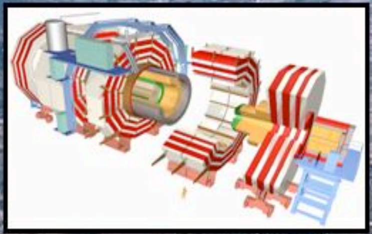
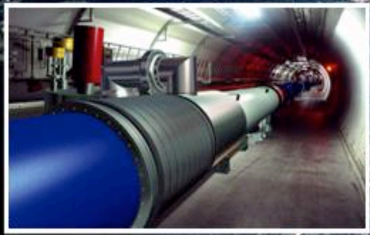
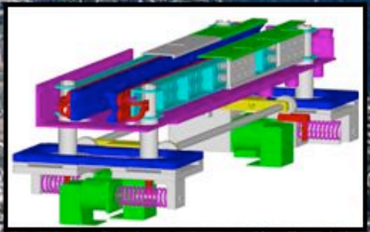
LHC: PAST, PRESENT, AND FUTURE



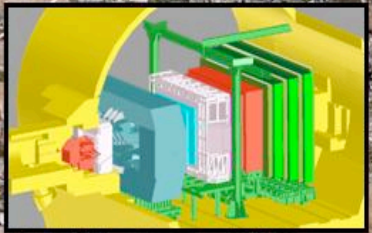



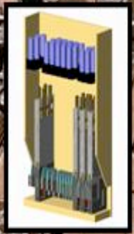
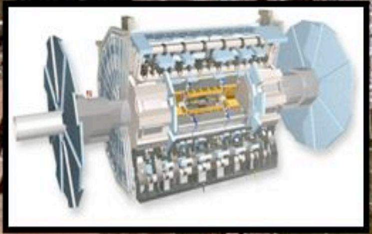
Greg Landsberg

Strings 2013

Seoul, South Korea

June 27, 2013



Outline

- ✦ LHC Performance
- ✦ Highlights from the LHC Run 1
- ✦ Preparations for Run 2
- ✦ Toward High-Luminosity LHC
- ✦ Conclusions

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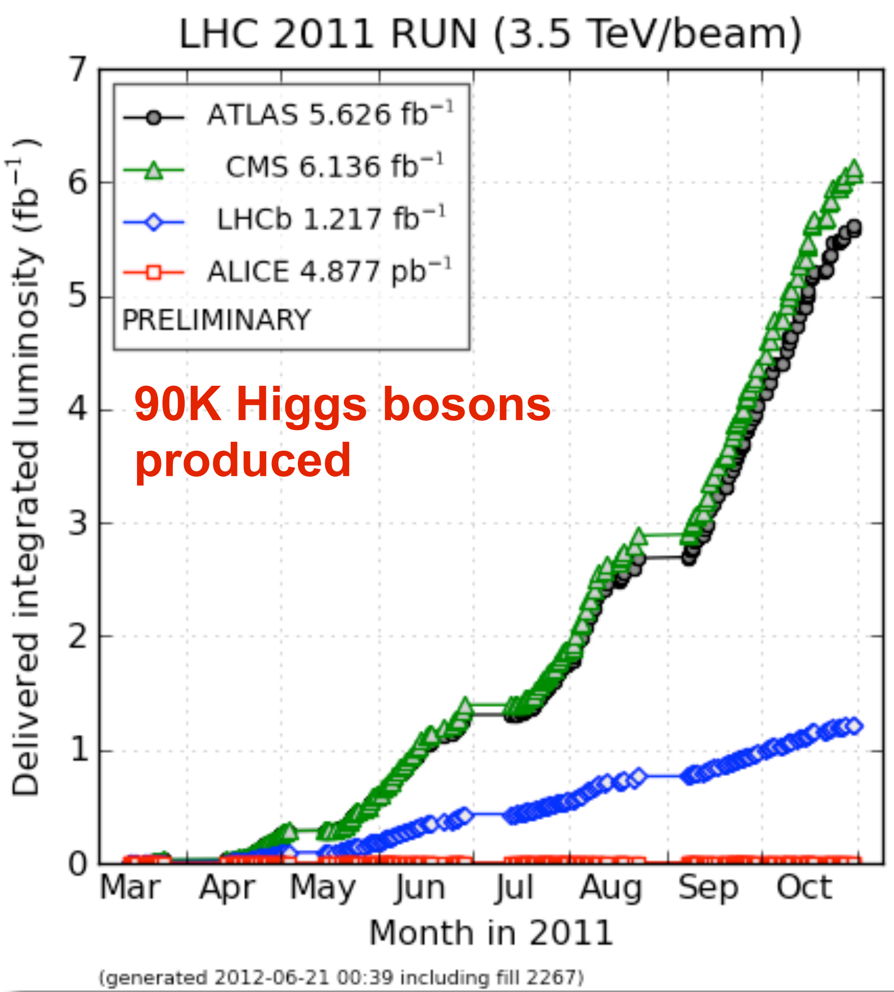
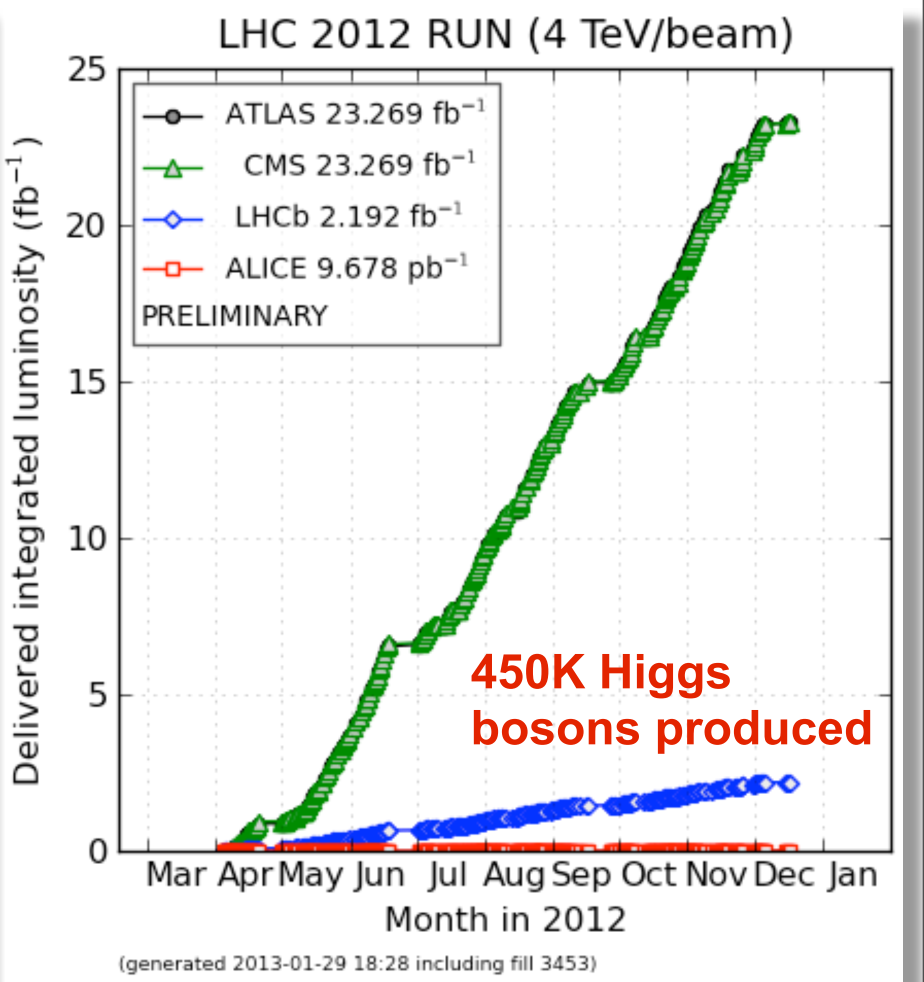
The LHC Playground

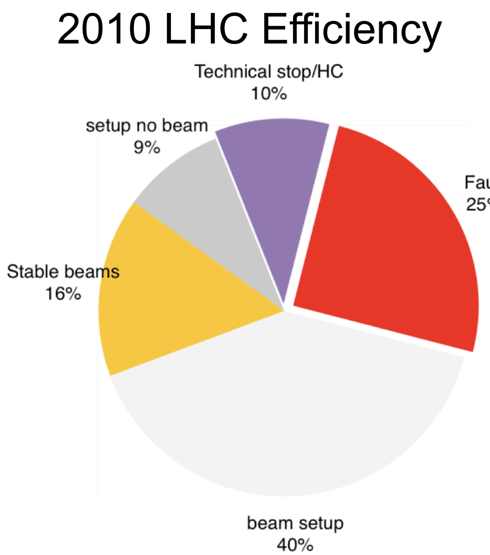
Measure of Our Success

✦ Thank you, the LHC, for spectacular 3 years and ~30/fb delivered (and half-a-million Higgs bosons produced)!

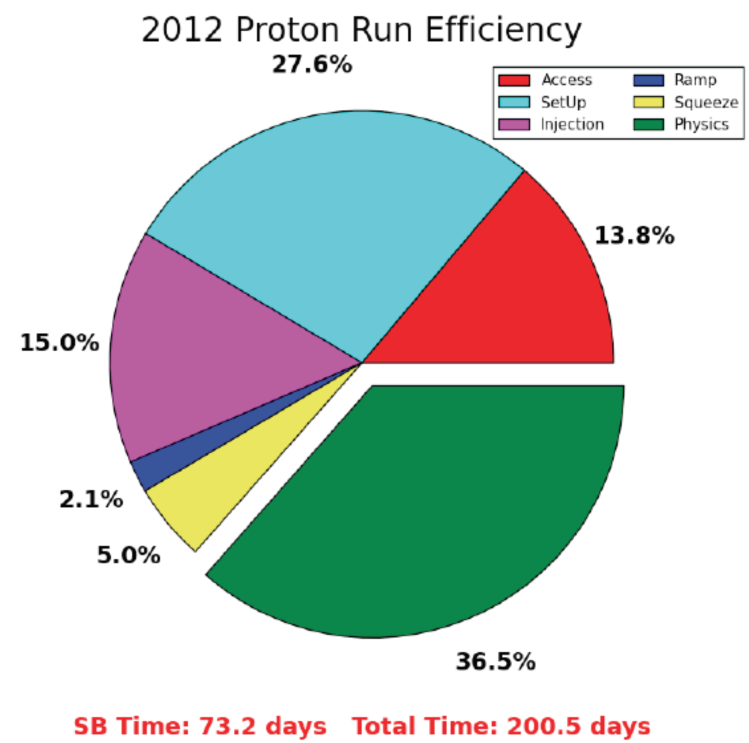




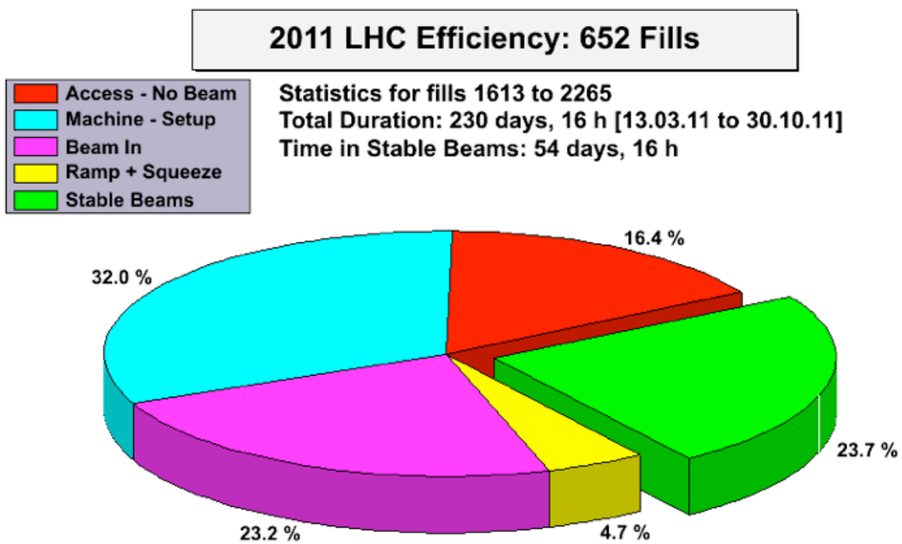
Great Running Efficiency



- Fraction of the LHC operations used for physics:
  - 2010: 16%
  - 2011: 23.7%
  - 2012: 36.5%



Alick Macpherson



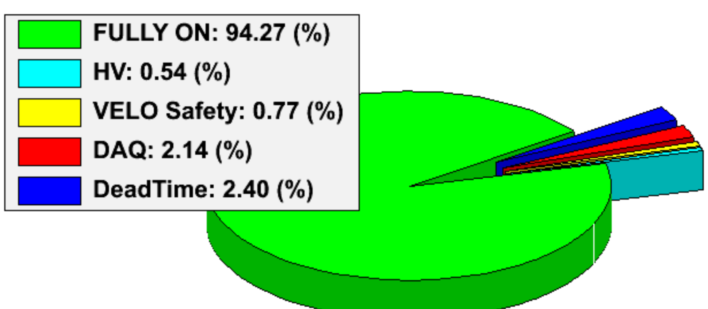
Excellent Detector Performance

- The LHC detectors have been working spectacularly with virtually no degradation in performance over the three years of LHC Run 1
  - In some cases, original losses in performance was recovered

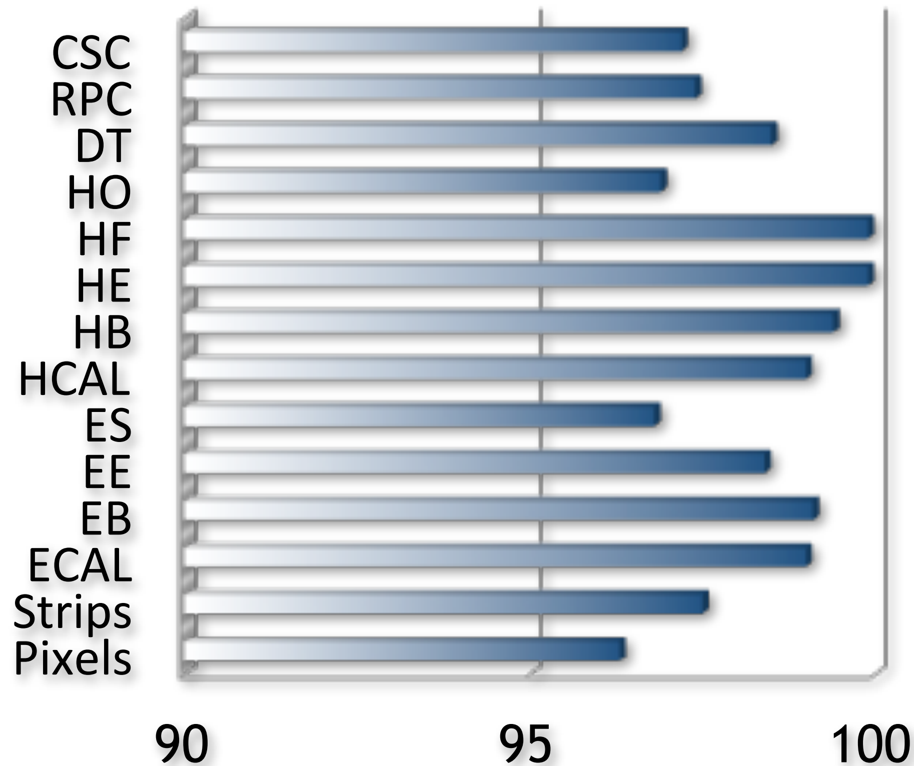
ATLAS Performance in 2012

Subdetector	Number of Channels	Approximate Operational Fraction
Pixels	80 M	95.0%
SCT Silicon Strips	6.3 M	99.3%
TRT Transition Radiation Tracker	350 k	97.5%
LAr EM Calorimeter	170 k	99.9%
Tile calorimeter	9800	98.3%
Hadronic endcap LAr calorimeter	5600	99.6%
Forward LAr calorimeter	3500	99.8%
LVL1 Calo trigger	7160	100%
LVL1 Muon RPC trigger	370 k	100%
LVL1 Muon TGC trigger	320 k	100%
MDT Muon Drift Tubes	350 k	99.7%
CSC Cathode Strip Chambers	31 k	96.0%
RPC Barrel Muon Chambers	370 k	97.1%
TGC Endcap Muon Chambers	320 k	98.2%

