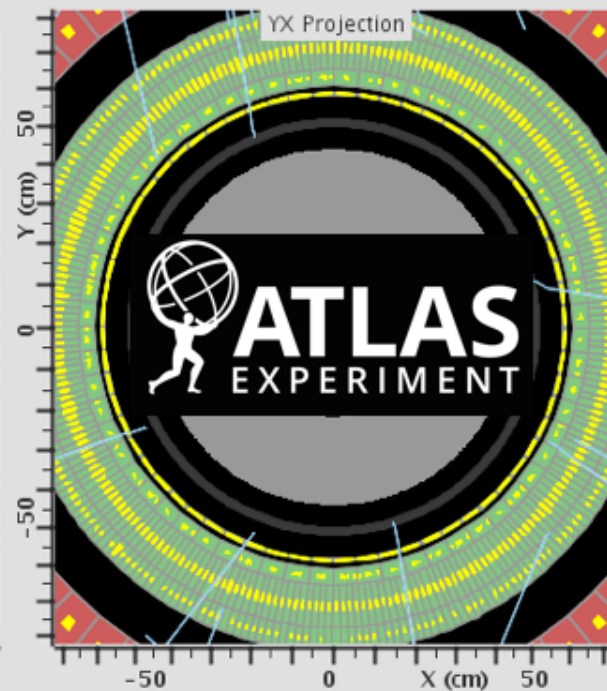
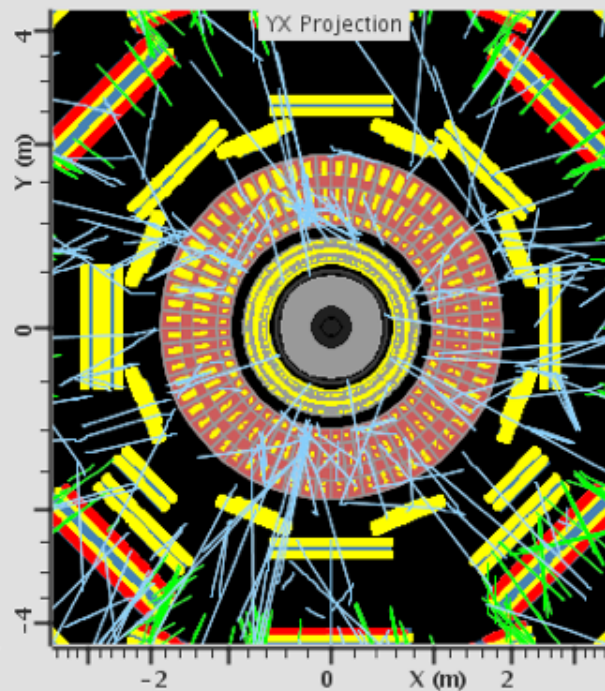
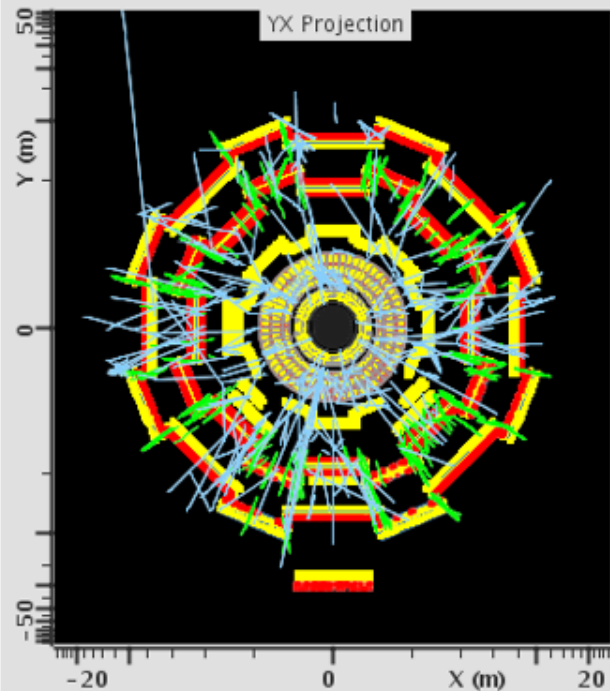


ATLAS

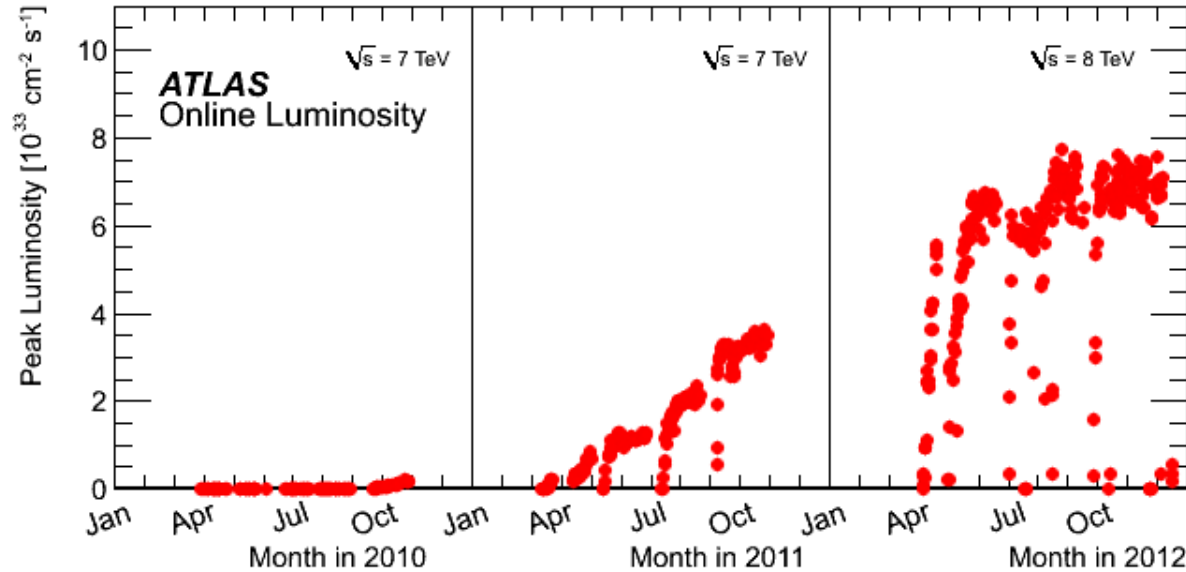
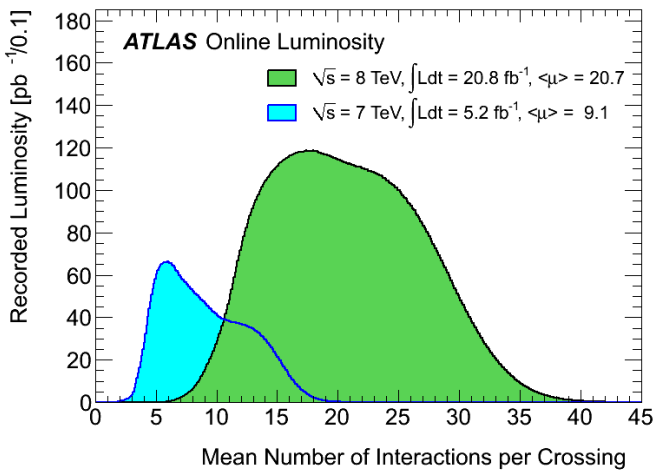
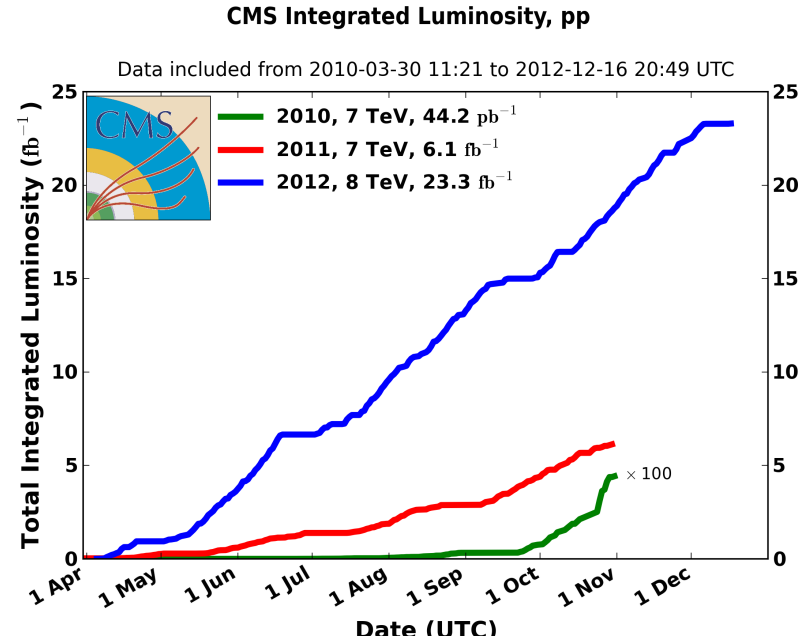
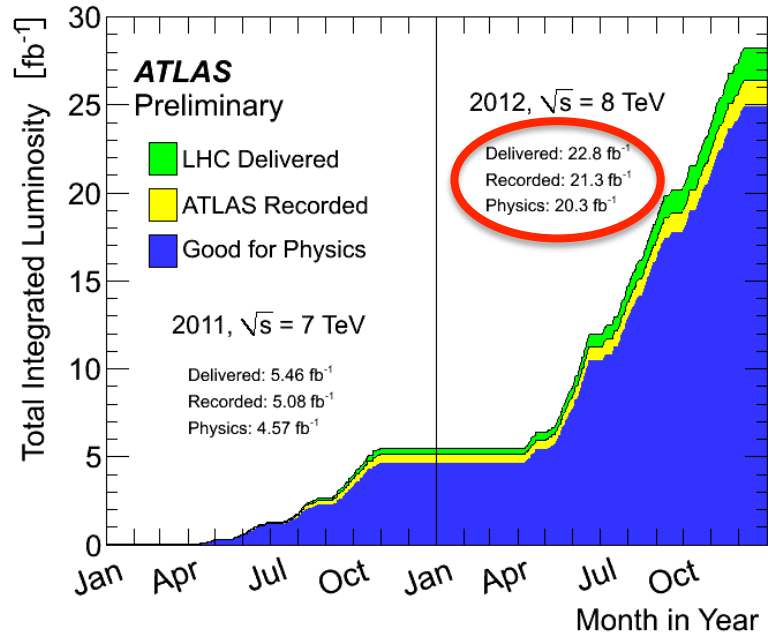
$\sqrt{s_{NN}} = 2.76$ TeV Pb-Pb in 2011

$\sqrt{s_{NN}} = 5$ TeV p-Pb in 2013

CMS



Luminosity



Data Quality & Trigger

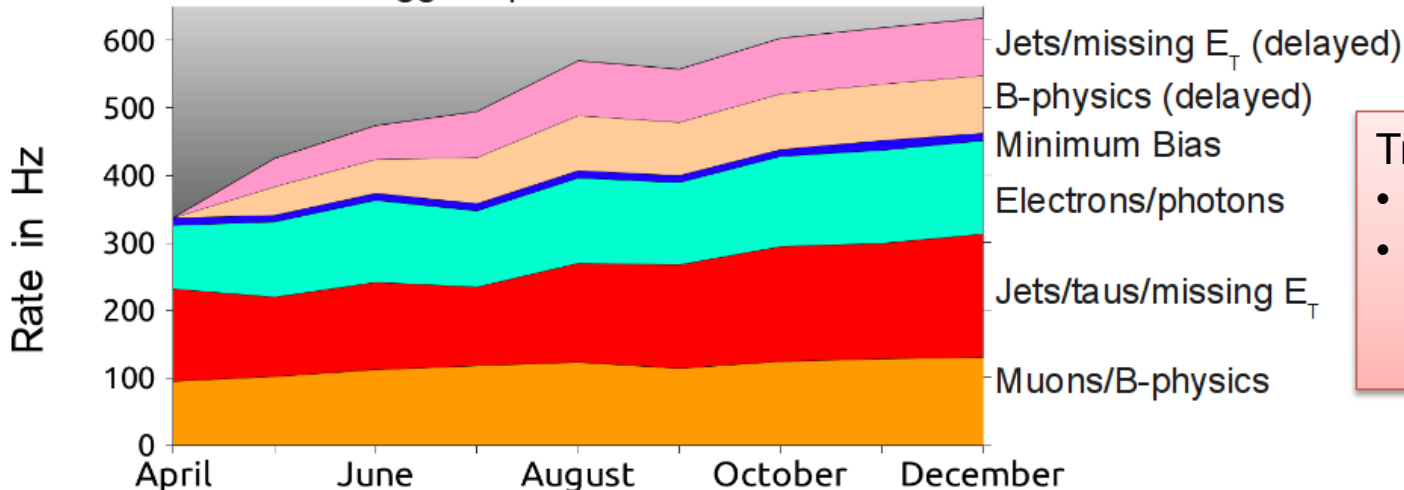
ATLAS p-p run: April-December 2012

Inner Tracker			Calorimeters		Muon Spectrometer				Magnets	
Pixel	SCT	TRT	LAr	Tile	MDT	RPC	CSC	TGC	Solenoid	Toroid
99.9	99.1	99.8	99.1	99.6	99.6	99.8	100.	99.6	99.8	99.5

All good for physics: 95.5%

Luminosity weighted relative detector uptime and good quality data delivery during 2012 stable beams in pp collisions at $\sqrt{s}=8$ TeV between April 4th and December 6th (in %) – corresponding to 21.3 fb⁻¹ of recorded data.

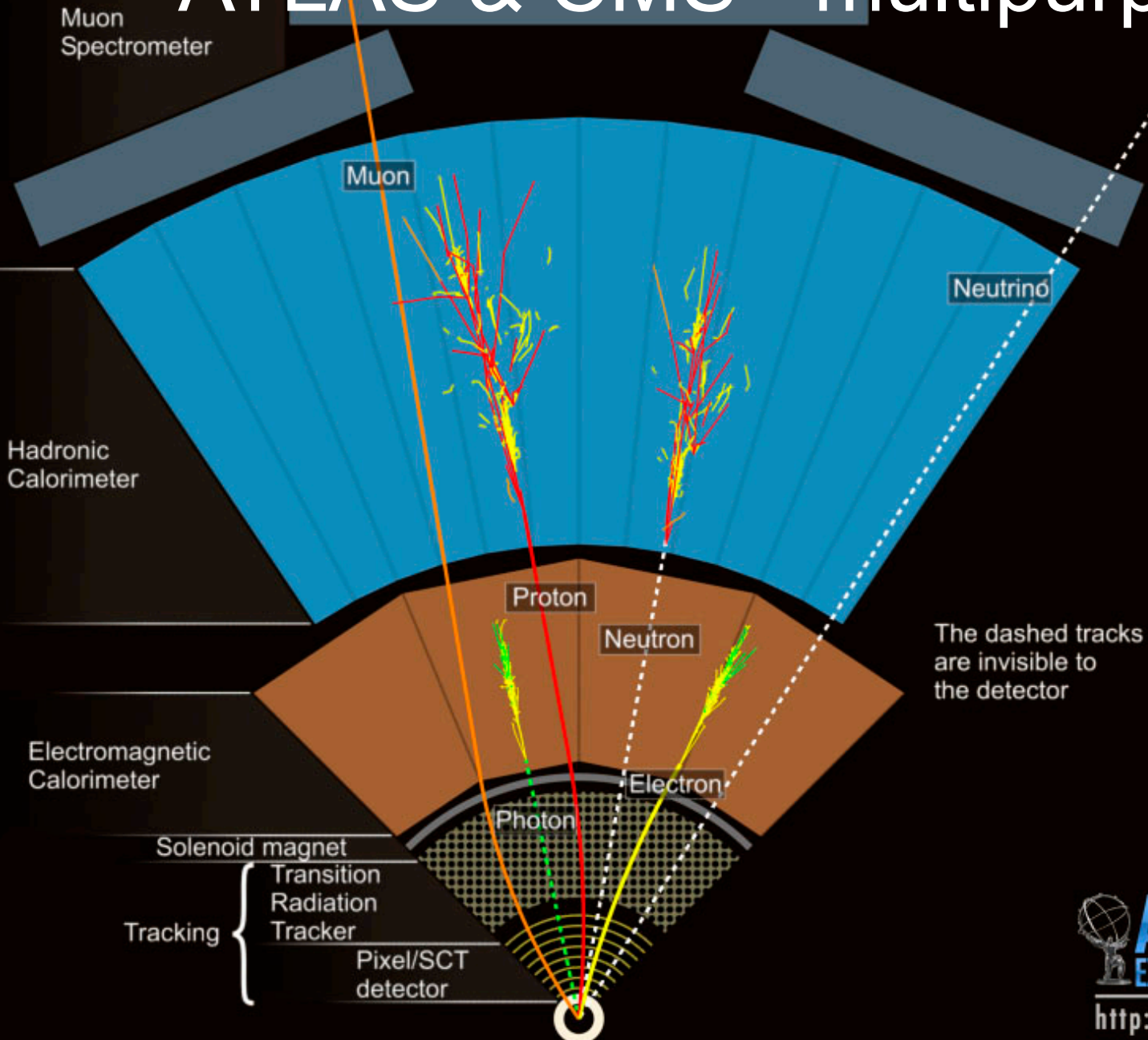
ATLAS Trigger Operation 2012



Trigger novelties in Run I:

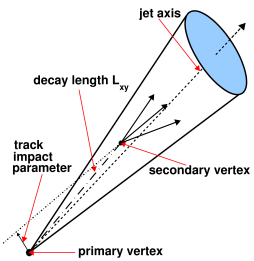
- Delayed streams
- Write out reduced event content (e.g. only jets) and increase rate

ATLAS & CMS - multipurpose

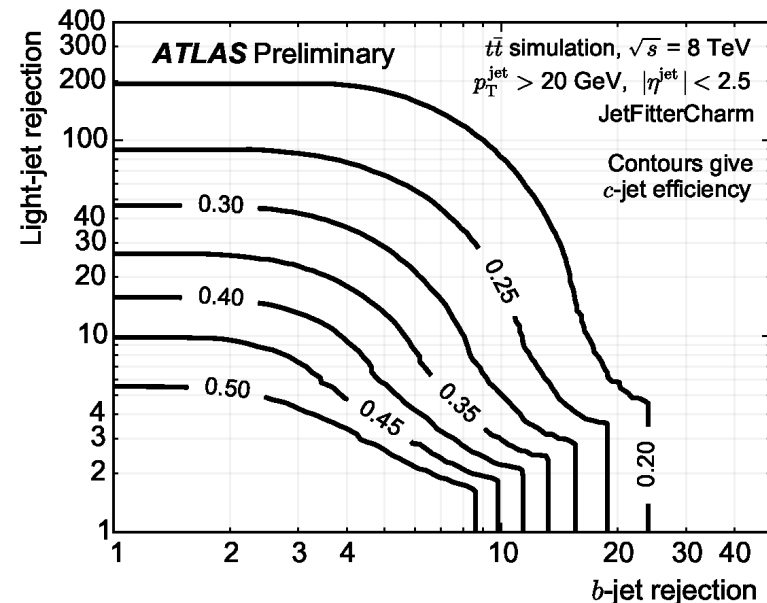
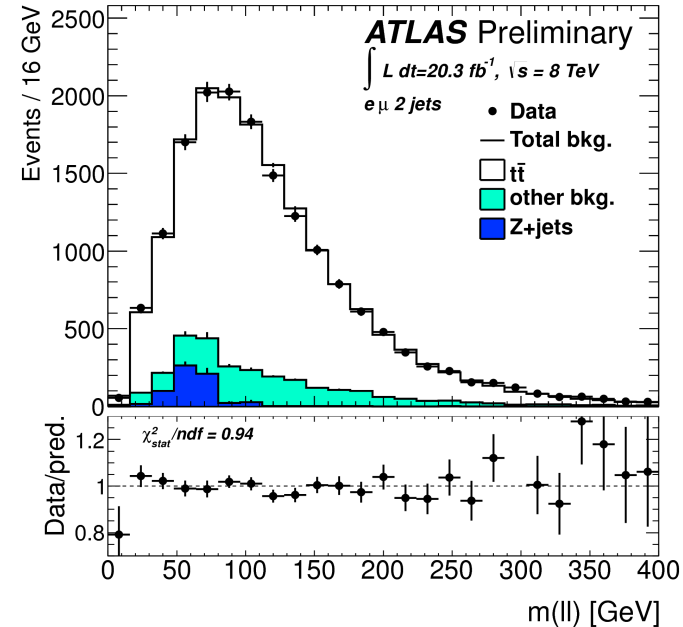
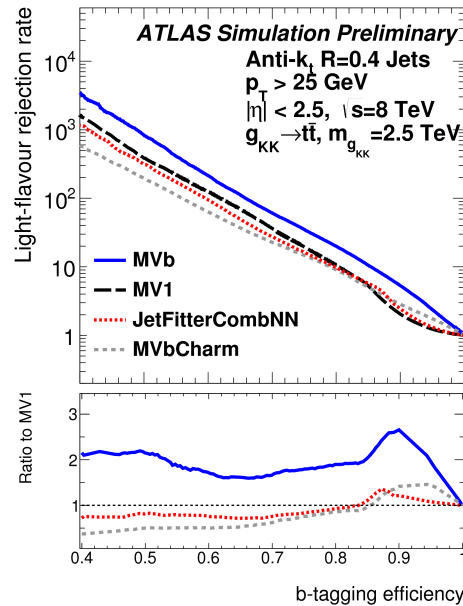


- Lepton/photon ID
 - $e/\gamma, \mu, \tau$
- Neutrinos = Missing E_T
- q & g = jets
 - b, c , light jets
 - **c-tagging**
- **Boosted top/W/Z/H objects**
 - LLP in ID, calo & MS
 - Lepton-jets
 - HIP, multi-charged particles,...

Jet-flavor tagging



- First Pixel detectors in hadron colliders
- Successful use of multivariate techniques
 - Still head room (e.g. Deep Learning)
- Excellent MC description
- First time inclusive b-tagging calibration using large $t\bar{t}$ sample
- First time c-tagging
- B-tagging in dense environments (high- p_T top), e.g. MVb algorithm
- Challenge: very high- p_T flavor-tagging



Hadronic W & Z decays

- Hadronic W, Z, H, top decays have dominant decay modes

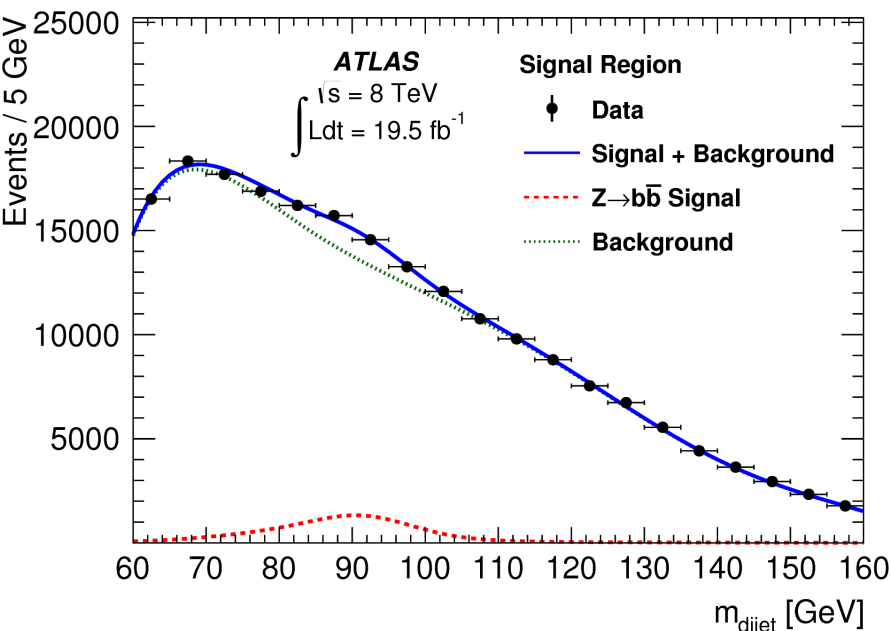
$BR(H \rightarrow \text{hadrons}) \approx 84\%$

$BR(Z \rightarrow \text{hadrons}) \approx 70\%$

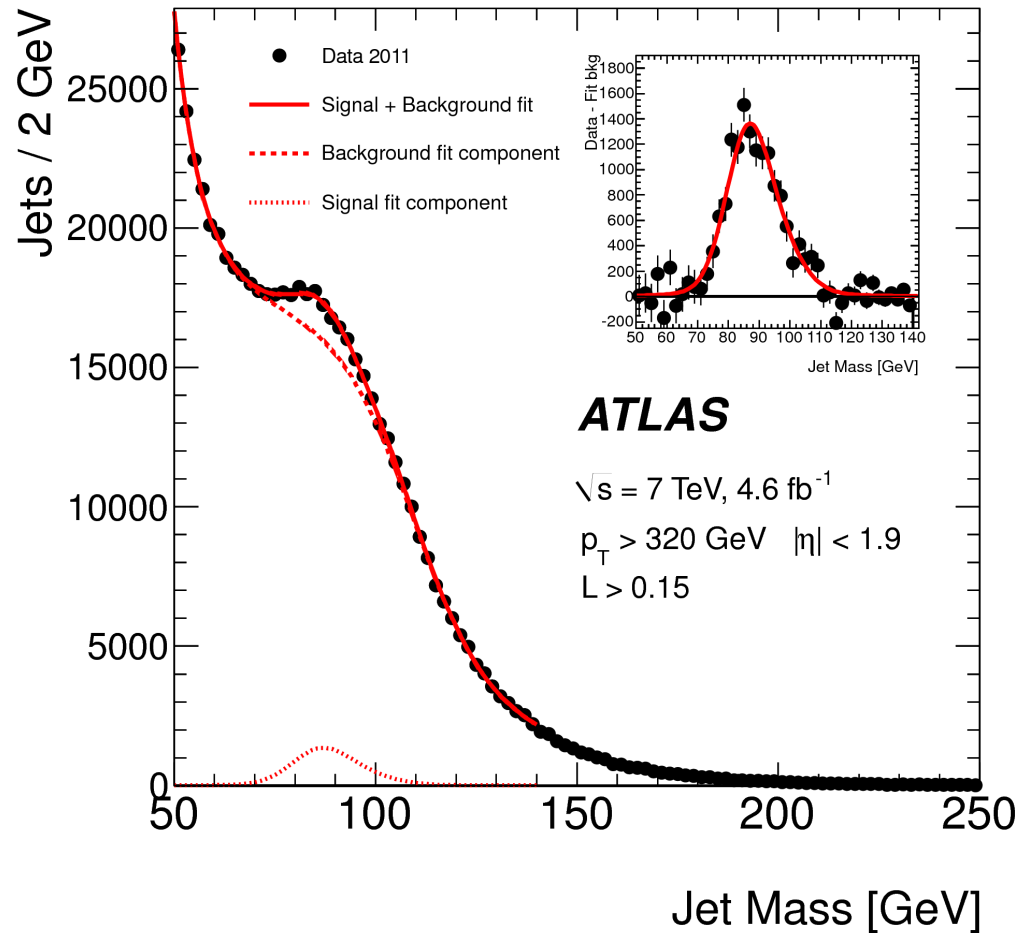
$BR(W \rightarrow \text{hadrons}) \approx 68\%$

- We can identify these decays

$Z \rightarrow b\bar{b}$ (important to study $H \rightarrow b\bar{b}$)

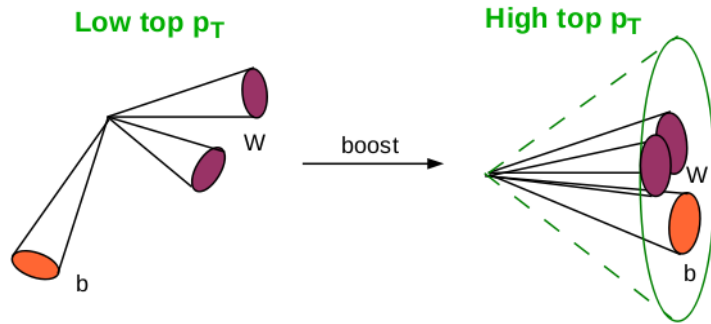
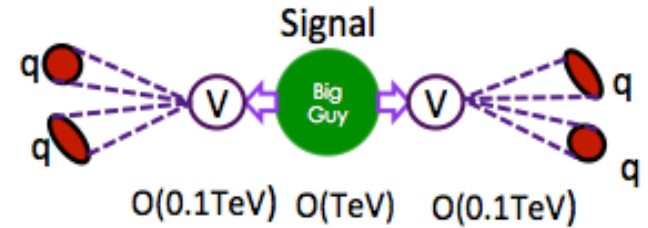


$W \rightarrow jj$, anti-kT clustering algorithm with $R=0.6$



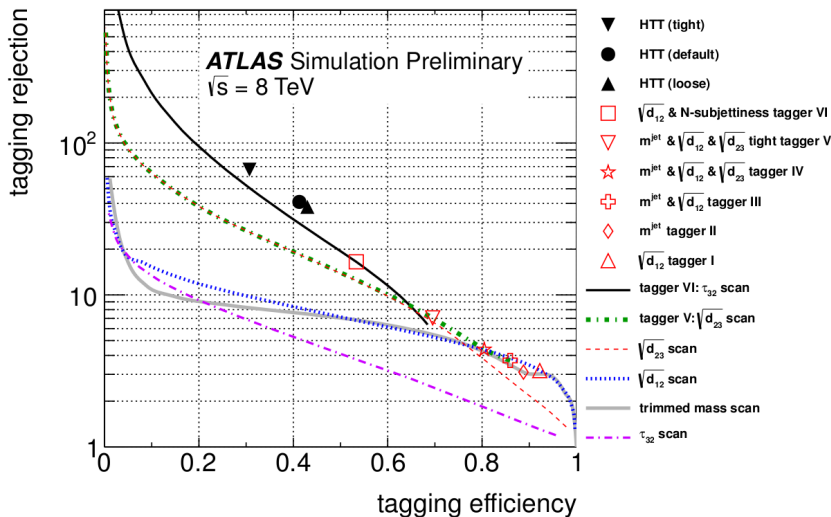
Boosted jets

- Hadronic W, Z, H, top decays crucial for high-mass searches

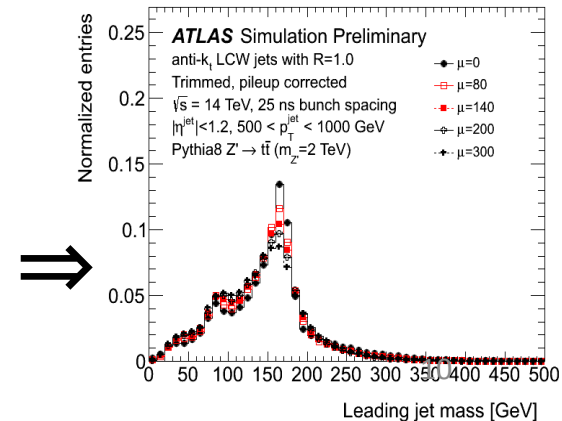
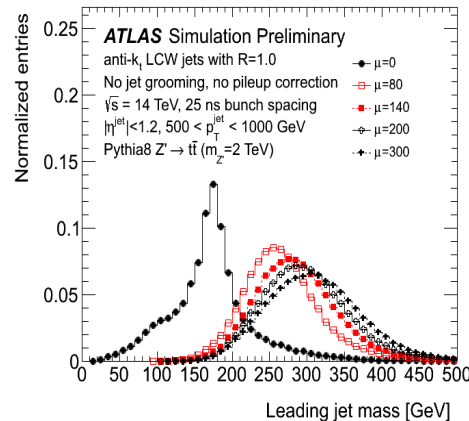


- Use fat jet to capture all daughters
- Grooming to remove pile-up
- Substructure to reject BG
- H → bb: use substructure and b-tagging

ATLAS-CONF-2013-084



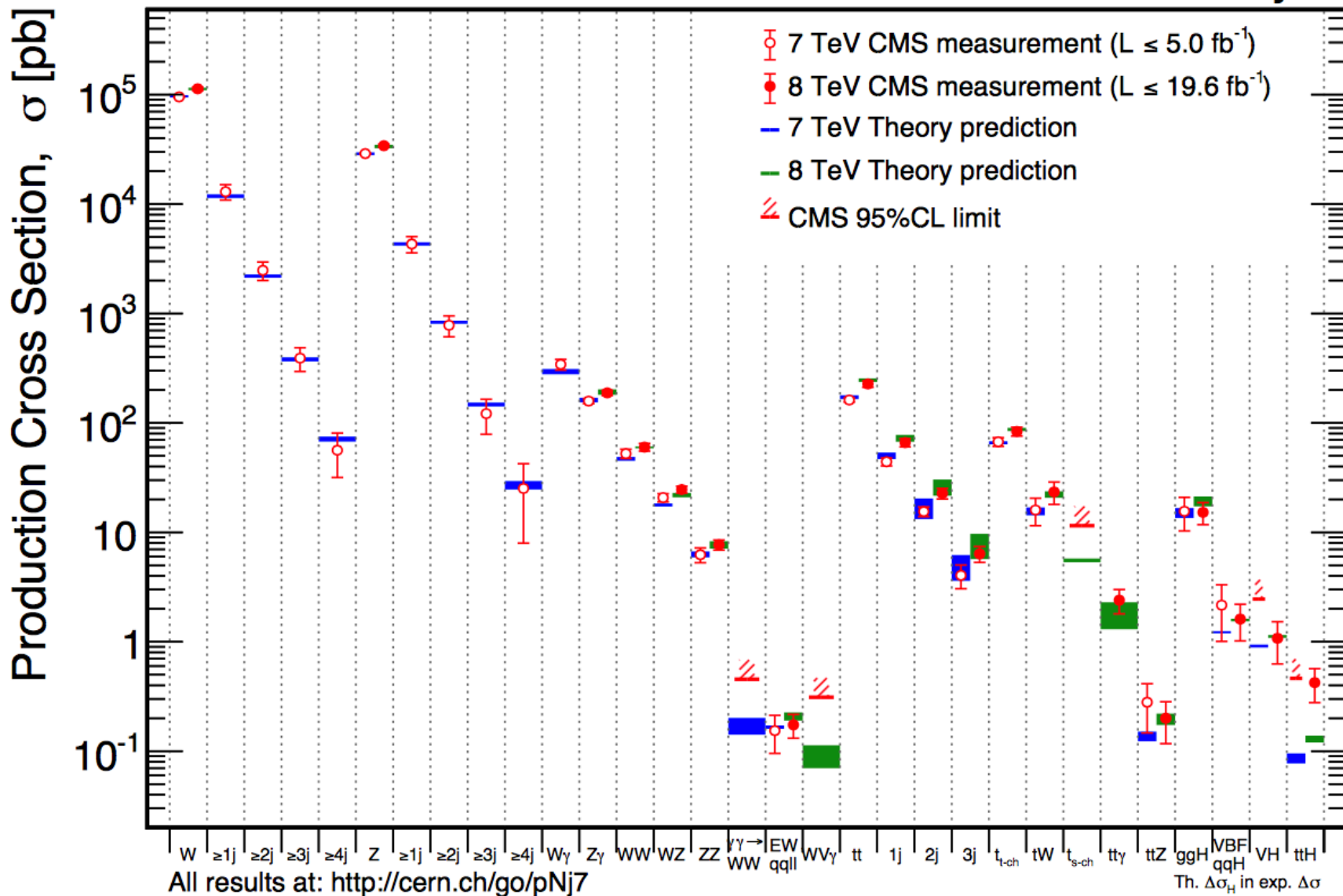
Grooming: recuperate the proper mass



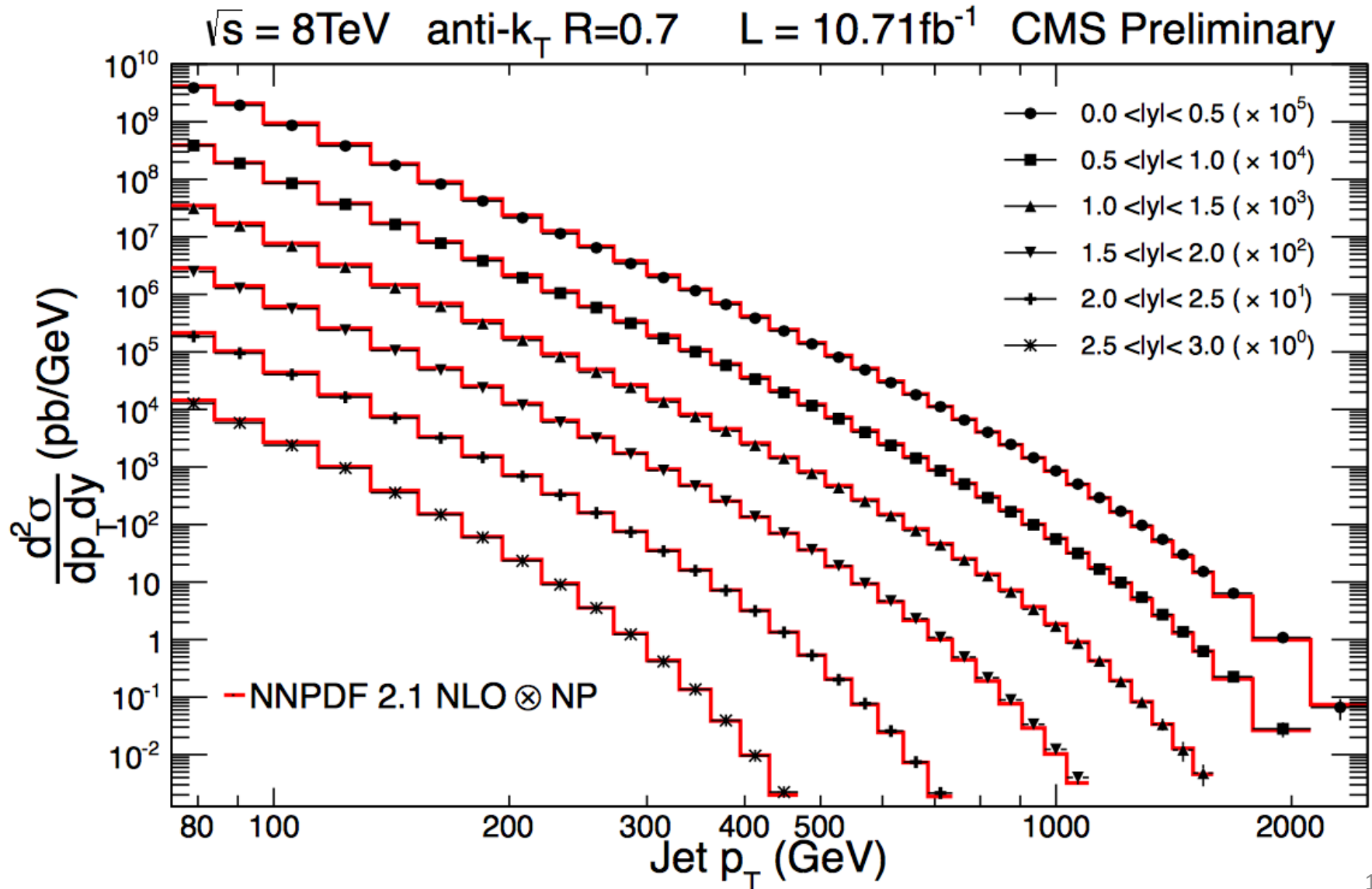
Precision Cross Section Measurements

Mar 2015

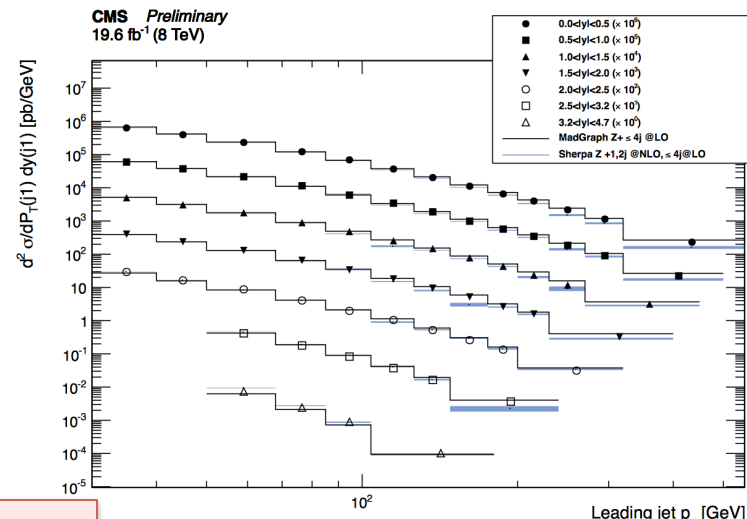
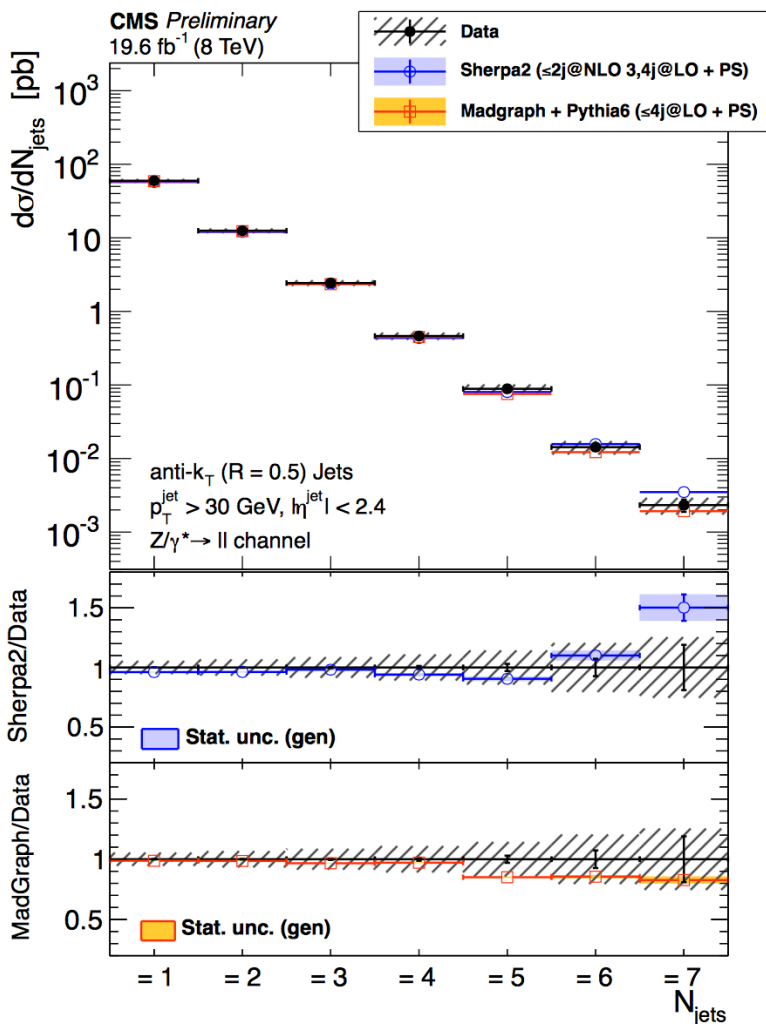
CMS Preliminary