LHCb Performance in 2012

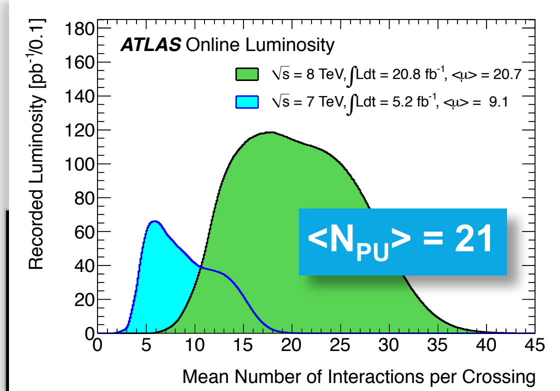


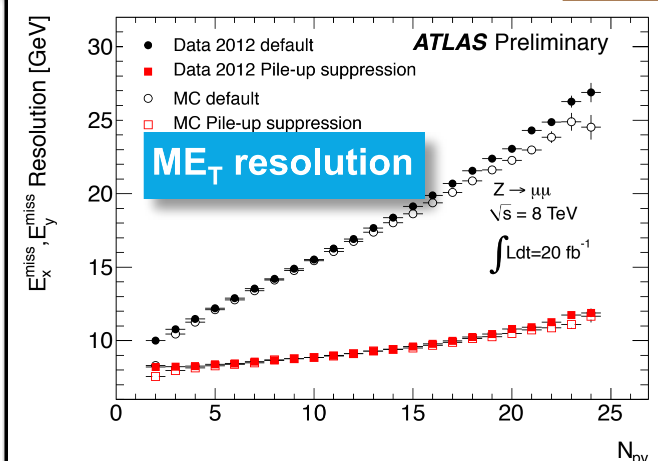
CMS Status in Feb 2013 (%)

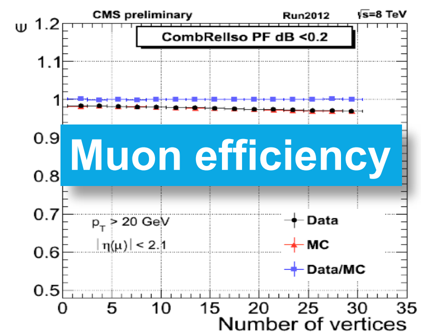


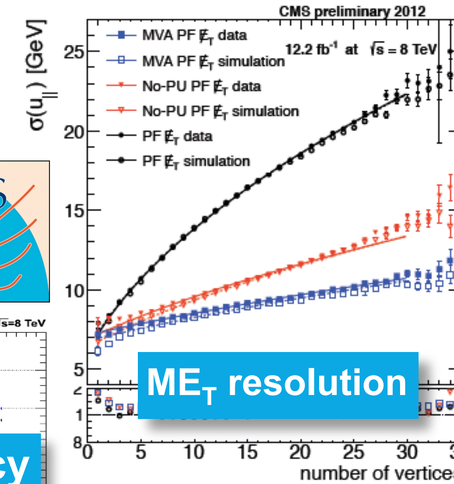
Successful Pileup Mitigation

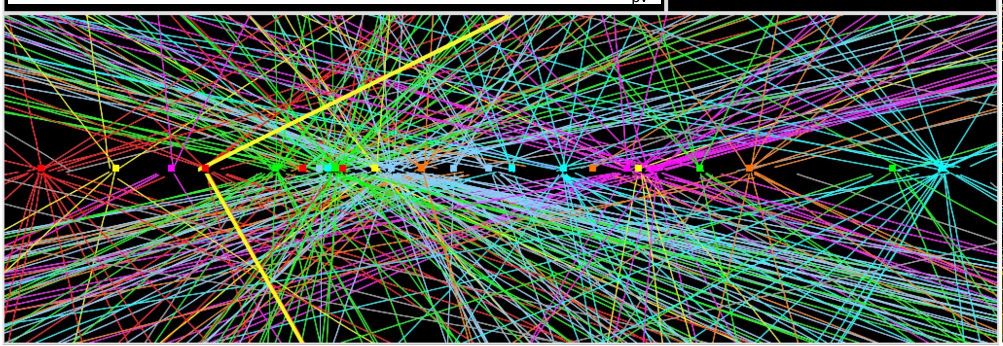
LHC already reached nominal pileup rate; experiments cope well!

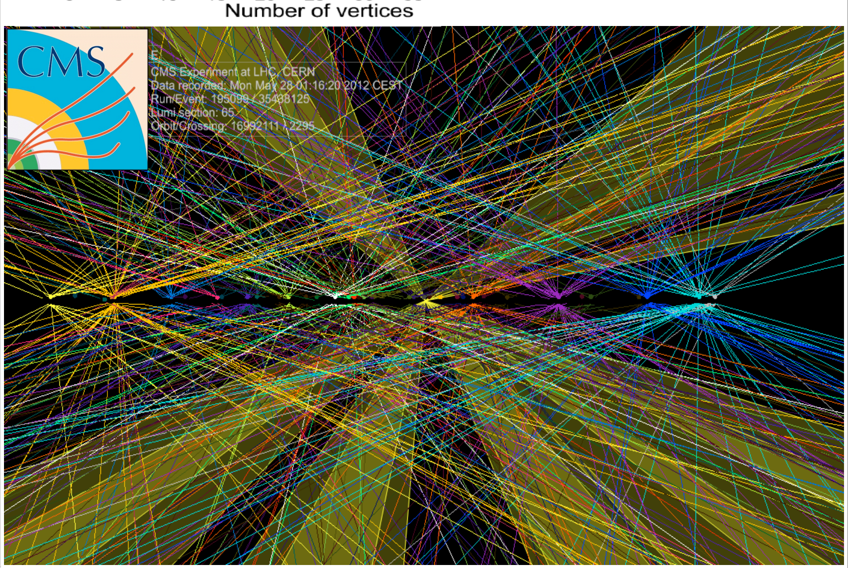










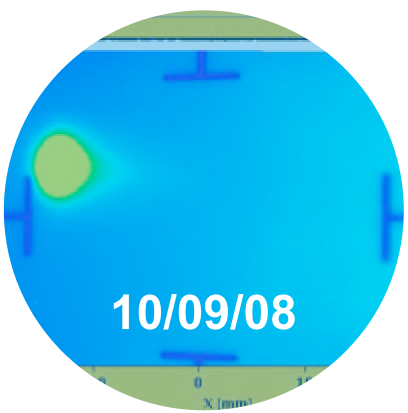


Greg Landsberg - LHC: Past, Present & Future - Strings 2013, Seoul

2008-2012: LHC Milestones

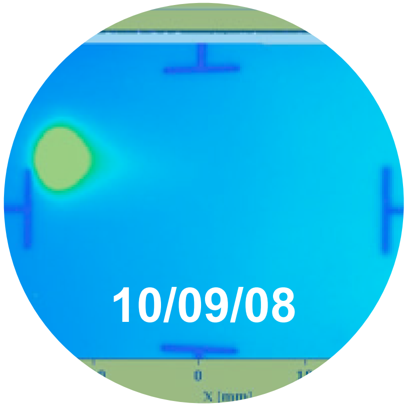
2008-2012: LHC Milestones

2008

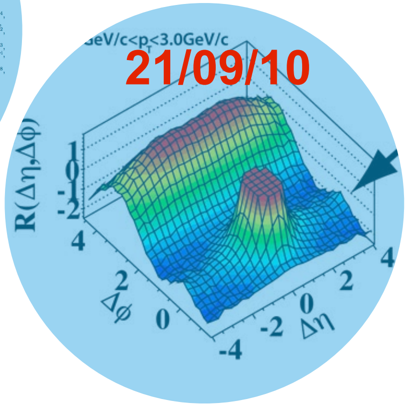


2008-2012: LHC Milestones

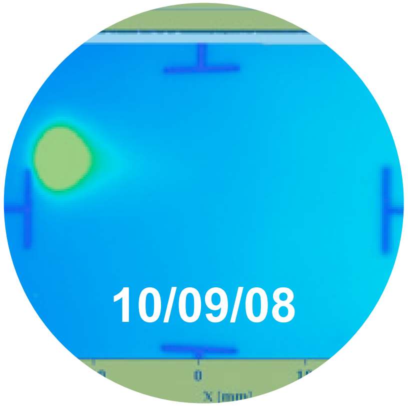
2008 2009

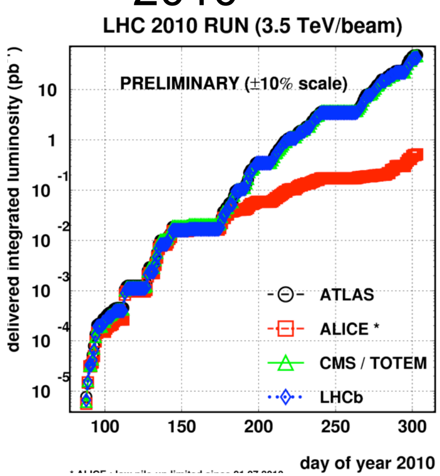


2008-2012: LHC Milestones

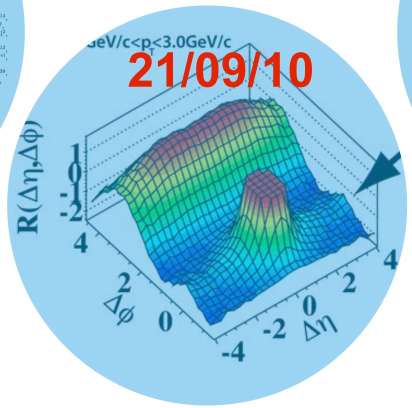


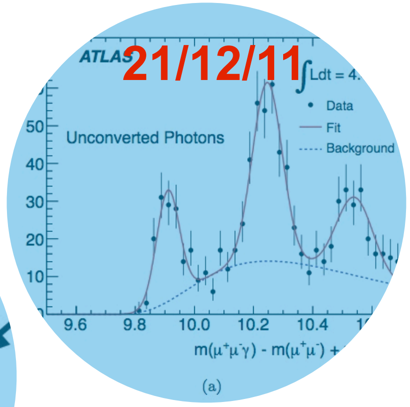
2008 2009 2010



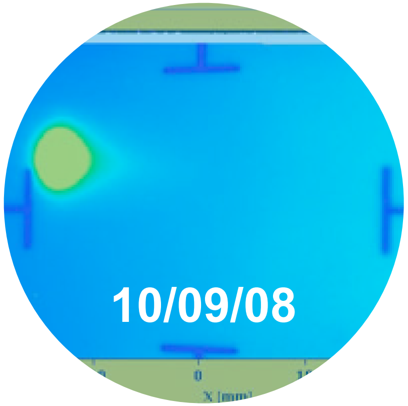


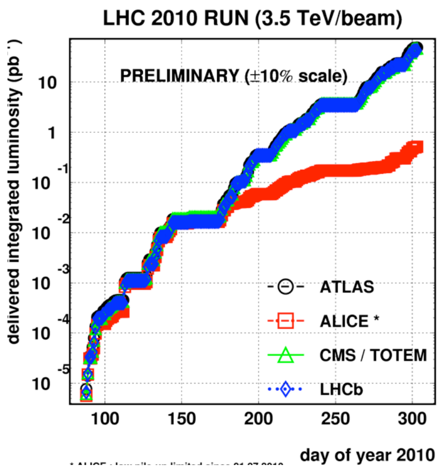
2008-2012: LHC Milestones

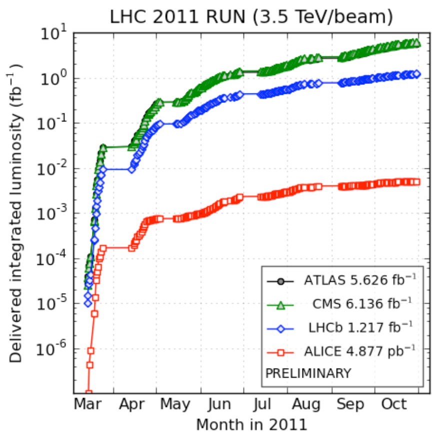




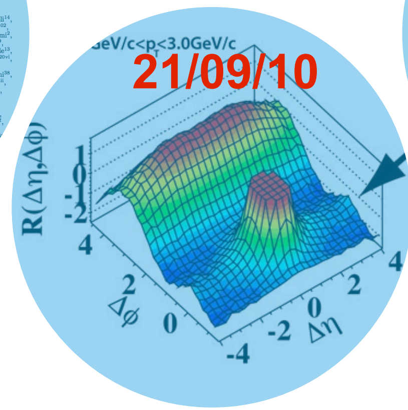
2008 2009 2010 2011

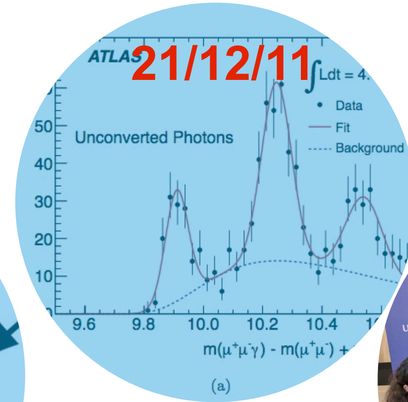


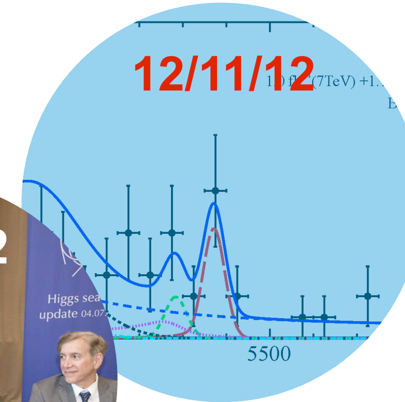




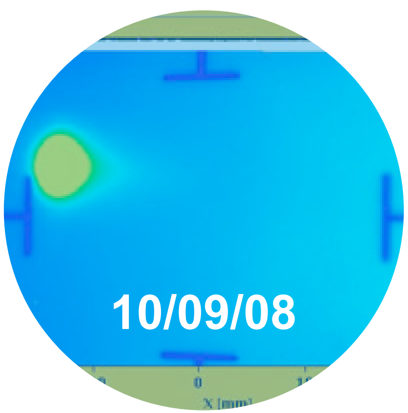
2008-2012: LHC Milestones

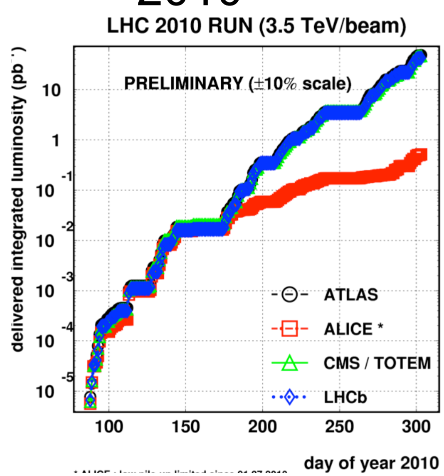


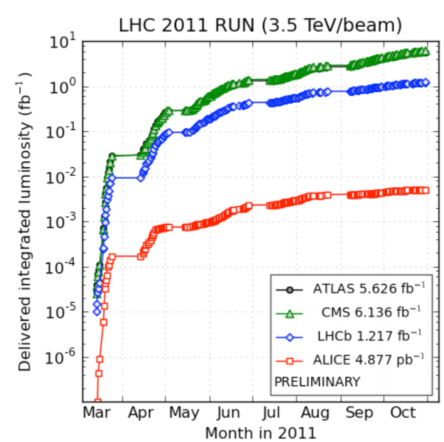


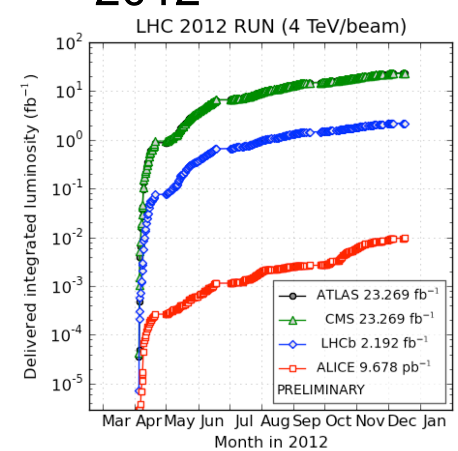


2008 2009 2010 2011 2012

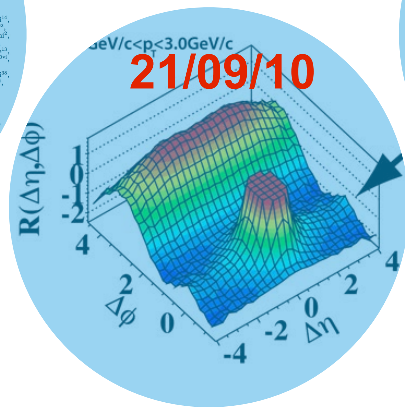


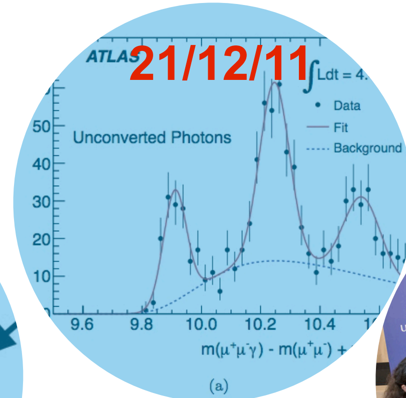


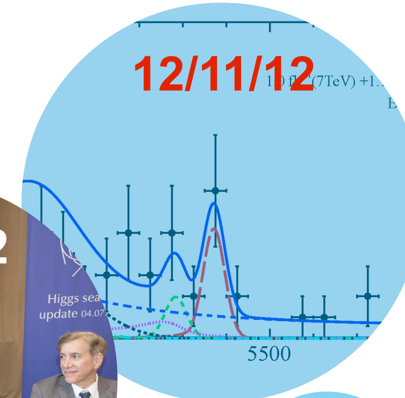




2008-2012: LHC Milestones







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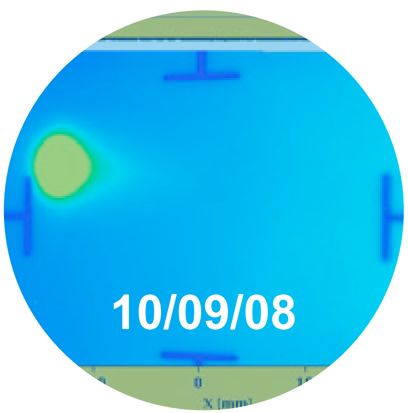
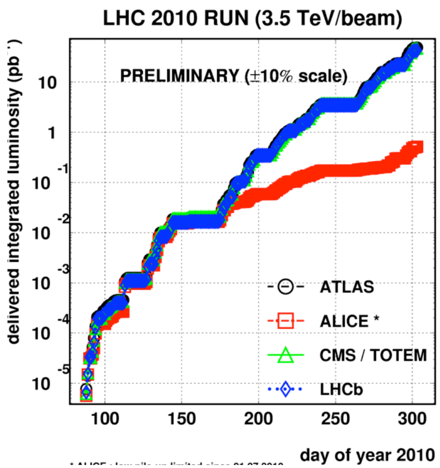
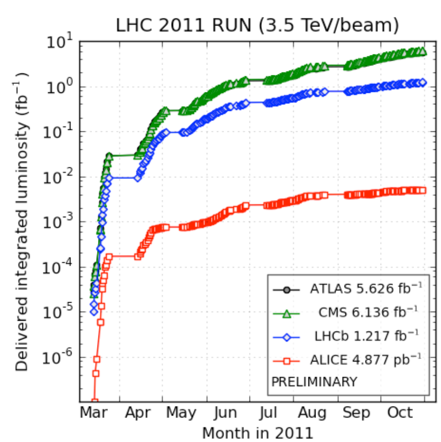
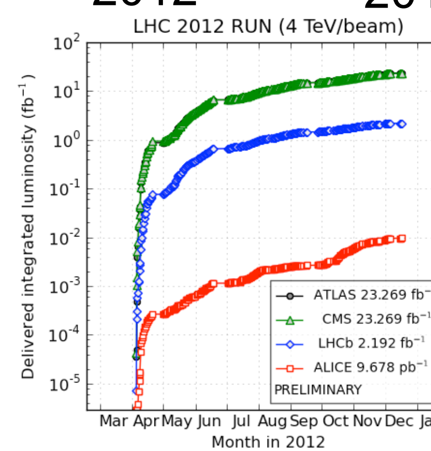
2008 2009 2010 2011 2012 2013









Three Machines in One!

The LHC Legacy

- The LHC has in fact (allegorically) replaced three machines in one go:
  - Tevatron (Higgs, BSM searches, top physics, and precision EW measurements)
  - Belle (precision B-physics)
  - RHIC (heavy-ion physics)
- The LHC experiments are very successful in all these three areas
- Would not be possible without theoretical and phenomenological breakthroughs of the past decade:
  - Higher-order calculations, modern Monte Carlo generators, reduced PDF uncertainties
- I'll present a few highlights of the first three years of the LHC operations in flavor physics, heavy-ion physics, and the discovery program, with the focus on the latter
- I'll emphasize some possible connections to string theory:
  - Strongly coupled systems (e.g., heavy-ion physics)
  - The Higgs story and SUSY searches (including dark matter search)
  - Searches for extra spatial dimensions

Flavor Physics

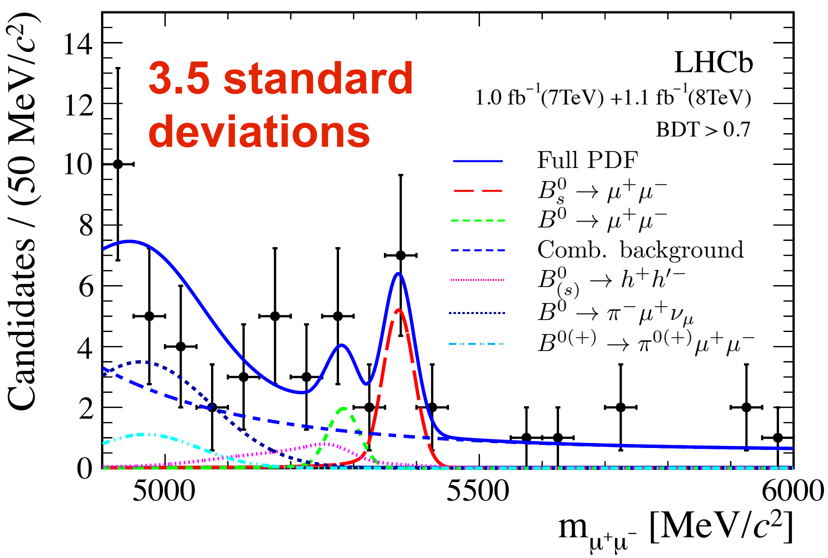
- The flavor program at the LHC is lead by the dedicated LHCb experiment
  - ATLAS and CMS are significant contributors in selected topics
- Among the highlights of the first three years are:
  - Observation of the $\chi_b(3P)$ quarkonium state - the first new particle discovered at the LHC (ATLAS, PRL **108** (2012) 252002) as well as Ξ_b^* baryon (CMS, PRL **108** (2012) 152001)
  - Measurement of $\Upsilon(nS)$, $\psi(2S)$, and J/ψ polarization (CMS, PRL **110** (2013) 081802; CMS PAS BPH-13-003)
  - First evidence for the $B_s(\mu\mu)$ decay (LHCb, PRL **110** (2013) 021801)
  - First observation of direct CP violation in B_s decays (LHCb, arXiv: 1304.6173)
  - Strong constraints on new physics in the bottom and charm sectors via precision measurement of a number of rare decays

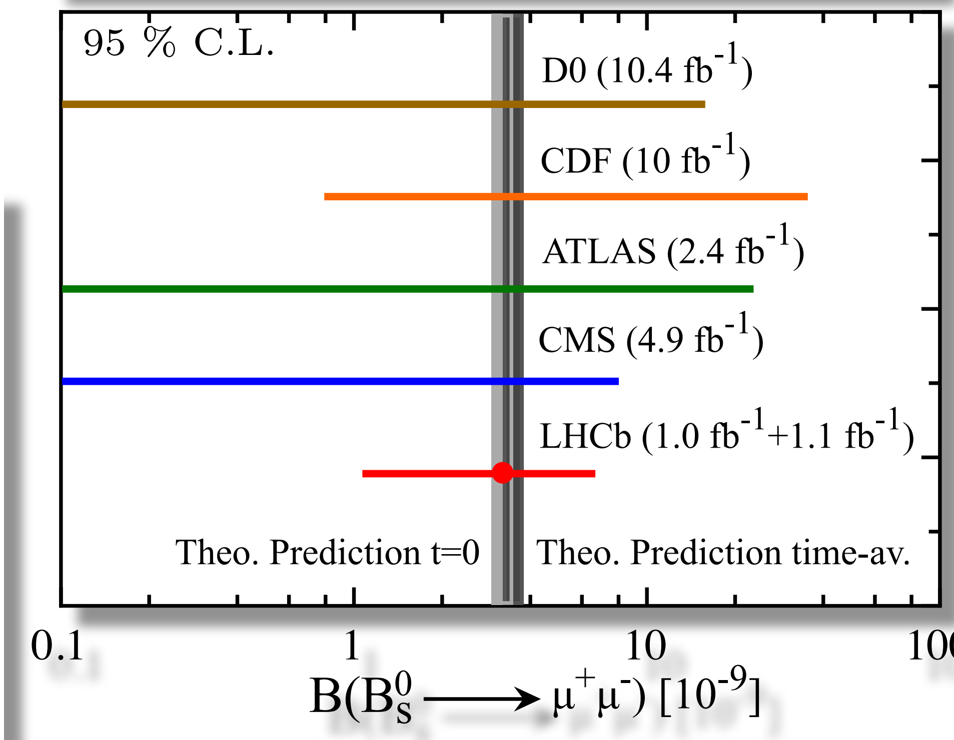
LHCb: Evidence for $B_s(\mu\mu)$

- The quest of many years to find a deviation from the SM predictions in the Bs(μμ) decay is coming to an end with the first evidence that the decay rate is consistent with the SM model
- Still awaits confirmation from ATLAS and CMS

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.2^{+1.5}_{-1.2}) \cdot 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 9.4 \cdot 10^{-10} \text{ @ 95 \% C.L.}$$

LHCb Collaboration
PRL 110 (2013) 021801

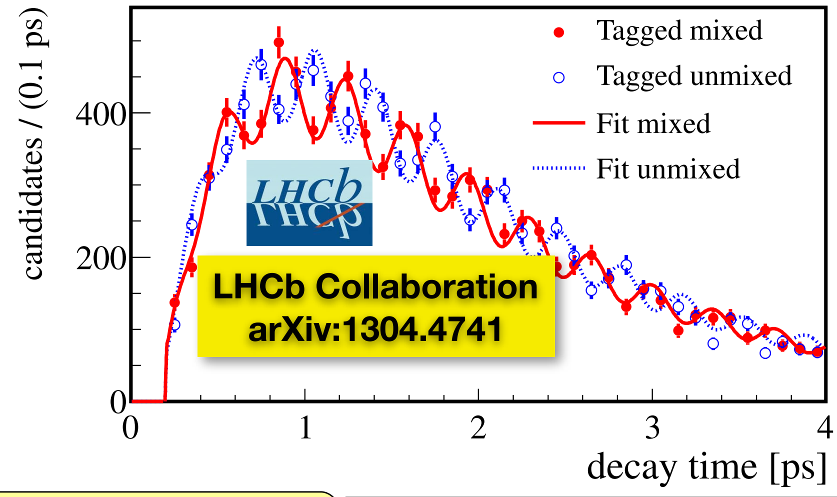




B_s Oscillations & CPV

- Most precise determination of B_s oscillation parameters using the $\pi^{\pm}D_s^{\mp}$ mode

$$\Delta m_s = 17.768 \pm 0.023(\mathrm{stat}) \pm 0.006(\mathrm{syst})\ \mathrm{ps}^{-1}$$

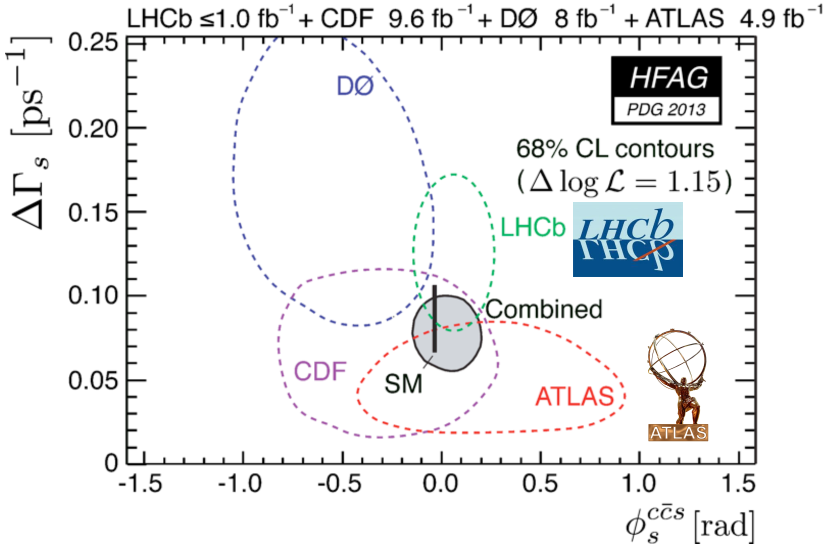


- First observation of direct CPV in the $B_s \to K\pi$ decays

$$A_{CP}(B_s^0 \to K\pi) = \frac{\Gamma(\overline{B}_s^0 \to K^+\pi^-) - \Gamma(B_s^0 \to K^-\pi^+)}{\Gamma(\overline{B}_s^0 \to K^+\pi^-) + \Gamma(B_s^0 \to K^-\pi^+)} = 0.27 \pm 0.04 \pm 0.01$$

LHCb-PAPER-2013-018

- No evidence for large CPV in $B_s \to J/\psi\phi$ decays
- Previous evidence for CPV in charm $D \to \pi\pi$, KK decays is not confirmed either



Heavy-Ion Program

- Very successful PbPb (2010, 2011) and pPb (2013) runs brought wealth of new data and allowed ALICE, ATLAS, and CMS to produce unprecedented and very exciting new results:
  - Detailed studies of jet quenching in PbPb collisions (ATLAS & CMS)
  - Elliptic flow and multiparticle correlations including studies of the "ridge" in pp, pPb, and PbPb collisions
  - Υ(2S) and Υ(3S) "melting" in PbPb collisions (CMS)
  - Number of other unique measurements:
    - W and Z production in PbPb collisions
    - Jet-photon correlations in PbPb collisions
    - Nuclear modification factor for b-tagged jet in PbPb collisions
  - LHCb is now joining the fun with the J/ψ suppression measurement in pPb collisions at forward rapidities
- Surprising finding: several phenomena that were only seen in PbPb collisions, seem to be pronounced in pPb, particularly when one matches the final-state multiplicity with that of PbPb

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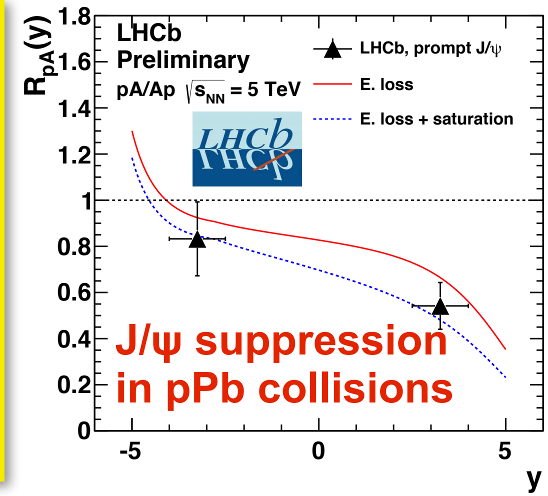
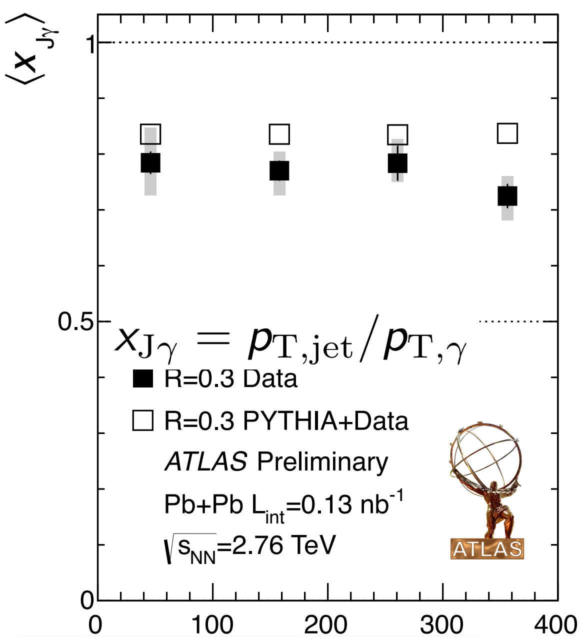
Heavy-Ion Highlights