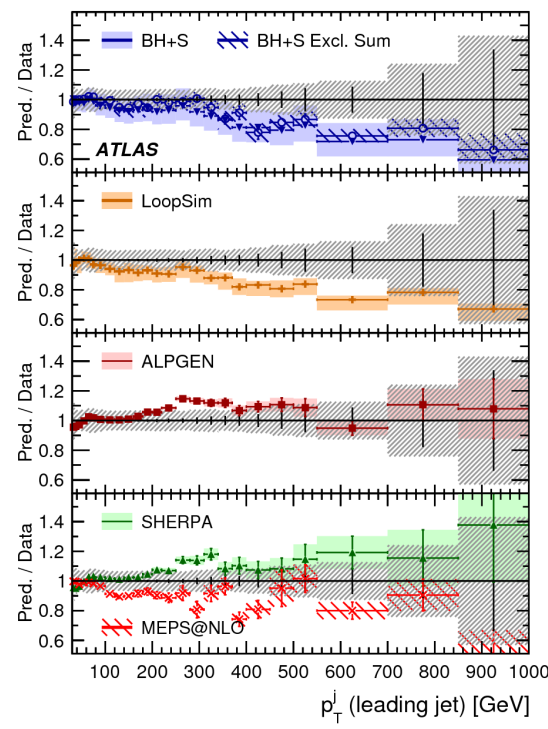
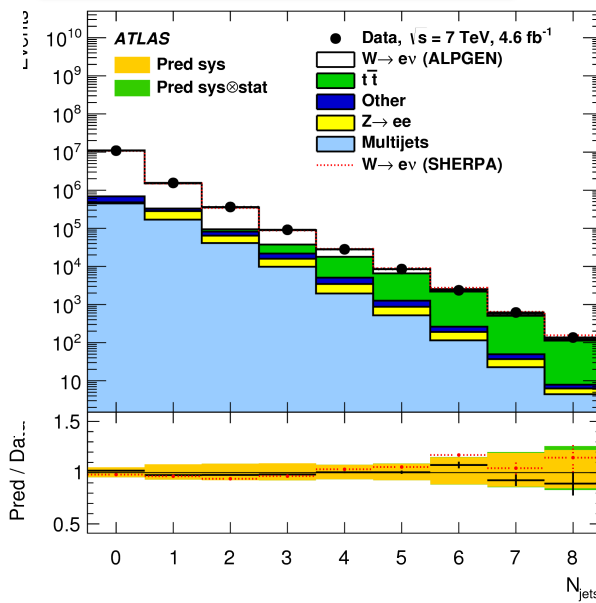
NLO pQCD agreement over ~ 12 orders of magnitude!



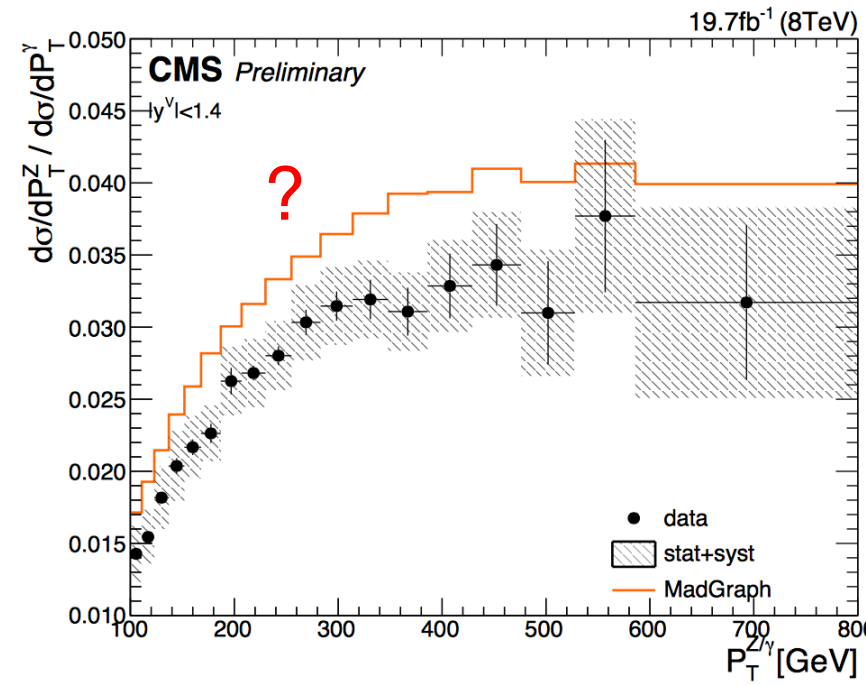
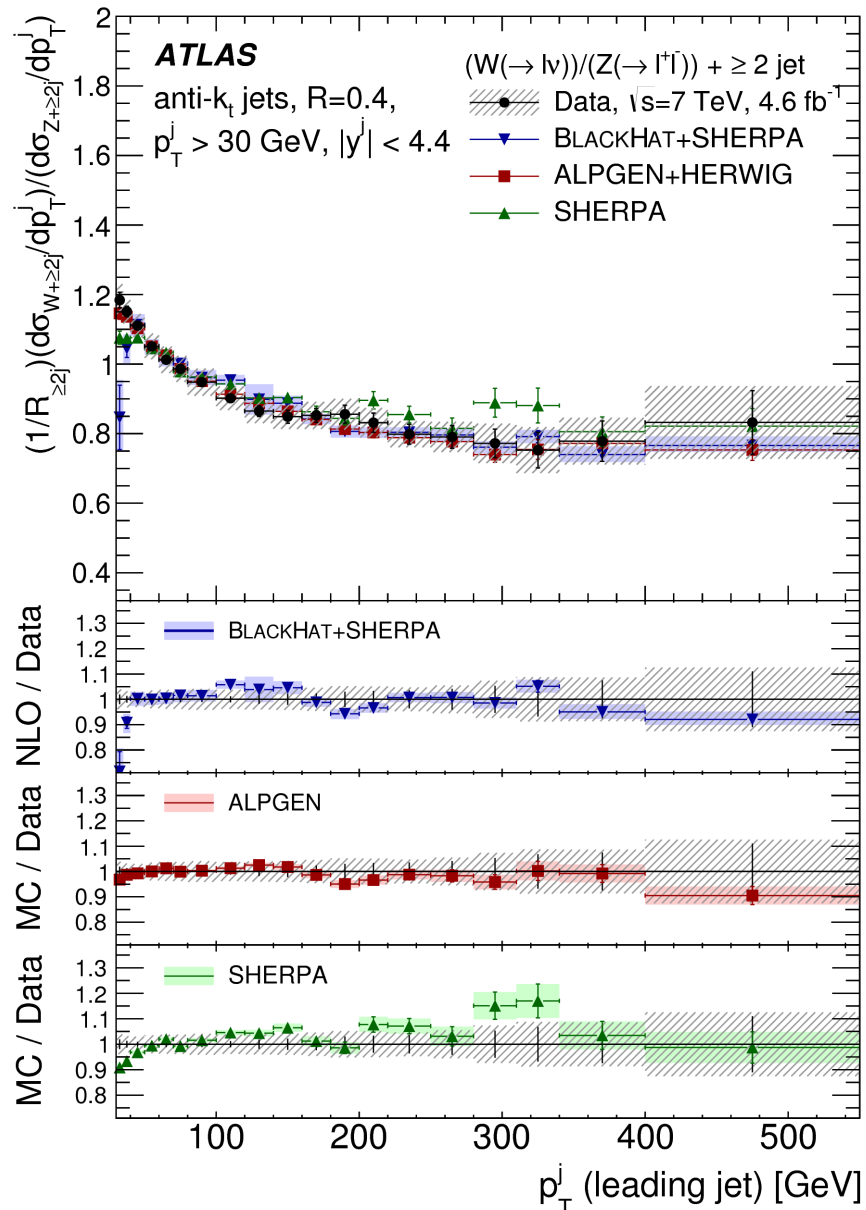
Other Extreme QCD tests



- W/Z+7 or more jets
- V+Jets out to a TeV
- BG for many searches



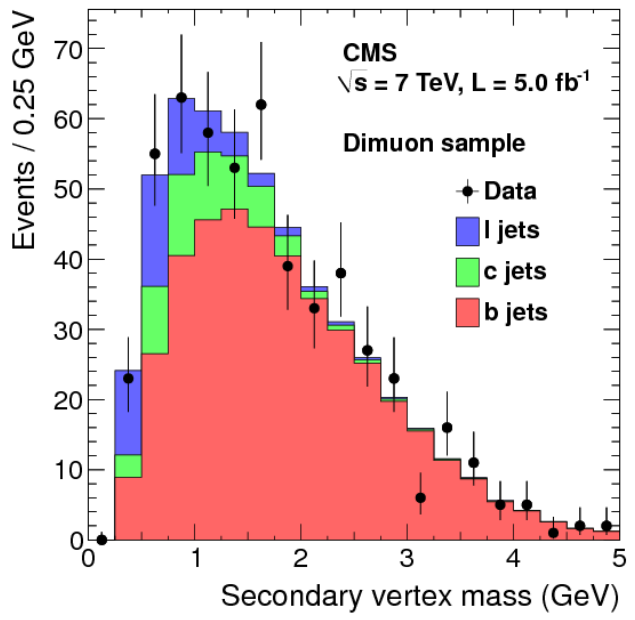
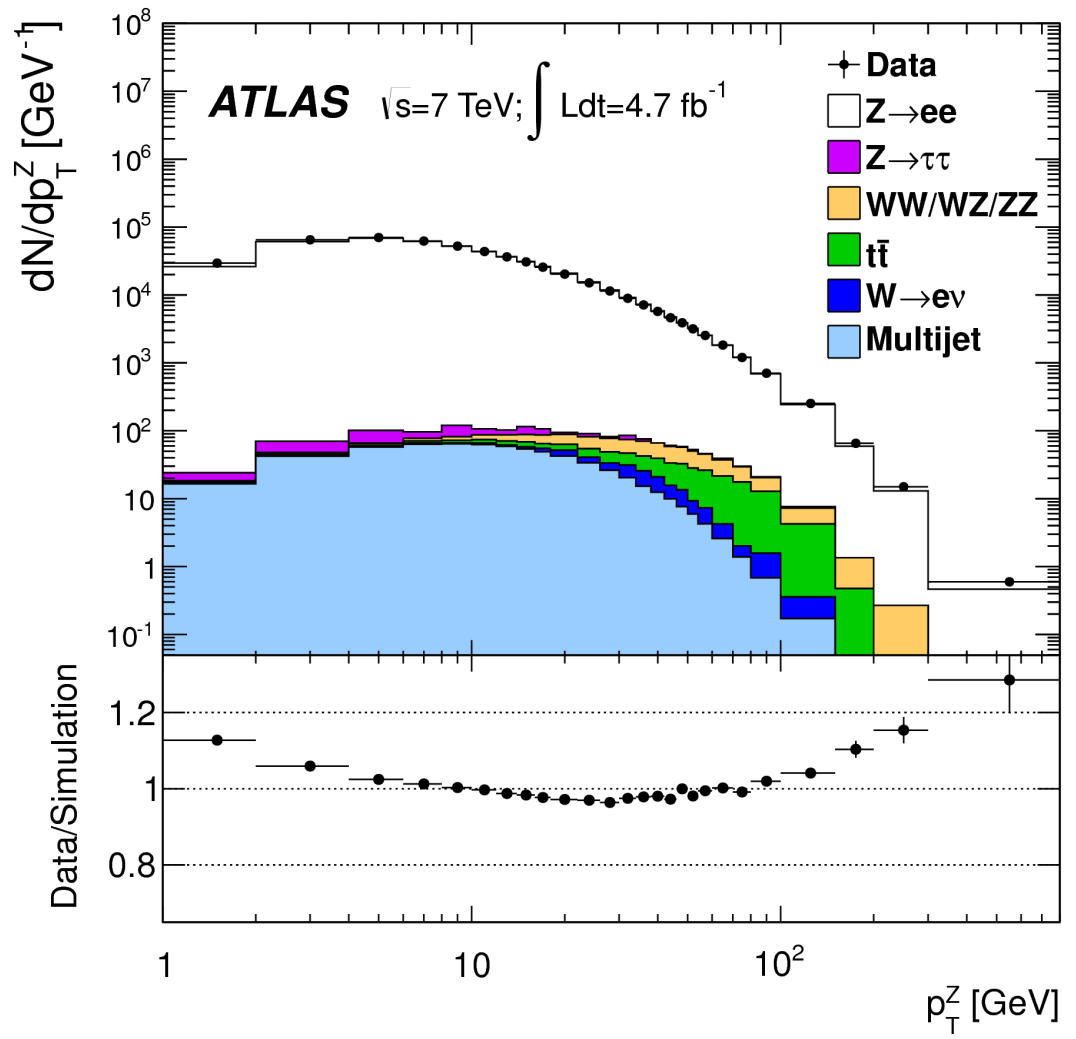
Ratios: W+jets/Z+jets & Z+jets/ γ +jets



- Increased precision due to cancellation of many systematic effects
- Used to estimate background, see later

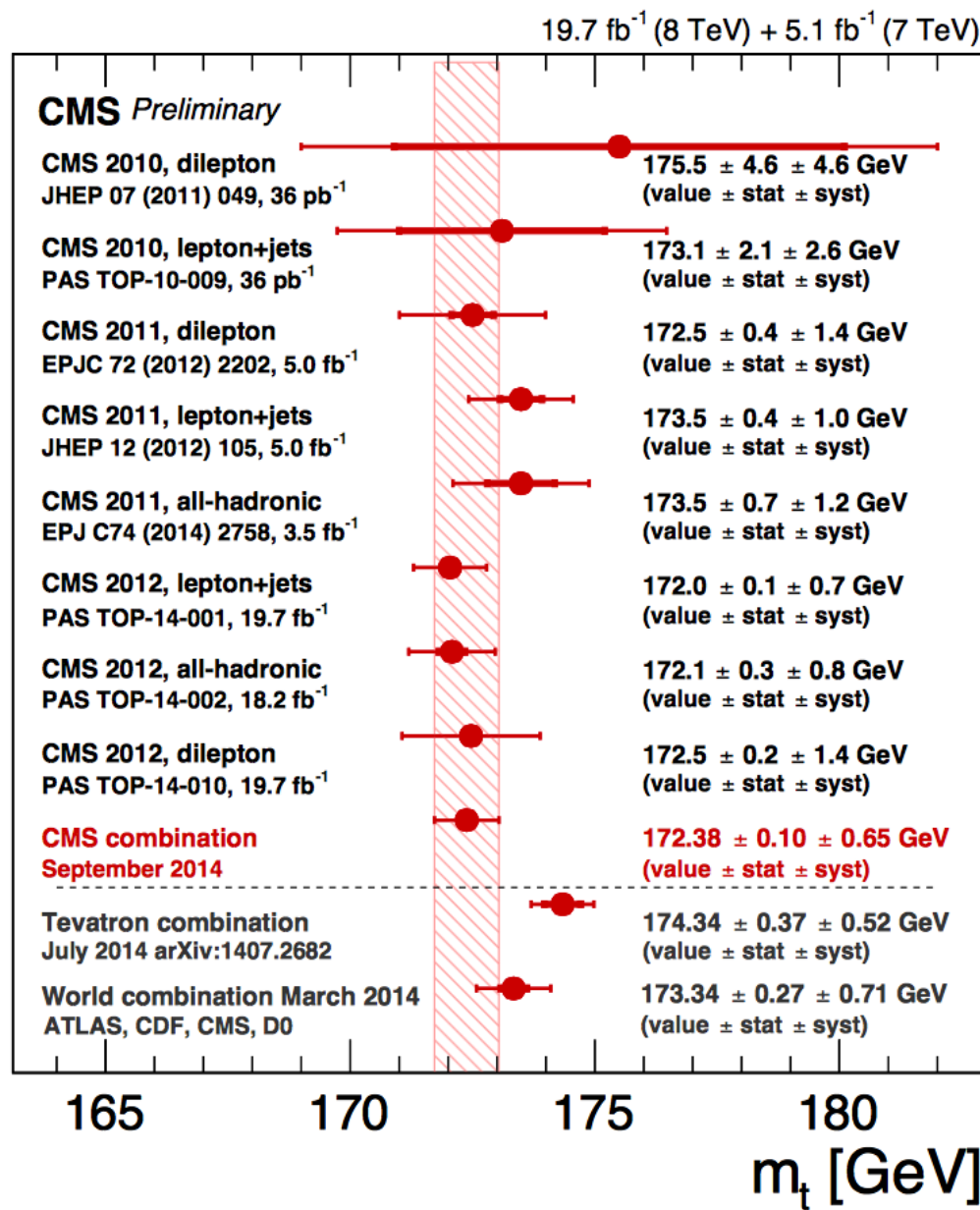
Z+b(b) & Z pT

- Z pT QCD ISR, pT distribution of partons in proton
- gluon PDF
- input for W mass → Run II
- Uncertainties < 1% below Z pT ~100 GeV



- Probe b content in proton
- Important BG for H → bb search

Top Mass

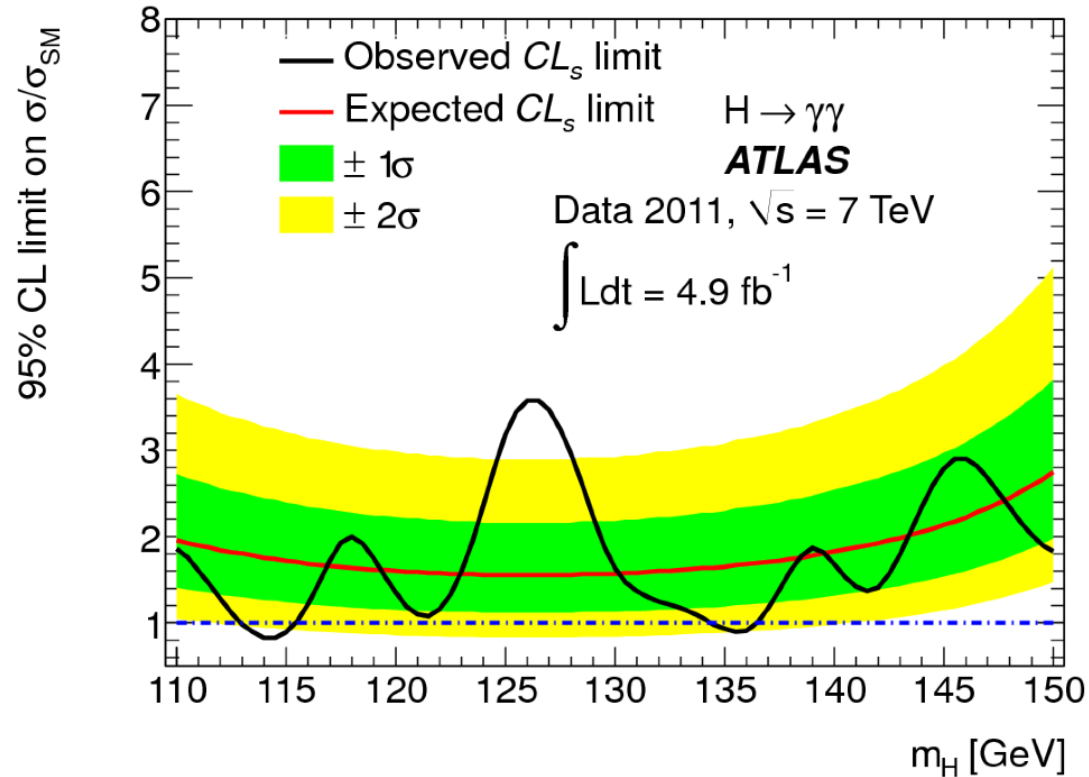
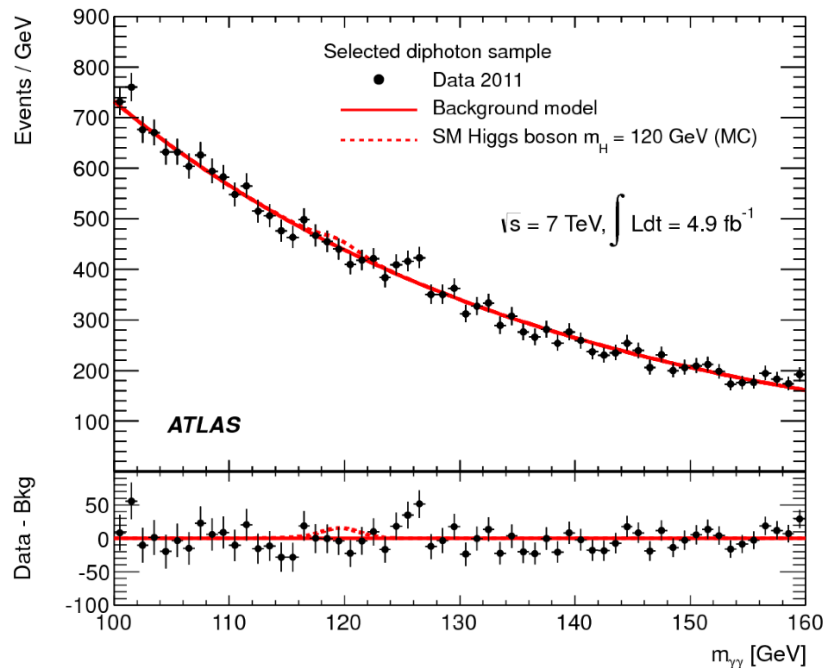


World Combination
173.34±0.76 GeV (0.4%)

- Dominant systematics: Flavor-dependent JES
- Final Run 1 measurements still to come
- Run 2 data should give access to even better precision

Remember Moriond 2012...

...how the Higgs discovery started



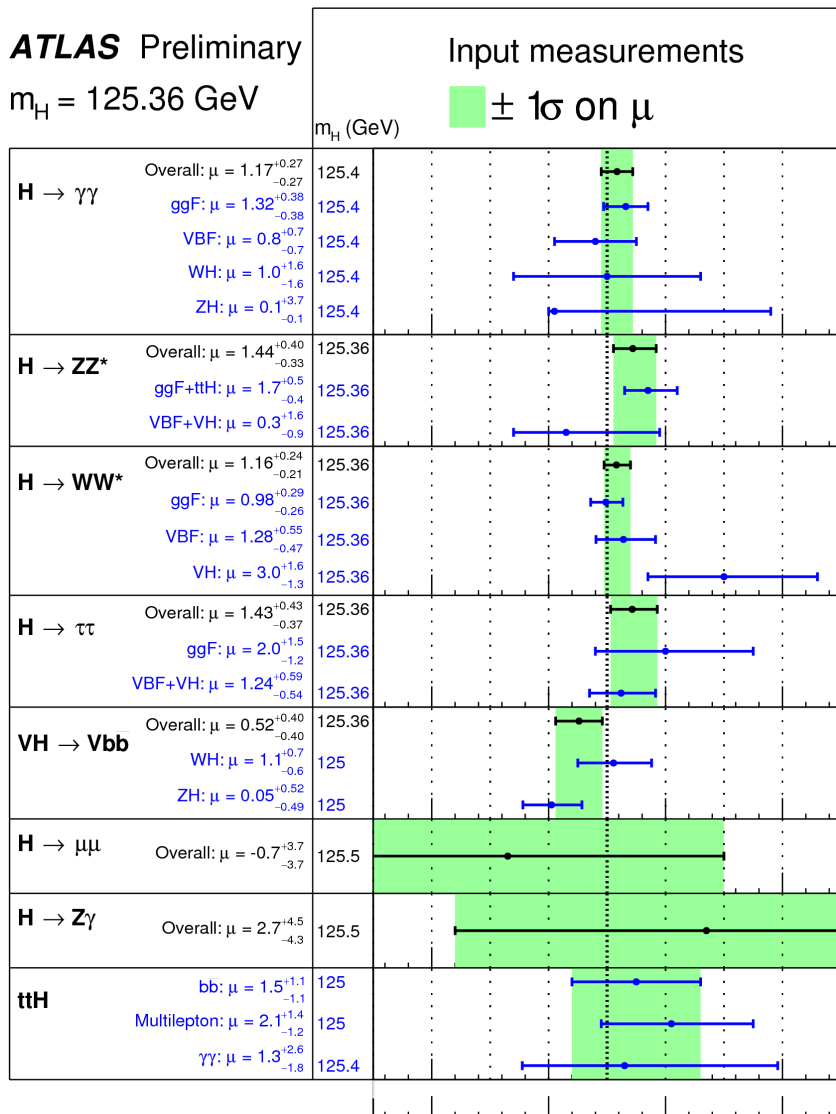
Today: Higgs Precision Measurements

	$H \rightarrow \gamma\gamma$	$H \rightarrow ZZ$	$H \rightarrow WW$	$H \rightarrow \tau\tau$	$H \rightarrow bb$	$H \rightarrow Z\gamma$	$H \rightarrow \mu\mu$
$gg \rightarrow H$	ATLAS CMS	ATLAS CMS	ATLAS CMS	ATLAS CMS		ATLAS CMS	ATLAS CMS
VBF	ATLAS CMS	ATLAS CMS	ATLAS CMS	ATLAS CMS		ATLAS CMS	ATLAS CMS
VH	ATLAS CMS	ATLAS CMS	ATLAS CMS	- CMS	ATLAS CMS	ATLAS CMS	- CMS
ttH	ATLAS CMS	ATLAS CMS	ATLAS CMS	ATLAS CMS	ATLAS CMS		

Measuring Signal Strength

ATLAS Preliminary

$m_H = 125.36$ GeV

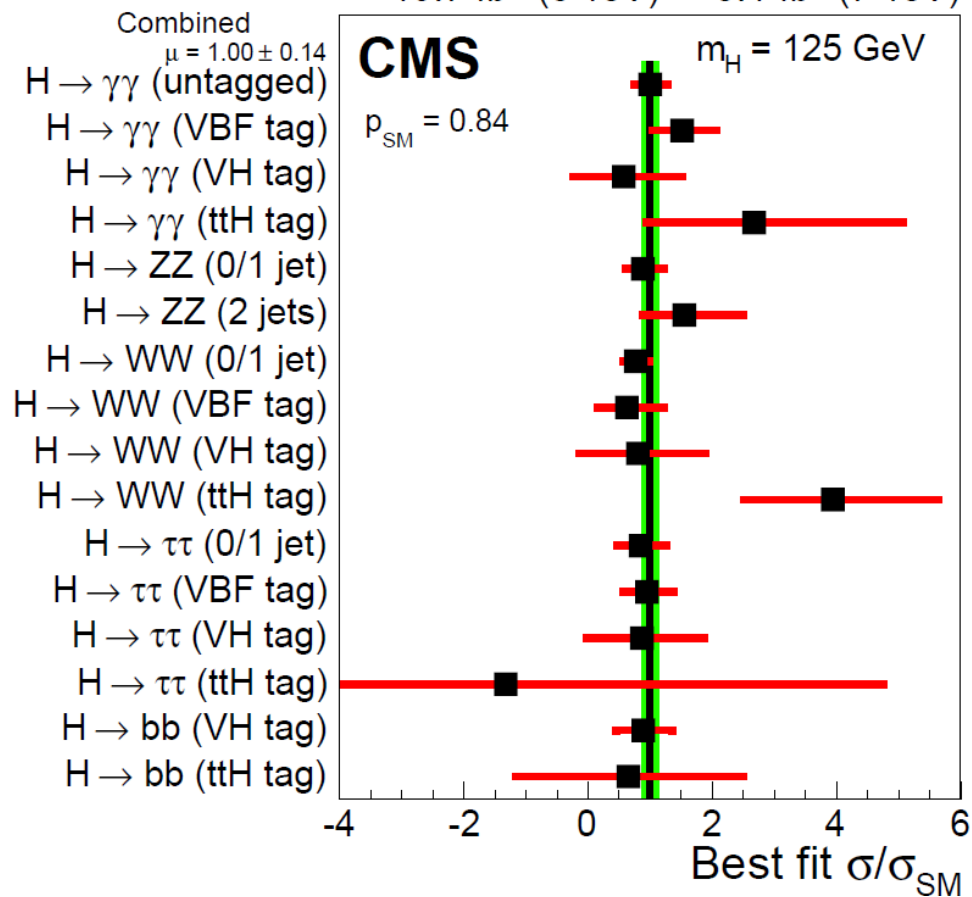


$\sqrt{s} = 7$ TeV, 4.5-4.7 fb^{-1}

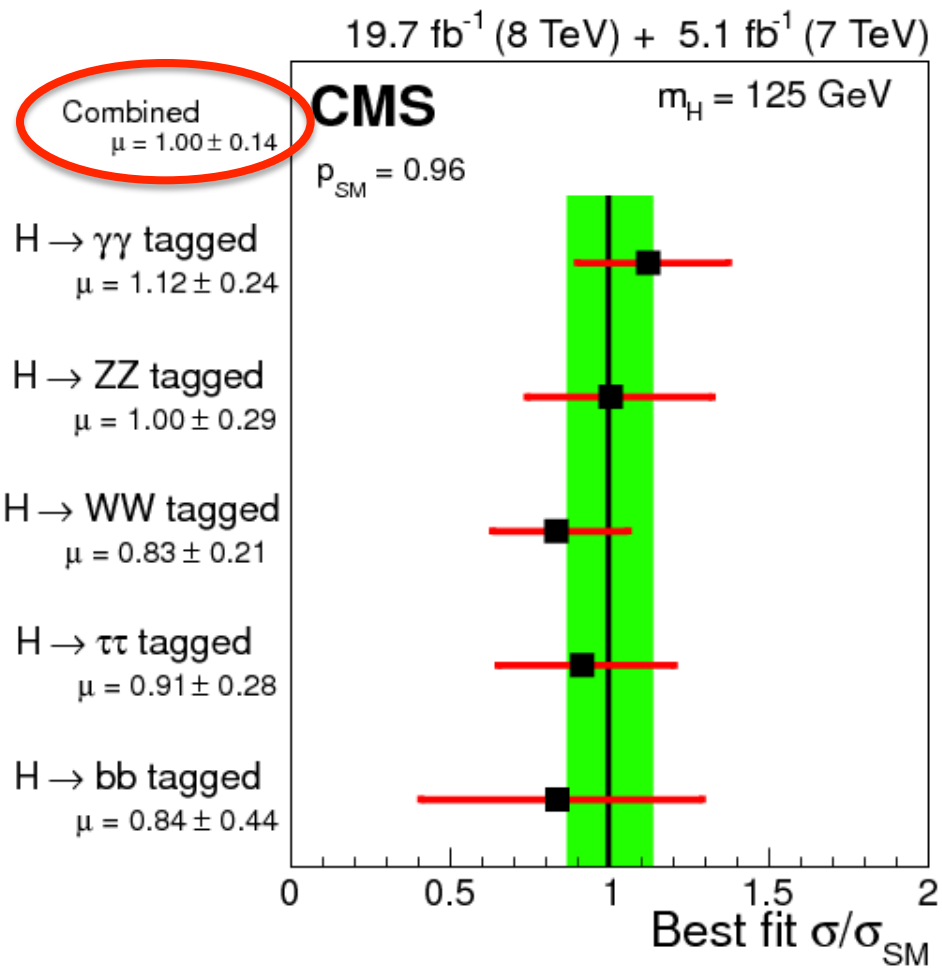
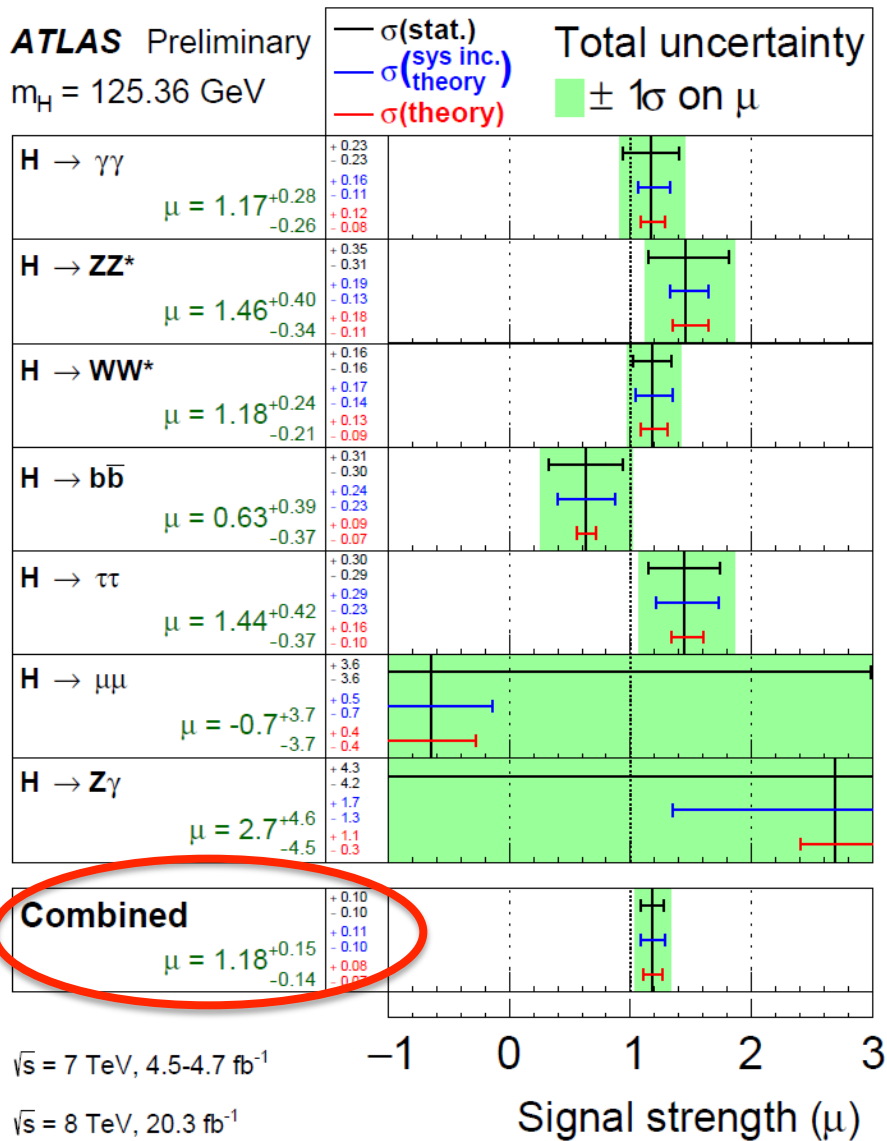
$\sqrt{s} = 8$ TeV, 20.3 fb^{-1}