- Some of the many heavy-ion highlights from the LHC
- Plus many more results with exclusive strange and charm hadron identification,as well as beauty tagging, completely unique to the LHC experiments

LHCb-PAPER-2013-008



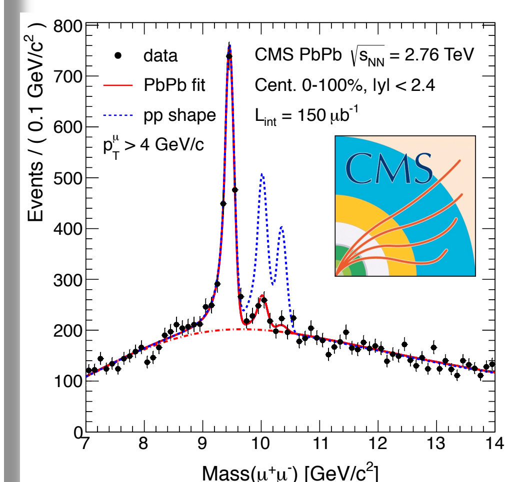
j+γ nuclear modification factor



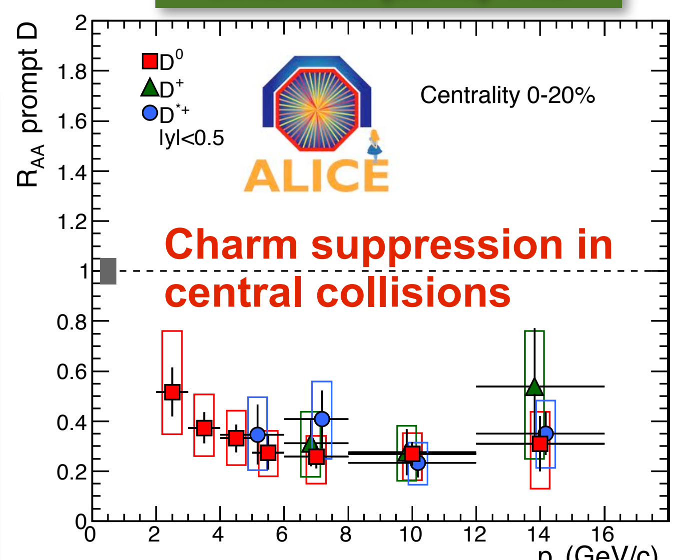
ATLAS-CONF-2012-121

CMS Collaboration
PRL 109 (2012) 222301

Υ(2S) and Υ(3S) melting

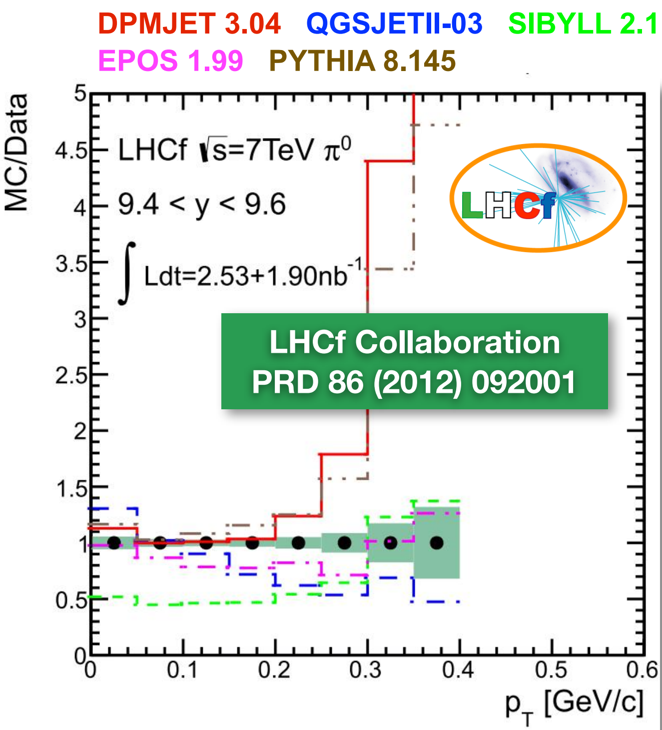


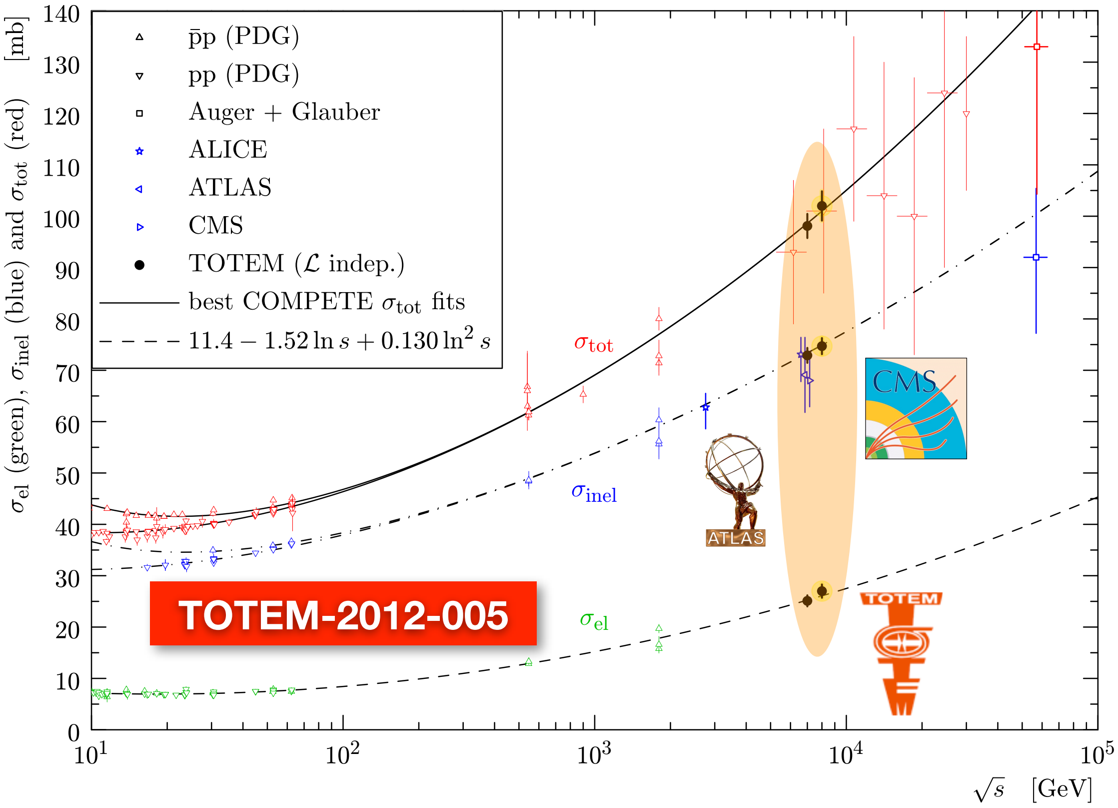
ALICE Collaboration
JHEP 09 (2012) 112



... and don't Forget LHCf & TOTEM

- LHCf: measurement of particle production in very forward region (8 < y < 15)
- Important input to cosmic-ray showering Monte Carlo generation
  - Latest results prefer EPOS 1.99 for forward π^0 p_T spectrum description
- TOTEM: elastic, inelastic, and total cross section measurements at 7 and 8 TeV





The Higgs Story

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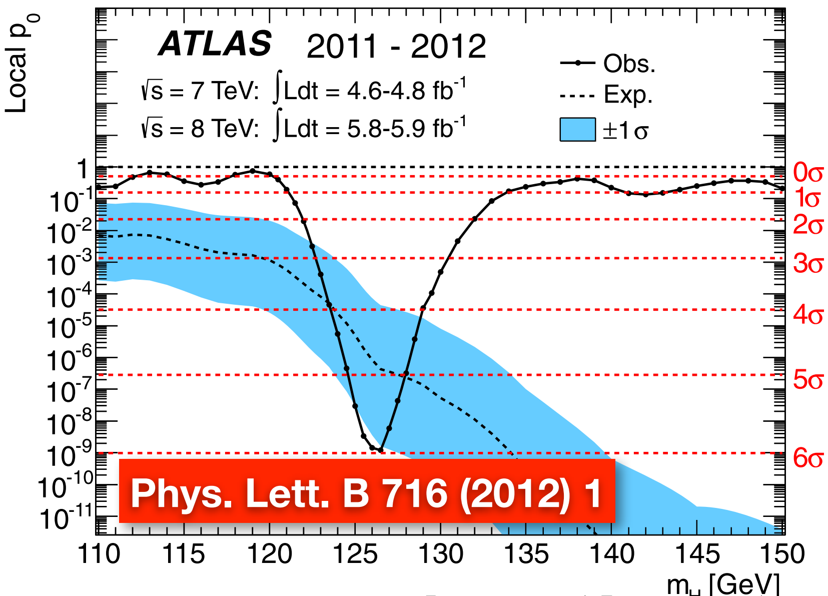
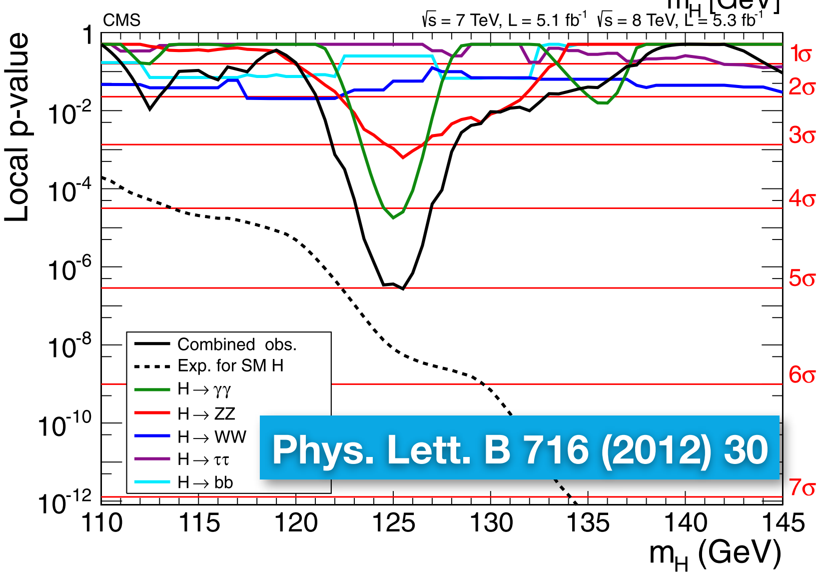
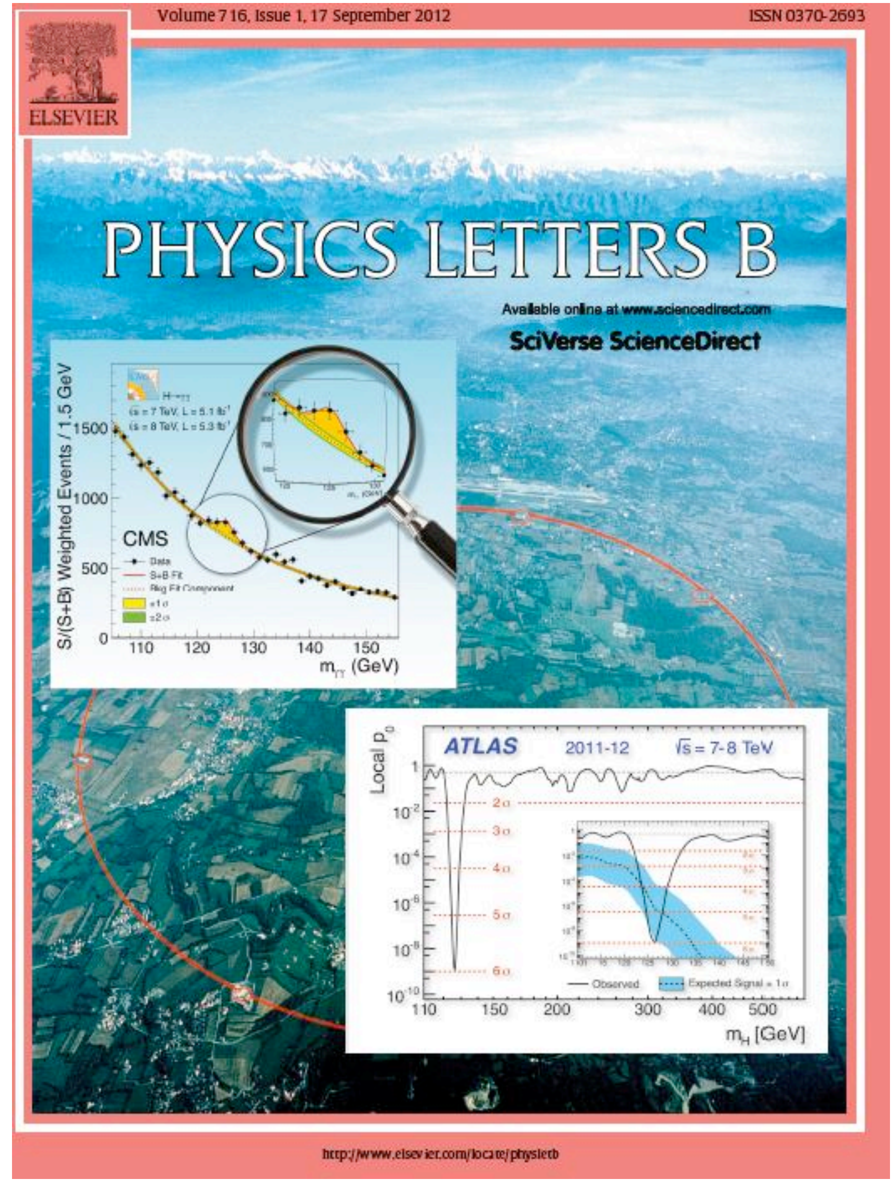
4th of July Fireworks

A New Boson Discovery

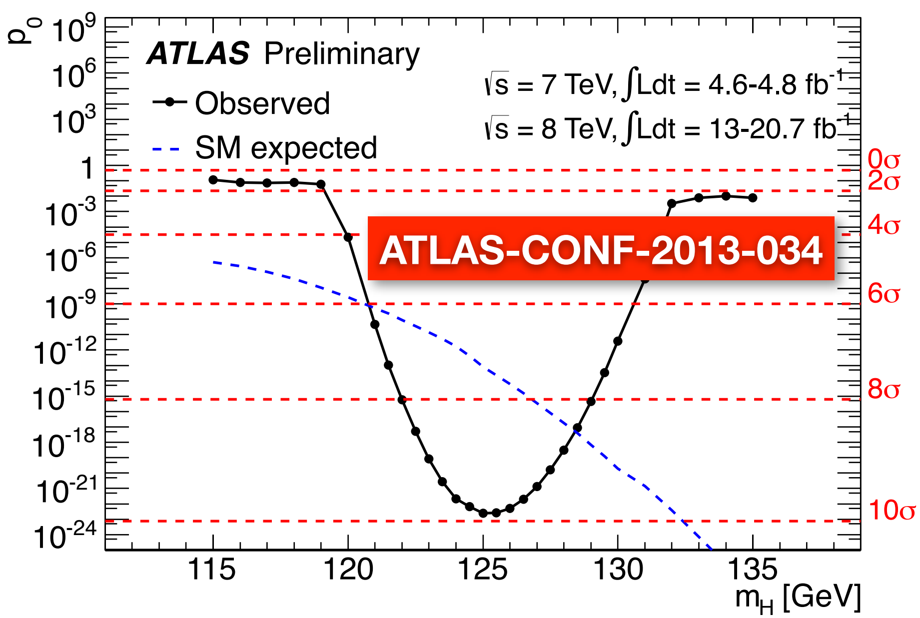






Higgs: 10 Months After

- Just a few highlights:
  - The existence of new particle has been established beyond any doubts; it is a 0^{++} boson responsible for EWSB, as evident from its relative couplings to W/Z vs. γ
  - It's properties are consistent with those of the SM Higgs boson within (sizable) uncertainties
  - There is mounting evidence (Tevatron, CMS), that it is couples to at least the third generation fermions

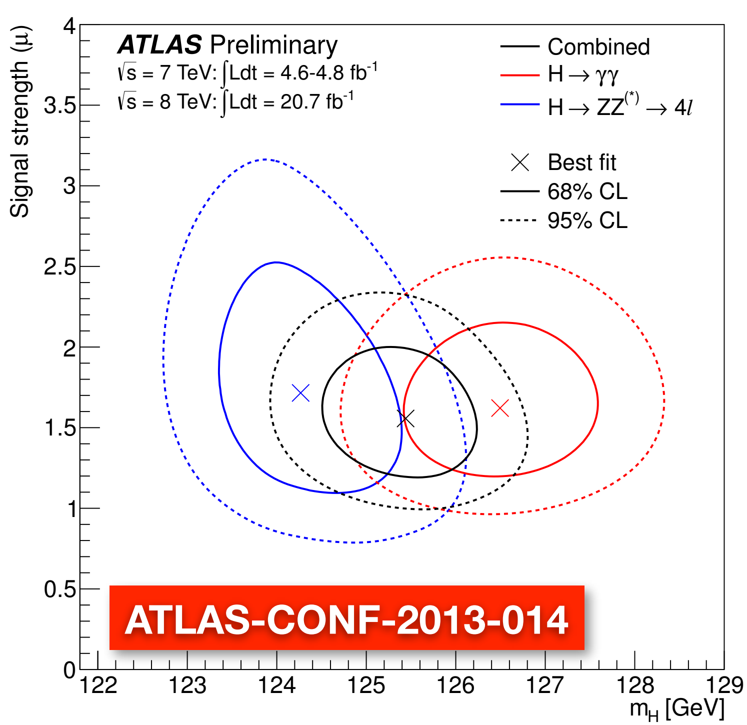


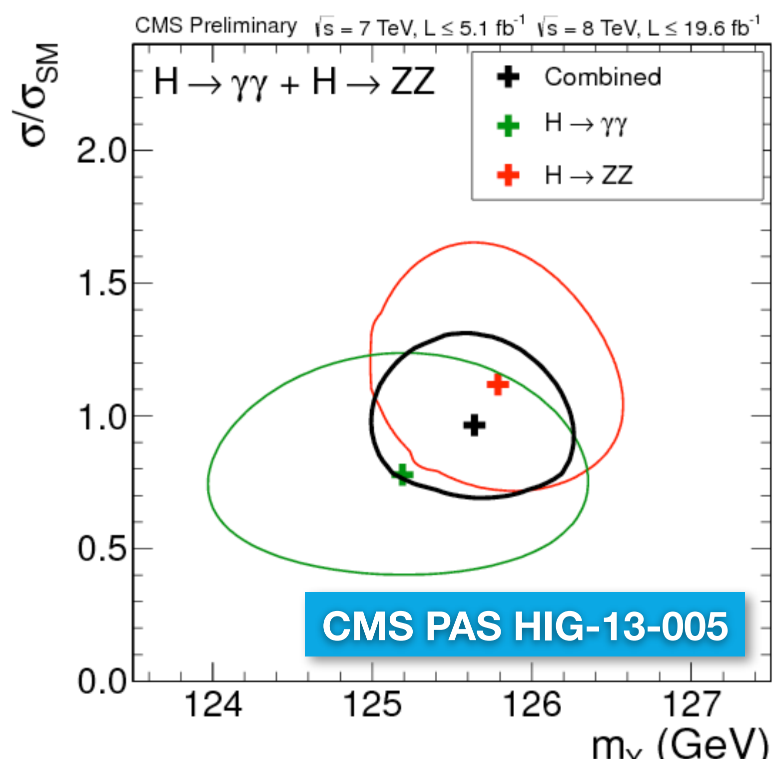
CMS PAS HIG-13-005

	Significance (m_H = 125.7 GeV)		
Combination	Expected (pre-fit)	Expected (post-fit)	Observed
$H\to ZZ$	7.1 σ	7.1 σ	6.7 σ
$H\to\gamma\gamma$	4.2 σ	3.9 σ	3.2 σ
$H\to WW$	5.6 σ	5.3 σ	3.9 σ
$H\to bb$	2.1 σ	2.2 σ	2.0 σ
$H\to\tau\tau$	2.7 σ	2.6 σ	2.8 σ
$H\to\tau\tau$ and $H\to bb$	3.5 σ	3.4 σ	3.4 σ

Higgs Boson Mass

- Higgs boson mass:
  - ATLAS: $M_H = 125.5 \pm 0.2\ ^{+0.5}_{-0.6}$ GeV (0.43% precision)
  - CMS: $M_H = 125.7 \pm 0.3 \pm 0.3$ GeV (0.34% precision)
- The Higgs boson mass has been already measured to a better precision than the top (or any other quark!) mass (0.50%)

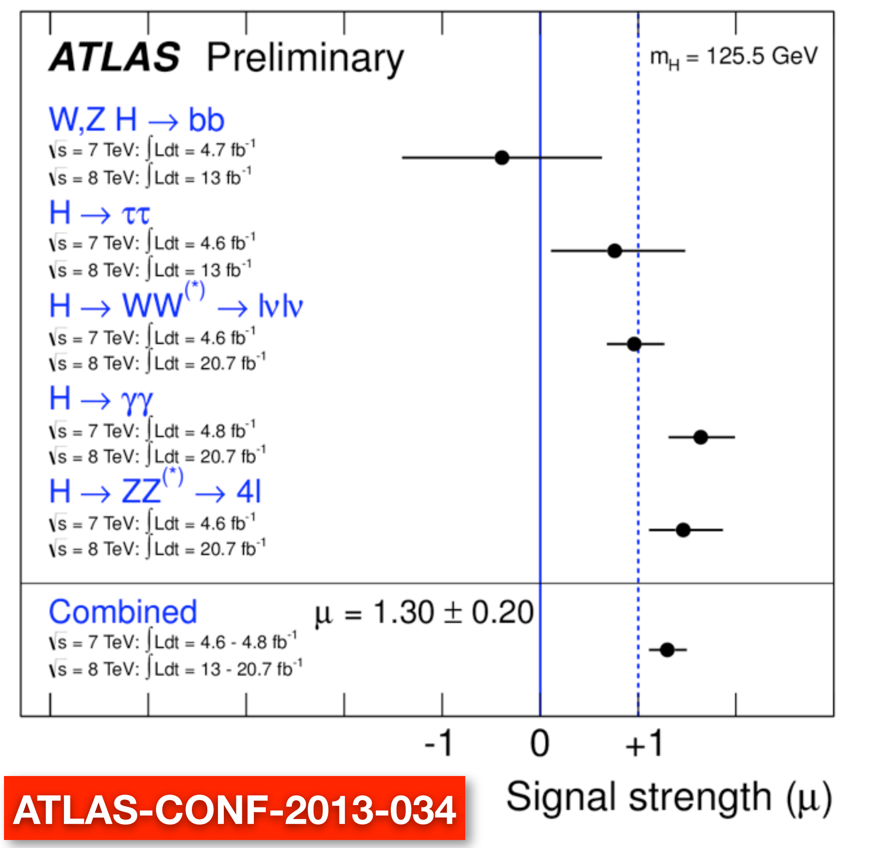




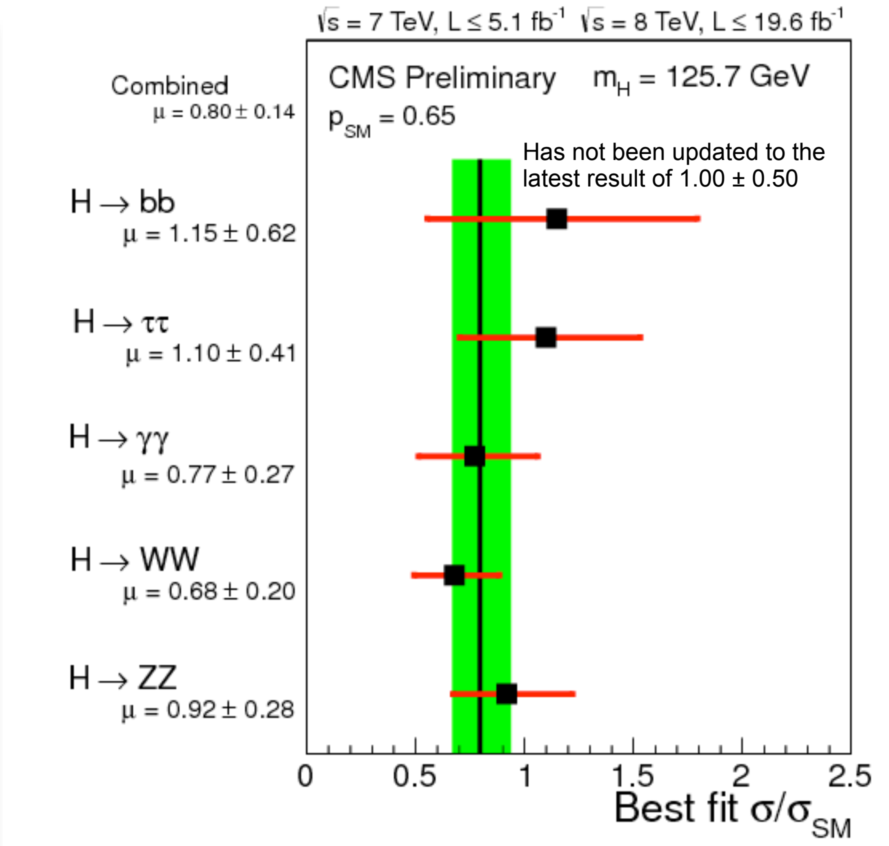
Higgs Boson Signal Strength

- Consistency with the SM Higgs boson:
  - ATLAS: $\mu = 1.30 \pm 0.20$ @ 125.5 GeV
  - CMS: $\mu = 0.80 \pm 0.14$ @ 125.7 GeV

CMS PAS HIG-13-005



ATLAS-CONF-2013-034



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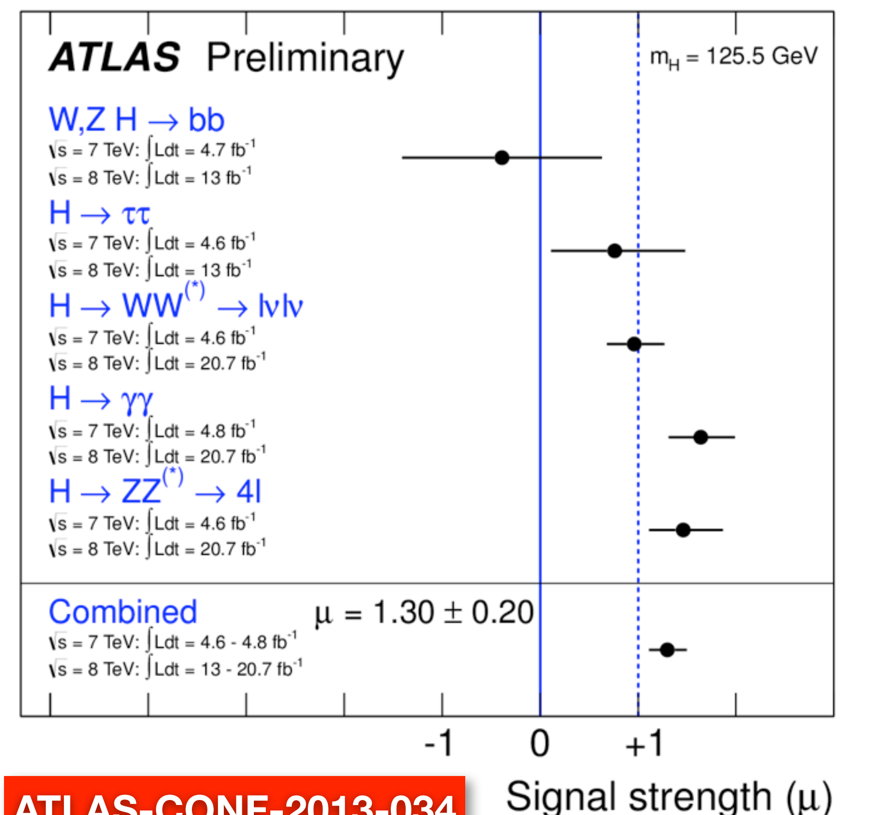

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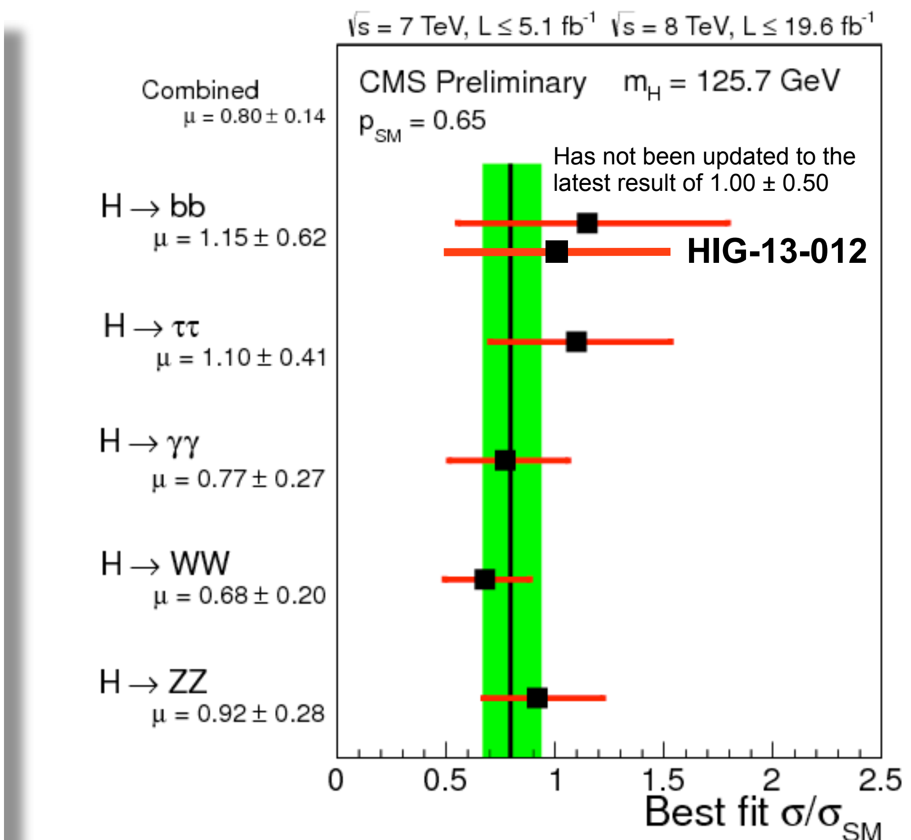


Higgs Boson Spin

- Both ATLAS and CMS strongly prefer $J^{PC} = 0^{++}$ over the alternatives
  - Pseudoscalar 0^{-+} and tensor 2^{++} hypotheses have been excluded at >3σ level by each experiment

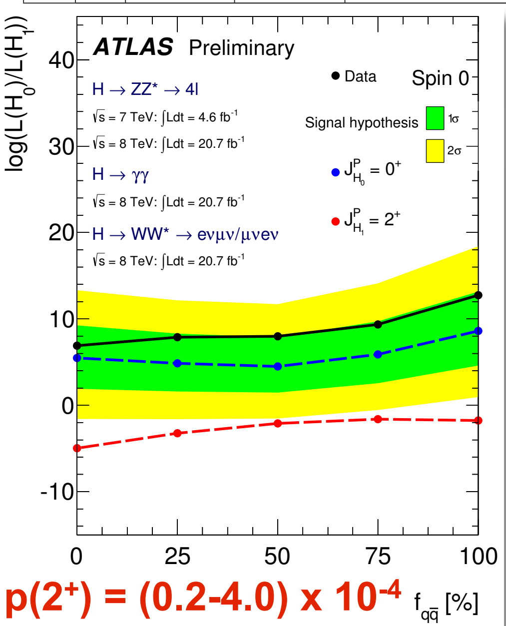
ATLAS-CONF-2013-013

		BDT analysis			
		tested J^P for an assumed 0^+		tested 0^+ for an assumed J^P	CL_s
		expected	observed	observed*	
0^-	p_0	0.0037	0.015	0.31	0.022
1^+	p_0	0.0016	0.001	0.55	0.002
1^-	p_0	0.0038	0.051	0.15	0.060
2^+_m	p_0	0.092	0.079	0.53	0.168
2^-	p_0	0.0053	0.25	0.034	0.258