Signal strength (μ)

19.7 fb^{-1} (8 TeV) + 5.1 fb^{-1} (7 TeV)

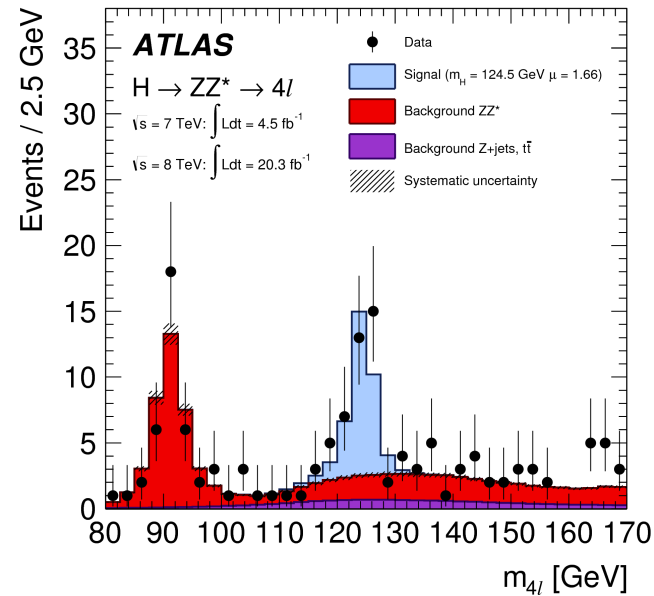


Signal Strength, grouped by decay



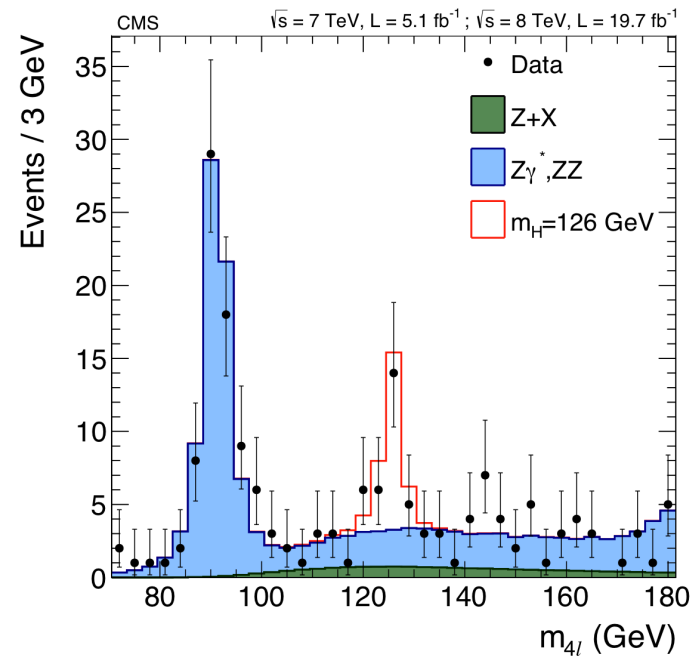
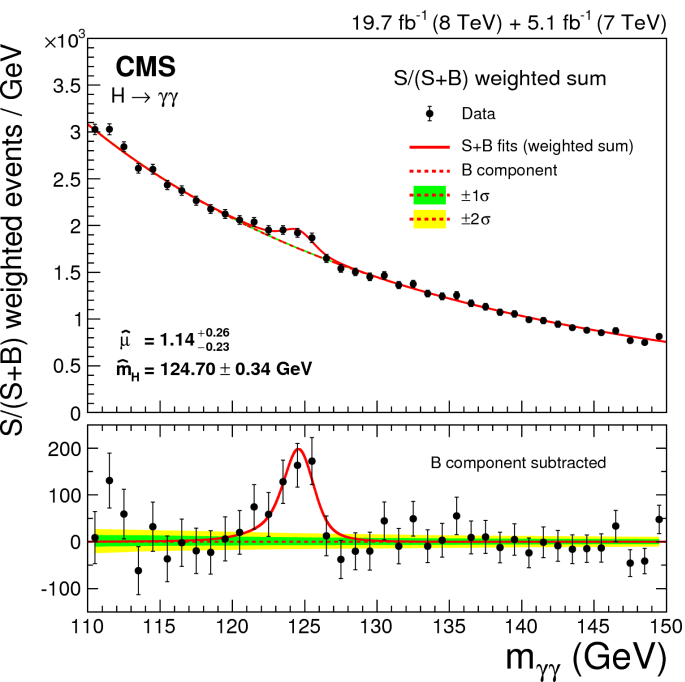
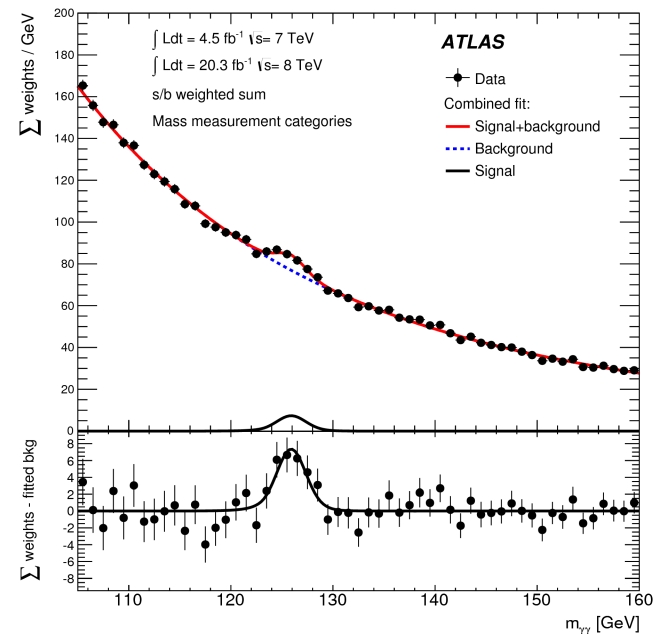
All consistent with SM!
 Including production & decay kinematics

Higgs Mass Combination

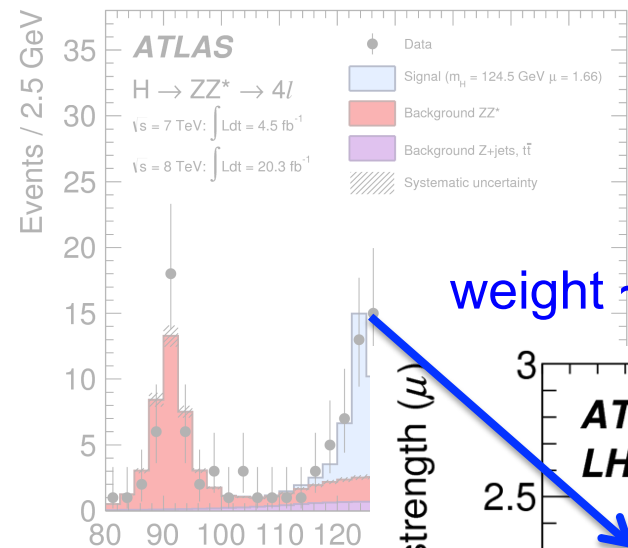


- 3 separate signal strength parameters

- $gg \rightarrow H \rightarrow gg$
- VBF $H \rightarrow gg$
- $H \rightarrow 4l$

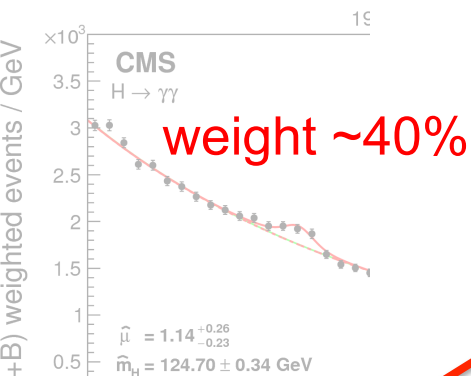
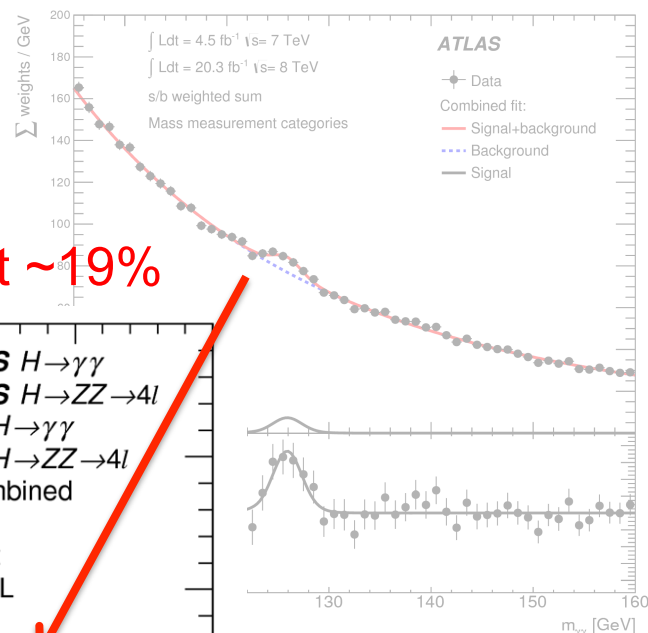
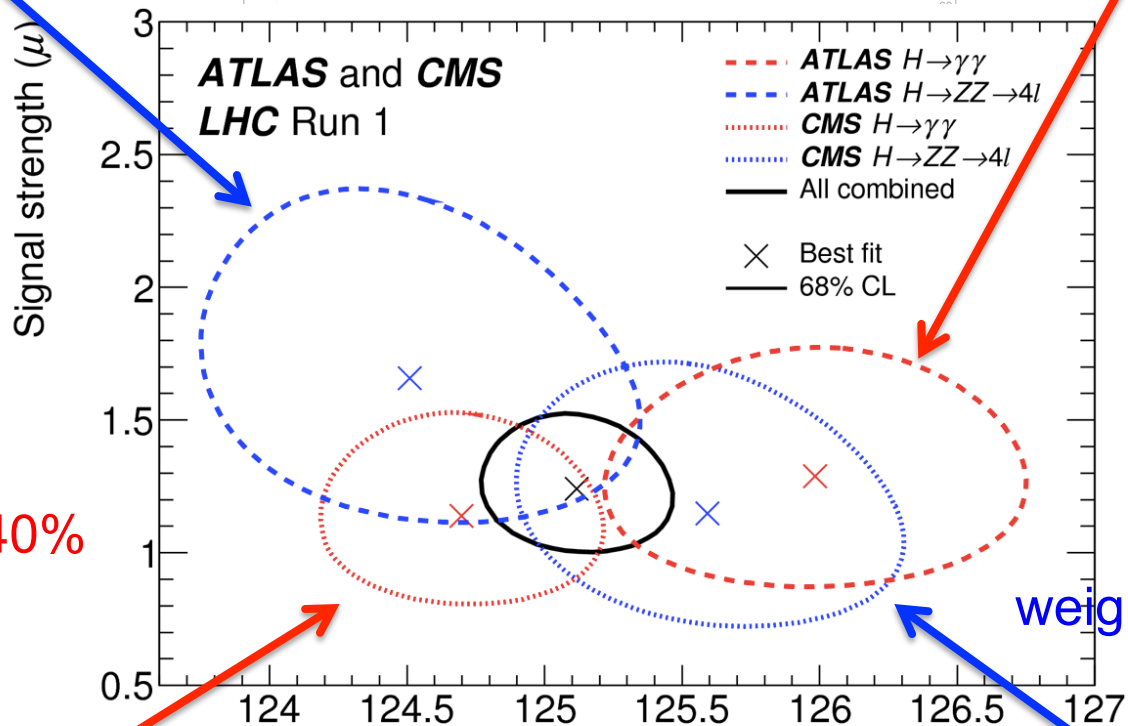


Higgs Mass Combination

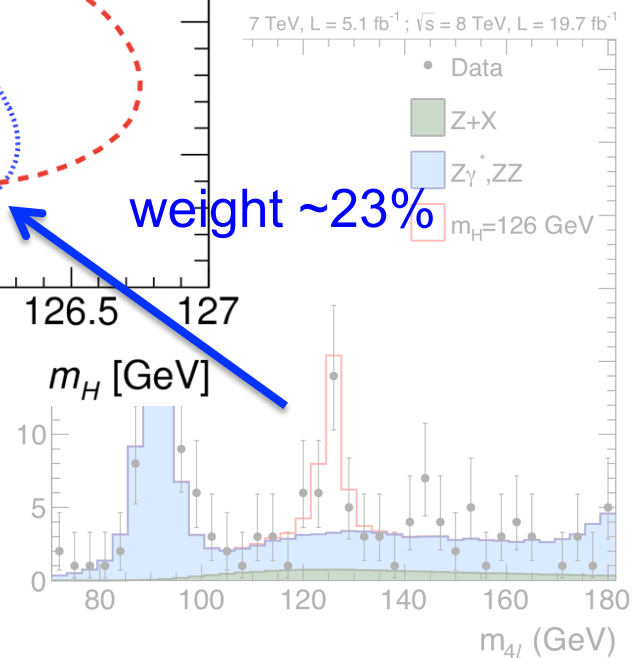
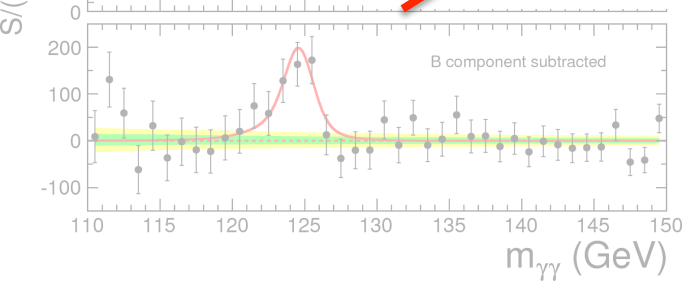


weight ~18%

weight ~19%



weight ~23%

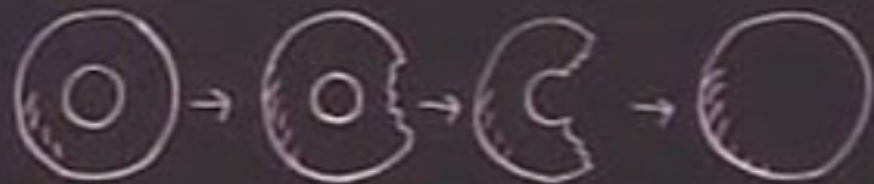




$$M(H^0) = 125.09 \pm 0.24 \text{ GeV}$$

$$3987^{12} + 4365^{12} = 4472^{12}$$

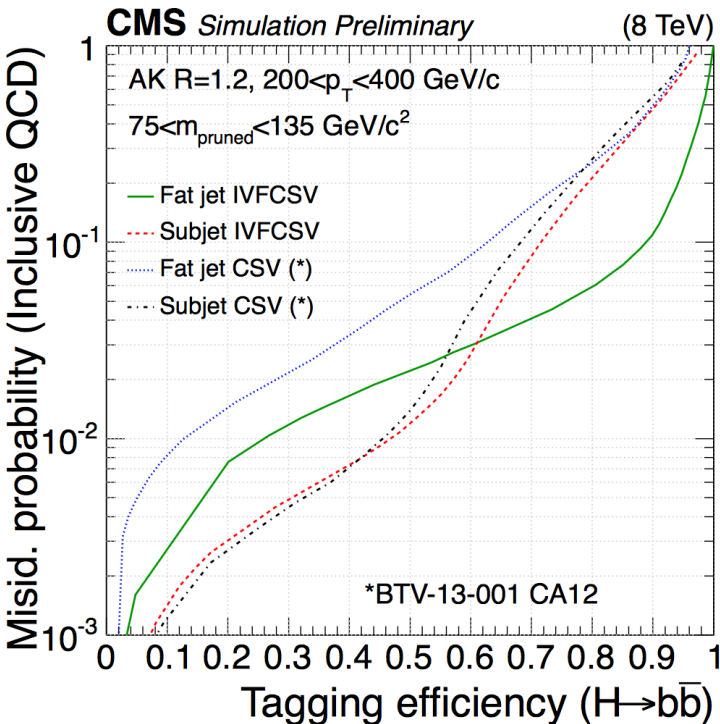
$$\Omega(t_0) > 1$$



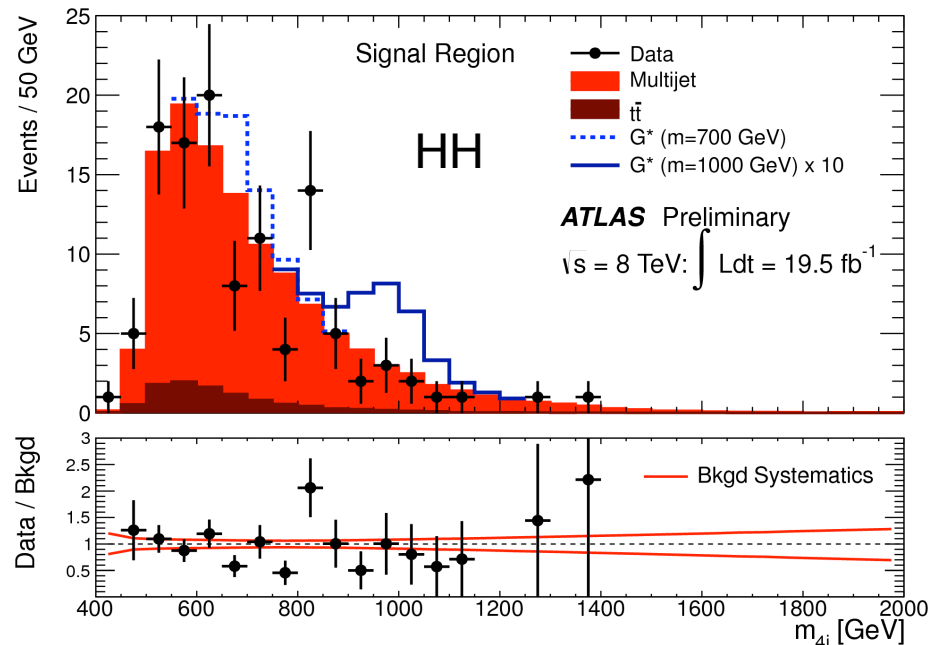
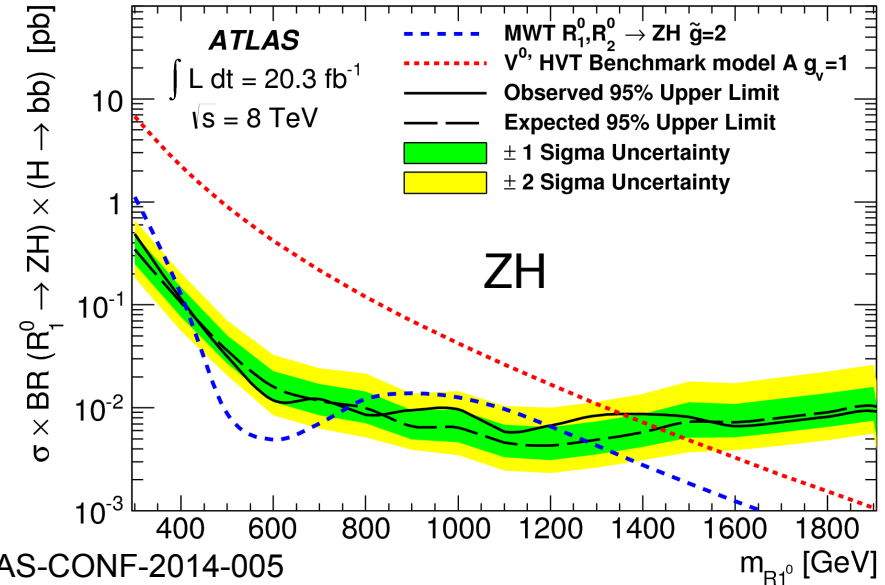
Higgs Bosons as a Tool for discovery

- VH, HH resonance search
- For high mass searches $H \rightarrow bb$ is best decay modes
- VLQ search $BB \rightarrow HbHb$ uses boosted Higgs tagging based on jet substructure (τ_{21}), subjet b-tagging and jet mass

CMS PAS B2G-14-001

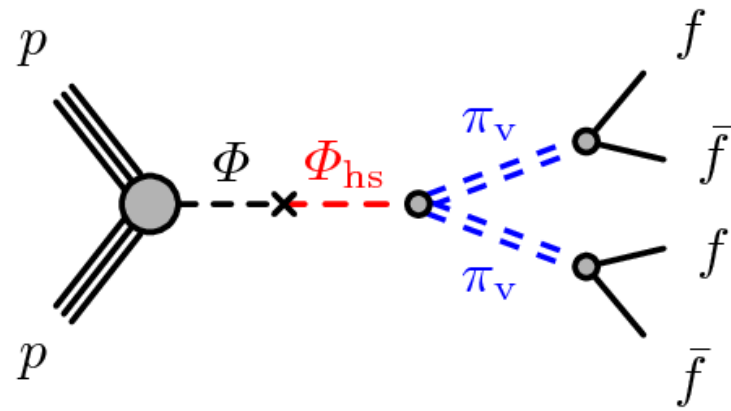


arXiv:1503.08089

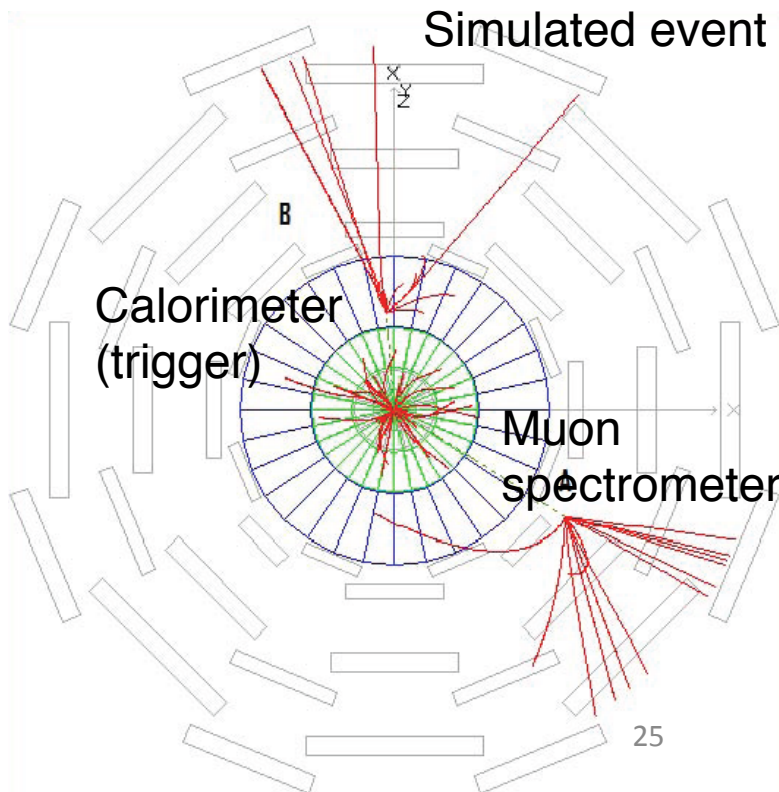
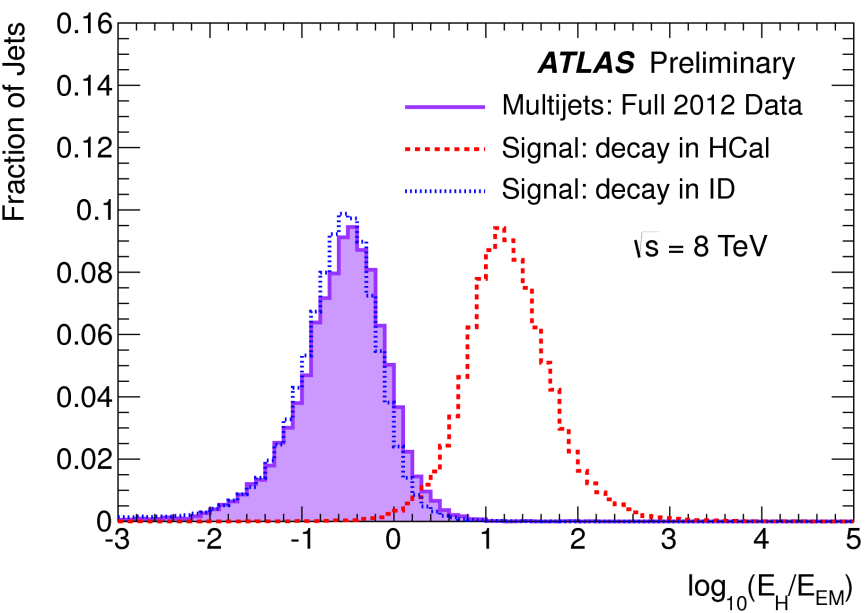


Exotics Higgs decays

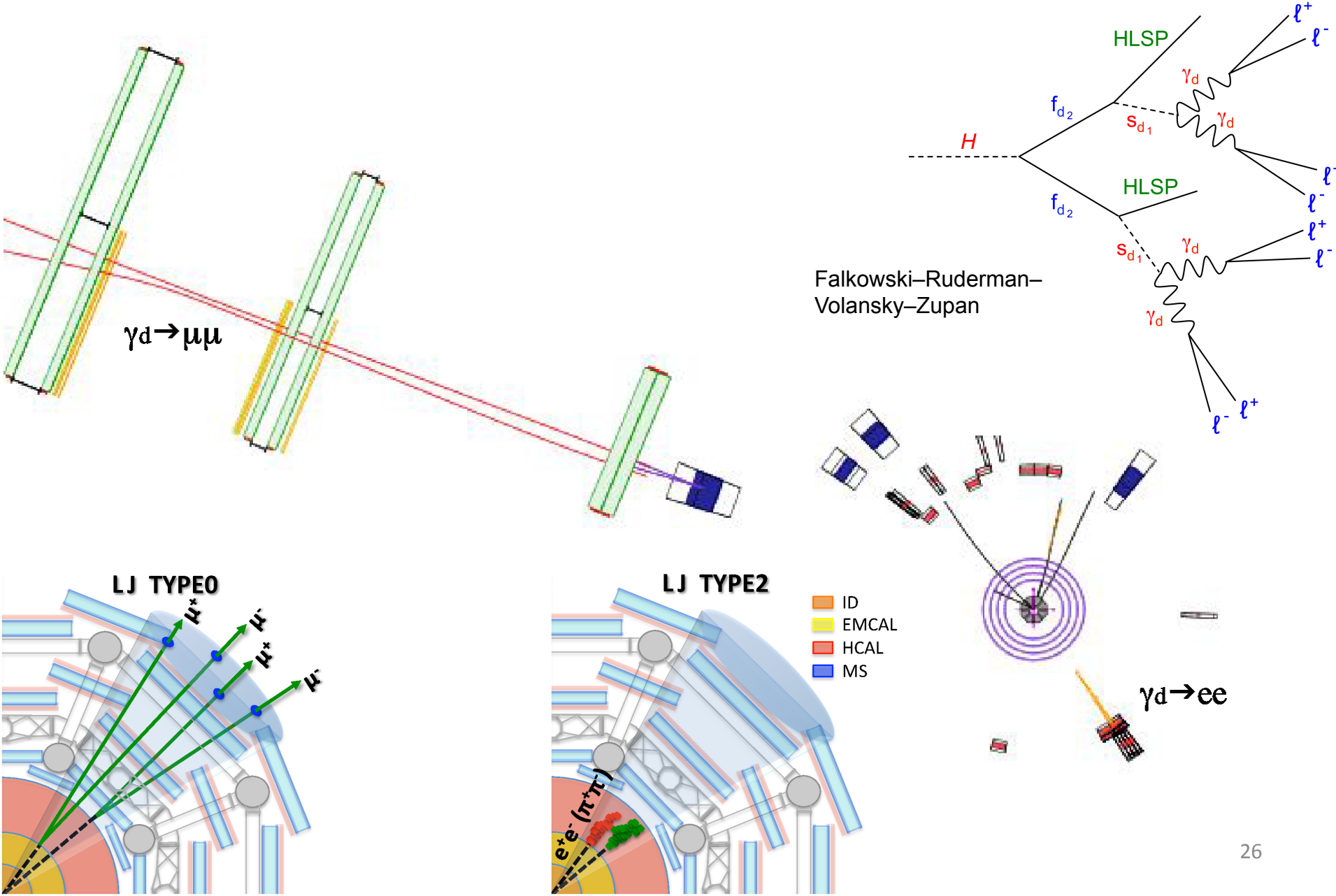
- Exotic Higgs decays to Long-Lived Particles (decays in ID, calo, MS) dark photons or dark Z bosons
- Detectors were not designed for this



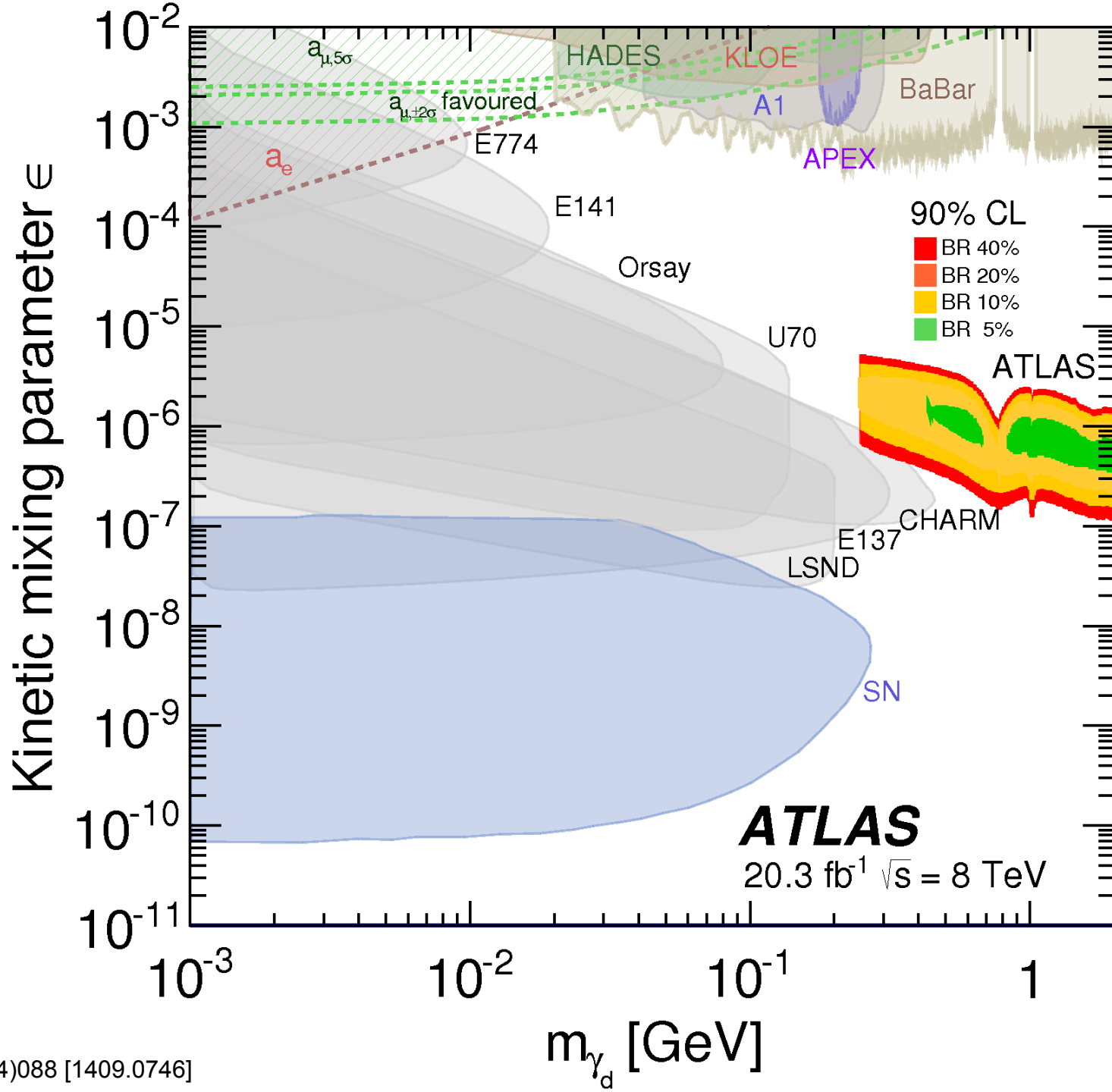
Narrow jets in HCal without tracks



Hidden Sector: Lepton-jets



Vector
Portal
Model

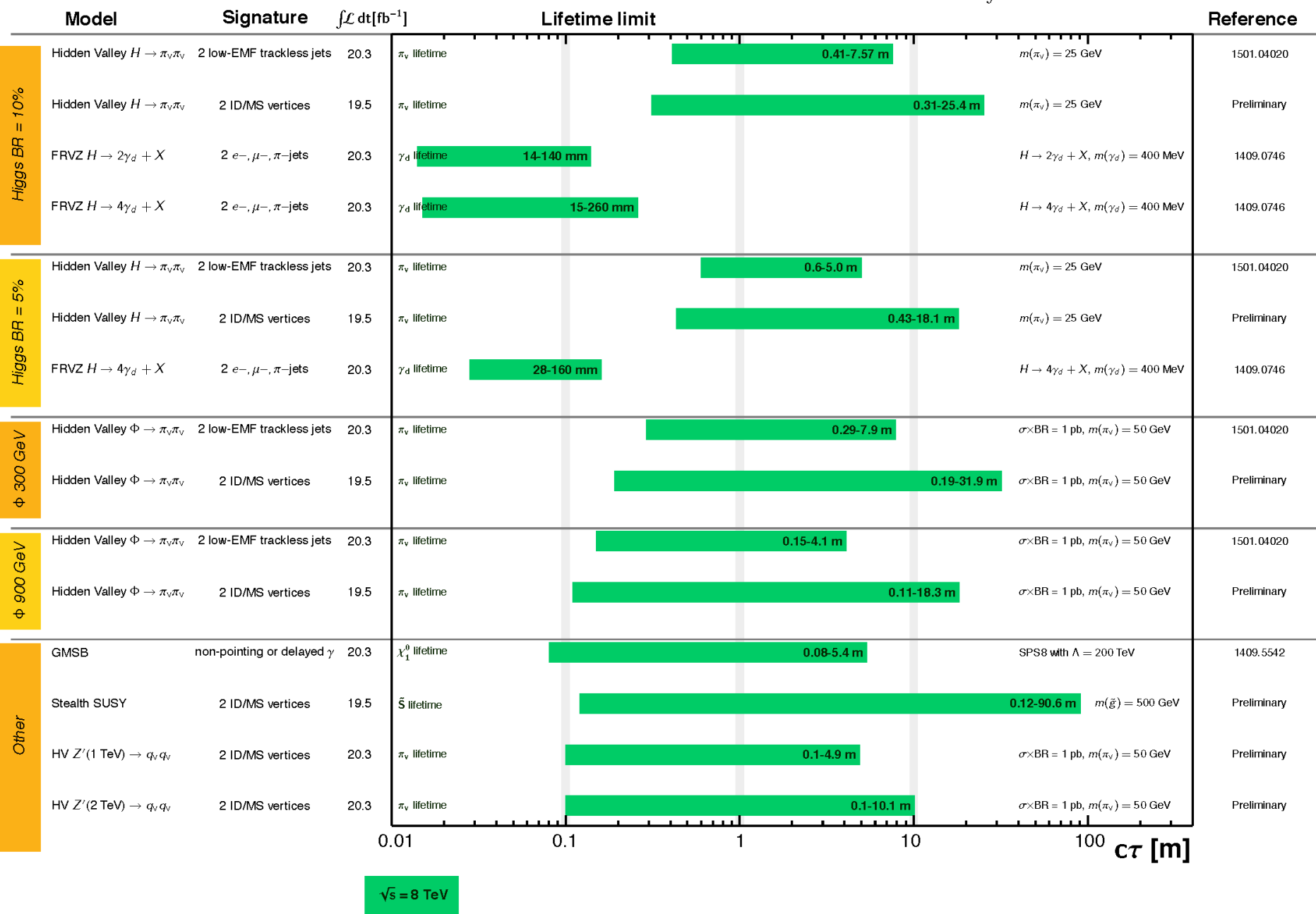


ATLAS Exotics Long-lived Particle Searches* - 95% CL Exclusion

Status: March 2015

ATLAS Preliminary

$\int \mathcal{L} dt = (19.5 - 20.3) \text{ fb}^{-1}$ $\sqrt{s} = 8 \text{ TeV}$



$\sqrt{s} = 8 \text{ TeV}$

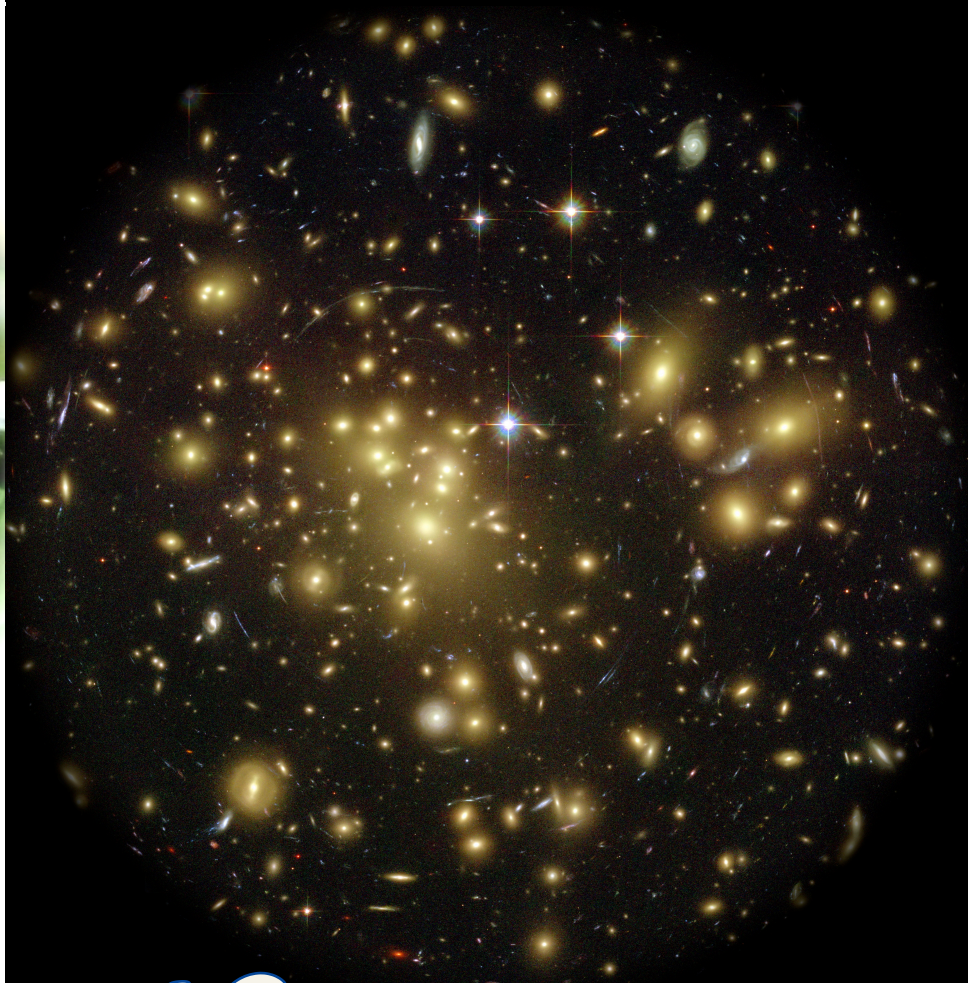
*Only a selection of the available lifetime limits on new states is shown.