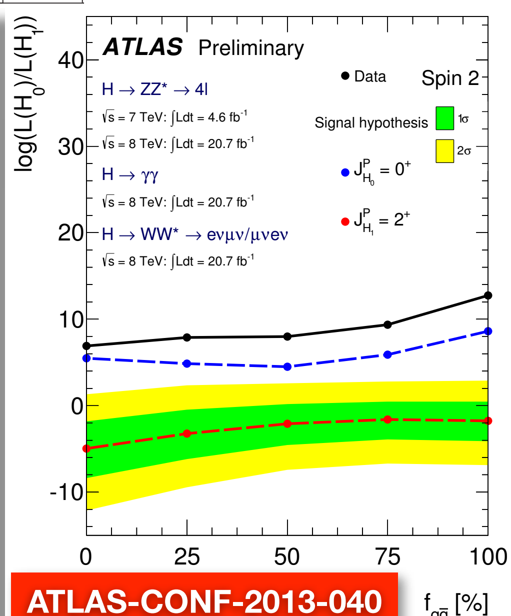
H(ZZ) alone

CMS PAS HIG-13-002

J^P	production	comment	expect (μ=1)	obs. 0^+	obs. J^P	CL_s
0^-	$gg \to X$	pseudoscalar	2.6σ (2.8σ)	0.5σ	3.3σ	0.16%
0^+_h	$gg \to X$	higher dim operators	1.7σ (1.8σ)	0.0σ	1.7σ	8.1%
2^+_{mgg}	$gg \to X$	minimal couplings	1.8σ (1.9σ)	0.8σ	2.7σ	1.5%
$2^+_{mq\bar{q}}$	$q\bar{q} \to X$	minimal couplings	1.7σ (1.9σ)	1.8σ	4.0σ	<0.1%
1^-	$q\bar{q} \to X$	exotic vector	2.8σ (3.1σ)	1.4σ	>4.0σ	<0.1%
1^+	$q\bar{q} \to X$	exotic pseudovector	2.3σ (2.6σ)	1.7σ	>4.0σ	<0.1%

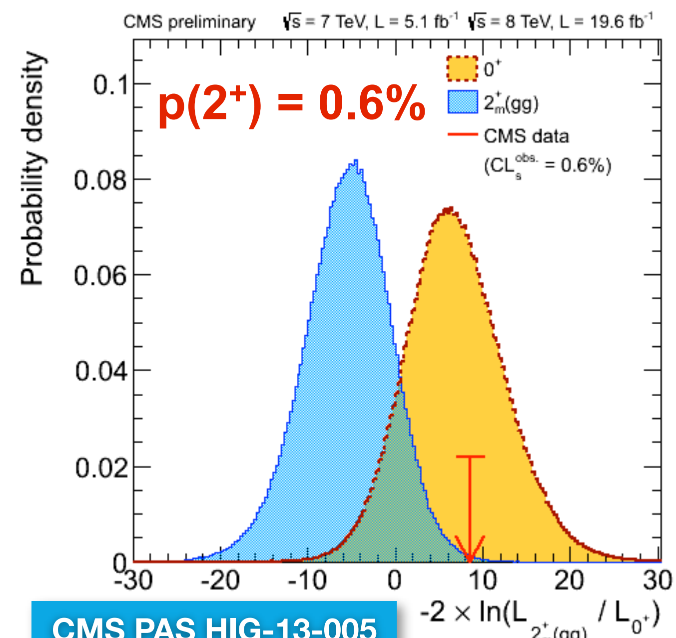


$p(2^+) = (0.2\text{-}4.0) \times 10^{-4}$



ATLAS-CONF-2013-040

Combination

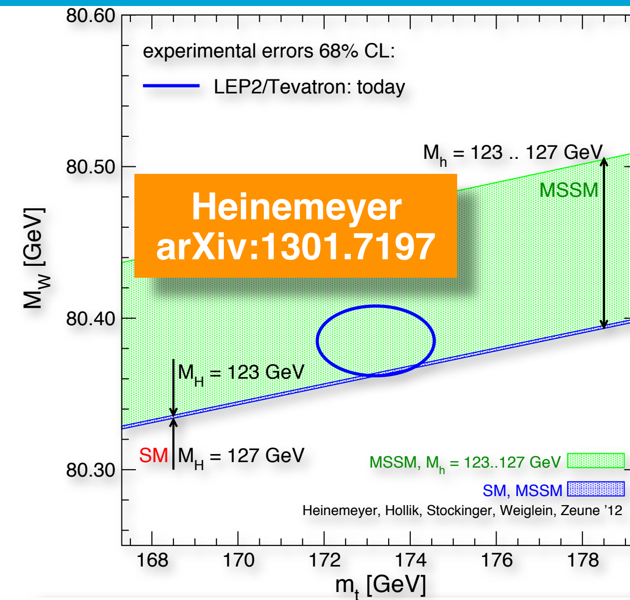


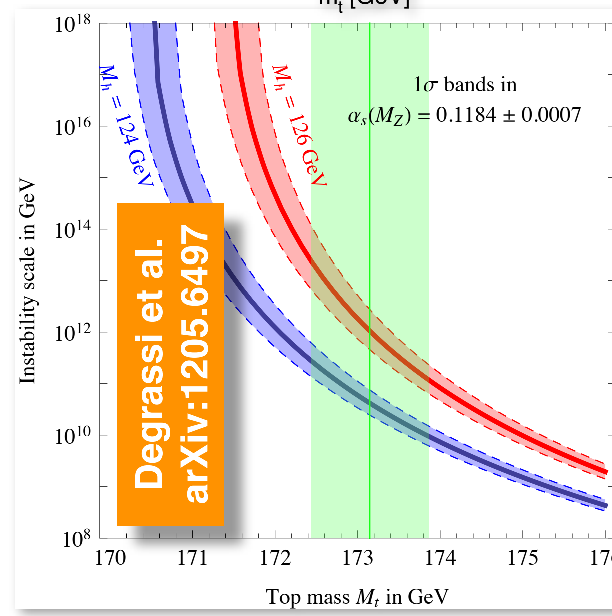
CMS PAS HIG-13-005

BROWN

Higgs Discovery Implications

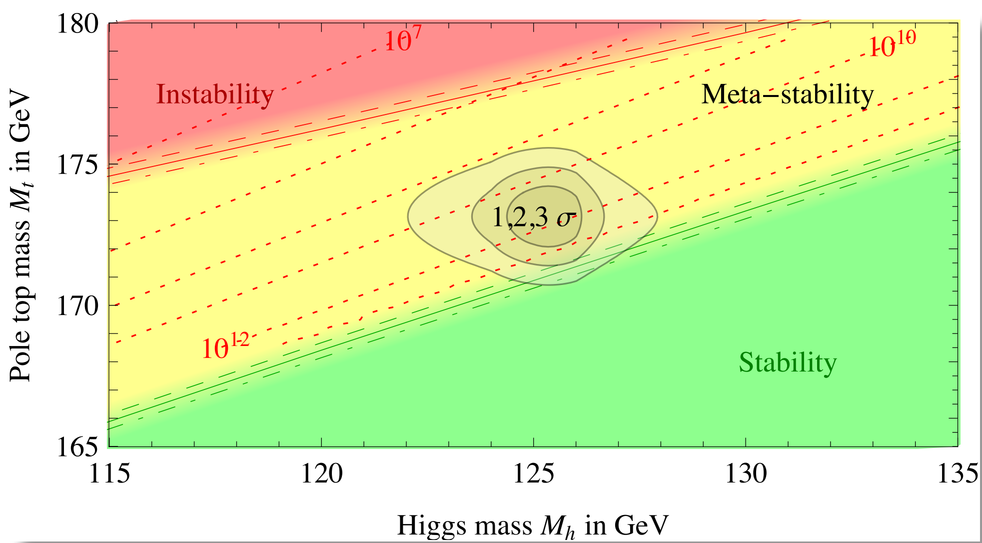
- Light Higgs boson discovery implies that the SM can not be a complete theory up to the Planck scale
- Vacuum stability arguments require new physics to come at a scale ~10^{11} GeV or less
  - Curiously points to a similar scale as suggested by the neutrino mass hierarchy via see-saw mechanism
- Nevertheless, a metastable vacuum could survive w/o new physics
- The new boson is light enough to be a MSSM Higgs, but yet too heavy to obviously prefer MSSM vs. SM!
  - Had it been just 10% heavier we would have probably stopped talking about low-scale SUSY!
- If we found the SM Higgs boson, we now need to explain the EWSB mechanism, i.e. what makes the Higgs potential what it is (i.e., explain the origin of the λ term in the Lagrangian)
  - It looks more and more like the SM Higgs boson, but there is still room for surprises!
- In a sense, a 125 GeV Higgs boson is maximally challenging and rich experimentally, but also inflicts “maximum pain” theoretically, as it is not so easy to accommodate



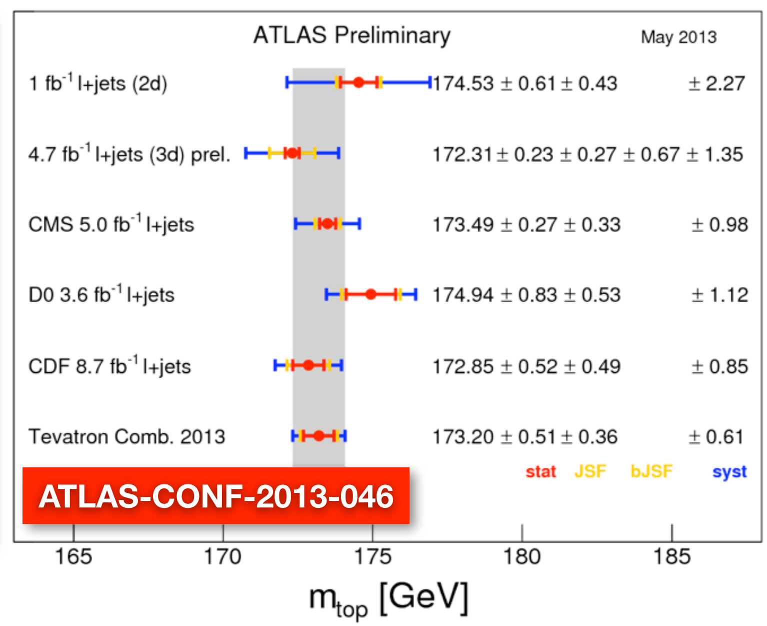


Just-So Higgs?

- The simultaneous measurement of the Higgs boson and top quark masses allowed for the first time to infer properties of the very vacuum we leave in!
  - We are in a highly fine-tuned situation: the vacuum is at the verge of being either stable or metastable!
  - ~1 GeV in either the top-quark or the Higgs boson mass is all it takes to tip the scales!
- Perhaps Nature is trying to tell us something here?
  - Very important to improve on the precision of top quark mass measurements, including various complementary methods and reduction of theoretical uncertainties
  - Tevatron is still leading with the new combined M_t result, but LHC is catching up quickly!



Degrassi et al, arXiv:1205.6497



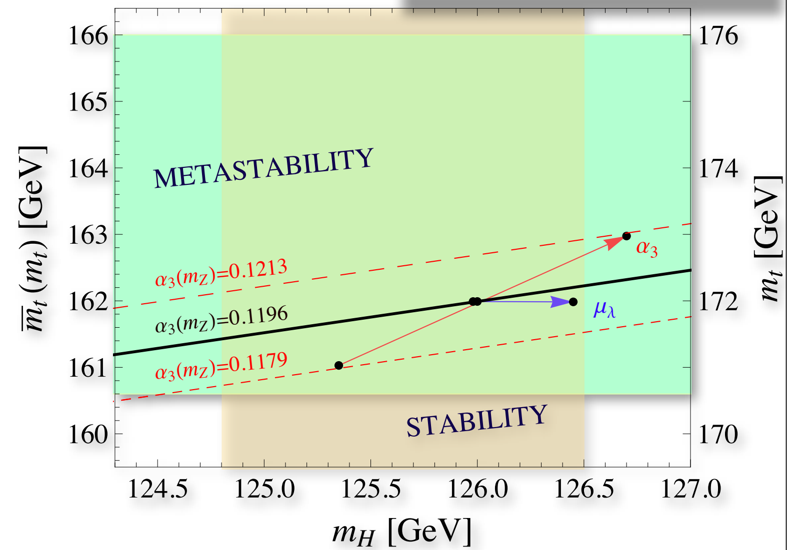
ATLAS-CONF-2013-046

What Vacuum Do We Live In?

- Stable vacuum?

- Metastable vacuum?

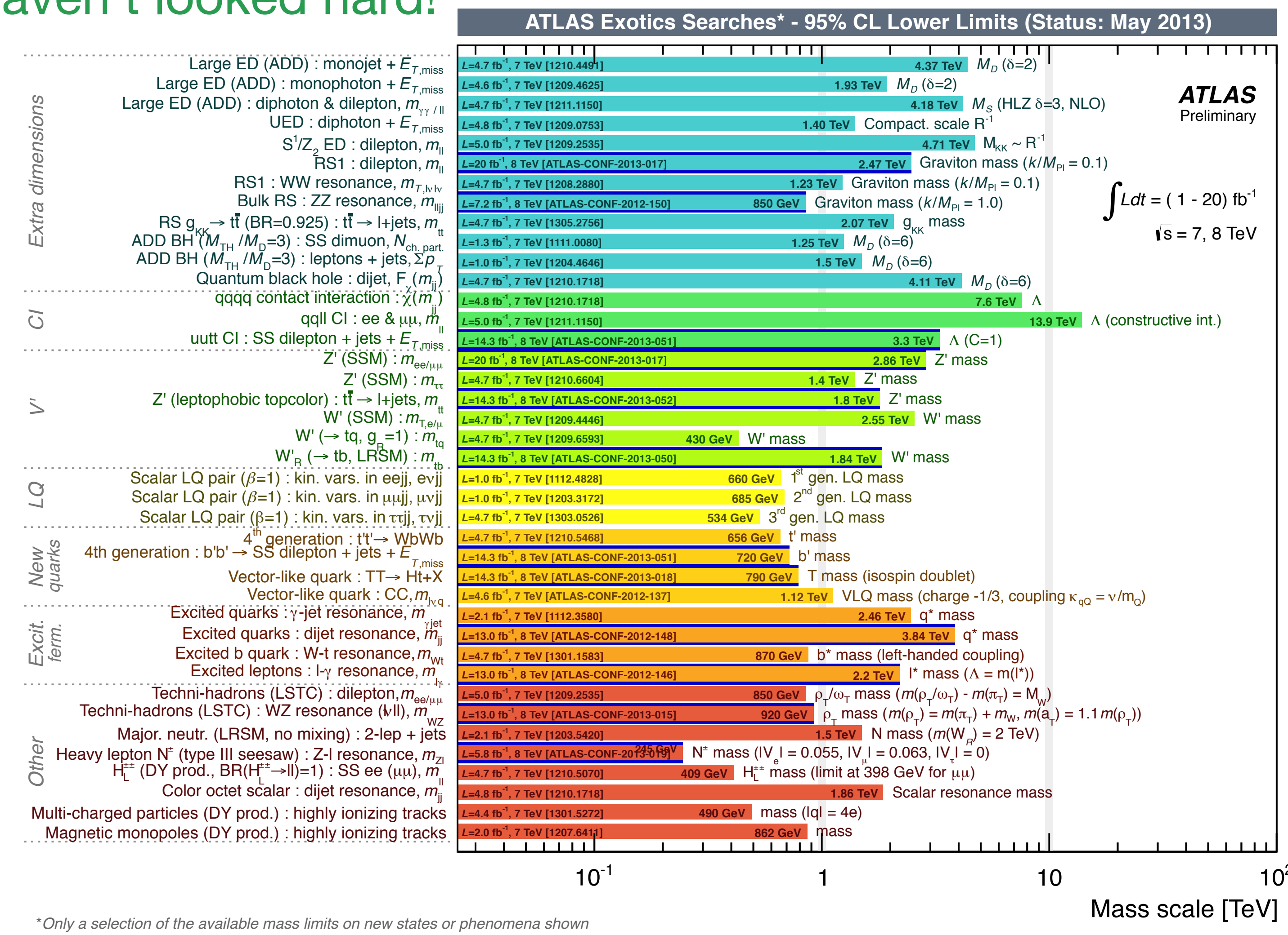
Masina arXiv:1301.2175



- Unstable vacuum?

And What About New Physics?

- The Higgs is there, but so far, no sign of new physics, and it's not like we haven't looked hard!



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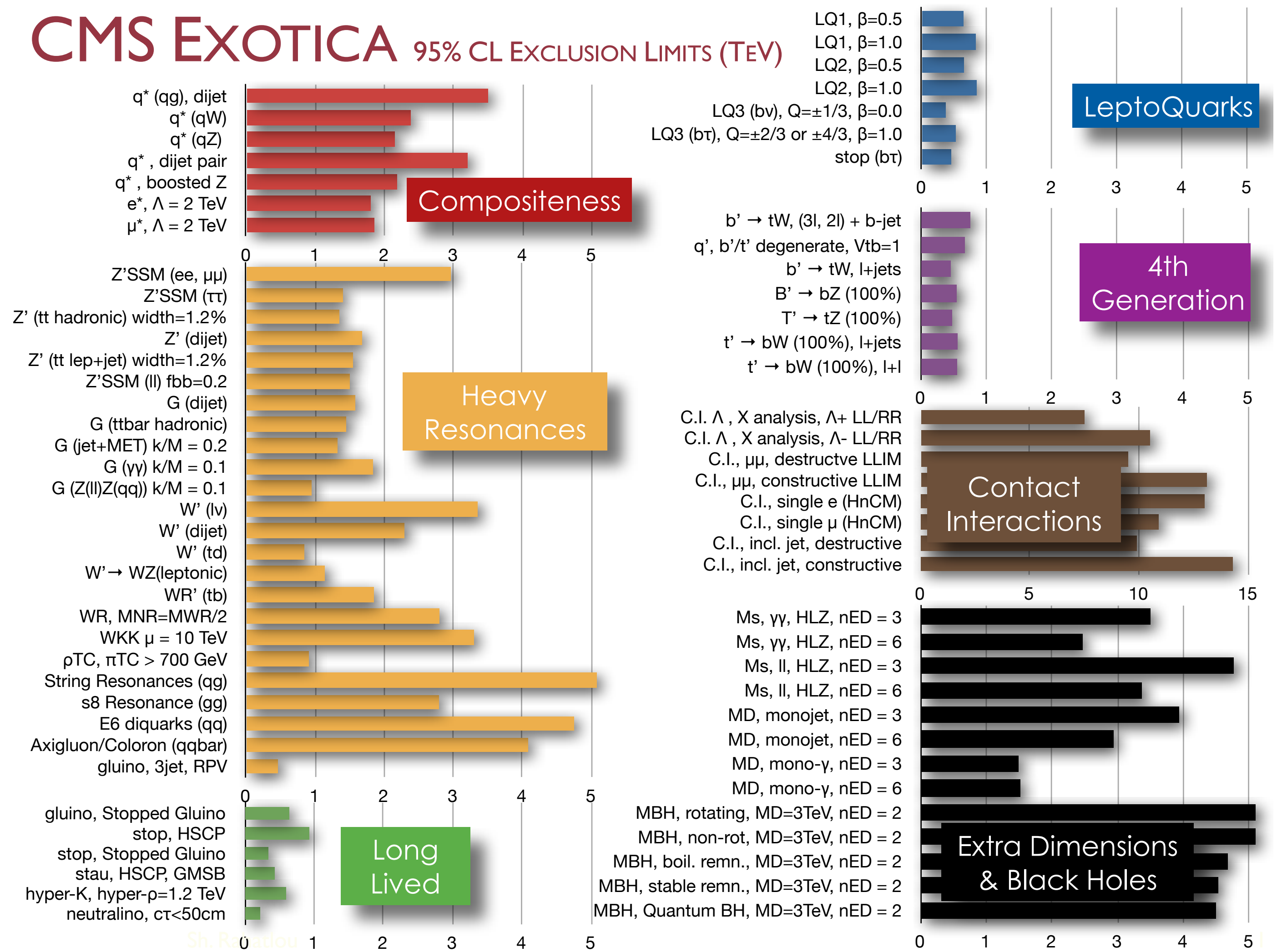
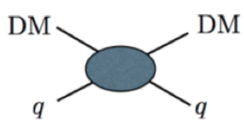
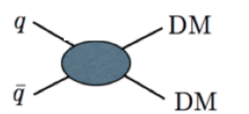


Extra Dimensions & Dark Matter

- Search for large extra dimensions and dark matter in monojet and monophoton final states (a la the direct detection experiments):
  - Limits are somewhat model-dependent as they are sensitive to the mass of the mediator; yet competitive
  - Offer unique sensitivity to DM-gluon couplings
- Ever Increasing interest since the recent CoGeNT/CRESST and CDMS (arXiv:1304.4279) excesses

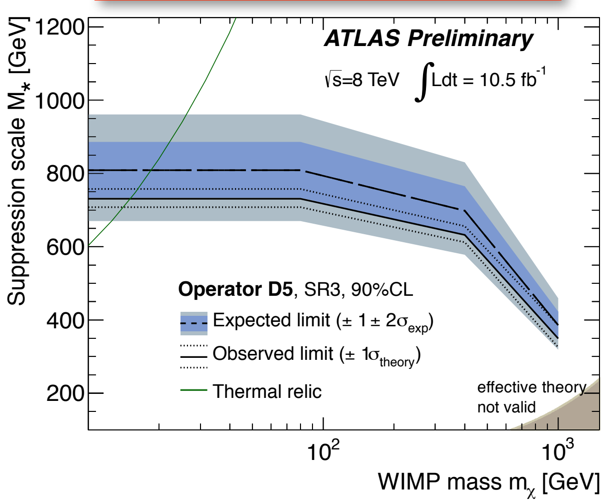


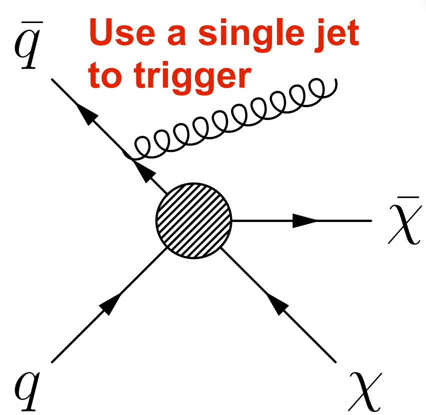
Direct Detection (t-channel)



Collider Searches (s-channel)

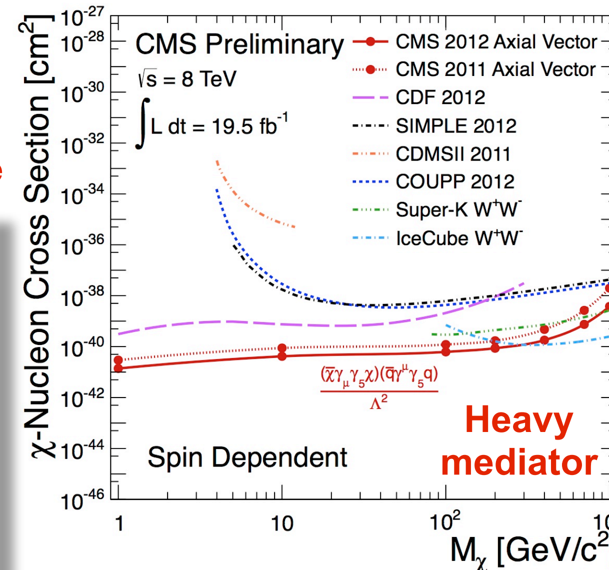
ATLAS-CONF-2012-147

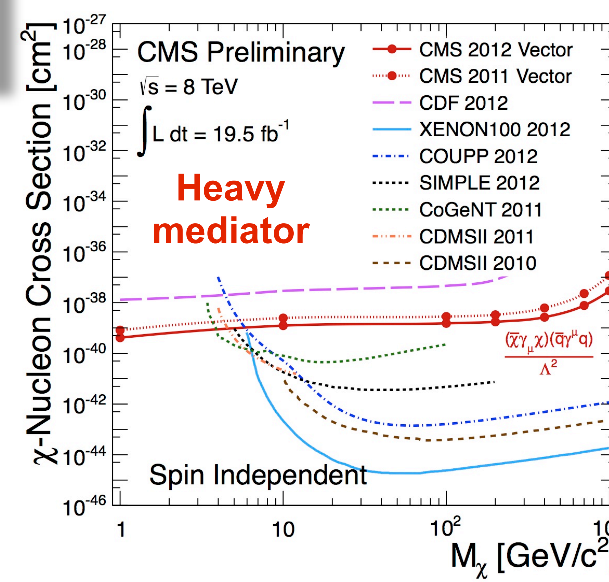




Monojet + MET

CMS PAS EXO-12-048





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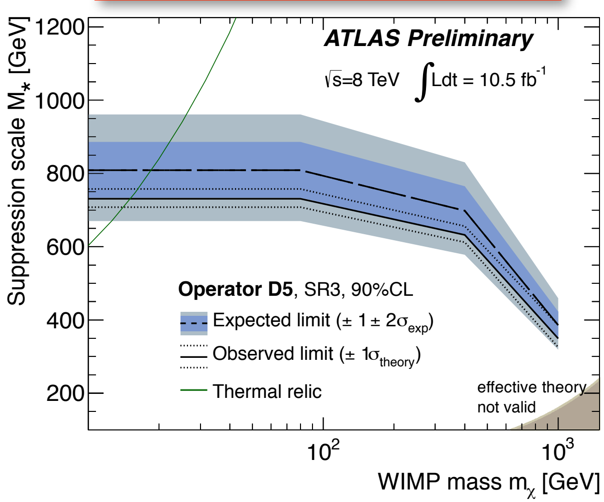
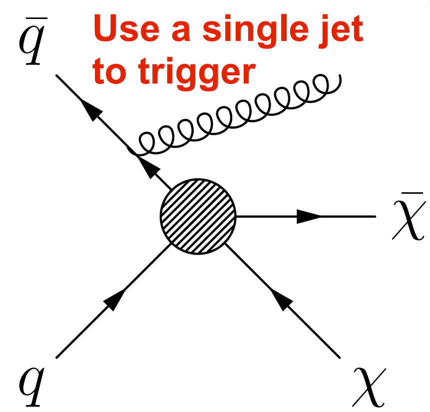
Direct Detection (t-channel) *Collider Searches (s-channel)*

ATLAS-CONF-2012-147





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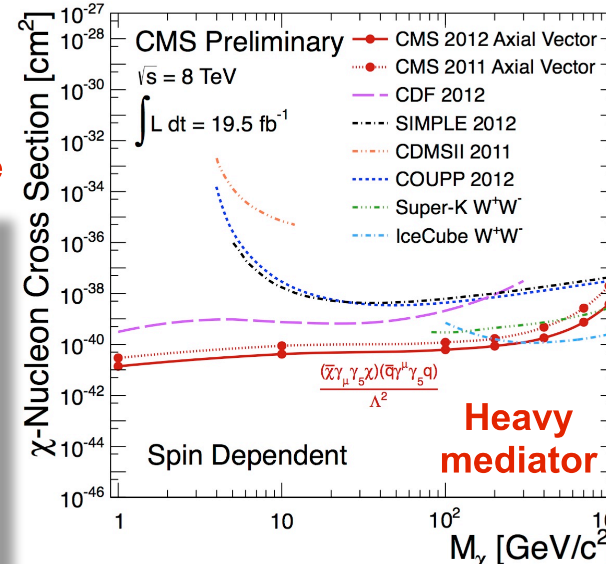

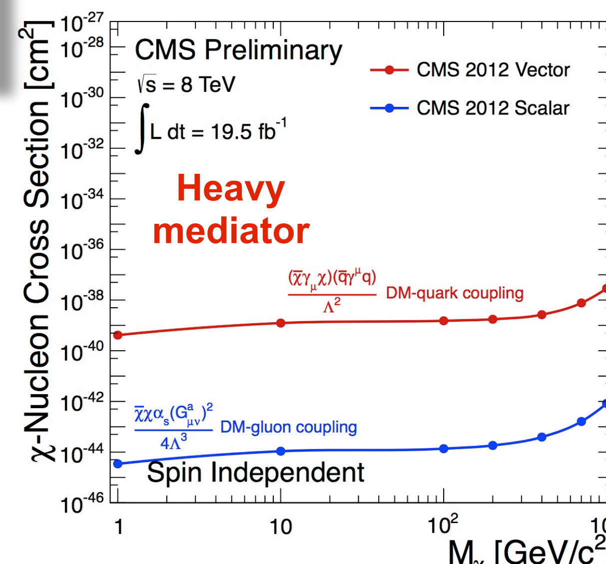

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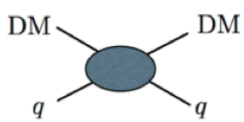

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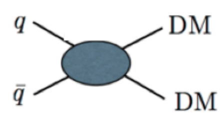

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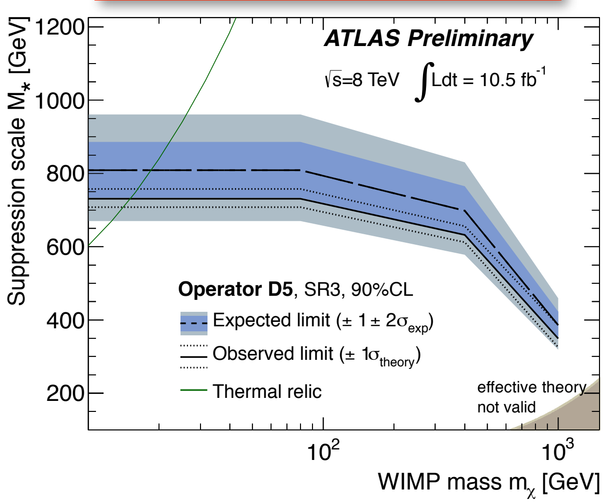
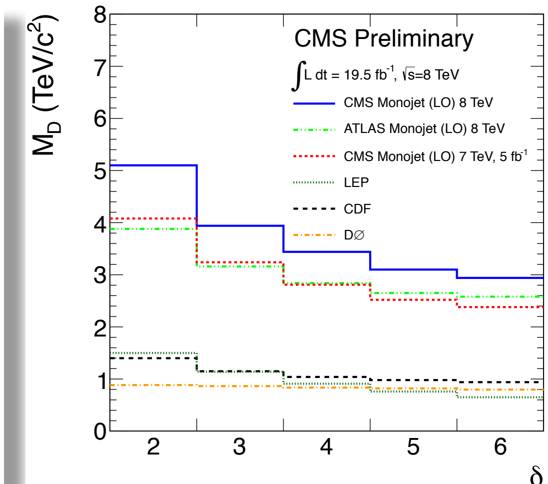
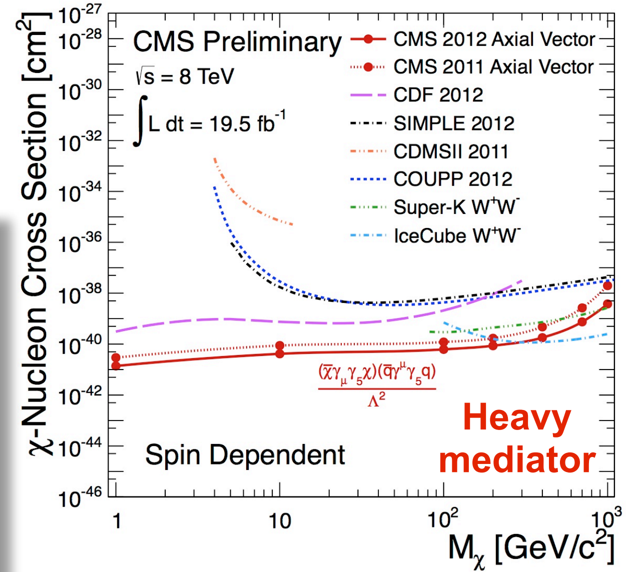
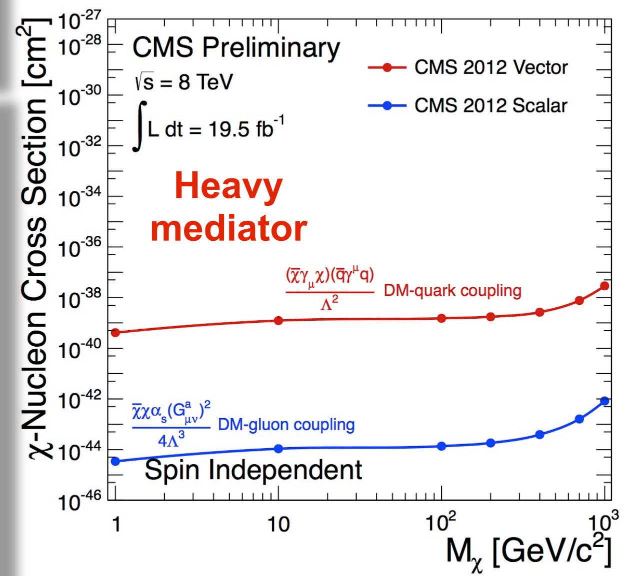
ATLAS-CONF-2012-147