2 Big Open Questions

Naturalness



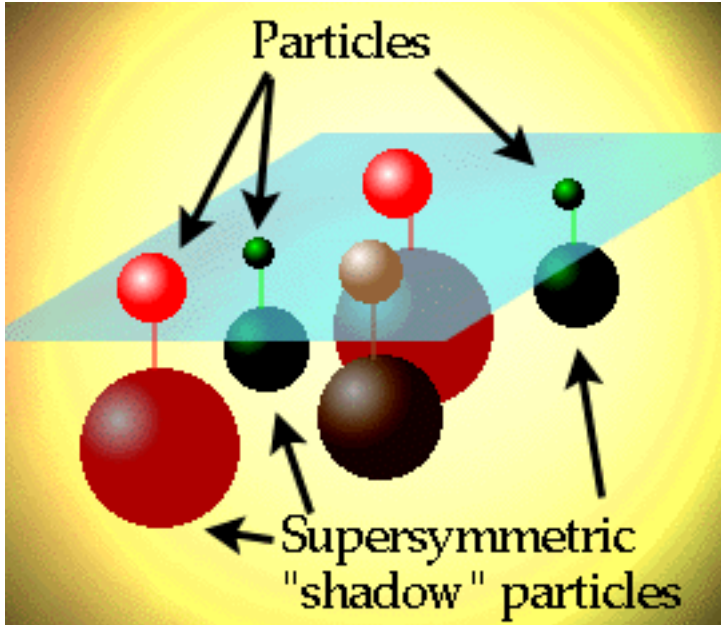
Dark Matter



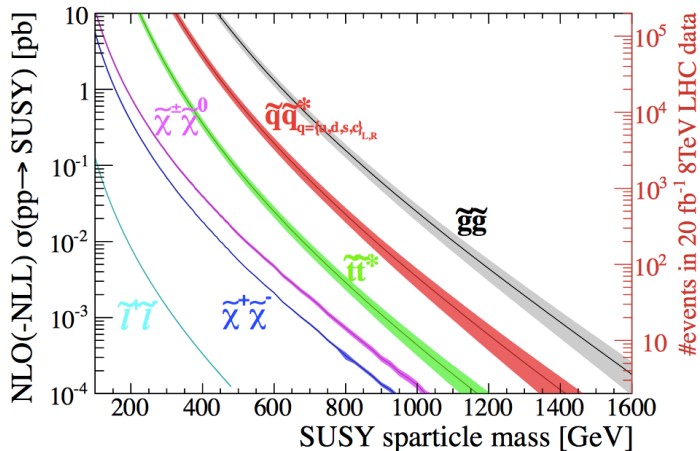
The LHC

2 Grand Ideas

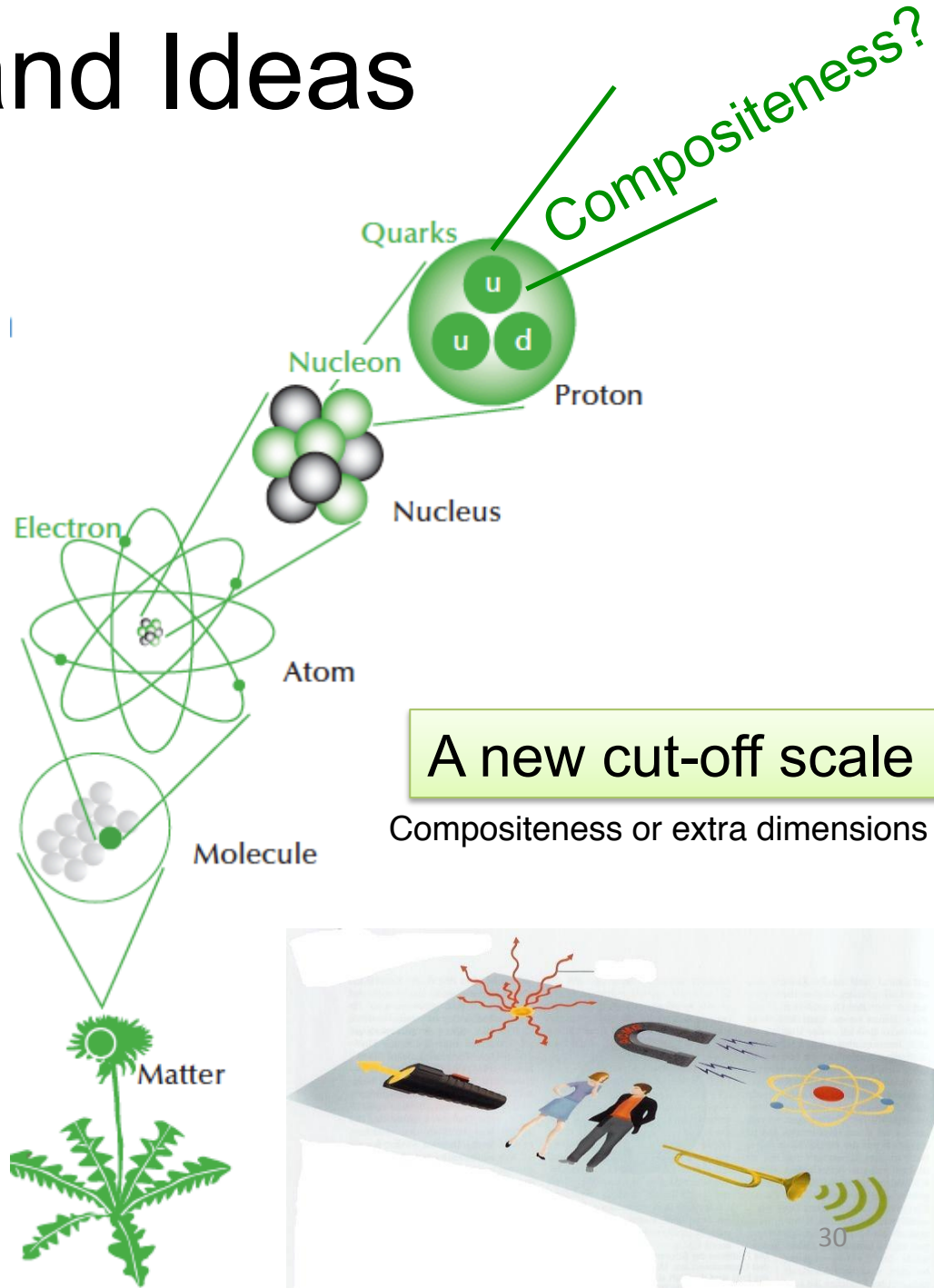
A new symmetry



LPCC SUSY σ WG



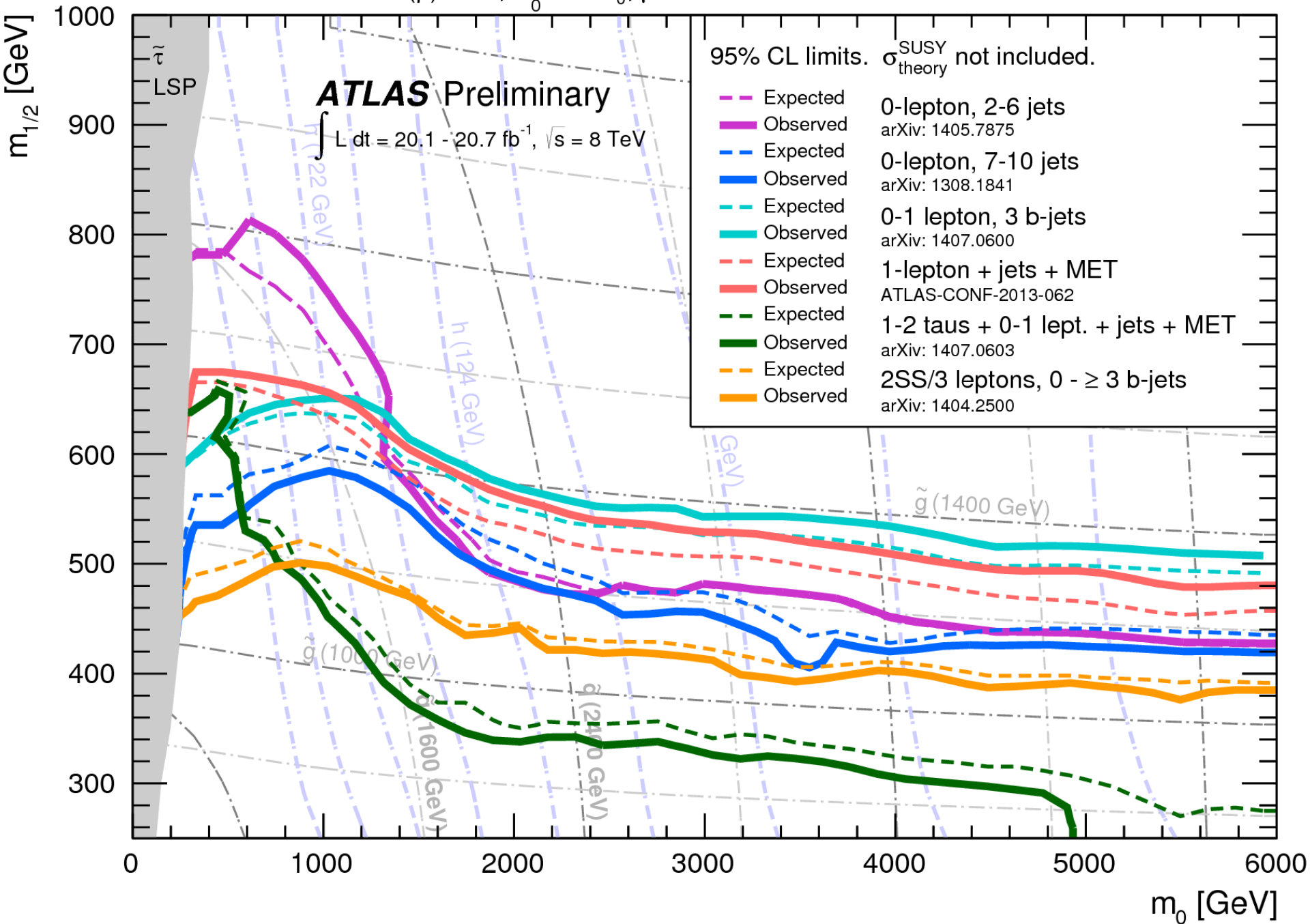
<https://twiki.cern.ch/twiki/bin/view/LHCPhysics/SUSYCrossSections> arXiv:1206.2892



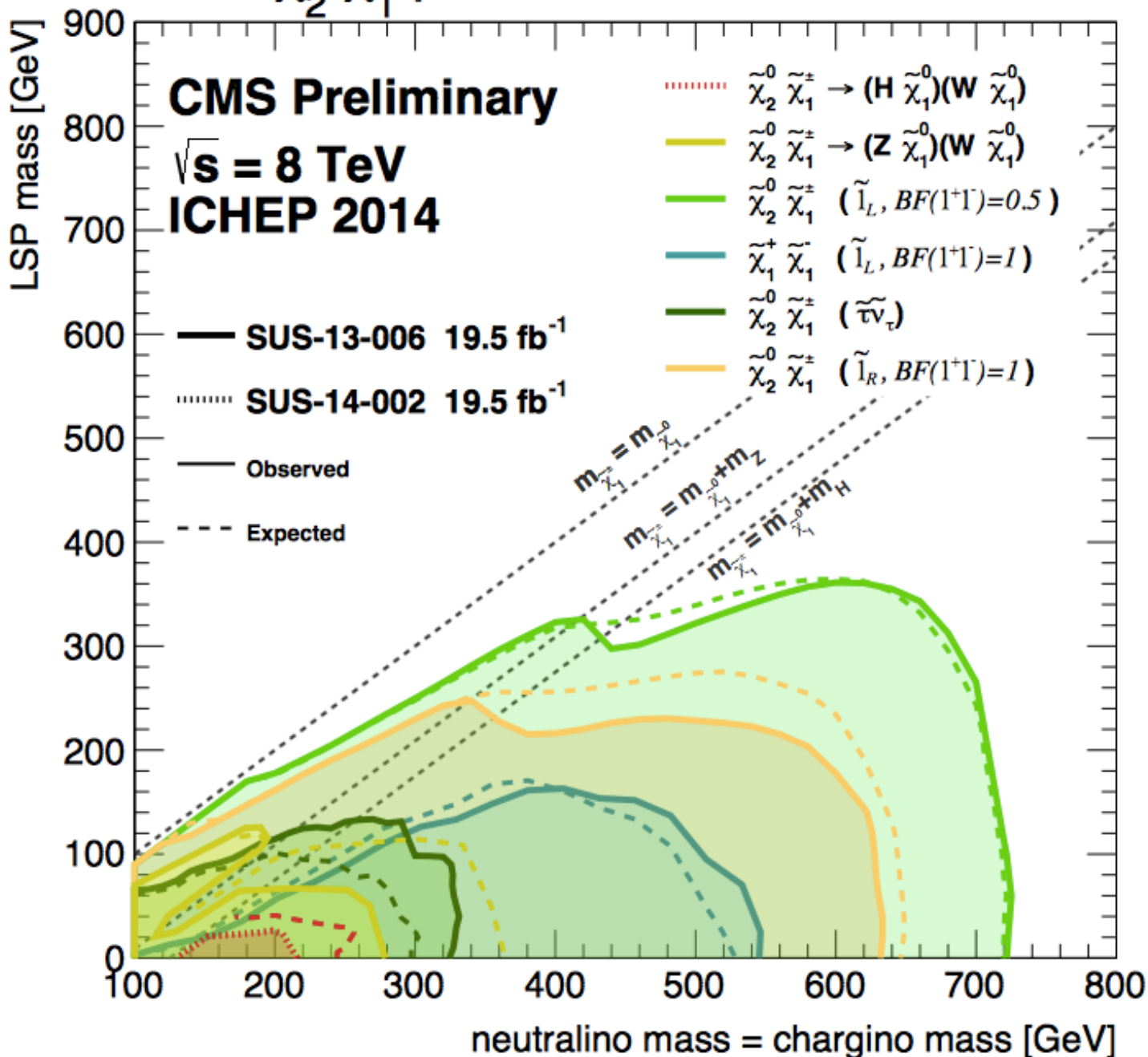
A new cut-off scale

Compositeness or extra dimensions

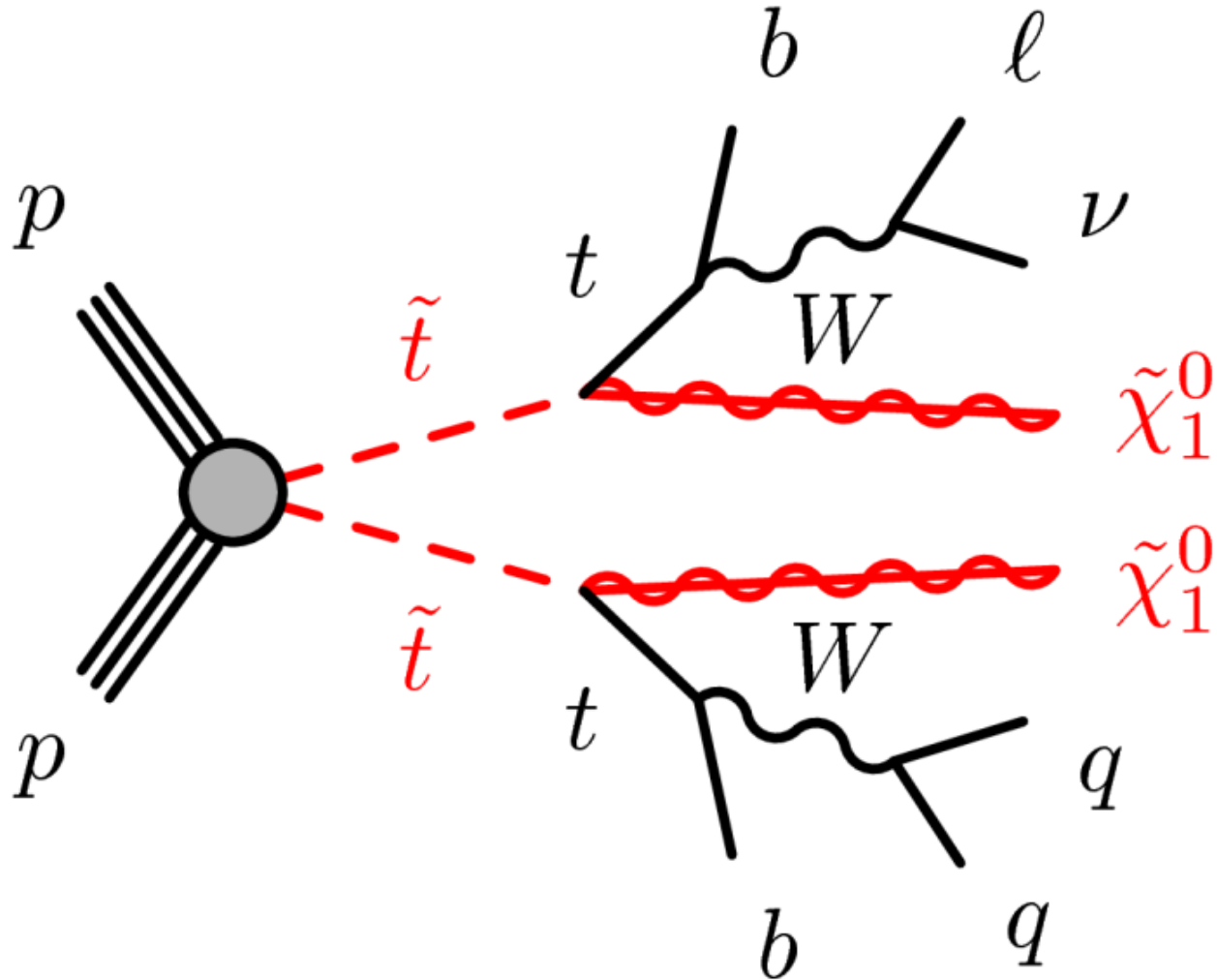




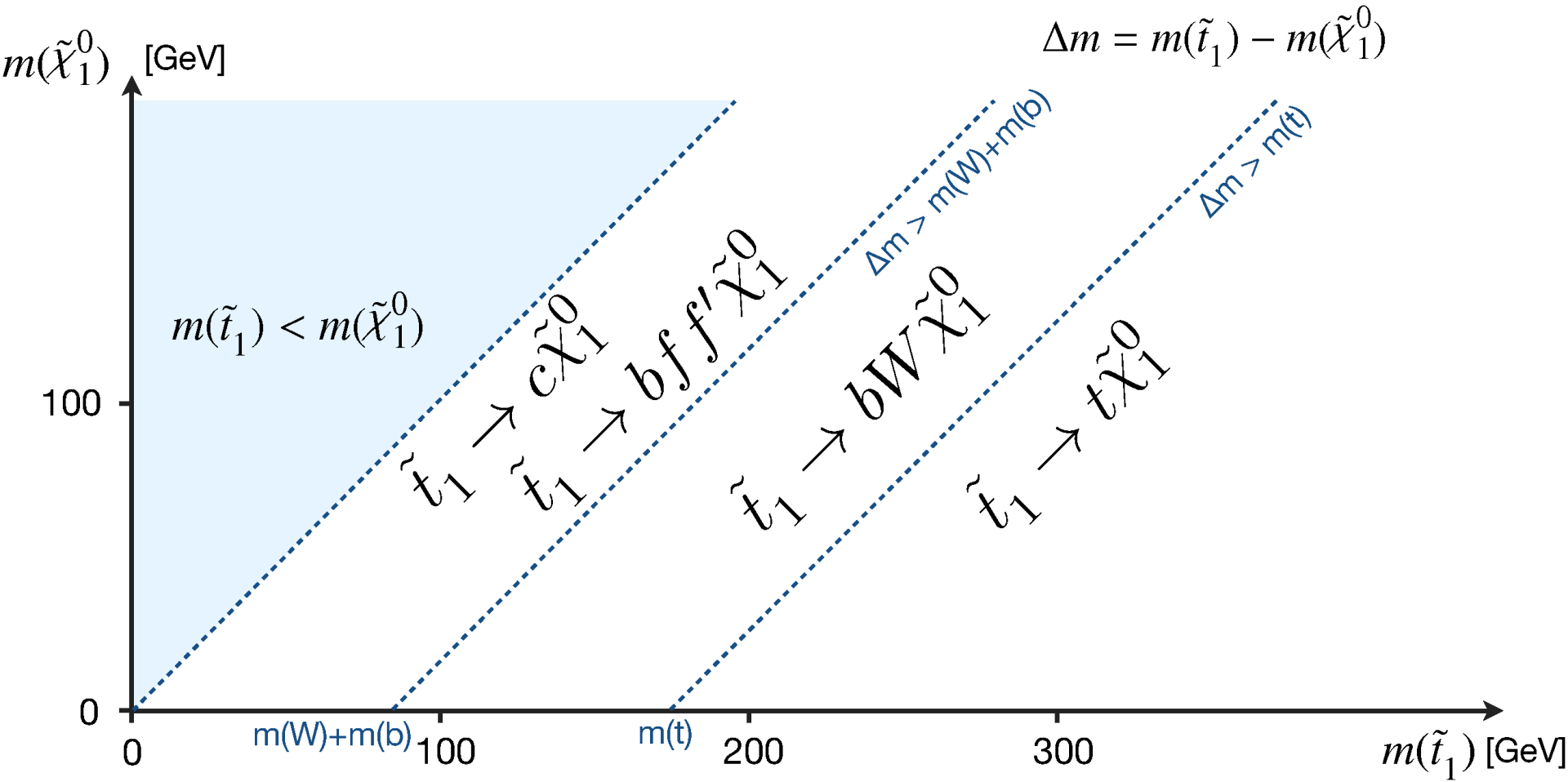
$\tilde{\chi}_2^0 - \tilde{\chi}_1^\pm$ production



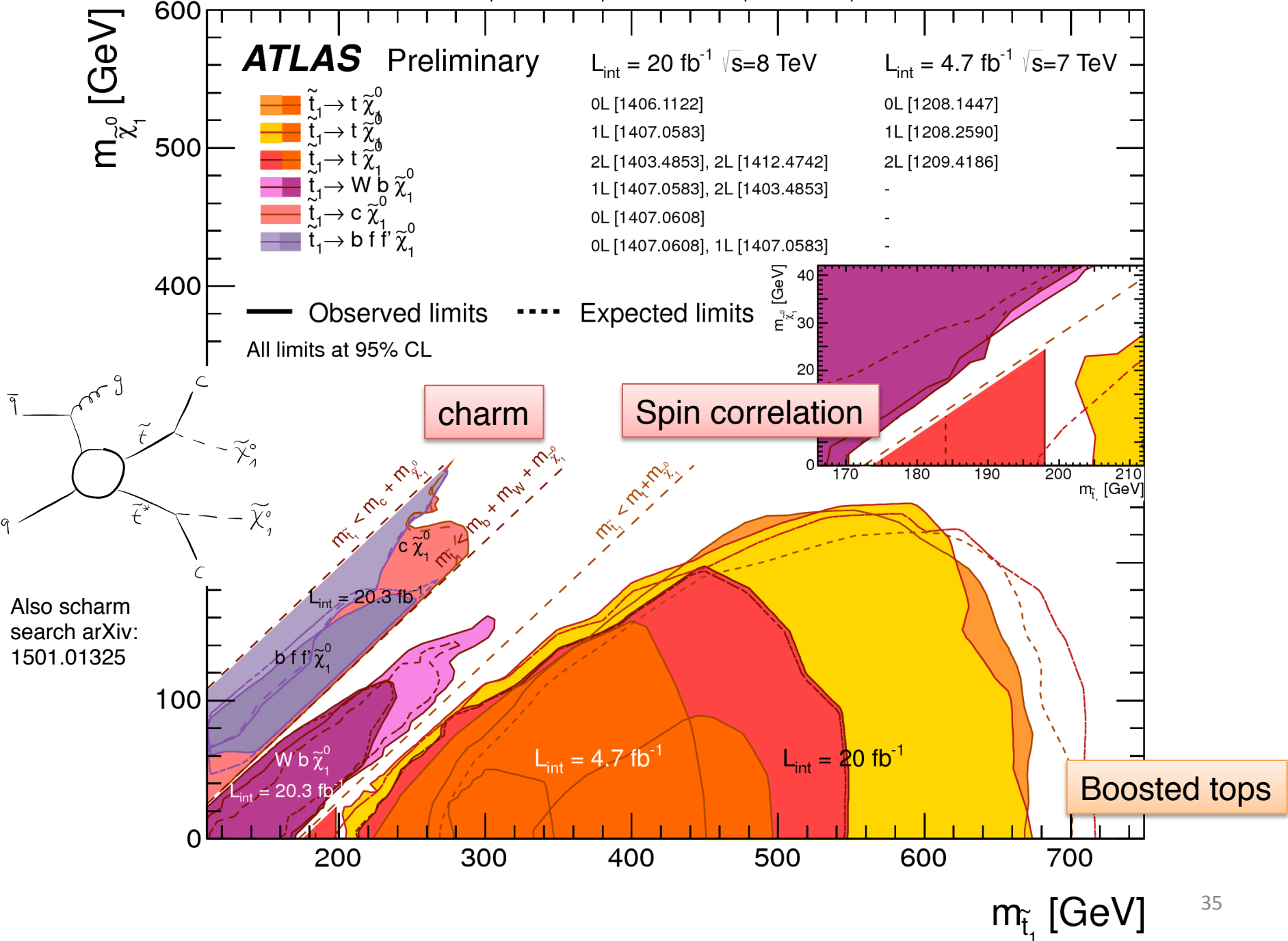
Natural SUSY: Stop



Stop Phenomenology

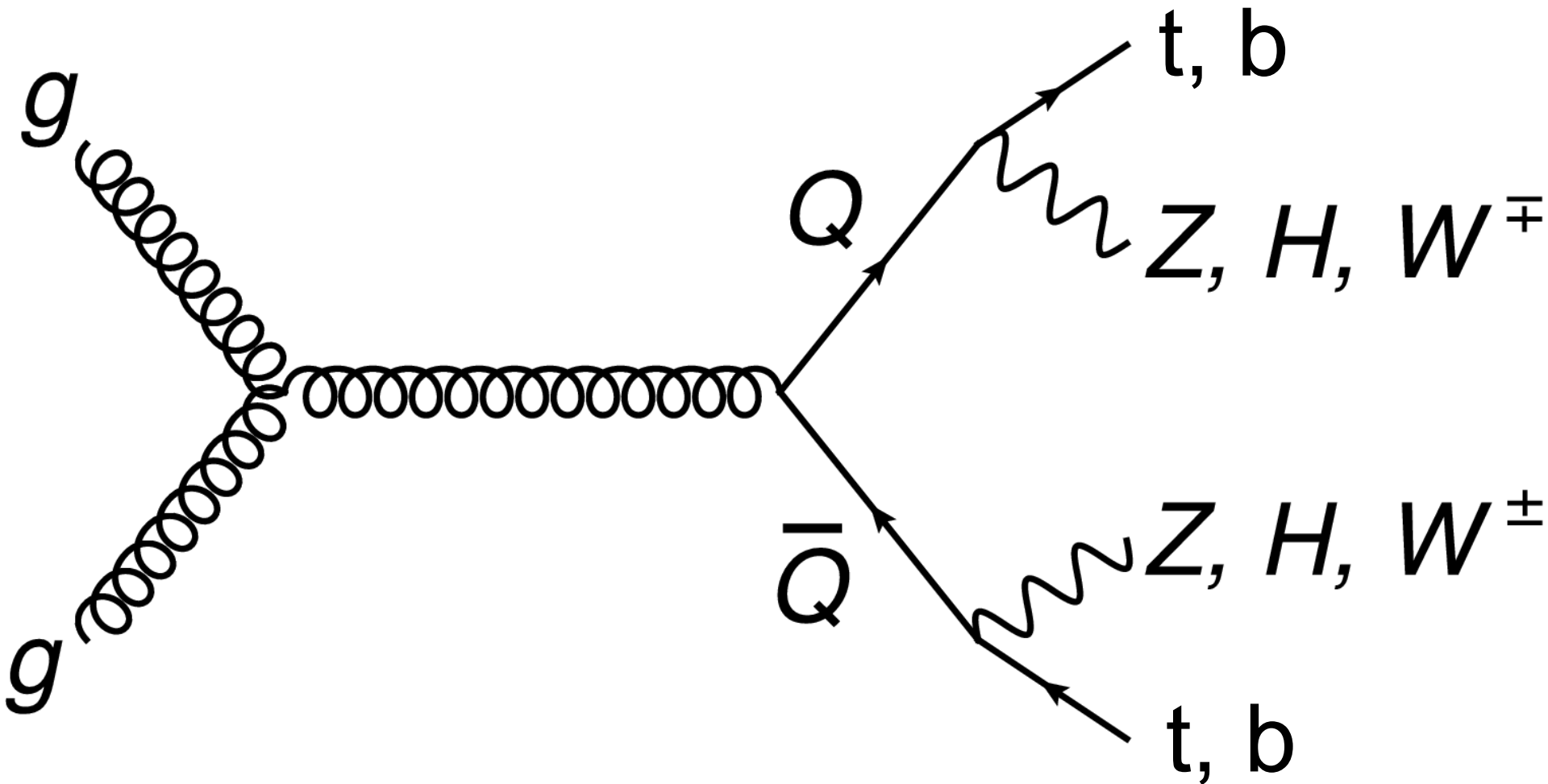


\tilde{t}_1, \tilde{t}_1 production, $\tilde{t}_1 \rightarrow b f f'$ $\tilde{\chi}_1^0 / \tilde{t}_1 \rightarrow c \tilde{\chi}_1^0 / \tilde{t}_1 \rightarrow W b \tilde{\chi}_1^0 / \tilde{t}_1 \rightarrow t \tilde{\chi}_1^0$

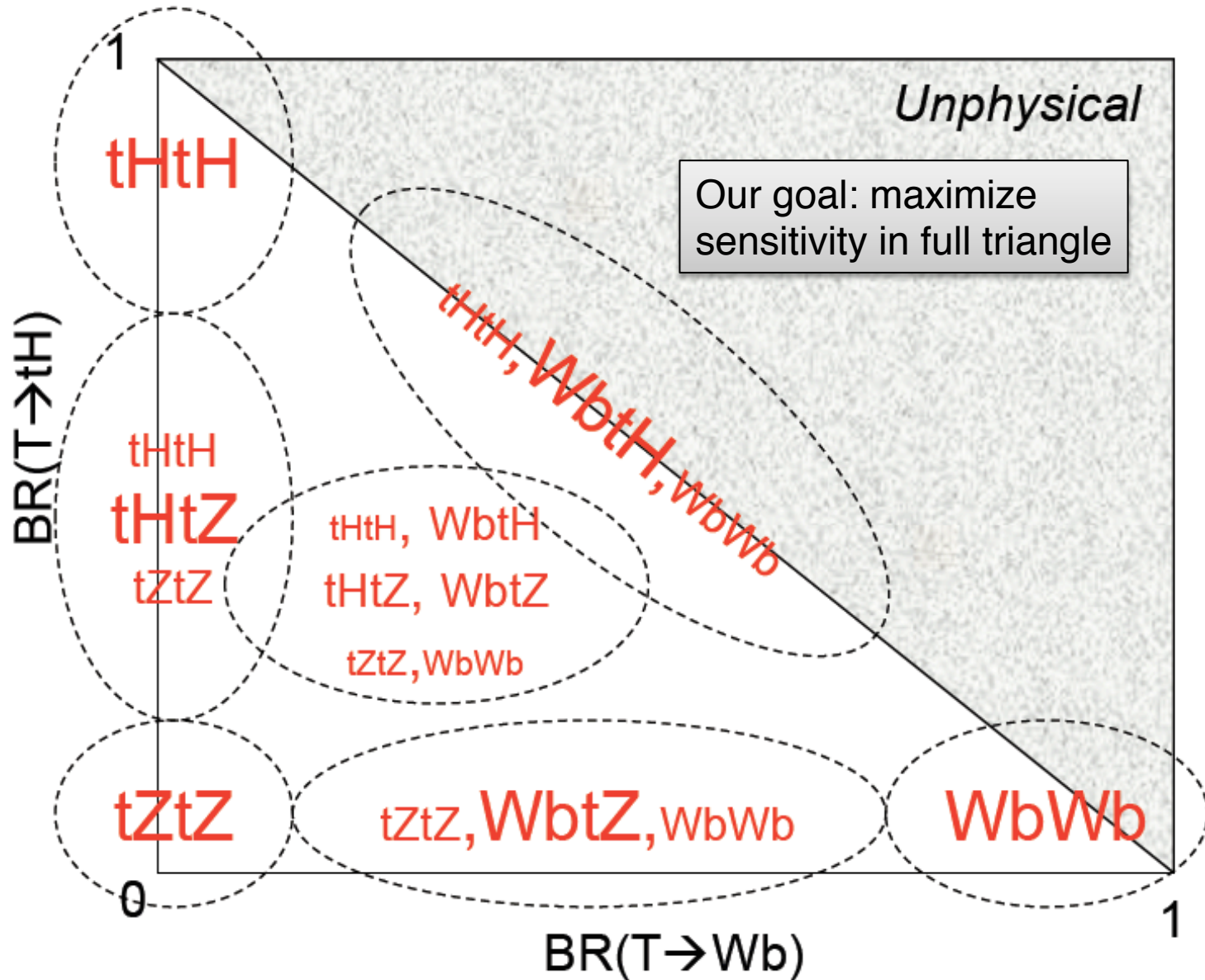


Vector Like Quarks (VLQ)

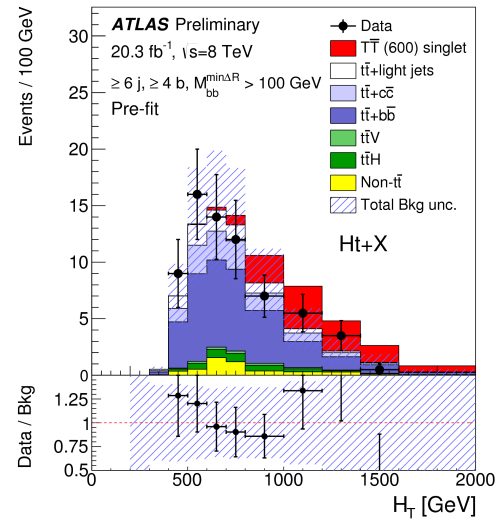
Spectacular signatures: boosted b-jets, tops, W, Z, H bosons



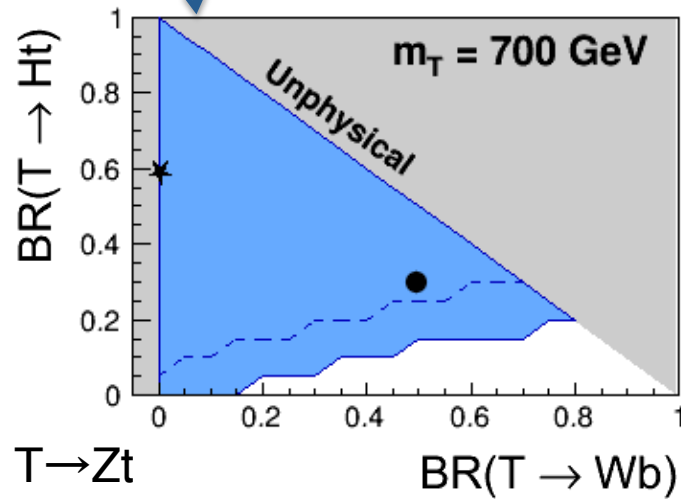
VLQ Pair Production: $T\bar{T}$



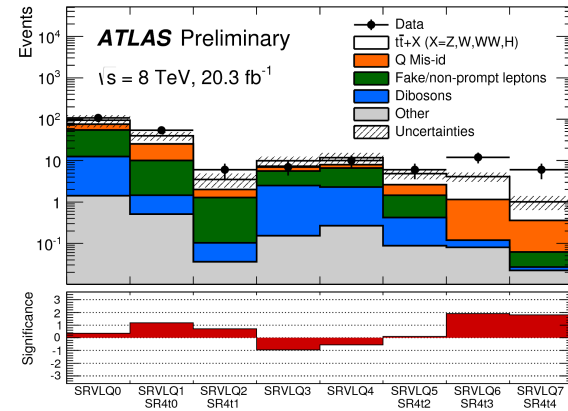
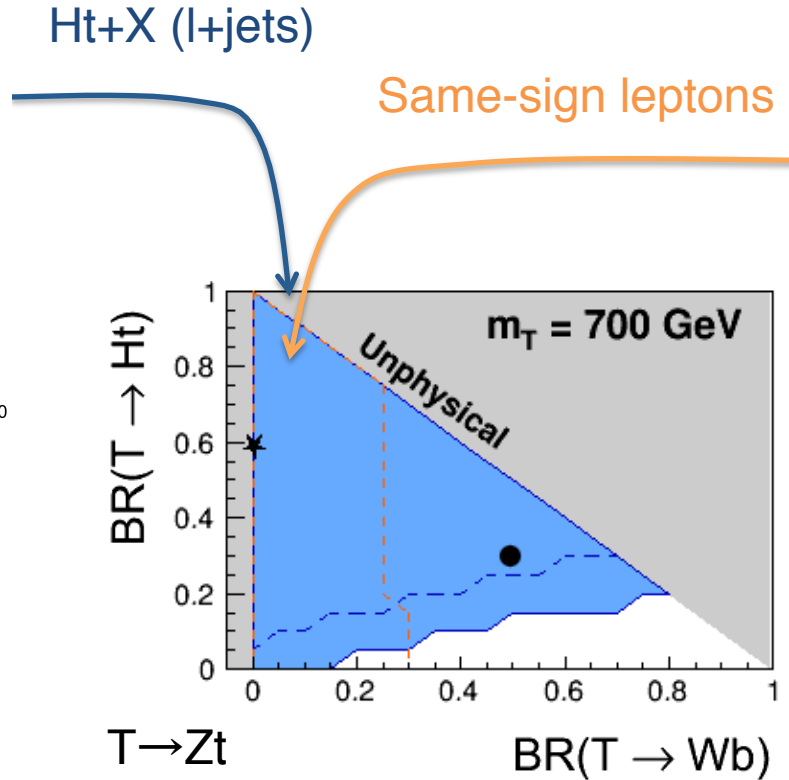
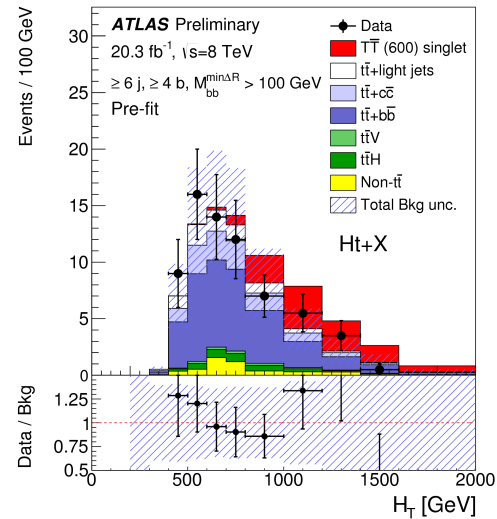
VLQ $T\bar{T}$ Search Strategy



Ht+X (l+jets)

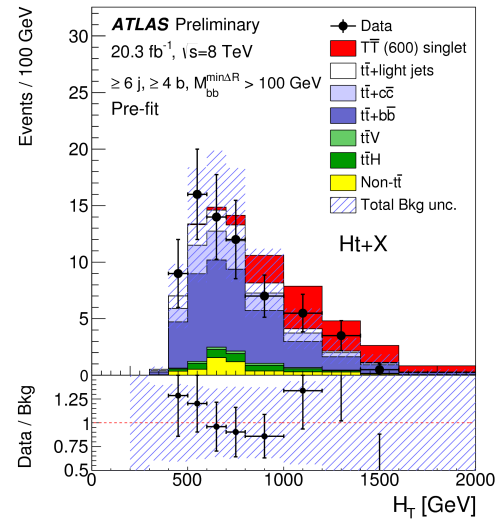


VLQ $T\bar{T}$ Search Strategy



(not a combination, just overlaying results)

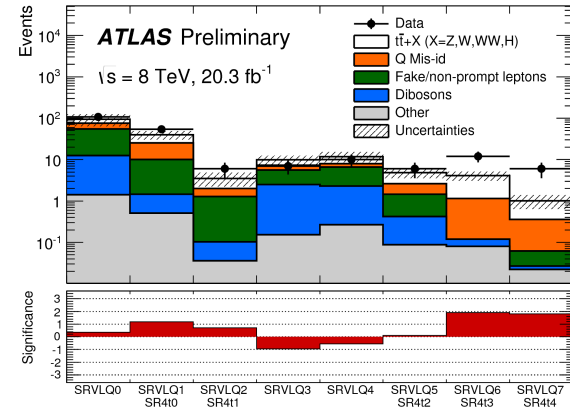
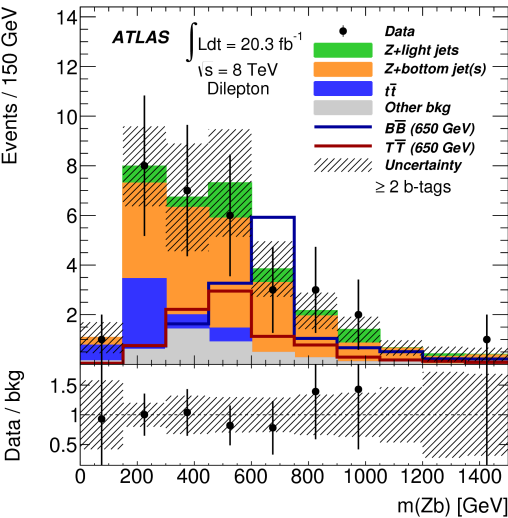
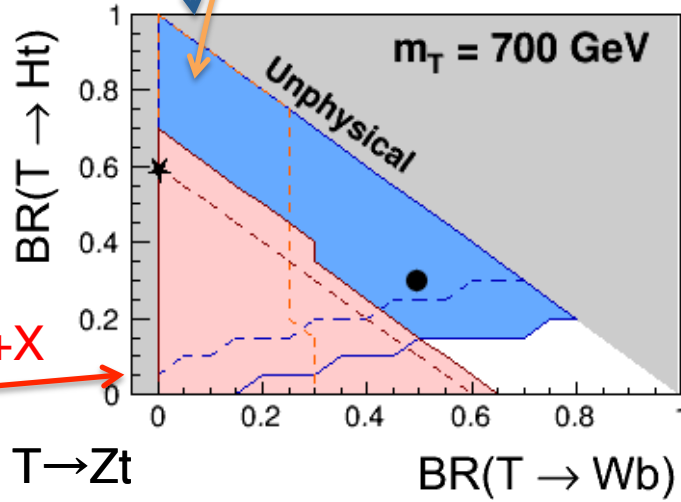
VLQ $T\bar{T}$ Search Strategy



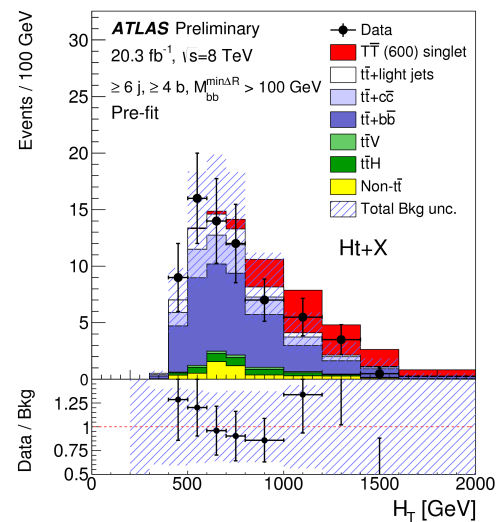
Ht+X (l+jets)

Same-sign leptons

$Z(\rightarrow ll)t+X$

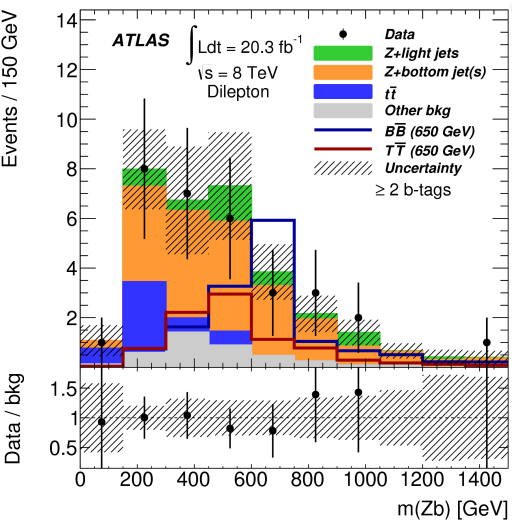
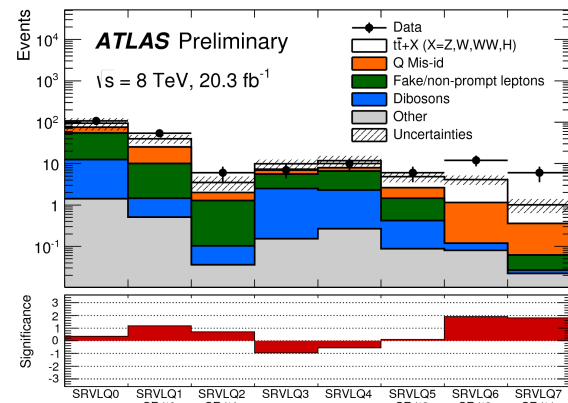


VLQ $T\bar{T}$ Search Strategy

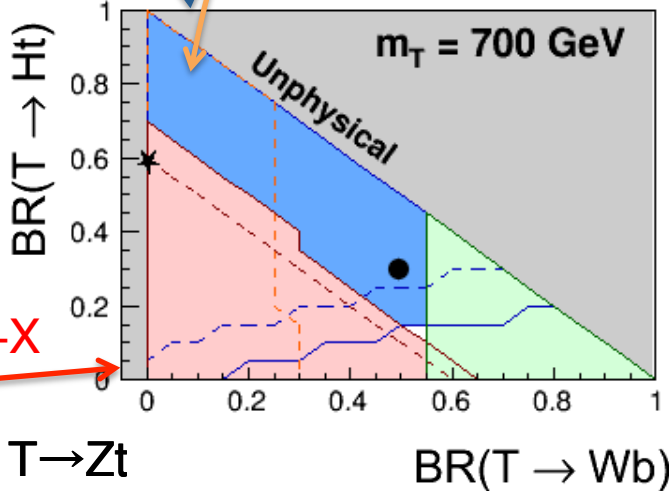


Ht+X (l+jets)

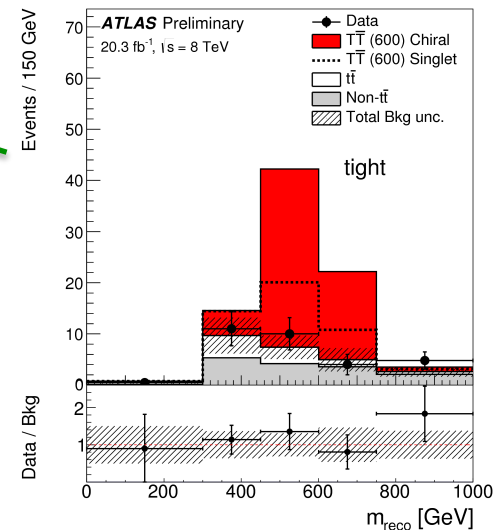
Same-sign leptons



Z($\rightarrow ll$)t+X



Wb+X (l+jets)



ATLAS Preliminary

Status: March 2015

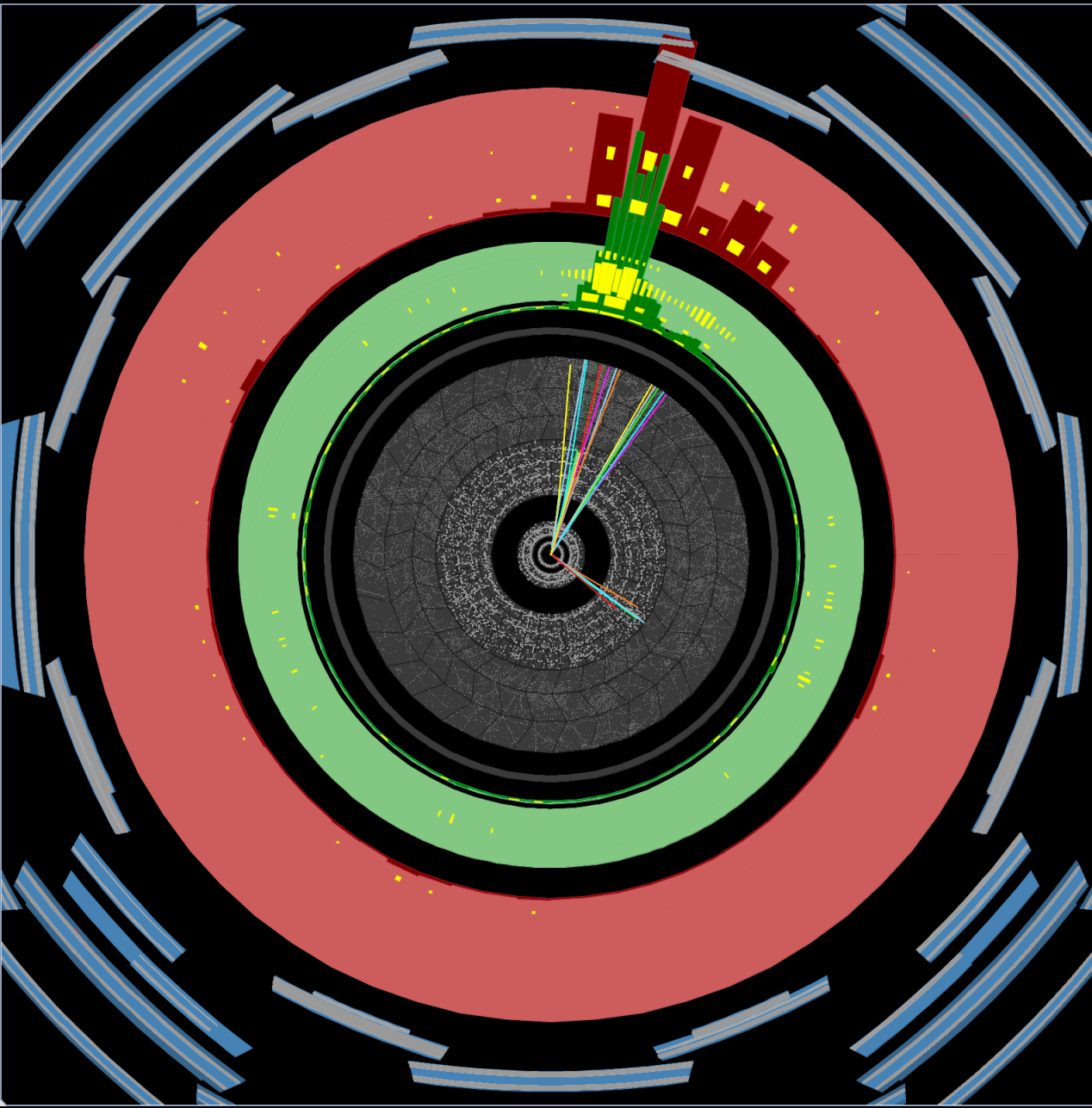
$\sqrt{s} = 8 \text{ TeV}, \int L dt = 20.3 \text{ fb}^{-1}$

--- 95% CL exp. excl. — 95% CL obs. excl.

- Ht+X [ATLAS-CONF-2015-012]
- Same-Sign ll [Preliminary]
- Zb/t+X [JHEP11 (2014) 104]
- Wb+X [ATLAS-CONF-2015-012]

★ SU(2) (T,B) doub. ● SU(2) singlet

MET+X Searches



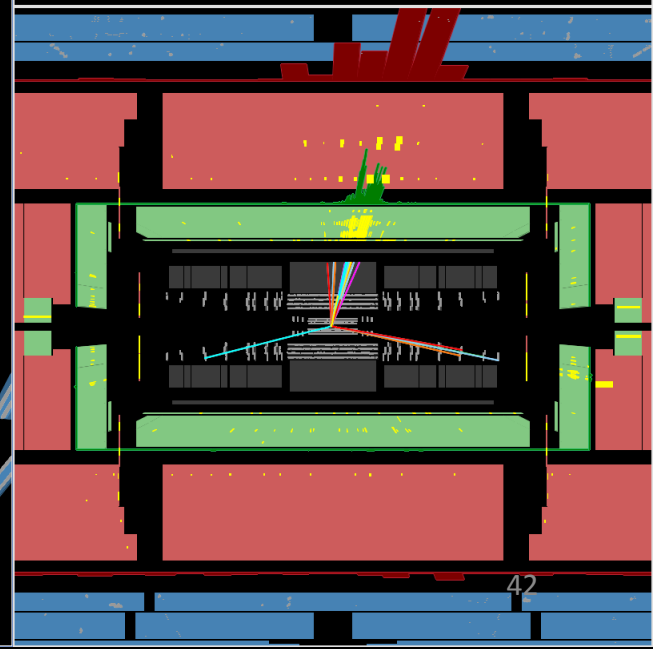
Mono-photon see
ATLAS-CONF-2012-085



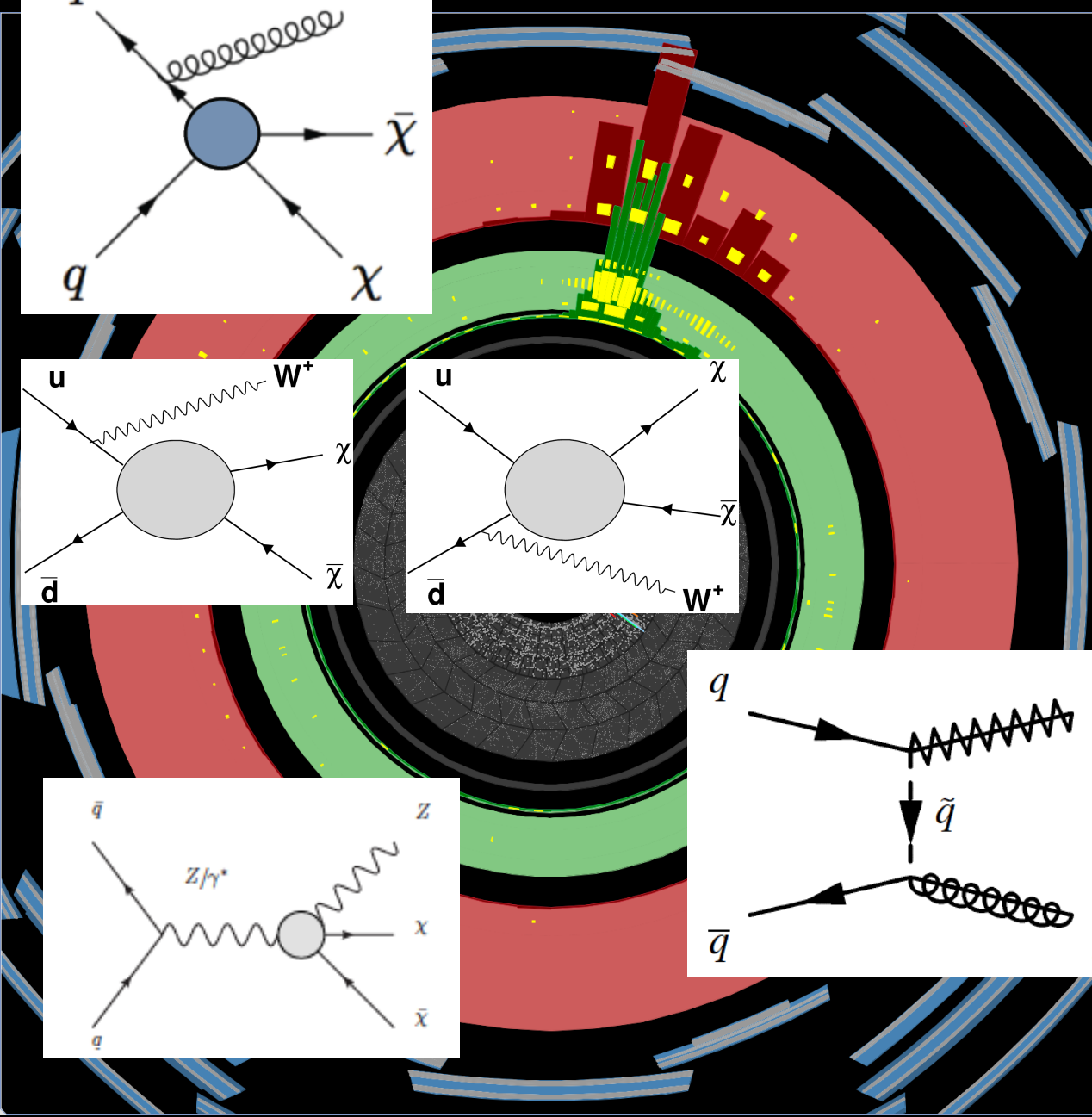
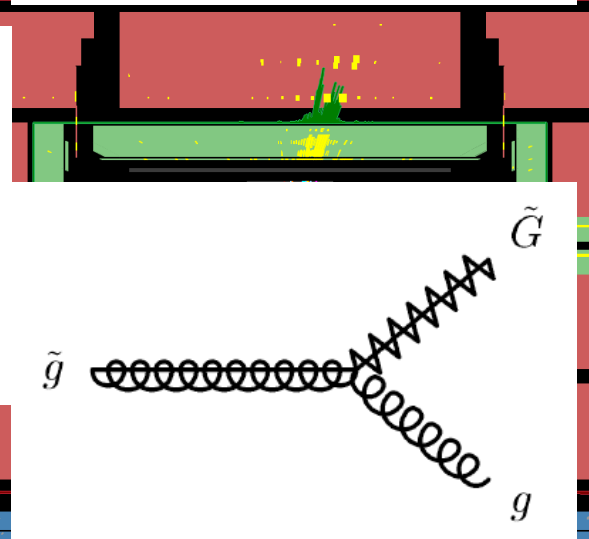
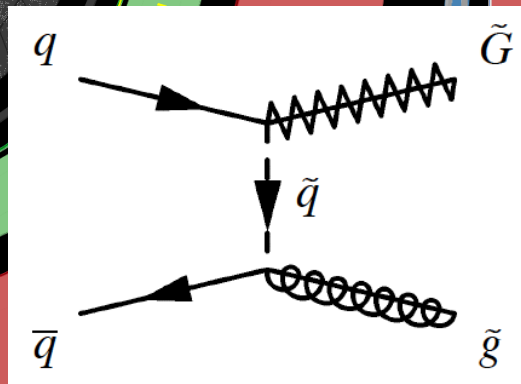
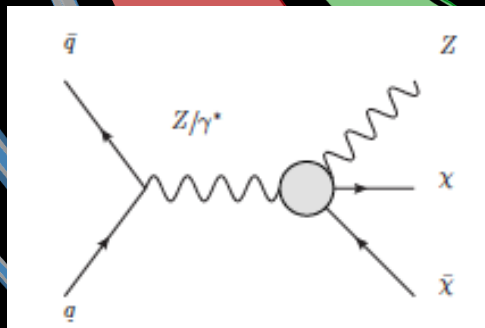
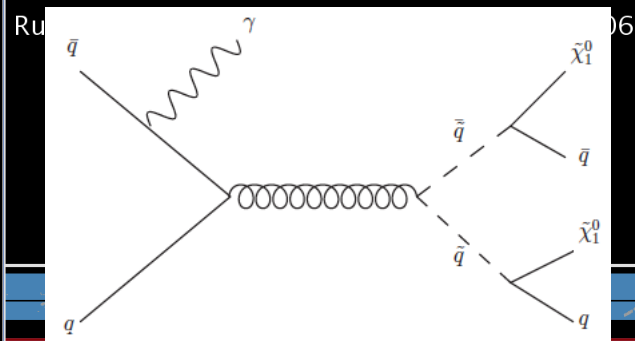
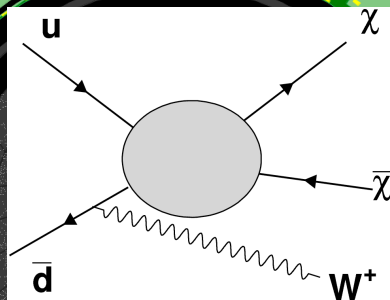
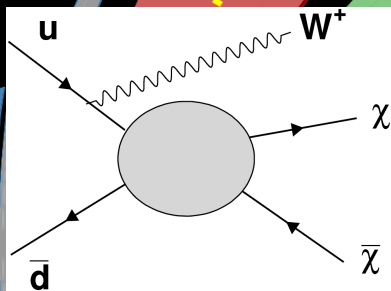
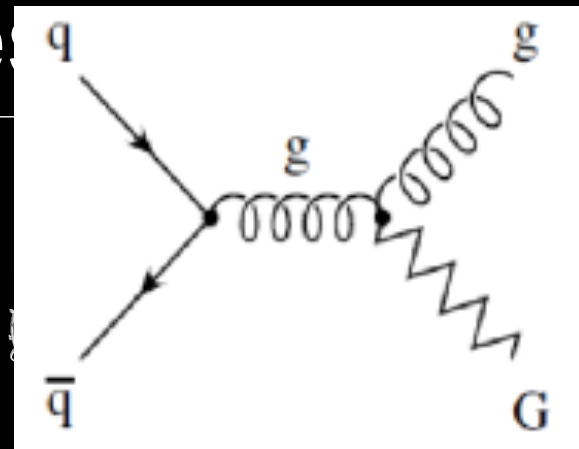
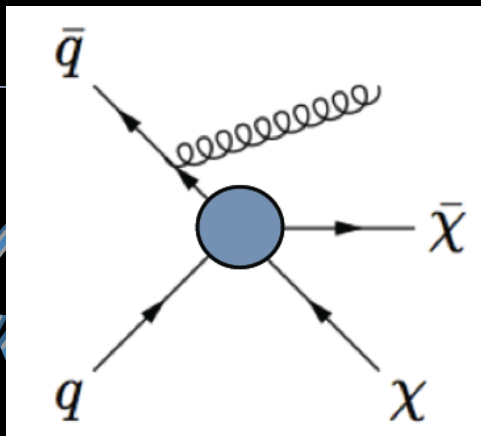
ATLAS EXPERIMENT

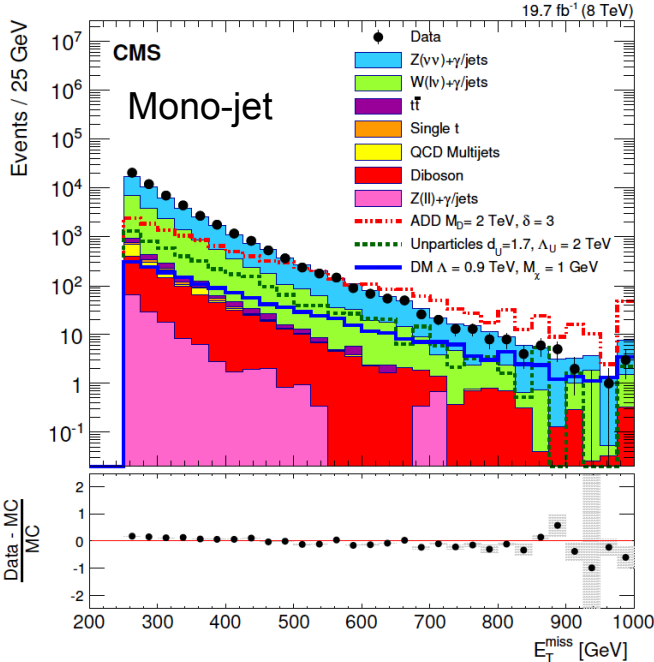
Run Number: 206962, Event Number: 55091306

Date: 2012-07-14 10:42:26 CEST



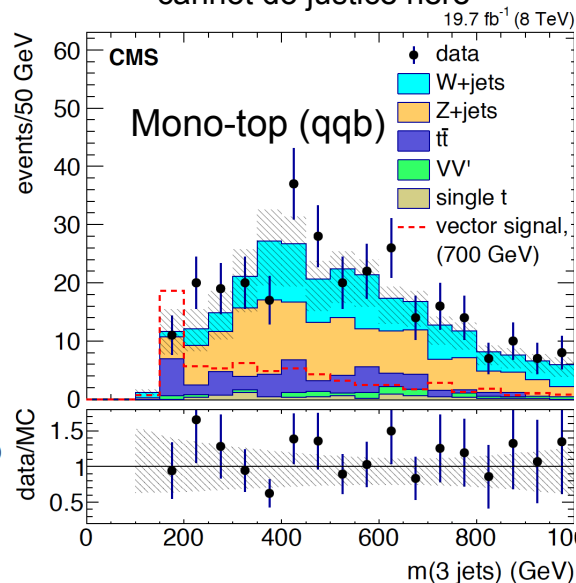
MET+X Searches



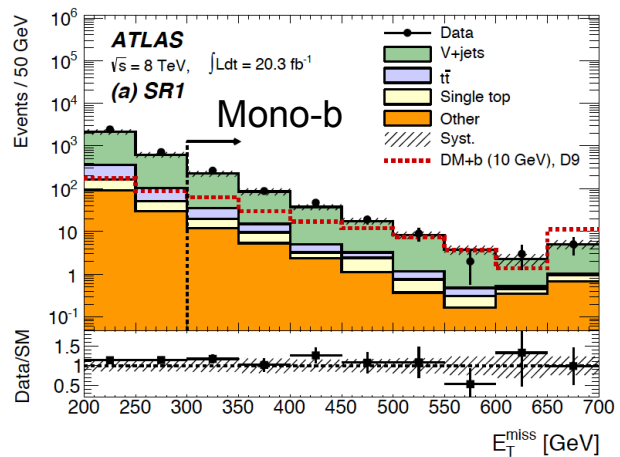
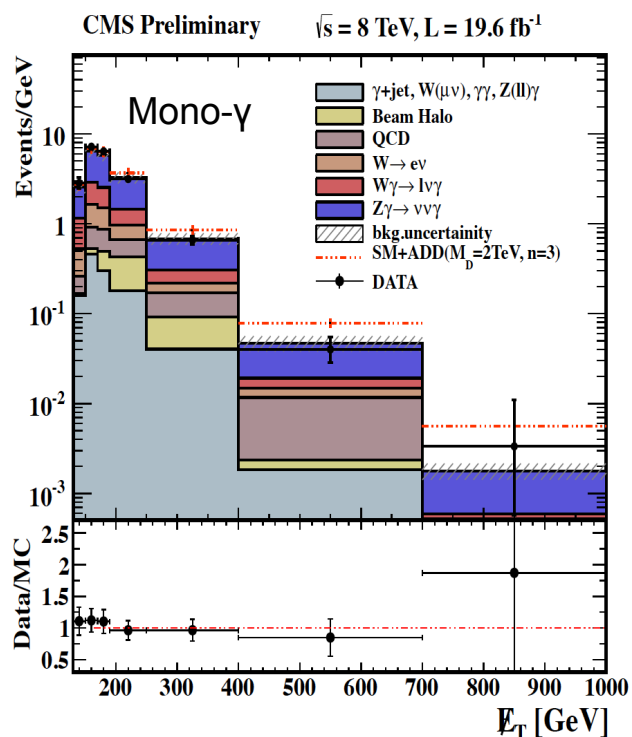
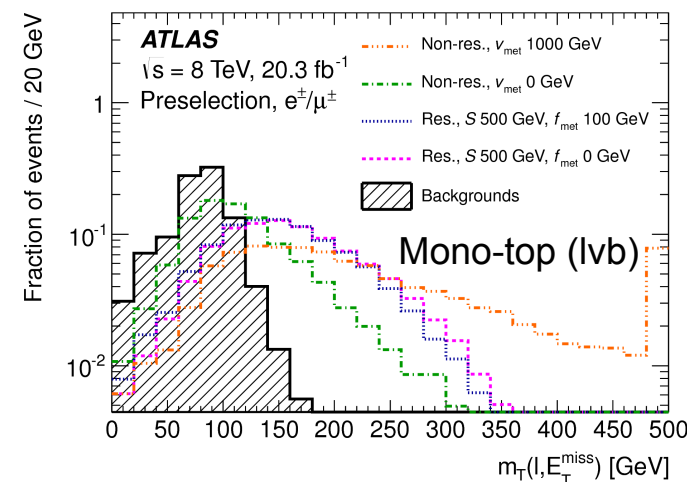


MET+X

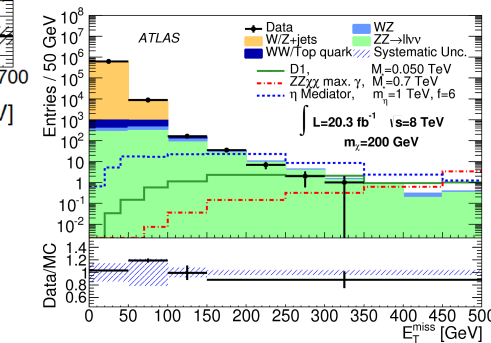
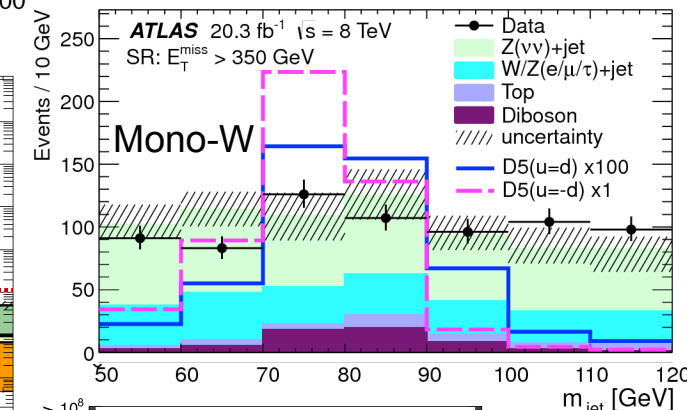
cannot do justice here



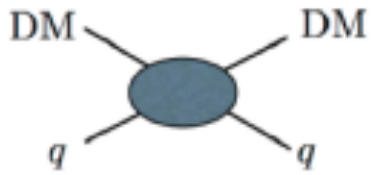
Mono-jet: 1408.3583, ATLAS-CONF-2012-147
 Mono- γ : CMS PAS EXO-12-047, ATLAS-CONF-2014-051
 Mono-top: 1410.1149, 1410.5404
 Mono-HF: 1410.4031, CMS-PAS-B2G-14-004, CMS-PAS-B2G-13-044
 Mono-W/Z (had): PRL 112 041802 (2014)
 Mono-Z (ll): PRD 90, 012004 (2014)



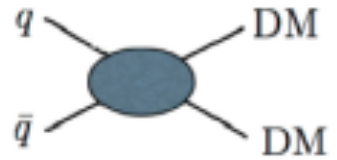
$t\bar{t}$ +MET à la stop search



WIMP – Direct Detection vs Collider Searches

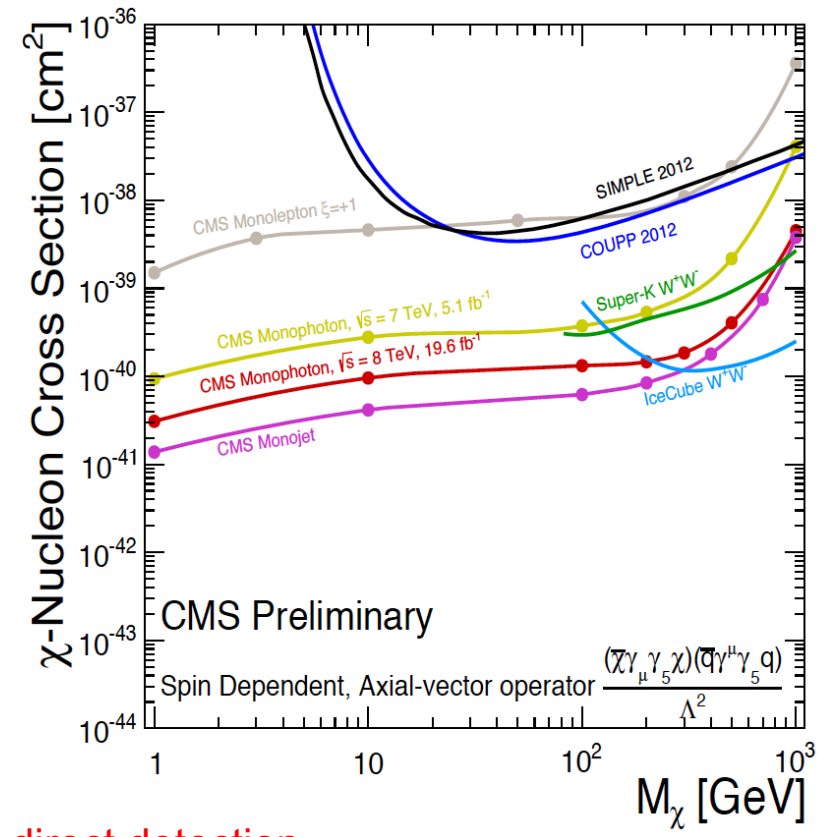
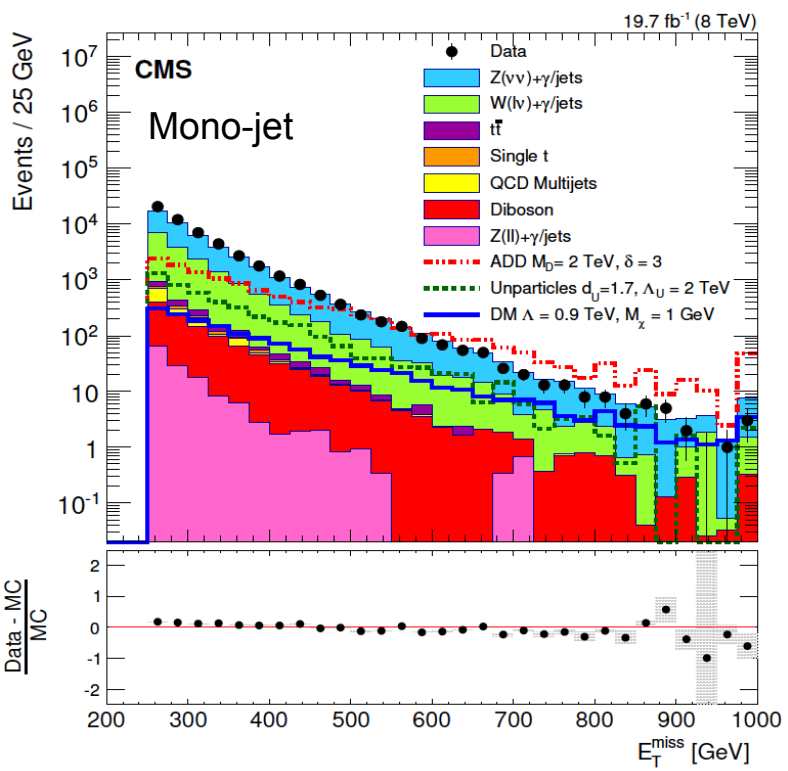


Direct Detection (t-channel)



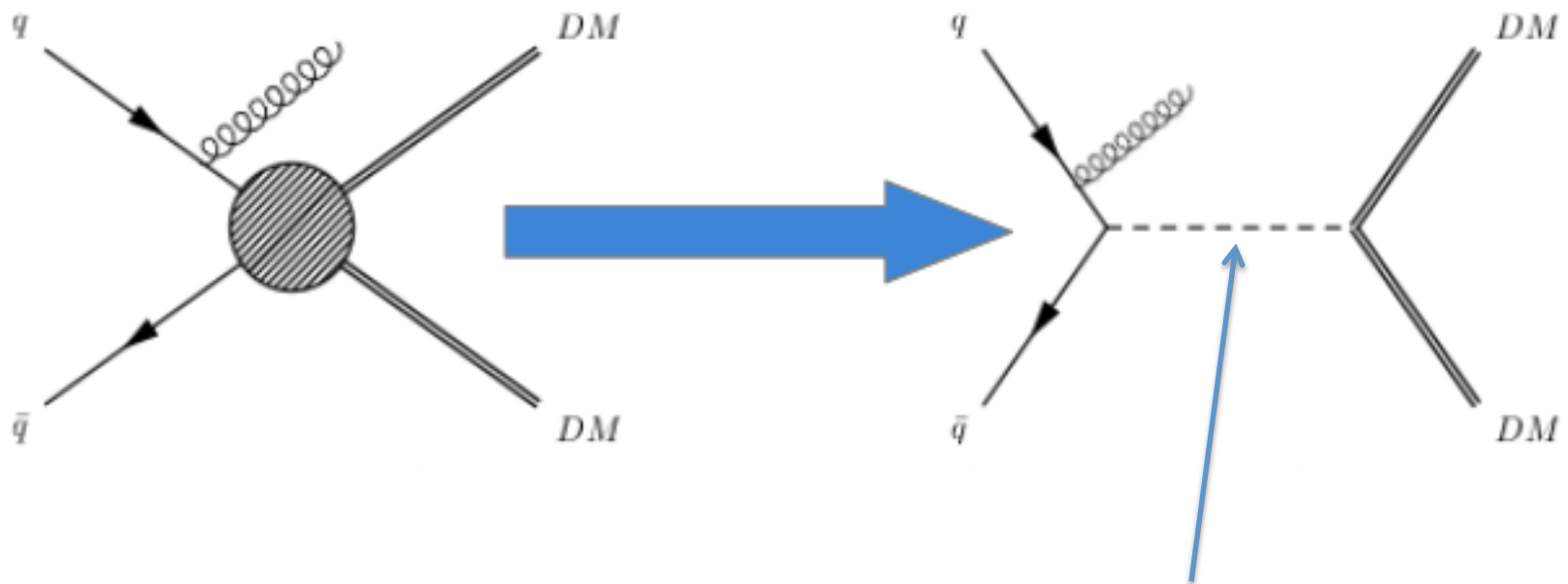
Collider Searches (s-channel)

[under certain assumptions]



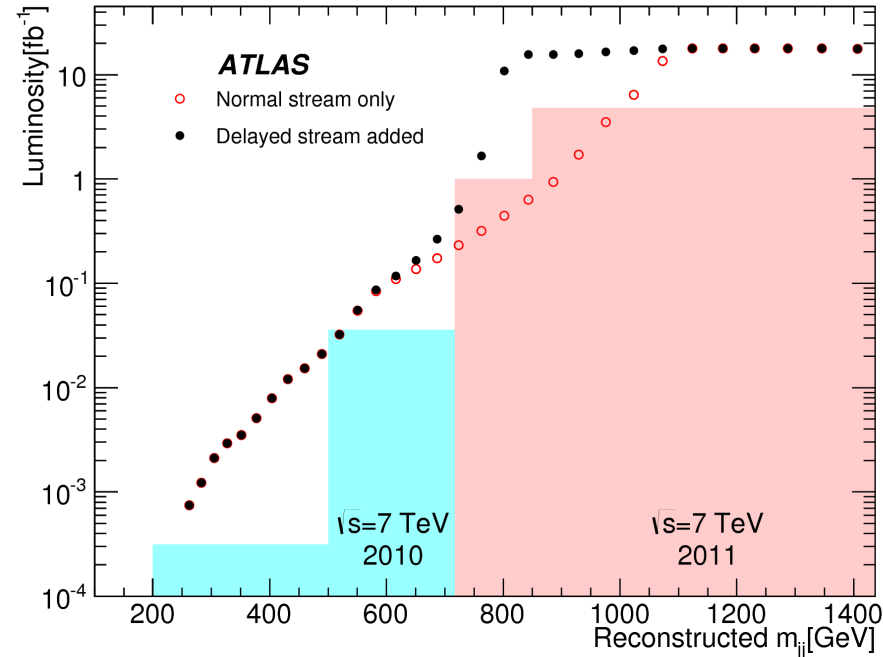
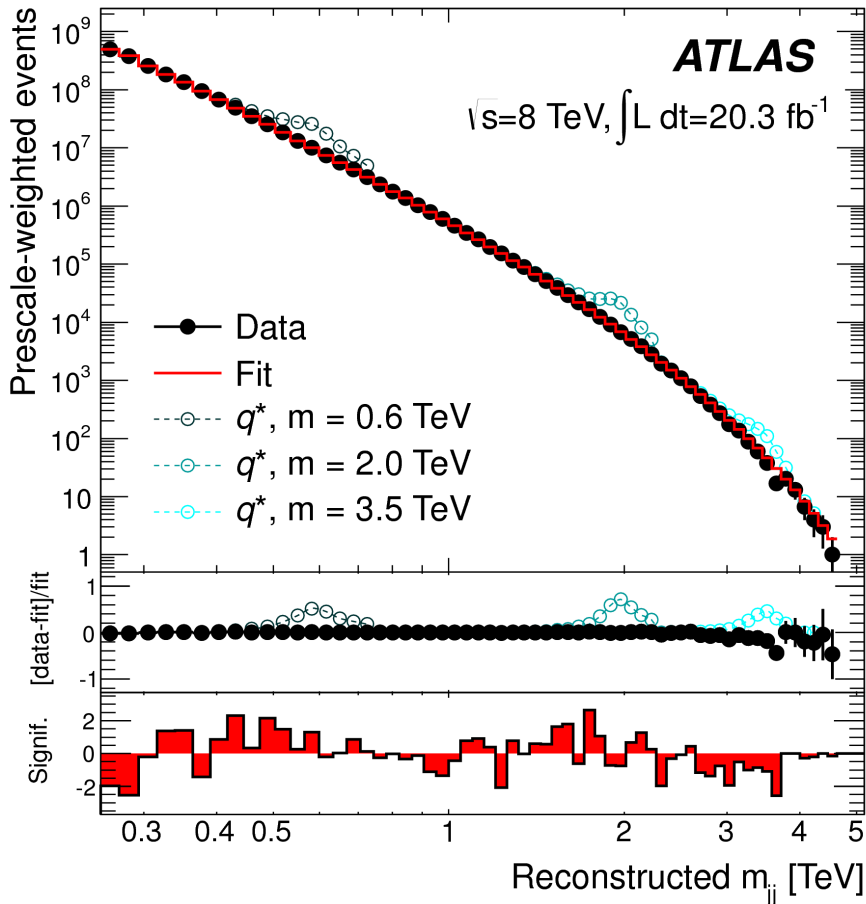
Complementary sensitivity to direct detection experiments, but model dependent...

WIMP Searches



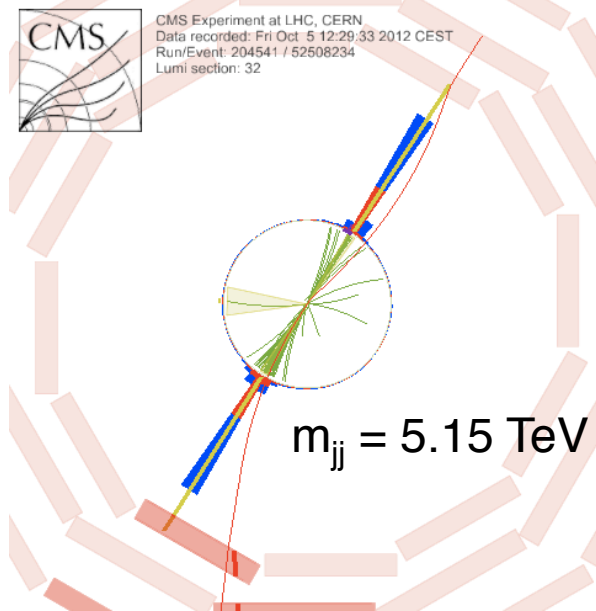
Complementary approach:
Direct searches for mediators

Dijets

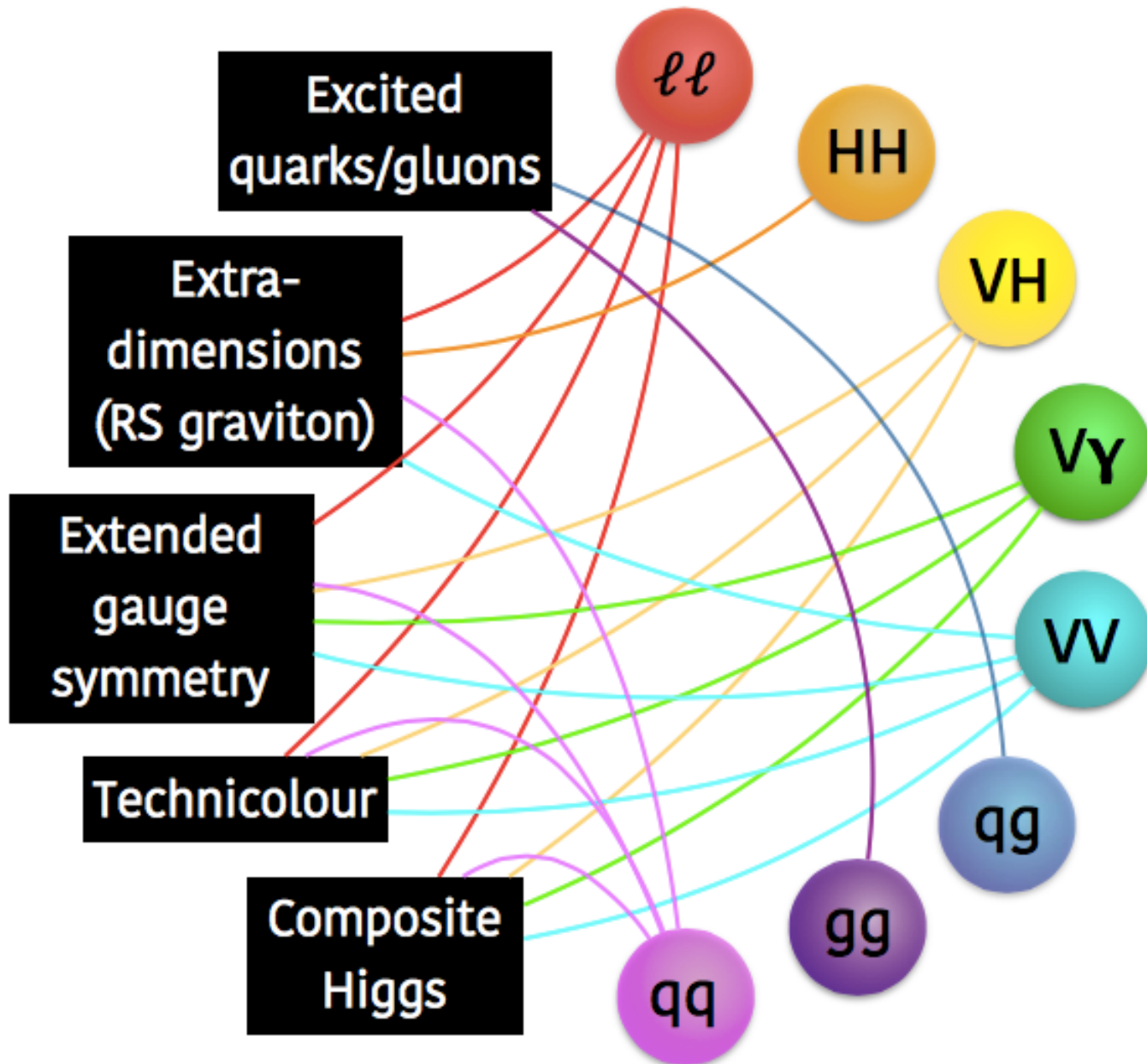


Large number of interpretations:

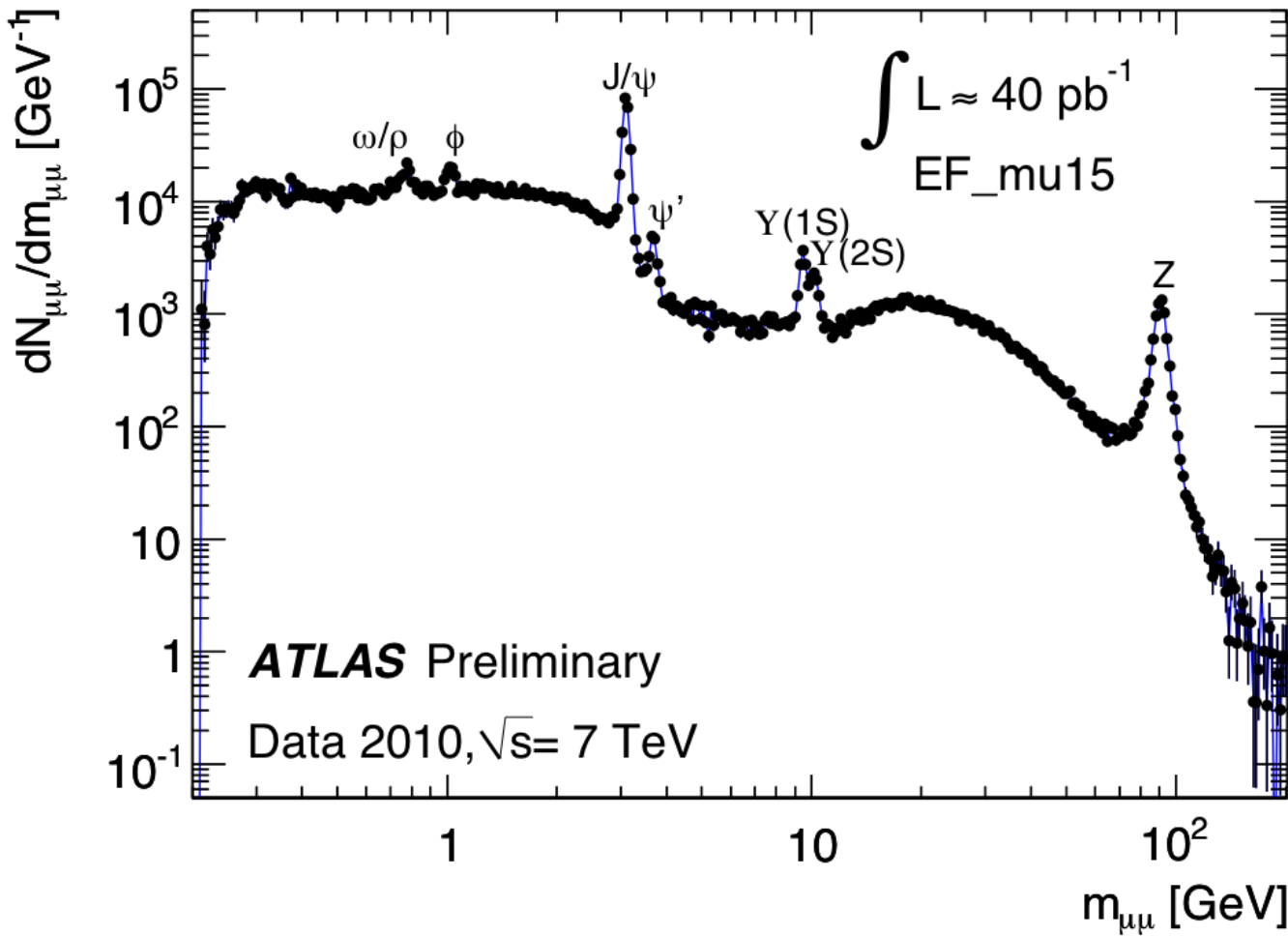
Model and Final State	95% CL Limits [TeV]	
	Expected	Observed
$q^* \rightarrow qq$	3.99	4.09
$s8 \rightarrow gg$	2.83	2.72
$W' \rightarrow q\bar{q}'$	2.51	2.45
Leptophobic $W^* \rightarrow q\bar{q}'$	1.93	1.75
Leptophilic $W^* \rightarrow q\bar{q}'$	1.67	1.66
QBH black holes	5.82	5.82
(q and g decays only)		
BLACKMAX black holes (all decays)	5.75	5.75



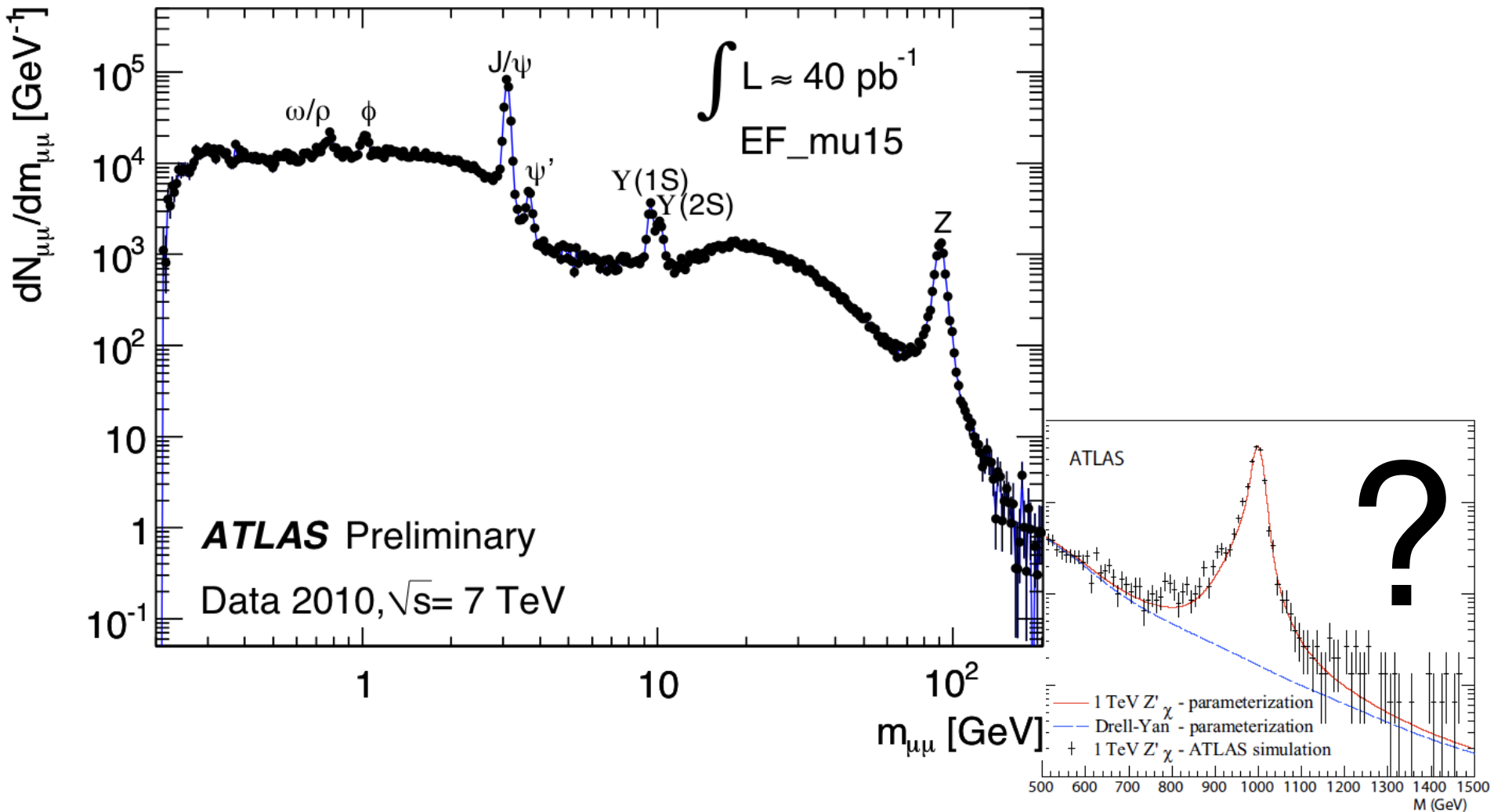
Resonances



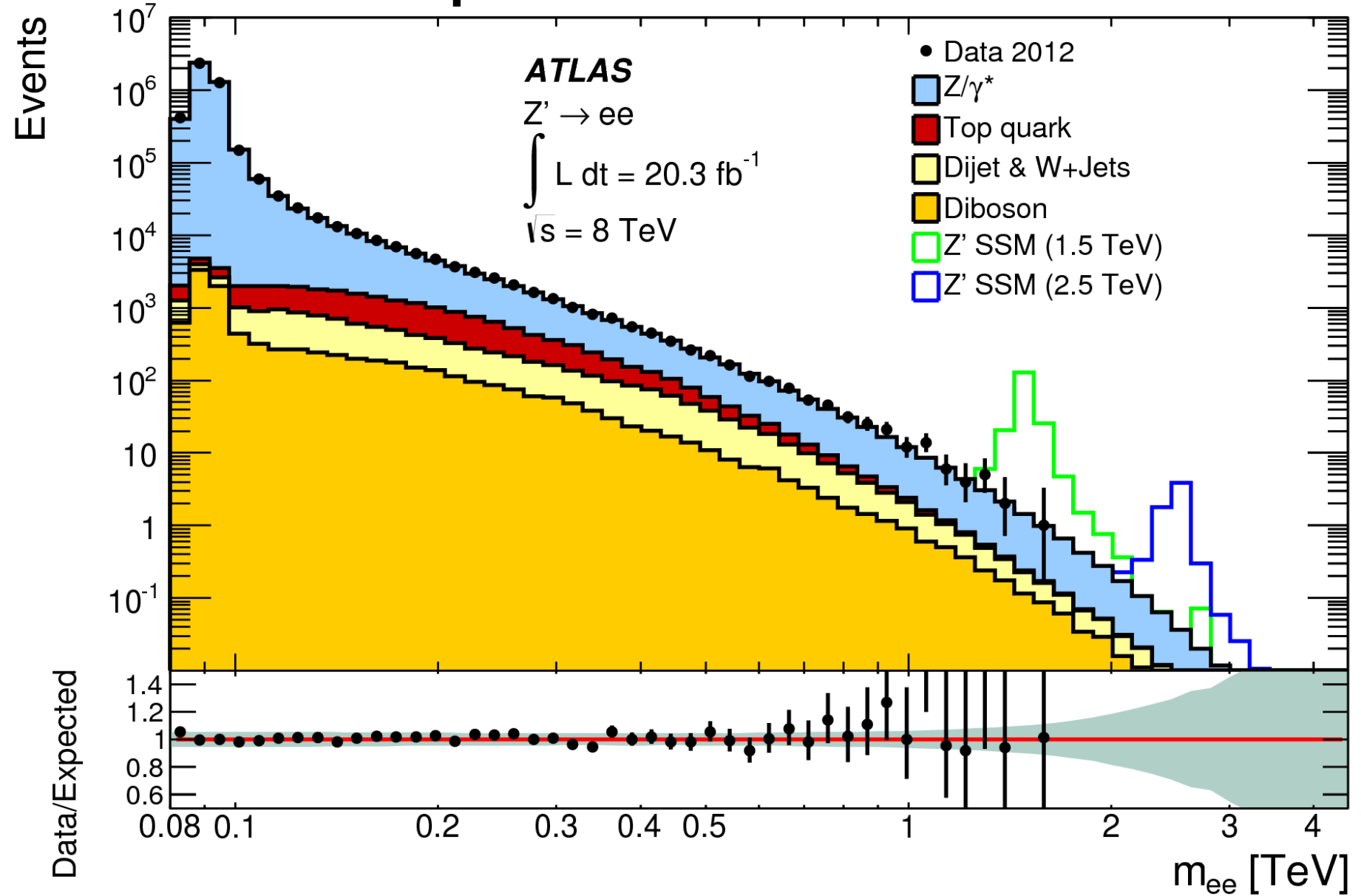
More Resonances in this Spectrum?



More Resonances in this Spectrum?



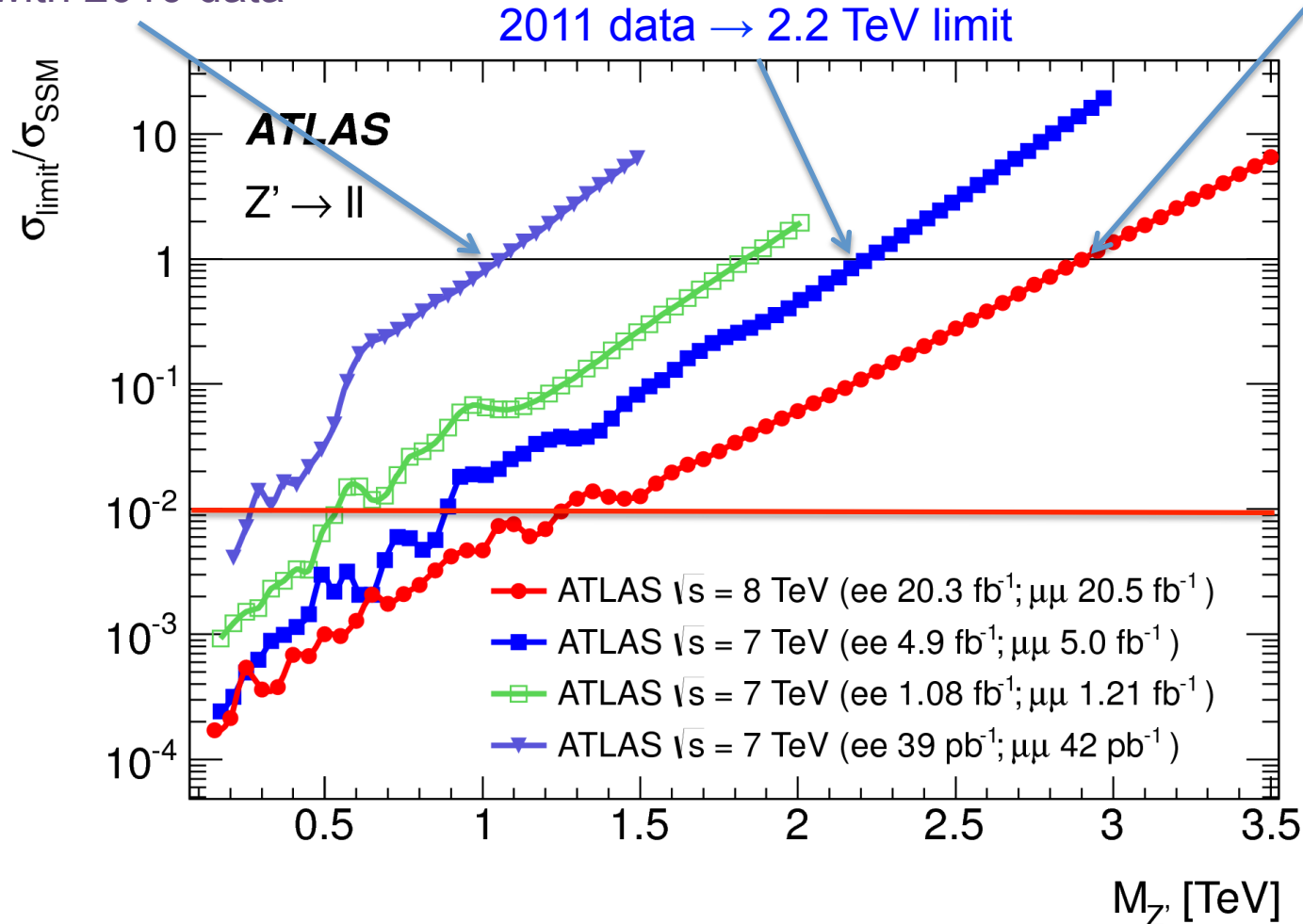
Dilepton Resonances



Development Over Years

Tevatron limits (approx. 1 TeV)
reached with 2010 data

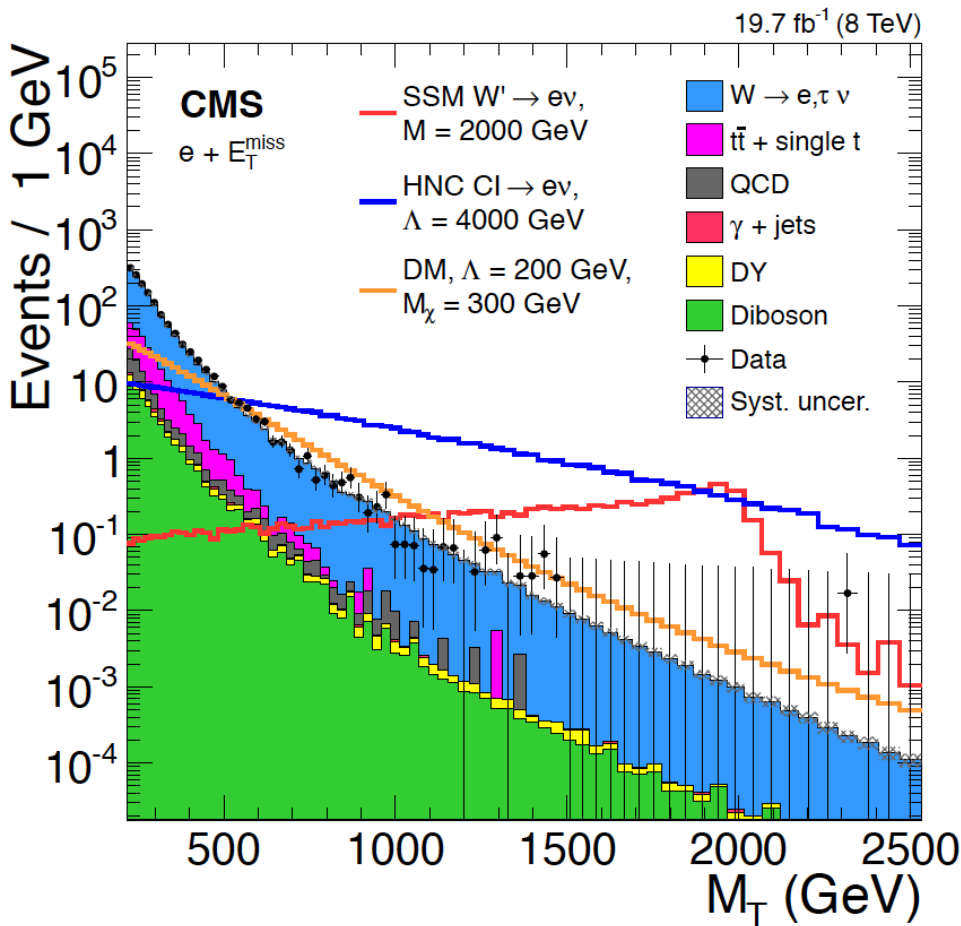
2012 data → 2.9 TeV limit



Fast increase in limits (1 TeV → 3 TeV) in short period of time

Also, narrow resonances with 100 times smaller cross section than SSM excluded up to 1.4 TeV

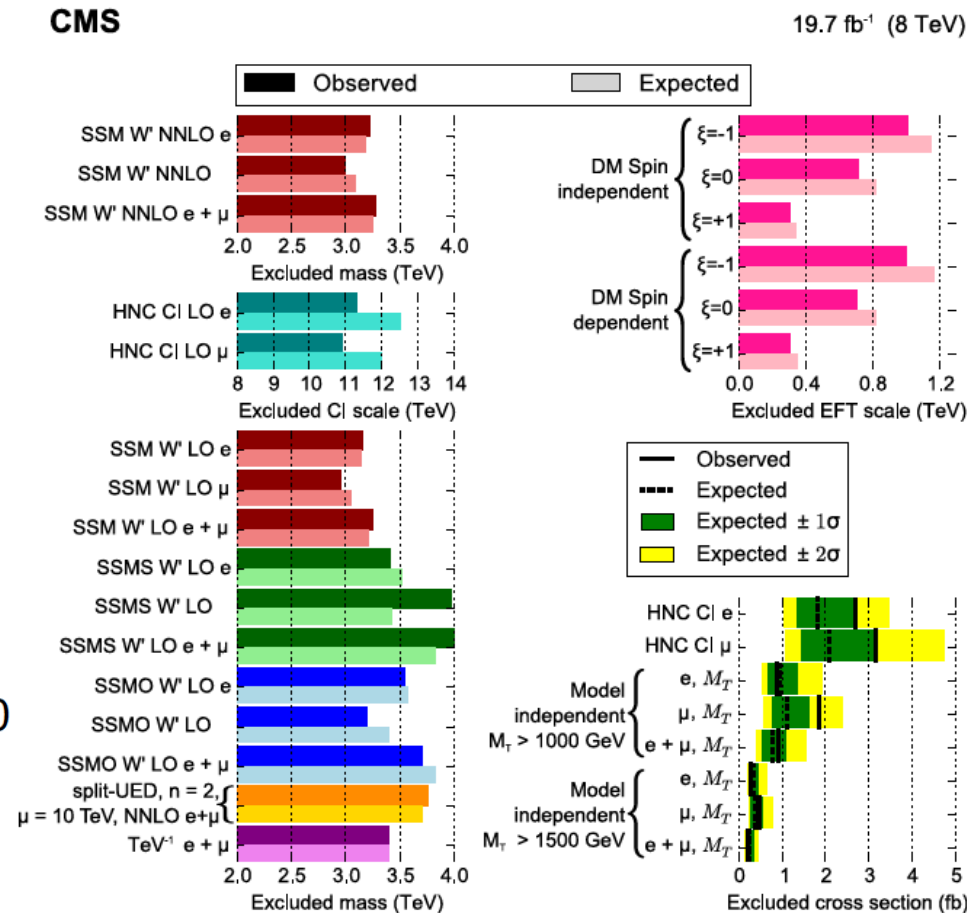
Lepton+ E_T^{miss} Resonance Search



$$m_T = \sqrt{2p_T E_T^{\text{miss}} (1 - \cos \varphi_{\ell\nu})}$$

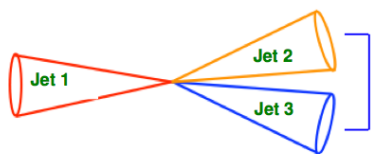
- EW backgrounds from MC
- Multijet BG from data driven method

Large number of interpretations

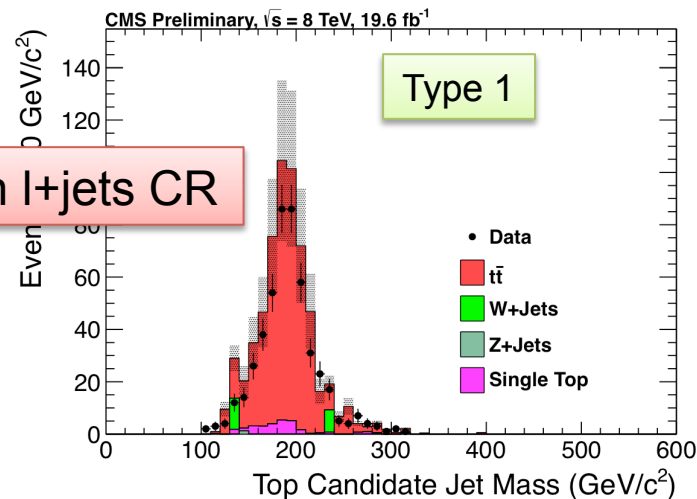
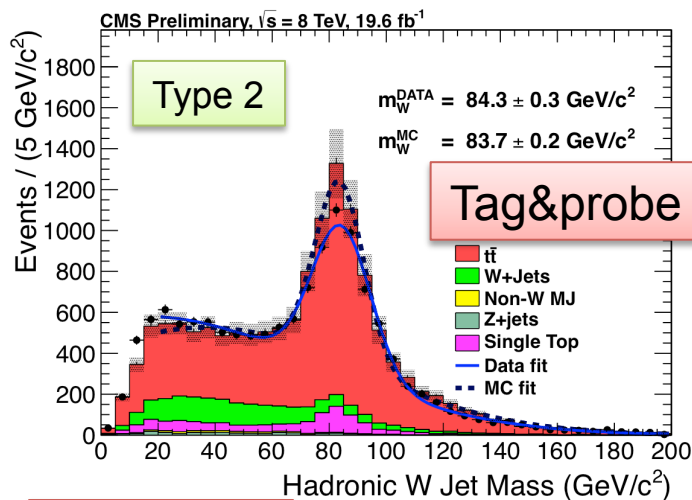
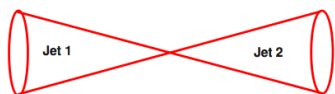


$t\bar{t}$ Resonances (all-jets)

Type 1 + Type 2

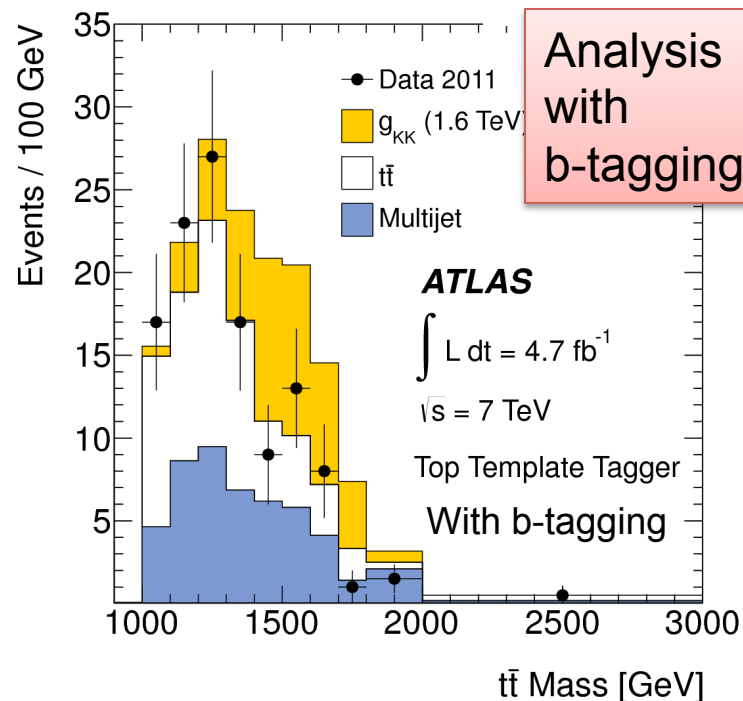


Type 1 + Type 1

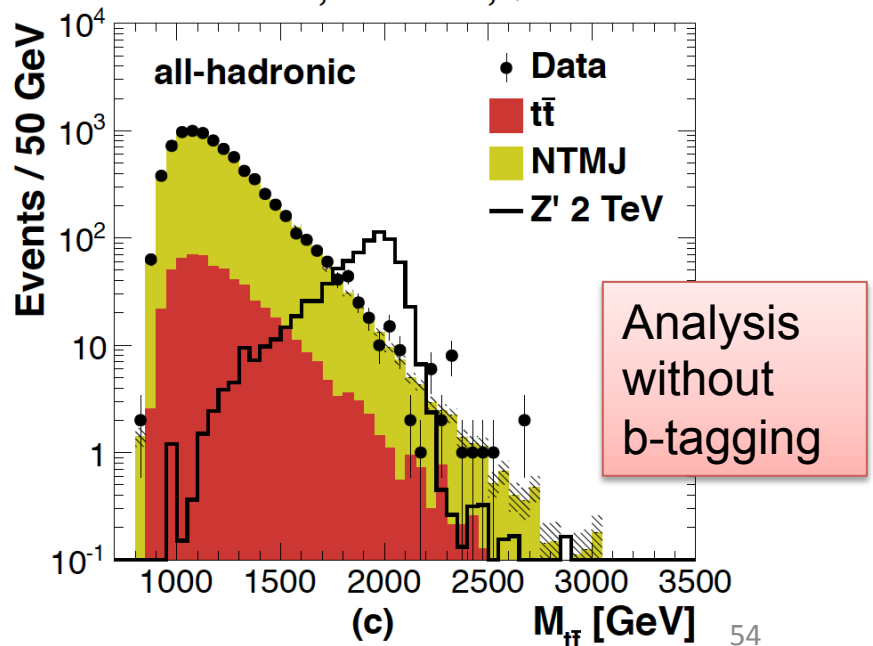


Tag&probe in I+jets CR

Analysis with b-tagging



CMS, 19.7 fb⁻¹, $\sqrt{s} = 8$ TeV

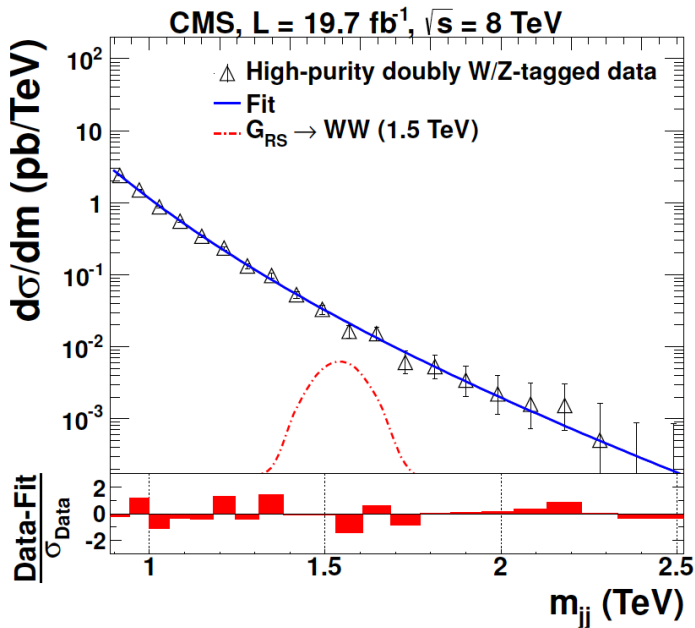


Analysis without b-tagging

$VV \rightarrow IIJ / IvJ / JJ$

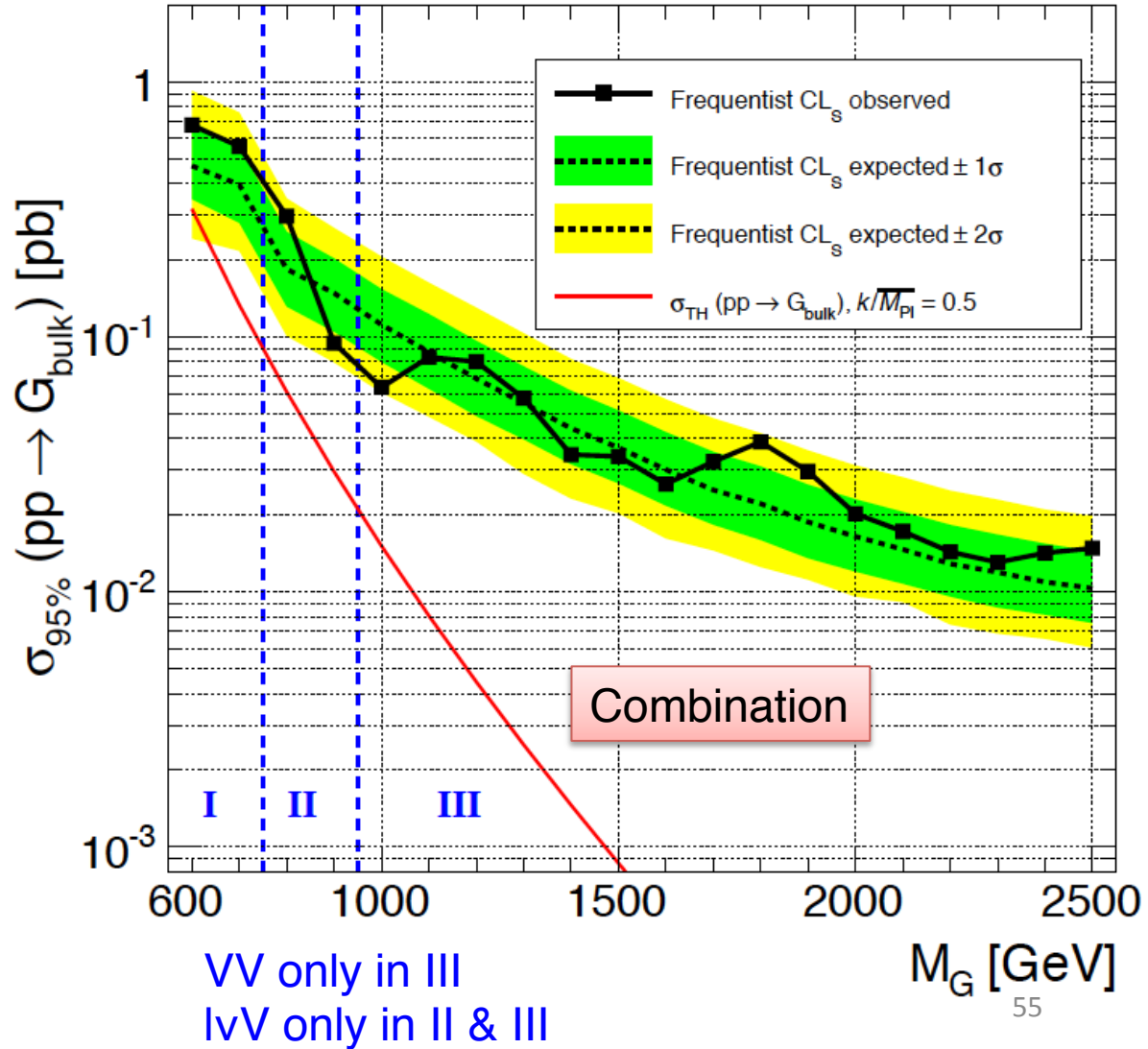
Bulk RS graviton benchmark ($k/\bar{M}_{PL} = 0.5$)

Use N-subjettiness for CA 0.8 jets to tag V-jets



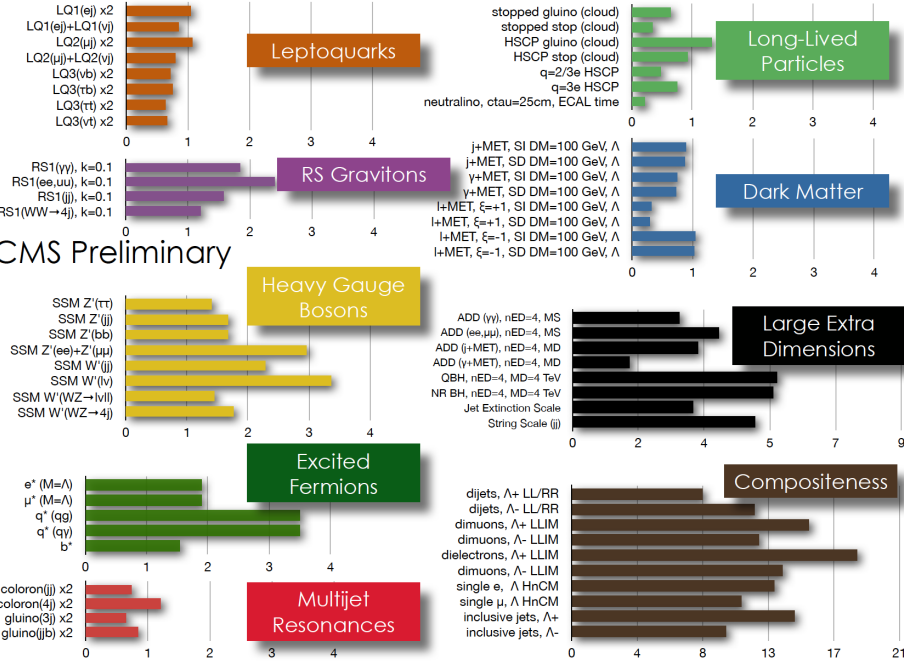
BG described by empirical fit

CMS $L = 19.7 \text{ fb}^{-1}$ at $\sqrt{s} = 8 \text{ TeV}$



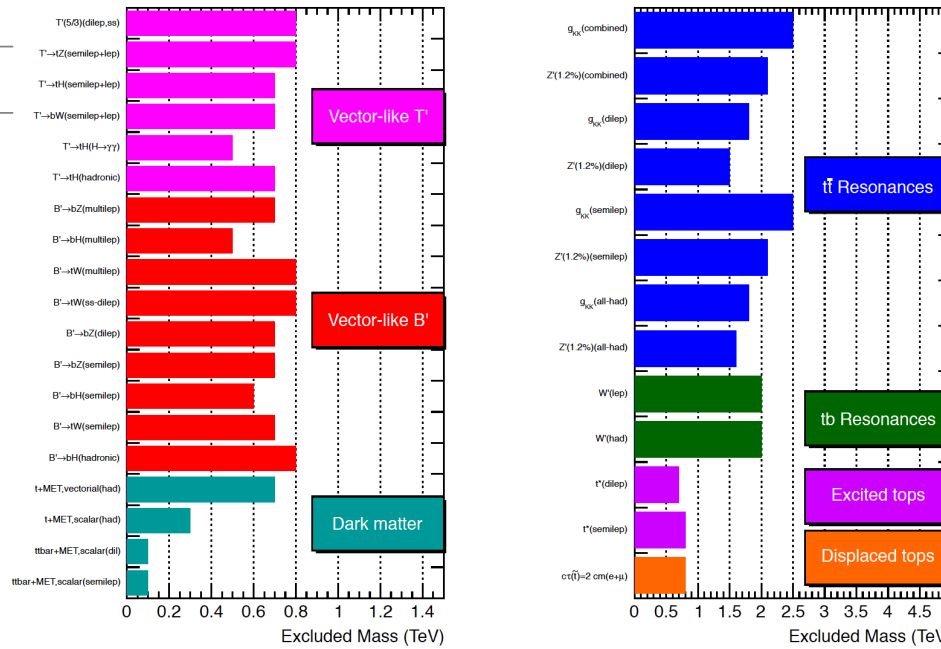
Model	ℓ, γ	Jets	Emiss	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Mass limit	Reference		
Extra dimensions	ADD $G_{XX} + g/\ell$	-	≥ 1 J	Yes	20.3	$M_{*} \geq 5.25 \text{ TeV}$	$n=2$ 1502.01518	
	ADD non-resonant $\ell\ell$	$2e, \mu$	-	-	20.3	$M_{*} \geq 4.7 \text{ TeV}$	$n=3$ PLZ 1407.2410	
	ADD OBH $\rightarrow \ell\ell$	$1e, \mu$	1 J	-	20.3	$M_{*} \geq 3.2 \text{ TeV}$	$n=6$ 1311.2086	
	ADD OBH	2 J	-	-	20.3	$M_{*} \geq 5.82 \text{ TeV}$	$n=6$ 1407.1376	
	ADD BH high N_{jet}	2μ (SS)	-	-	20.3	$M_{*} \geq 4.7 \text{ TeV}$	$n=6, M_{D_0} = 3 \text{ TeV}$, non-nk BH 1308.4075	
	ADD BH high $\sum p_T$	$\geq 1e, \mu$	≥ 2 J	-	20.3	$M_{*} \geq 5.8 \text{ TeV}$	$n=6, M_{D_0} = 3 \text{ TeV}$, non-nk BH 1405.4254	
	ADD BH high multijet	$\geq 1e, \mu$	≥ 2 J	-	20.3	$M_{*} \geq 5.8 \text{ TeV}$	$n=6, M_{D_0} = 3 \text{ TeV}$, non-nk BH Preliminary	
	RS1 $G_{XX} \rightarrow \ell\ell$	$2e, \mu$	-	-	20.3	$G_{XX} \text{ mass} \geq 2.68 \text{ TeV}$	$k/M_{*} = 0.1$ 1405.4123	
	RS1 $G_{XX} \rightarrow \gamma\gamma$	2γ	-	-	20.3	$G_{XX} \text{ mass} \geq 2.88 \text{ TeV}$	$k/M_{*} = 0.1$ Preliminary	
	Bulk RS $G_{XX} \rightarrow ZZ \rightarrow \text{qq}\ell\ell$	$2e, \mu$	2 J/1J	-	20.3	$G_{XX} \text{ mass} \geq 7.00 \text{ GeV}$	$k/M_{*} = 1.0$ 1409.6190	
	Bulk RS $G_{XX} \rightarrow WW \rightarrow \text{qq}\ell\nu$	$1e, \mu$	2 J/1J	Yes	20.3	$W_{\text{mass}} \geq 700 \text{ GeV}$	$k/M_{*} = 1.0$ 1522.0677	
	Bulk RS $G_{XX} \rightarrow HH \rightarrow b\bar{b}b\bar{b}$	$1e, \mu$	4 b	-	19.5	$G_{XX} \text{ mass} \geq 590.710 \text{ GeV}$	$k/M_{*} = 1.0$ BR = 0.985 ATLAS-COMF-2014-005	
	Bulk RS $G_{XX} \rightarrow t\bar{t}$	$1e, \mu$	$\geq 1b, \geq 1W$	Yes	20.3	$h_{\text{mass}} \geq 2.2 \text{ TeV}$	ATLAS-COMF-2015-009	
	ZUED/RPP	$2e, \mu$ (SS)	$\geq 1b, \geq 1$ J	Yes	20.3	$h_{\text{mass}} \geq 568 \text{ GeV}$	Preliminary	
	Gauge bosons	SSM $Z' \rightarrow \ell\ell$	$2e, \mu$	-	-	20.3	$Z' \text{ mass} \geq 2.9 \text{ TeV}$	1405.4123
SSM $Z' \rightarrow \tau\tau$		2τ	-	-	19.5	$Z' \text{ mass} \geq 2.02 \text{ TeV}$	1520.0777	
SSM $W' \rightarrow \ell\nu$		$1e, \mu$	Yes	-	20.3	$W' \text{ mass} \geq 1.54 \text{ TeV}$	1407.2494	
EGM $W' \rightarrow WZ \rightarrow \ell\nu\ell\ell'$		$3e, \mu$	-	Yes	20.3	$W' \text{ mass} \geq 1.52 \text{ TeV}$	1406.4456	
EGM $W' \rightarrow WZ \rightarrow \text{qq}\ell\ell'$		$2e, \mu$	2 J/1J	-	20.3	$W' \text{ mass} \geq 1.59 \text{ TeV}$	1409.6190	
WFT $W' \rightarrow WH \rightarrow \ell\nu b\bar{b}$		$1e, \mu$	2 b	-	20.3	$W' \text{ mass} \geq 1.47 \text{ TeV}$	20.3	
LRSM $W'_{\ell} \rightarrow WH \rightarrow \ell\nu b\bar{b}$		$1e, \mu$	$2b, 0-1$ J	Yes	20.3	$W' \text{ mass} \geq 1.92 \text{ TeV}$	$\beta_V = 1$ Preliminary	
LRSM $W'_{\ell} \rightarrow \ell\bar{\nu}$		$0e, \mu$	$\geq 1b, 1$ J	-	20.3	$W' \text{ mass} \geq 1.76 \text{ TeV}$	1410.4103 1408.0888	
CI		CI $\text{qq}\ell\ell$	-	2 J	-	17.3	$A \geq 12.0 \text{ TeV}$ $\eta_{LL} = -1$	Preliminary
		CI $\text{qq}\ell\ell$	$2e, \mu$	-	-	20.3	$A \geq 21.8 \text{ TeV}$ $\eta_{LL} = -1$	1407.2410
	CI uutt	$2e, \mu$ (SS)	$\geq 1b, \geq 1$ J	Yes	20.3	$A \geq 4.35 \text{ TeV}$ $ \zeta_{LL} = 1$	Preliminary	
DM	EFT D5 operator (Dirac)	$0e, \mu$	≥ 1 J	Yes	20.3	$M_{*} \geq 97.4 \text{ GeV}$	at 90% CL for $m_{\chi_1} < 100 \text{ GeV}$ 1502.01518	
	EFT D9 operator (Dirac)	$0e, \mu$	$1J, \leq 1$ J	Yes	20.3	$M_{*} \geq 2.4 \text{ TeV}$	$\beta = 1$ at 90% CL for $m_{\chi_1} < 100 \text{ GeV}$ 1509.1017	
LQ	Scalar LQ 1^{st} gen	$2e$	≥ 2 J	-	1.0	$LQ \text{ mass} \geq 660 \text{ GeV}$	$\beta = 1$ 1112.4828	
	Scalar LQ 2^{nd} gen	2μ	≥ 2 J	-	1.0	$LQ \text{ mass} \geq 495 \text{ GeV}$	$\beta = 1$ 1203.3722	
	Scalar LQ 3^{rd} gen	$1e, \mu, 1\tau$	$1b, 1$ J	-	4.7	$LQ \text{ mass} \geq 534 \text{ GeV}$	$\beta = 1$ 1503.0526	
Heavy quarks	VLO $TT \rightarrow Hh + X, Wb + X$	$1e, \mu$	$\geq 1b, \geq 1$ J	Yes	20.3	$T \text{ mass} \geq 785 \text{ GeV}$	isospin singlet ATLAS-COMF-2015-012	
	VLO $TT \rightarrow Zt + X$	$2b, 3e, \mu$	≥ 2 J, $1b$	-	20.3	$T \text{ mass} \geq 735 \text{ GeV}$	T in (T, B) doublet 1409.5500	
	VLO $BB \rightarrow Zb + X$	$2b, 3e, \mu$	≥ 2 J, $1b$	-	20.3	$B \text{ mass} \geq 753 \text{ GeV}$	B in (T, B) doublet 1409.5500	
	VLO $BB \rightarrow Wt + X$	$1e, \mu$	$\geq 1b, \geq 1$ J	Yes	20.3	$B \text{ mass} \geq 640 \text{ GeV}$	isospin singlet Preliminary	
	VLO $BB \rightarrow Wt + X$	$1e, \mu$	$\geq 1b, \geq 1$ J	Yes	20.3	$B \text{ mass} \geq 640 \text{ GeV}$	isospin singlet Preliminary	
Excited fermions	Excited quark $q^* \rightarrow q\gamma$	1γ	1 J	-	20.3	$q^* \text{ mass} \geq 3.5 \text{ TeV}$	only u^* and d^* , $A = m(q^*)$ 1509.5250	
	Excited quark $q^* \rightarrow qg$	-	2 J	-	20.3	$q^* \text{ mass} \geq 4.09 \text{ TeV}$	only u^* and d^* , $A = m(q^*)$ 1407.1376	
	Excited quark $b^* \rightarrow Wt$	1 or $2e, \mu, 1b, 2$ J or 1 J	Yes	4.7	$b^* \text{ mass} \geq 870 \text{ GeV}$	left-handed coupling 1501.1588		
	Excited lepton $\ell^* \rightarrow \ell\gamma$	$2e, \mu, 1\gamma$	-	-	13.0	$\ell^* \text{ mass} \geq 2.2 \text{ TeV}$	$A = 2.2 \text{ TeV}$ 1508.1364	
	Excited lepton $\nu^* \rightarrow \nu W, \nu Z$	$3e, \mu, \tau$	-	-	20.3	$\ell^* \text{ mass} \geq 1.6 \text{ TeV}$	$A = 1.6 \text{ TeV}$ 1411.2921	
Other	LSTC $\tau^+ \rightarrow W\gamma$	$1e, \mu, 1\gamma$	-	Yes	20.3	$h_{\text{mass}} \geq 568 \text{ GeV}$	1407.8150	
	LRSM $M_{\text{Majorana}} \nu$	$2e, \mu$	2 J	-	20.3	$N_{\text{H}} \text{ mass} \geq 1.5 \text{ TeV}$	$m(W_{\nu}) = 2 \text{ TeV}$ no mixing 1509.5400	
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\ell$	$2e, \mu$ (SS)	-	-	20.3	$H^{\pm\pm} \text{ mass} \geq 551 \text{ GeV}$	DY production, BR $H^{\pm\pm} \rightarrow \ell\ell = 1$ 1412.0527	
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\tau$	$3e, \mu, \tau$	-	-	20.3	$H^{\pm\pm} \text{ mass} \geq 400 \text{ GeV}$	DY production, BR $H^{\pm\pm} \rightarrow \ell\tau = 1$ 1411.2921	
	Monopole (non-res. prod)	$1e, \mu$	$1b$	Yes	20.3	$h_{\text{mass}} \geq 657 \text{ GeV}$	$\beta_{\text{mon}} = 0.2$ 1410.5404	
Multi-charged particles						DY production, $ \eta = 5e$ Preliminary		
Magnetic monopoles						DY production, $ \eta = 1e_{\text{G}}$ 1207.6411		

*Only a selection of the available mass limits on new states or phenomena is shown.



Many more searches all empty-handed so far

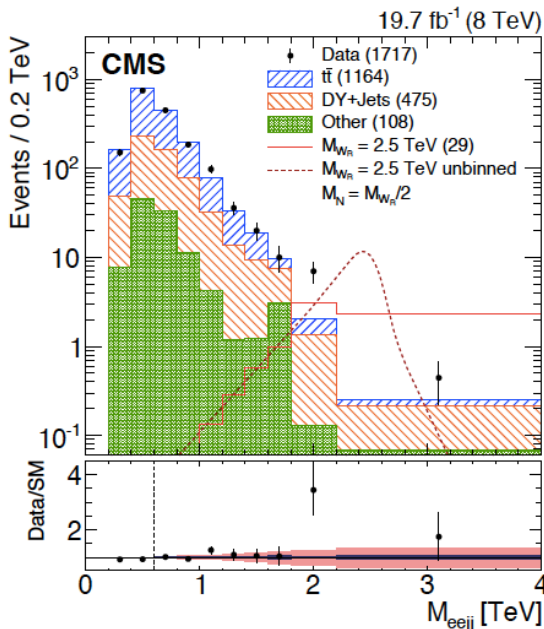
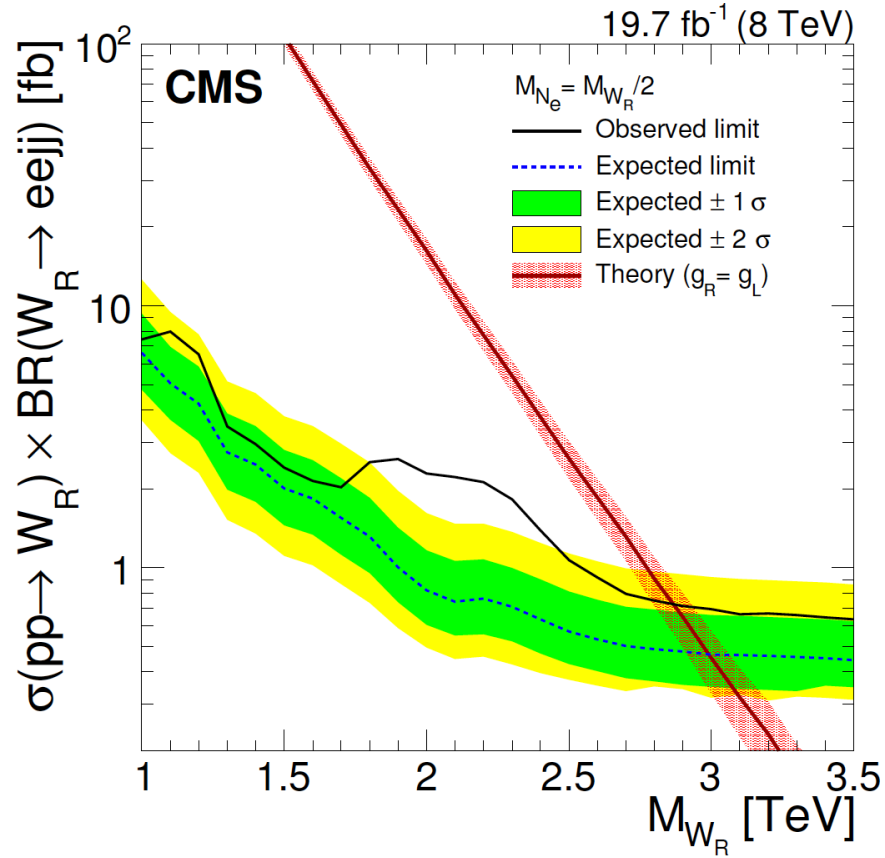
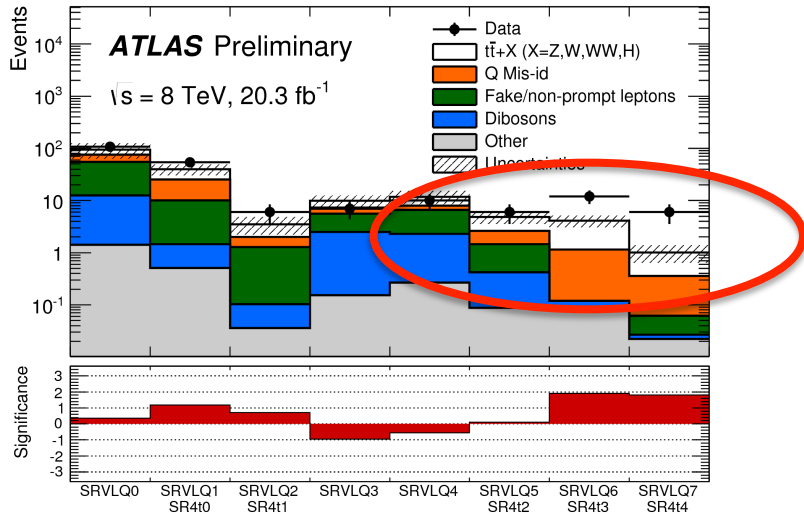
CMS Searches for New Physics Beyond Two Generations (B2G)
 95% CL Exclusions (TeV)



- <https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO>
- <https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsB2G>
- <https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults>
- <https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults>

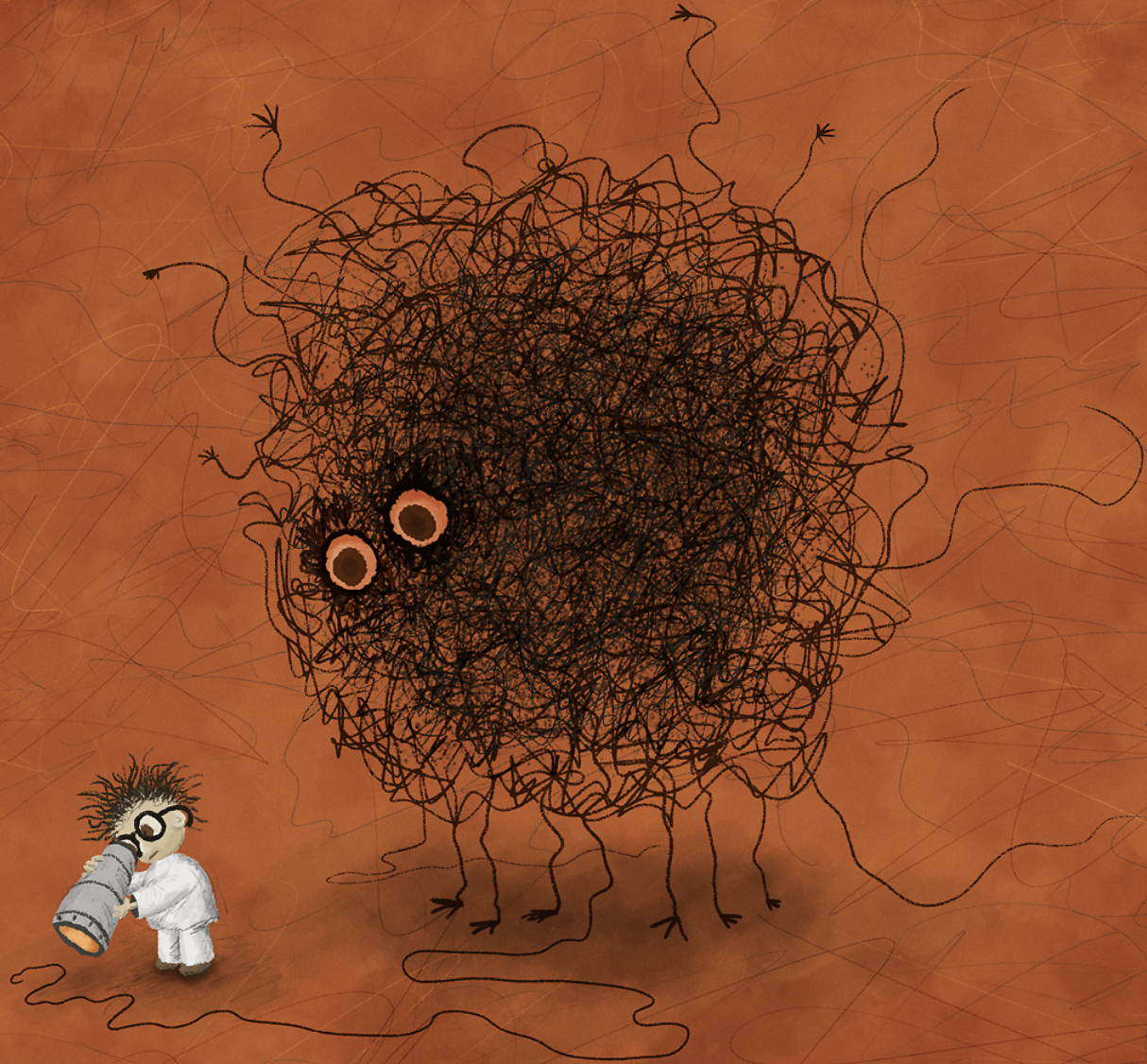
First signs of New Physics?

SS leptons + b-jets, to be submitted

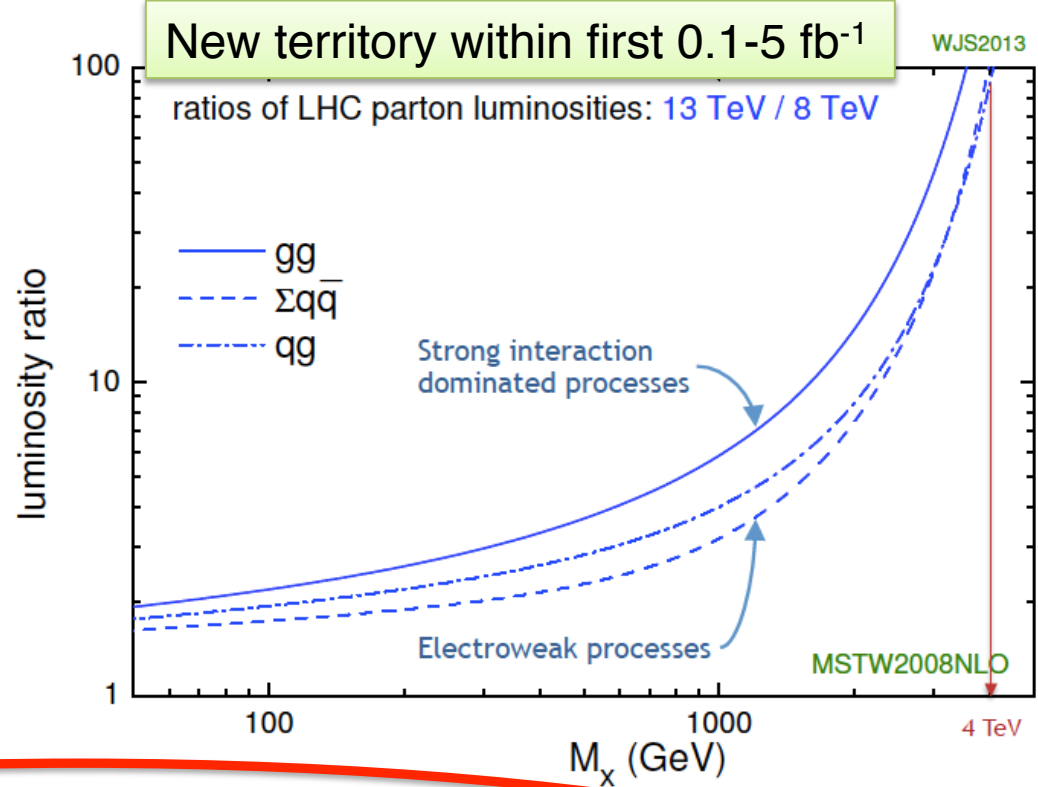
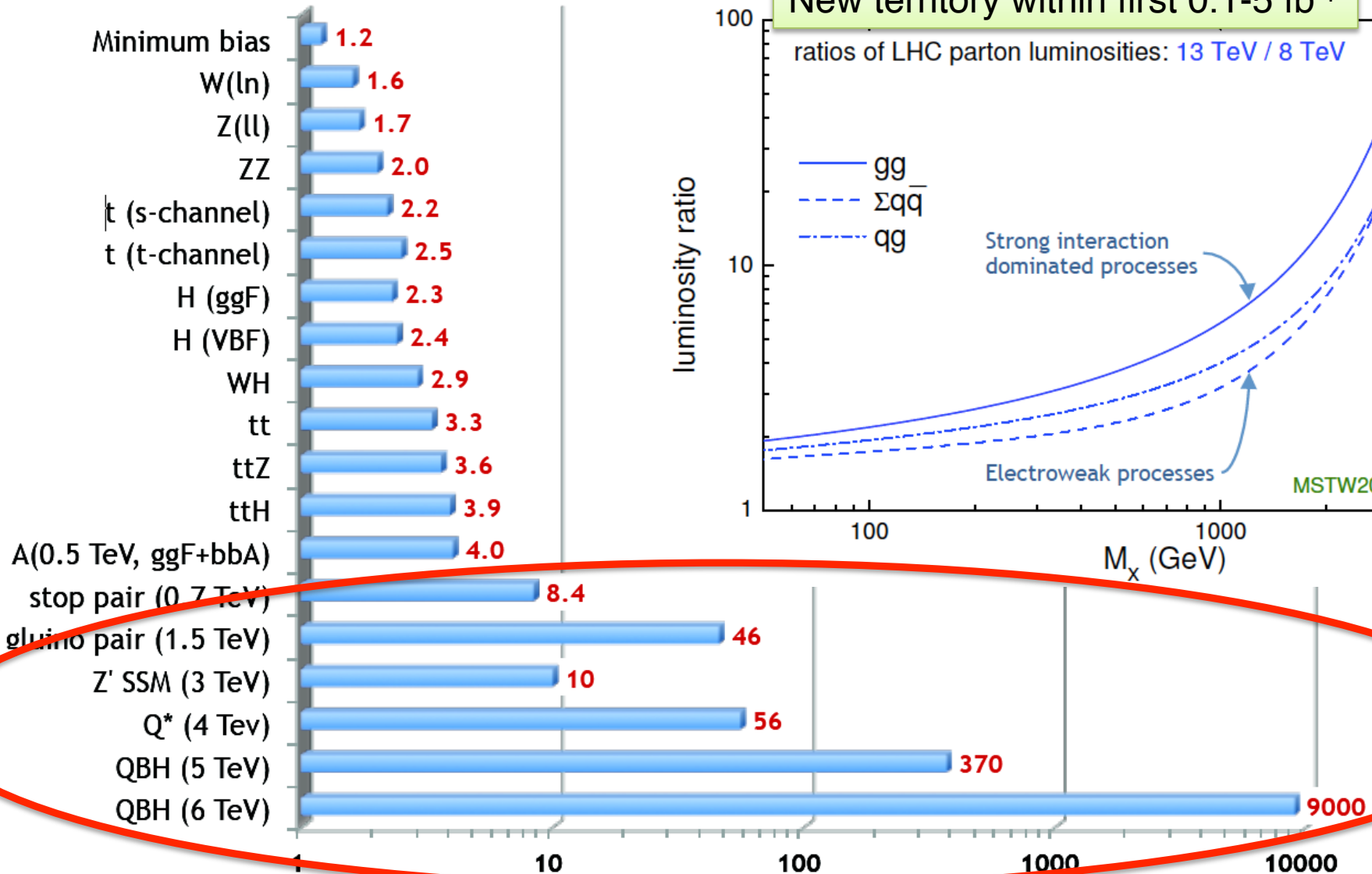


W_R and Heavy Neutrinos

More of these might be coming as we finish up Run I searches...



Run II Outlook

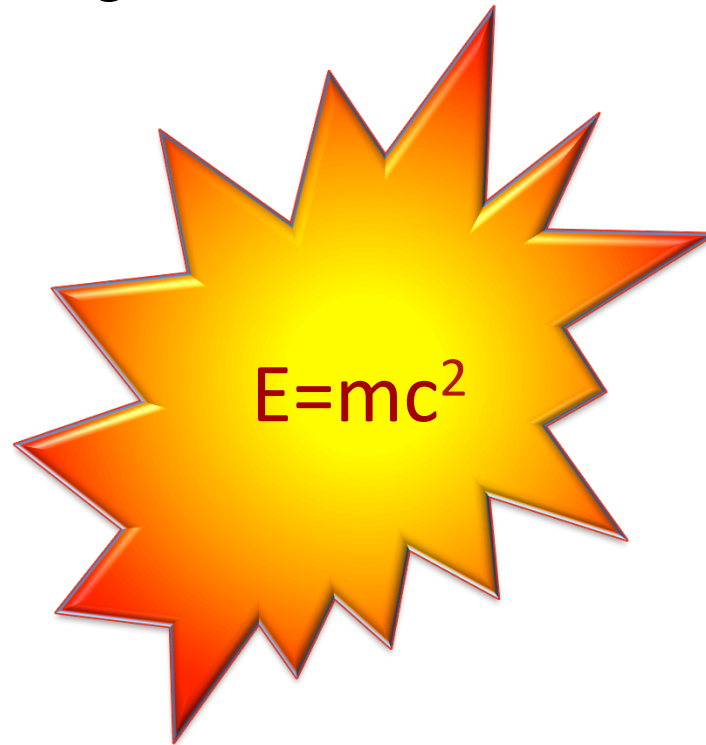


Cross section ratios: 13 TeV / 8 TeV

LHC's Run 2 – Epochal Event

- Substantial energy increase for the world's highest energy collider
- Will not happen again for another 2+ decades.

8 TeV (Run 1)



13-14 TeV (Run 2)

Summary & Conclusion

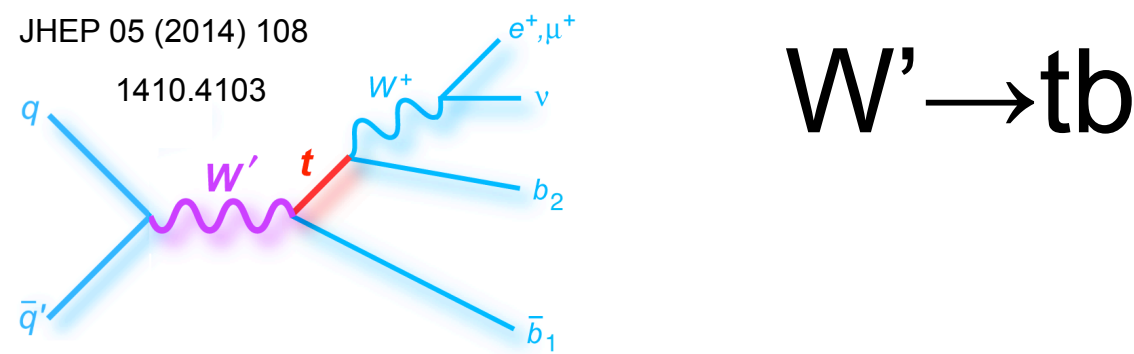
- Excellent detector and accelerator performance
- Detectors & triggers used in ways they were not designed for
- Wealth of data: many precision tests of W, Z, top
- We did our duty – Higgs boson found – but we did not show off... yet
- Naturalness arguments motivate new physics to show up in Run II
- Fingers crossed that nature will smile on us...

We might be this close!

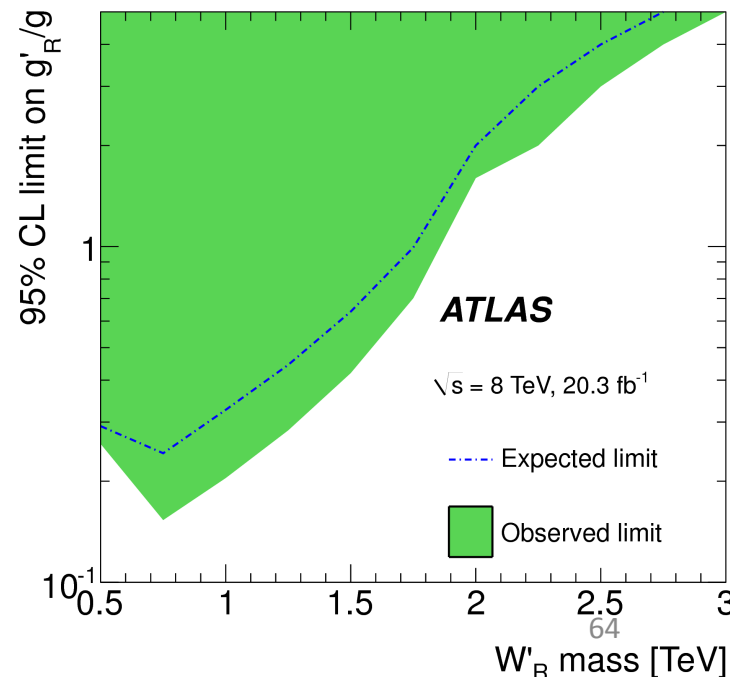
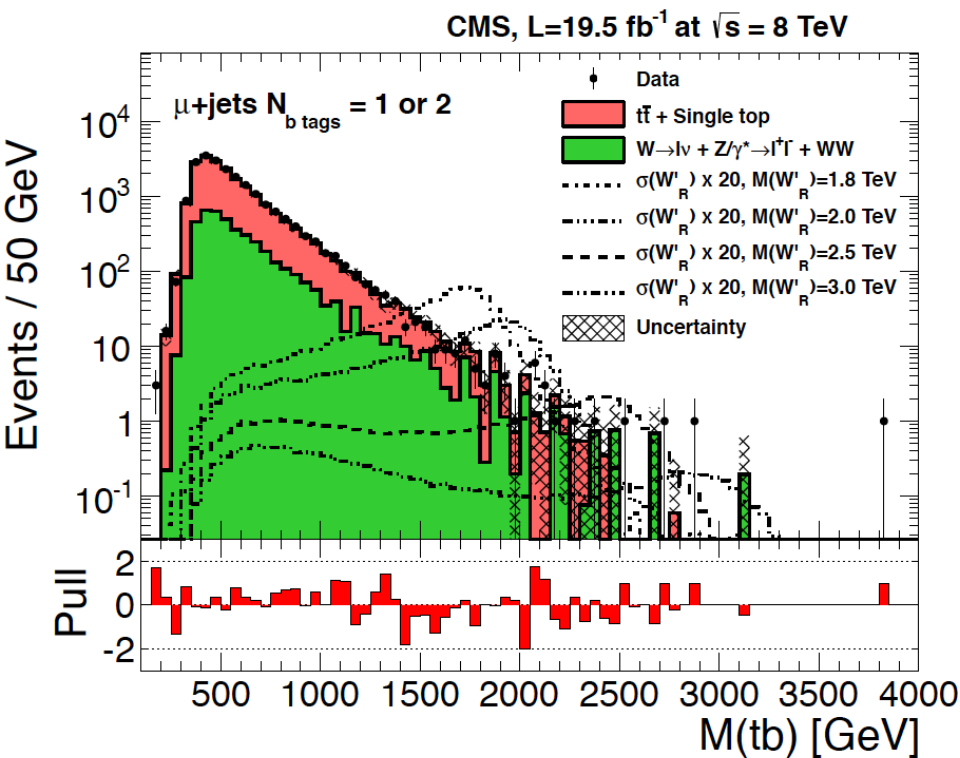
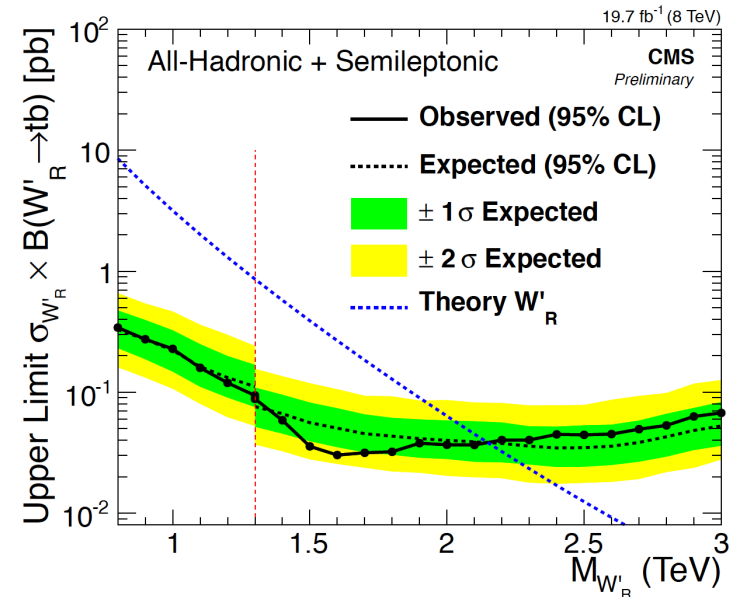


Thank You!

Backup

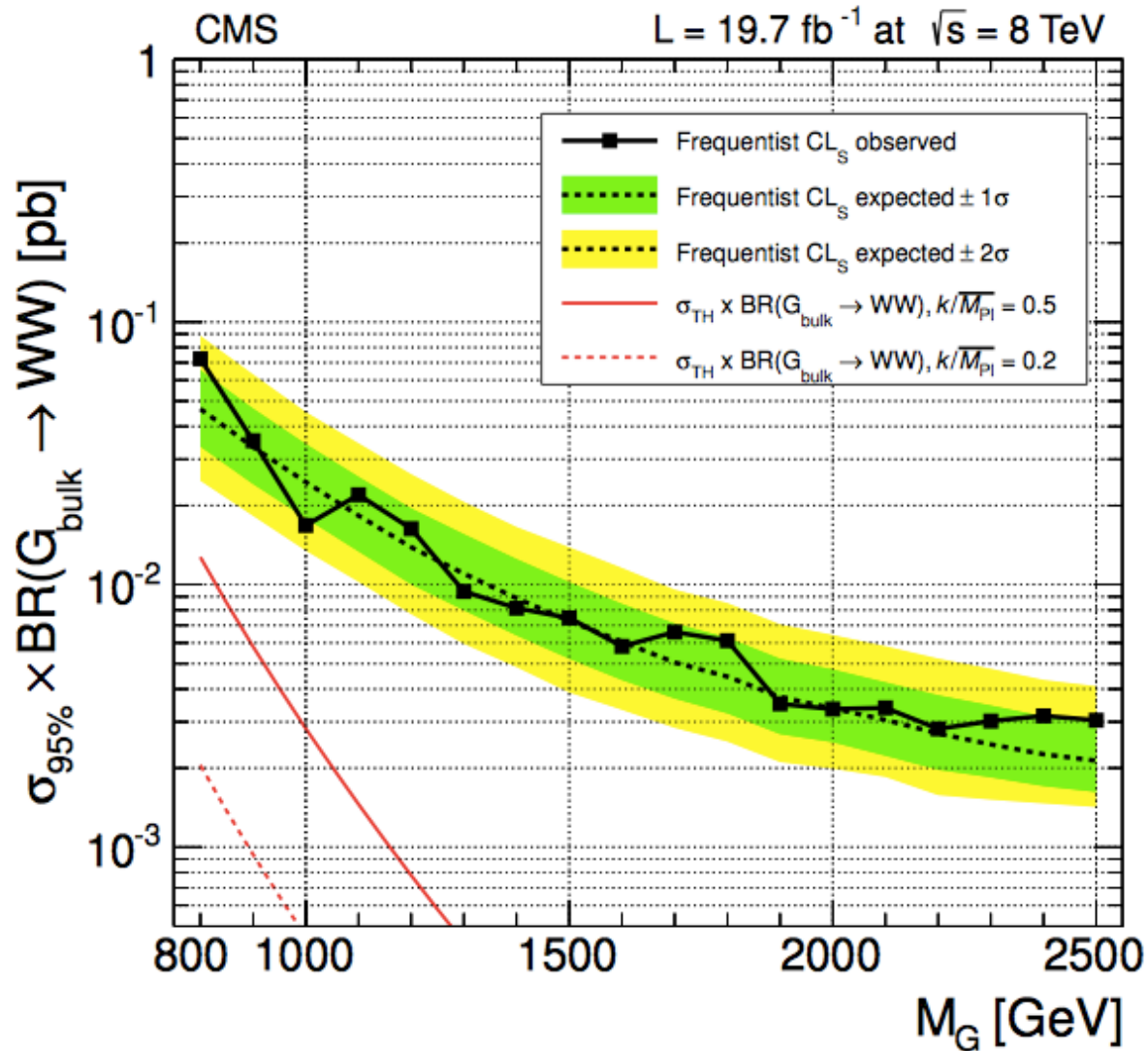
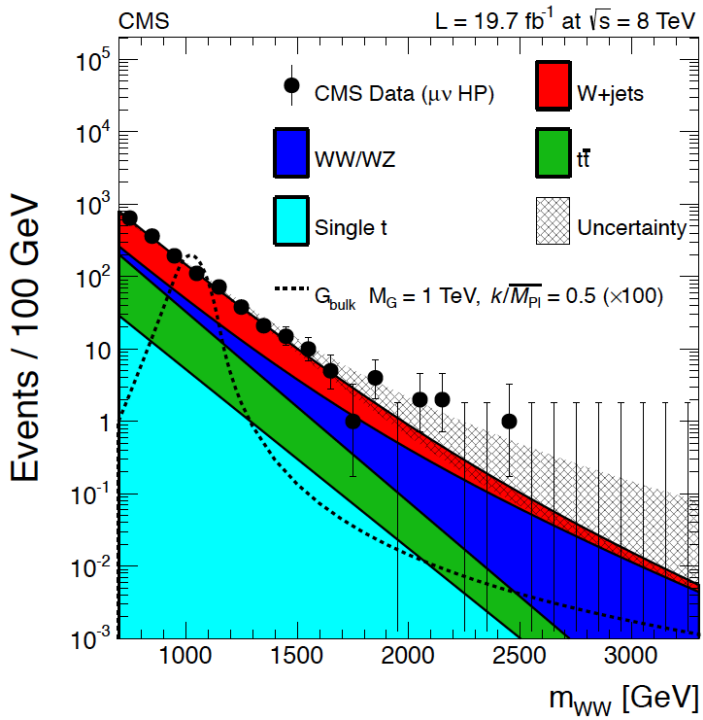
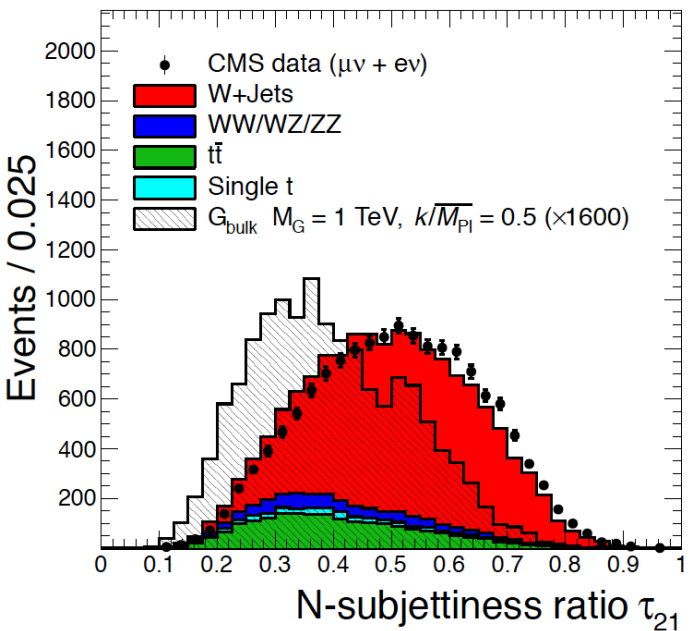


- Discriminant: m_{tb} or BDT
- Also present limits vs coupling



$WV \rightarrow l\nu J$

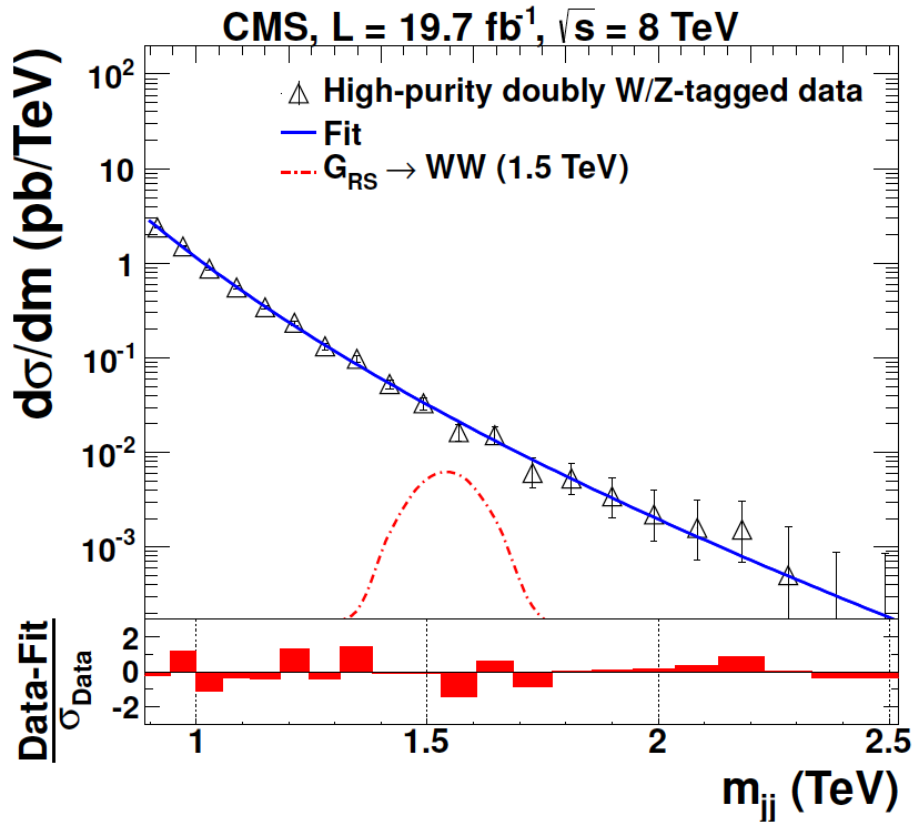
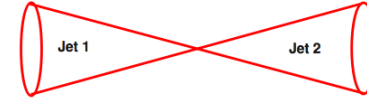
Use N-subjettiness for CA 0.8 jets to tag V-jets



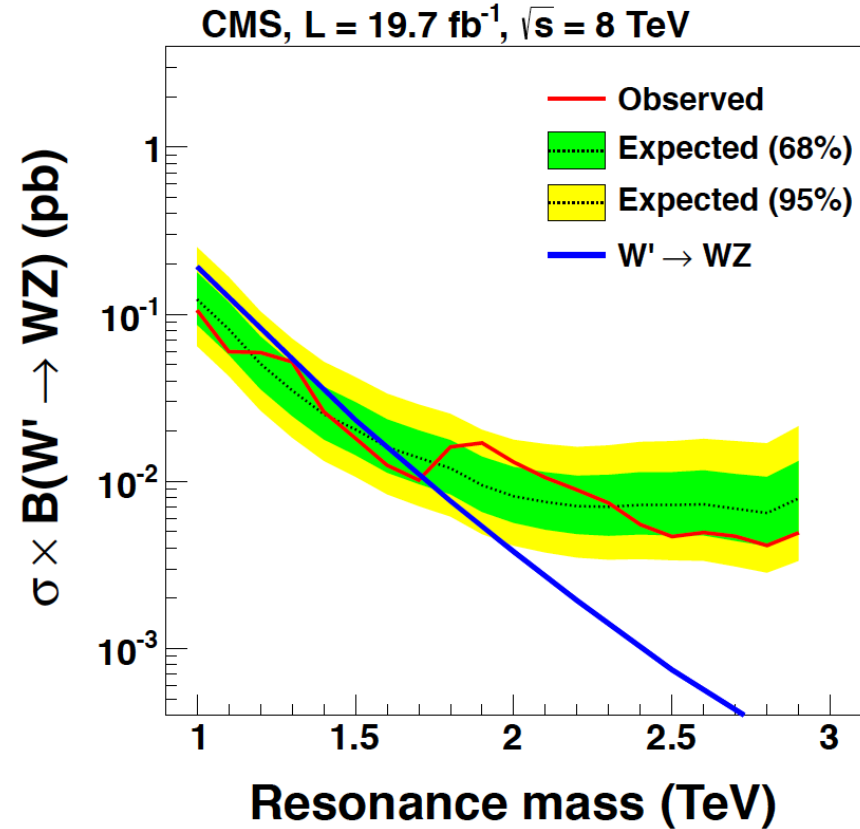
W+jets BG from V-mass sidebands

VV → JJ

Same V-jet tagger as on previous slide



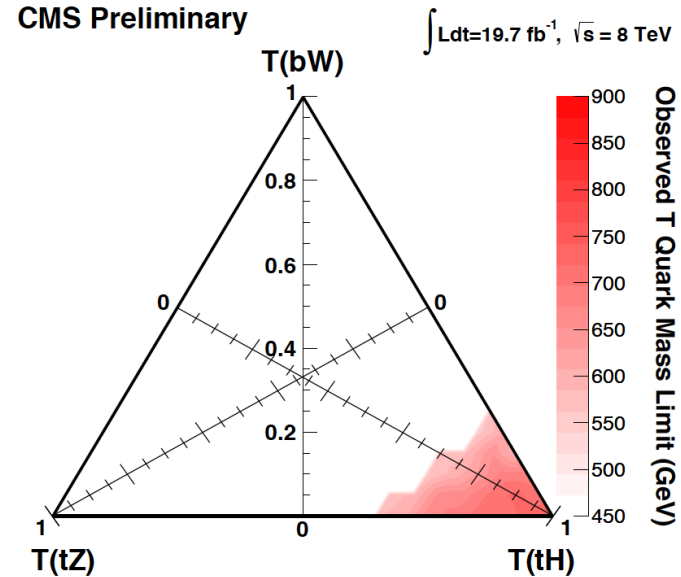
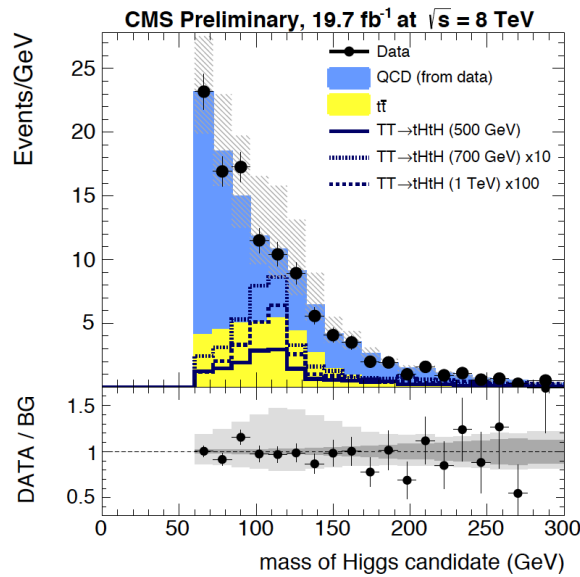
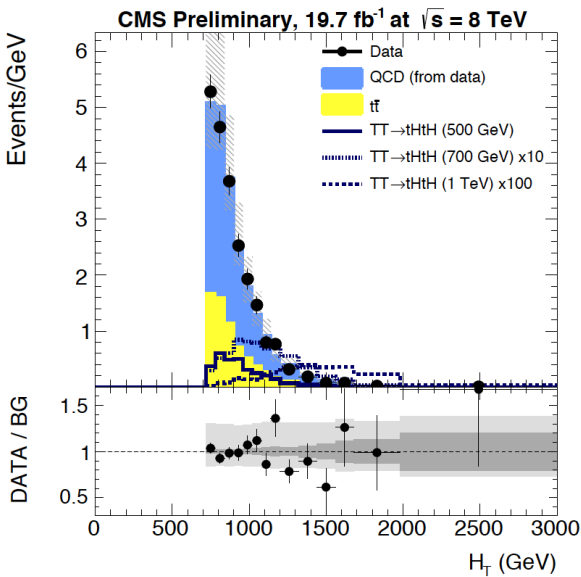
BG described by empirical fit



VLQ $T\bar{T} \rightarrow HtH\bar{t}$ (all-hadronic)

- ≥ 2 CA $R=1.5$ jets, $p_T > 150$ GeV
 - ≥ 1 top candidate : HTT-tag + ≥ 1 b-tagged subjet
 - ≥ 1 Higgs candidate: 2 subjet b-tags & $m_{bb} > 60$ GeV

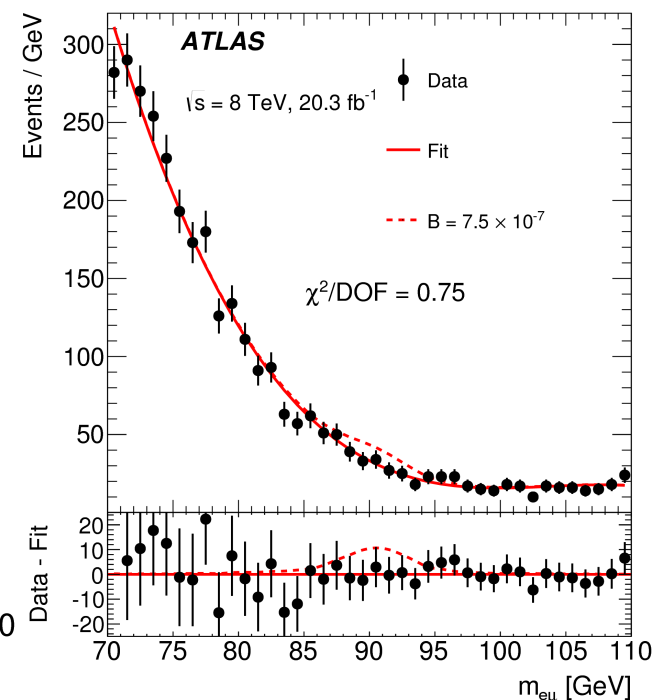
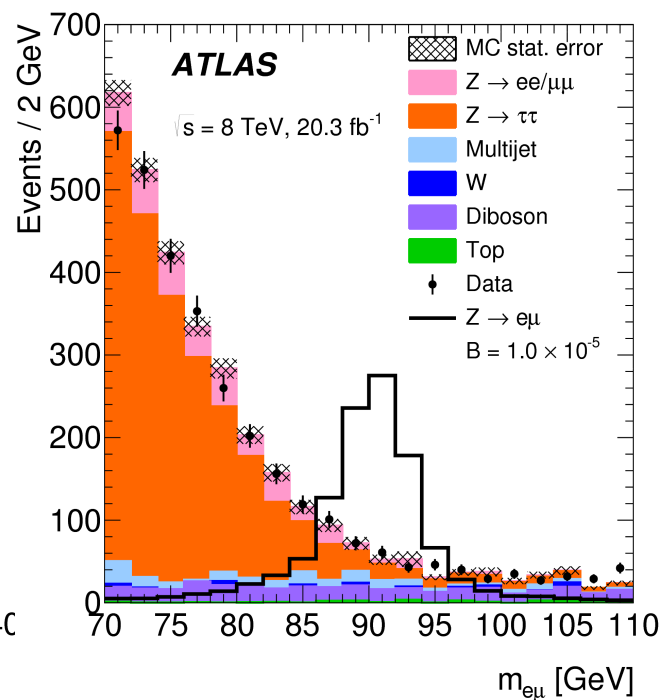
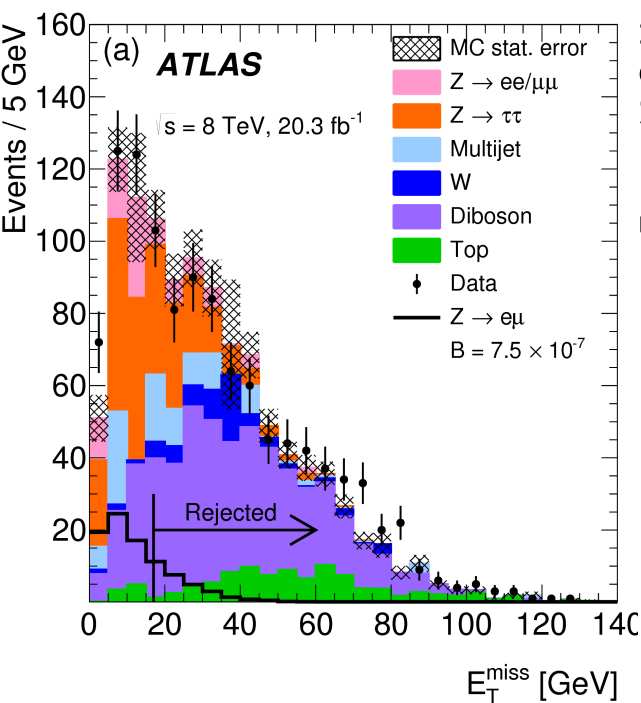
QCD BG estimated from data from sidebands of top- and Higgs-tag

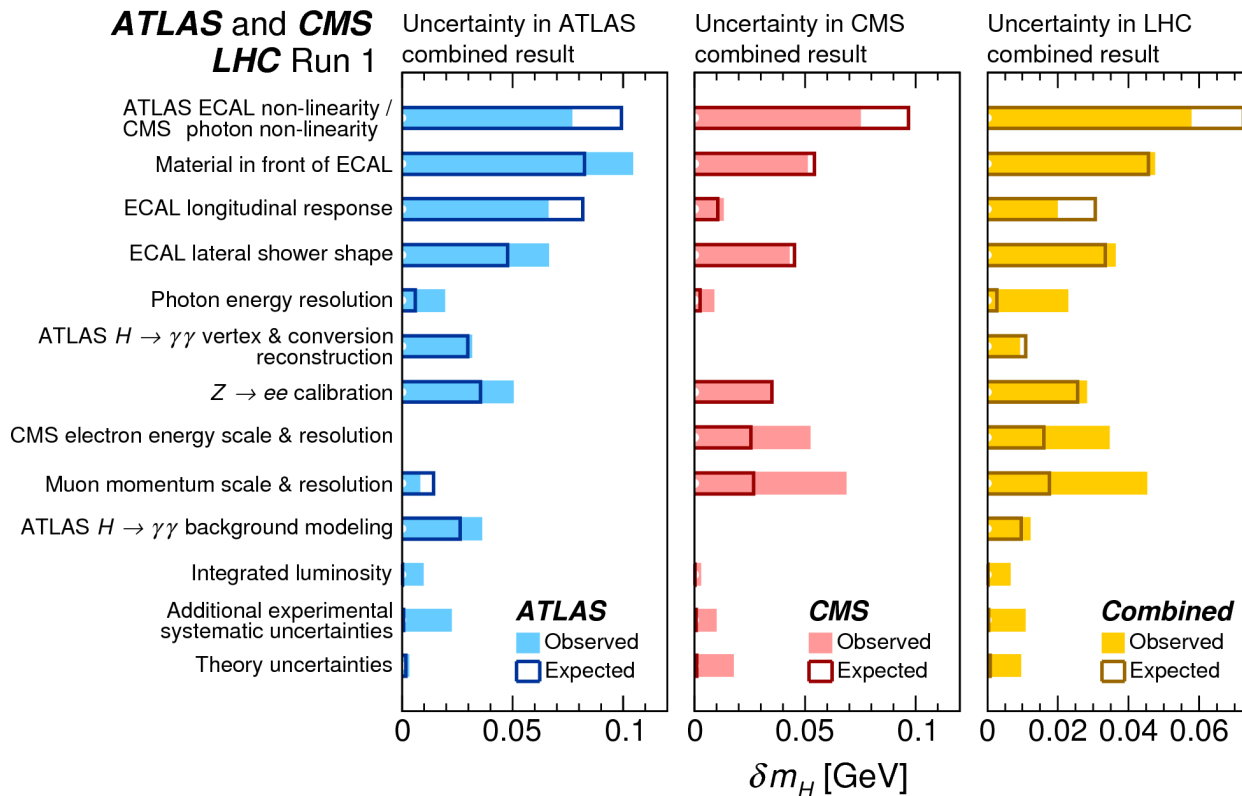
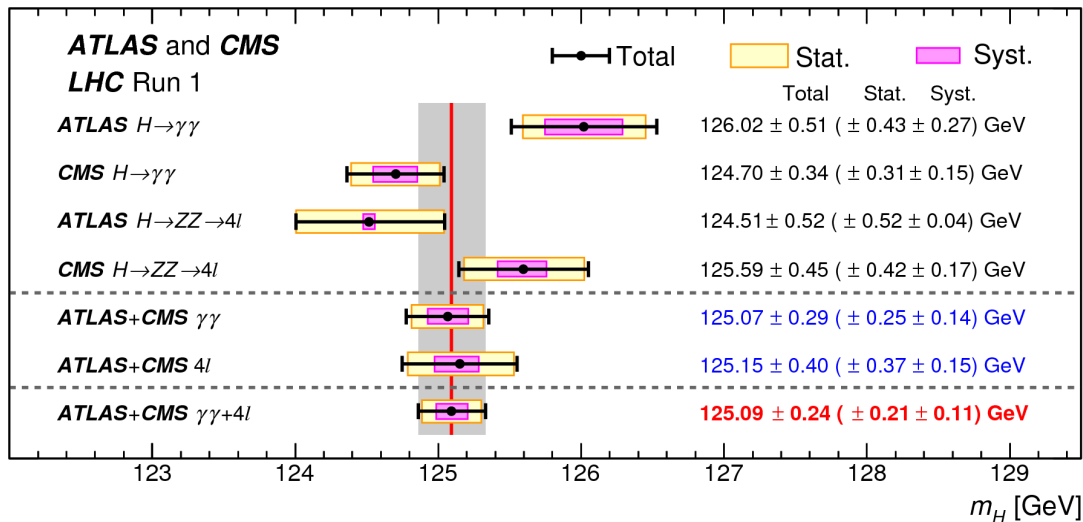


HTT = HEPTopTagger [1112.4441]

Lepton Flavor Violation

$$B(Z \rightarrow e\mu) < 7.5 \times 10^{-7} \quad (\text{more than factor of 2 better than LEP})$$

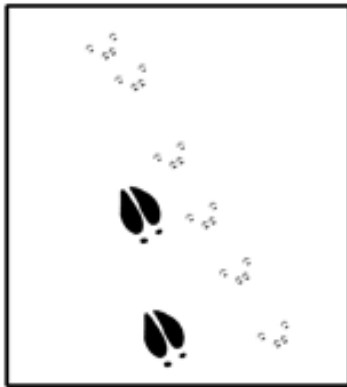




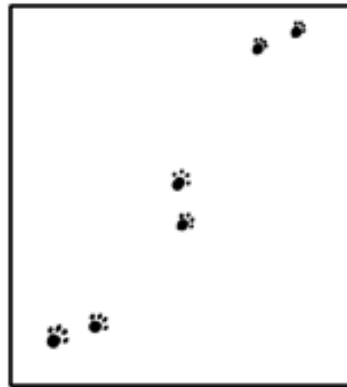
BACKYARD SNOW TRACKING GUIDE



CAT



MOOSE AND SQUIRREL



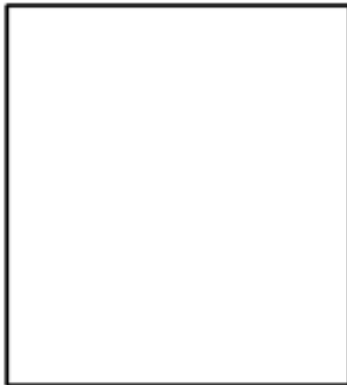
LONGCAT



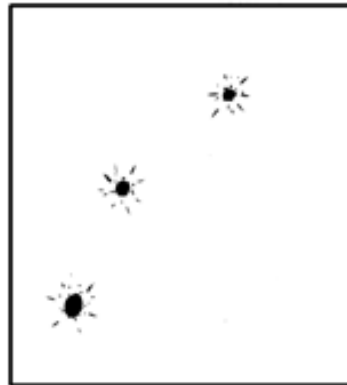
MOUSE RIDING BICYCLE



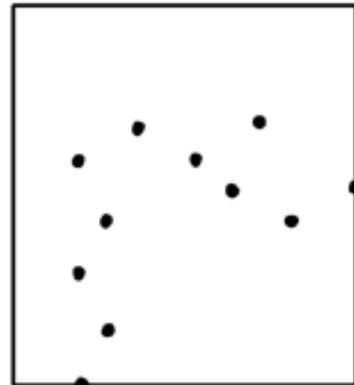
RABBIT STOPPING
TO USE HAIR DRYER



LEGOLAS



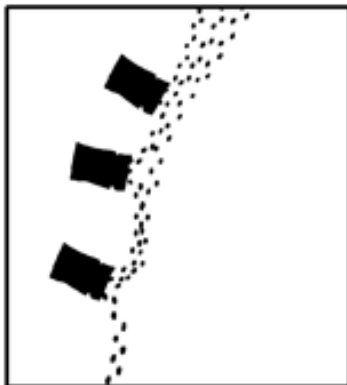
BOBCAT ON POGO STICK



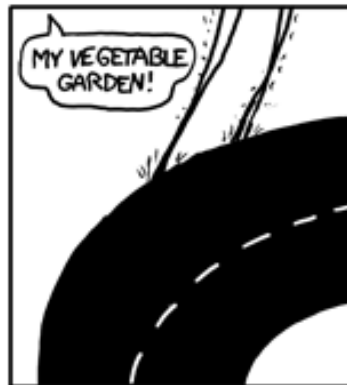
KNIGHT



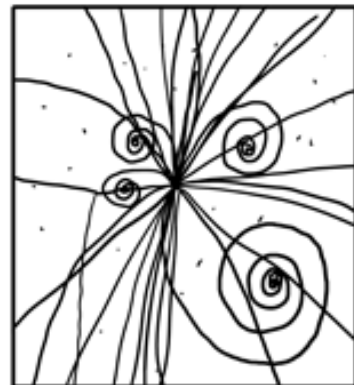
KID WITH
TRANSMOGRIFIER



KID WITH DUPLICATOR



PRIUS



HIGGS BOSON

Signature-Driven Searches

■ Many extensions of the SM have been developed over the past decades:

- Supersymmetry
- Extra-Dimensions
- Technicolor(s)
- Little Higgs
- No Higgs
- GUT
- Hidden Valley
- Leptoquarks
- Compositeness
- 4th generation (t', b')
- LRSM, heavy neutrino
- etc...

- 1 jet + MET
- jets + MET
- 1 lepton + MET
- Same-sign di-lepton
- Dilepton resonance
- Diphoton resonance
- Diphoton + MET
- Multileptons
- Lepton-jet resonance
- Lepton-photon resonance
- Gamma-jet resonance
- Diboson resonance
- Z+MET
- W/Z+Gamma resonance
- Top-antitop resonance
- Slow-moving particles
- Long-lived particles
- Top-antitop production
- Lepton-Jets
- Microscopic blackholes
- Dijet resonance
- etc...

• Not yet thought of

• Uncovered signature
• ...

- Broad mandate, agnostic way of searching: signature-based & model-independent
- Use models as guidance where to look
- Try to cover all possible signatures
- Interpret results using benchmarks

Many More Searches

- Lepton Flavor Violation
- Black Hole / TeV gravity / Jet extinction
- Heavy Neutrinos / See-saw / Vector-Like Leptons
- Many other resonance searches: bb , $\pi\pi$, $\gamma\gamma$, γjet , $W\gamma$, $Z\gamma$,...
- Excited leptons
- Contact interactions: jj , ll ,...
- Monopoles & multi-charged particles
- Generic multi-lepton and same-sign lepton searches
- ...