CMS PAS EXO-12-048

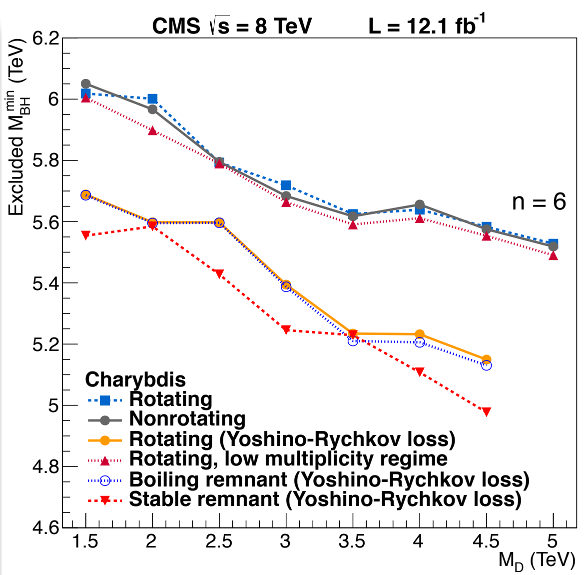


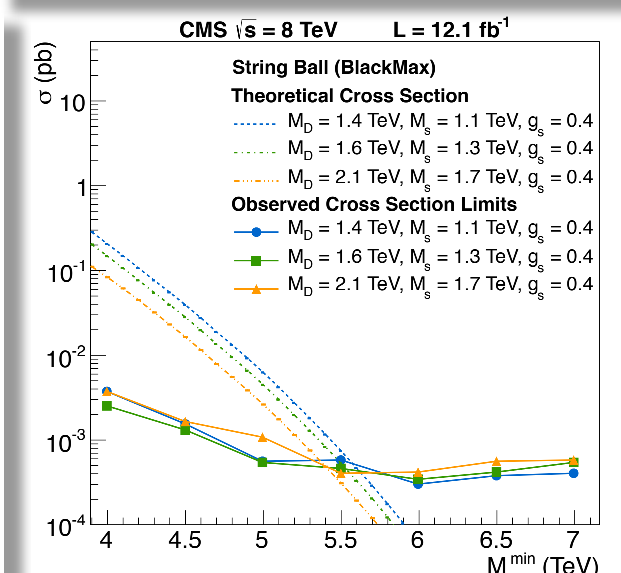


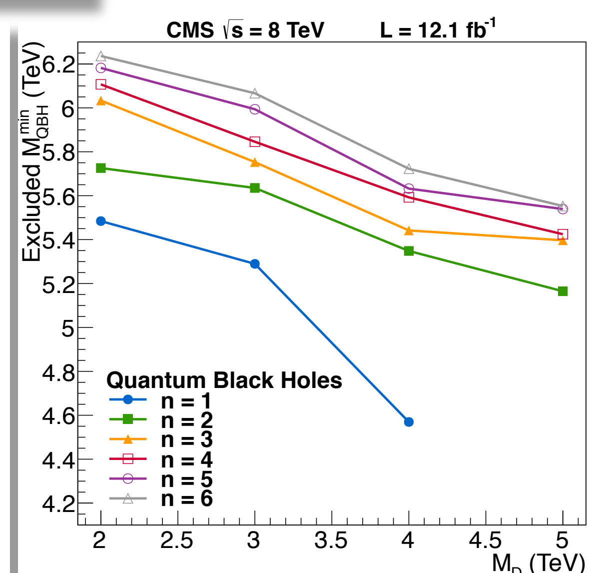
(No) Black Holes at the LHC

- If the scale of quantum gravity is ~1 TeV, copious production of black holes at the LHC is expected [Giddings/Thomas, PRD **65** (2002) 056010; Dimopoulos/GL, PRL **87** (2001) 161602]
  - Could be semi-classical ($M_{BH} \gg M_{Pl}$) or quantum (more likely!)
  - Production cross section: $\sigma \sim 1/R_S^2 \sim \text{TeV}^{-2} \sim 100$ pb ($\sim\sigma_{tt}$)
  - Signatures: large (semiclassical) or low (quantum) number of very energetic (~1 TeV) particles in the final state after evaporation, mostly jets from quark/gluon fragmentation
- Excluded semiclassical and quantum black holes with minimum masses ~5 TeV

CMS Collaboration, arXiv:1303.5338

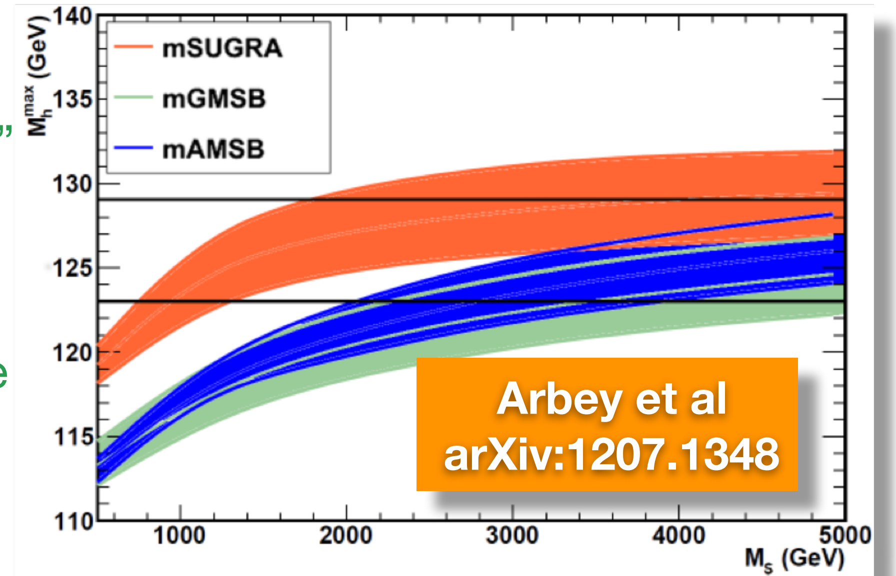


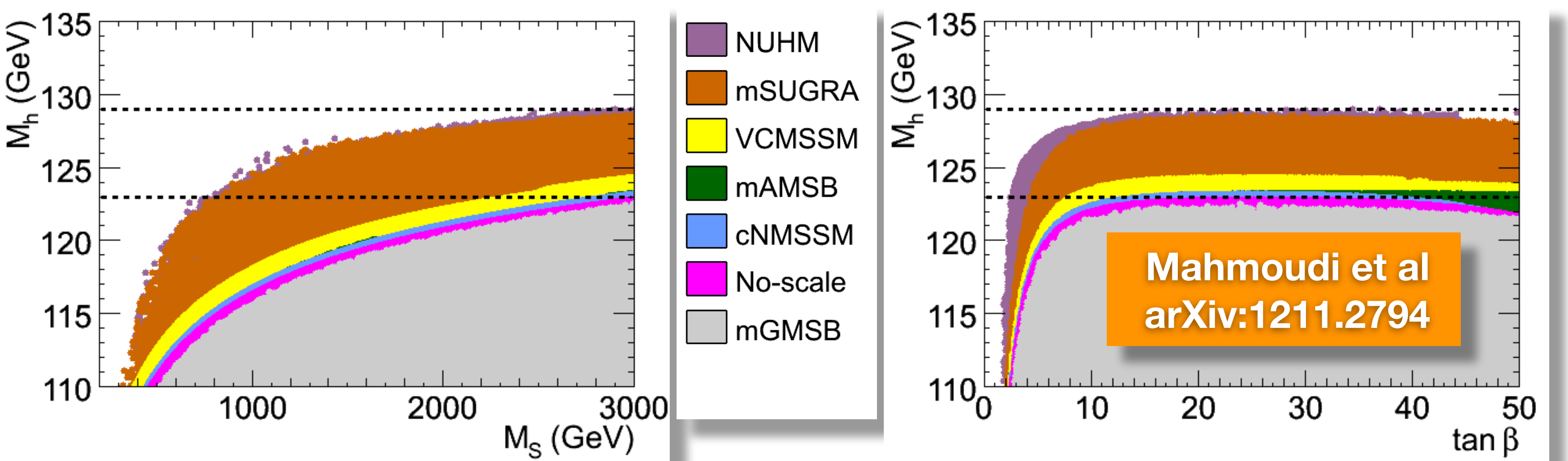




SUSY: the Higgs Aftermath

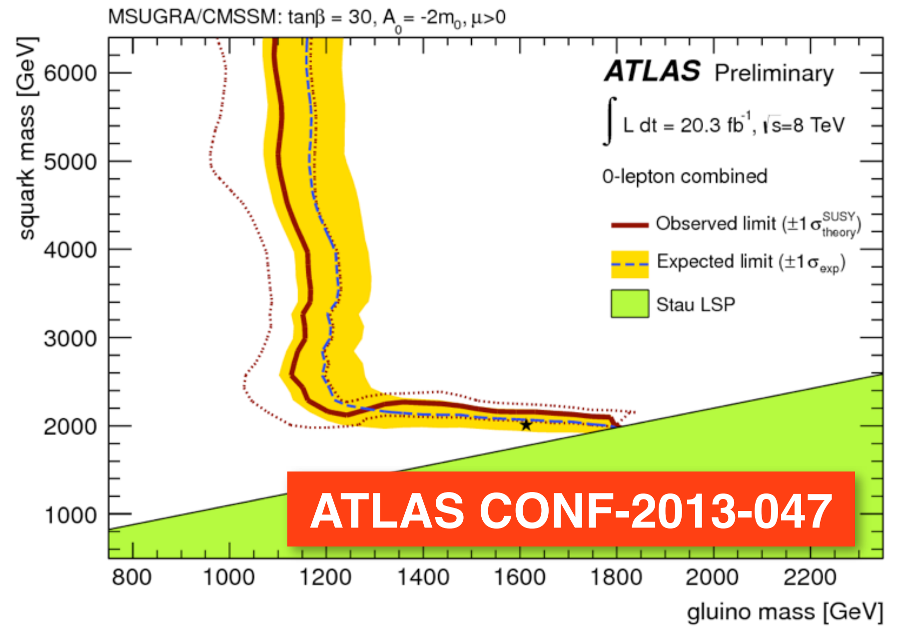
- A 125 GeV Higgs boson is challenging to accommodate in (over)constrained versions of SUSY, particularly for “natural” values of superpartner masses
  - Started to constrain some of the simpler models
- Big question: if SUSY exists, can it still be “natural”, i.e. offer a non-fine-tuned solution to the hierarchy problem
  - If not, we would be giving up at least one of the three SUSY “miracles”

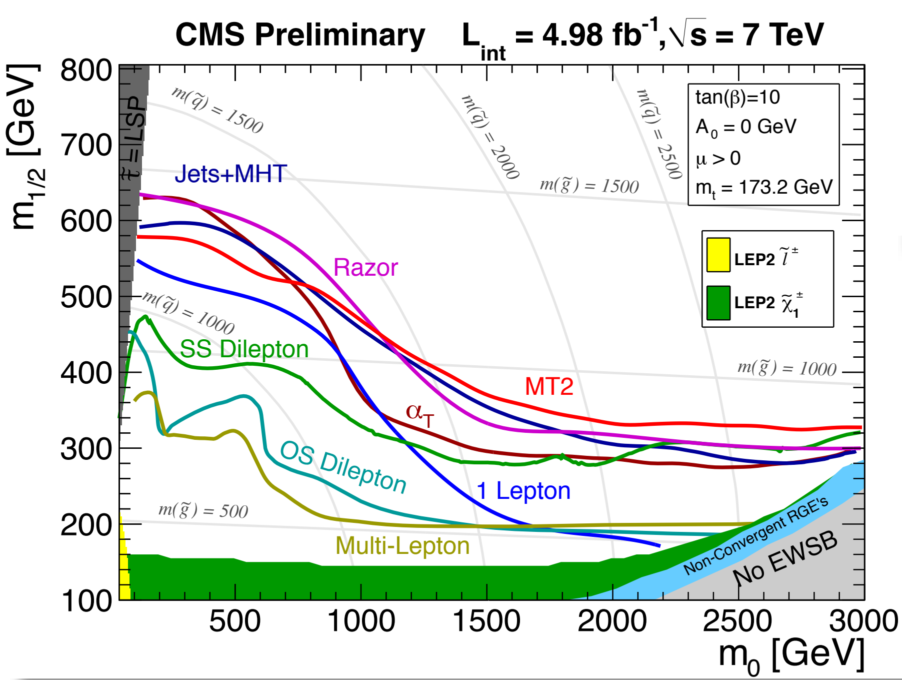




SuperSymmetry or SuperCemetery?

- Excluded squarks to ~2.0 TeV and gluinos to ~1.2 TeV - or did we?





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Read the fine print!

What SUSY Have We Excluded?

- We set strong limits on squarks and gluinos, and yet we have not excluded SUSY
  - Moreover, we basically excluded VERY LITTLE!
- We ventured for an "easy-SUSY" or "lazy-SUSY" and we basically failed to find it
  - So what? - Nature could be tough!
- What we probed is a tiny sliver of multidimensional SUSY space, simply most "convenient" from the point of view of theory

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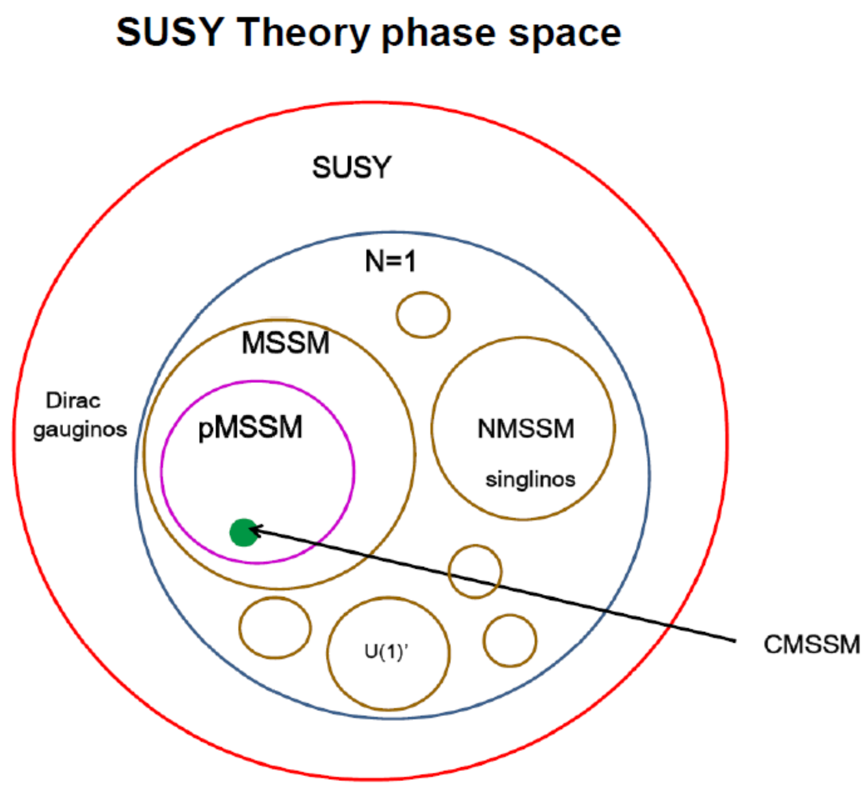
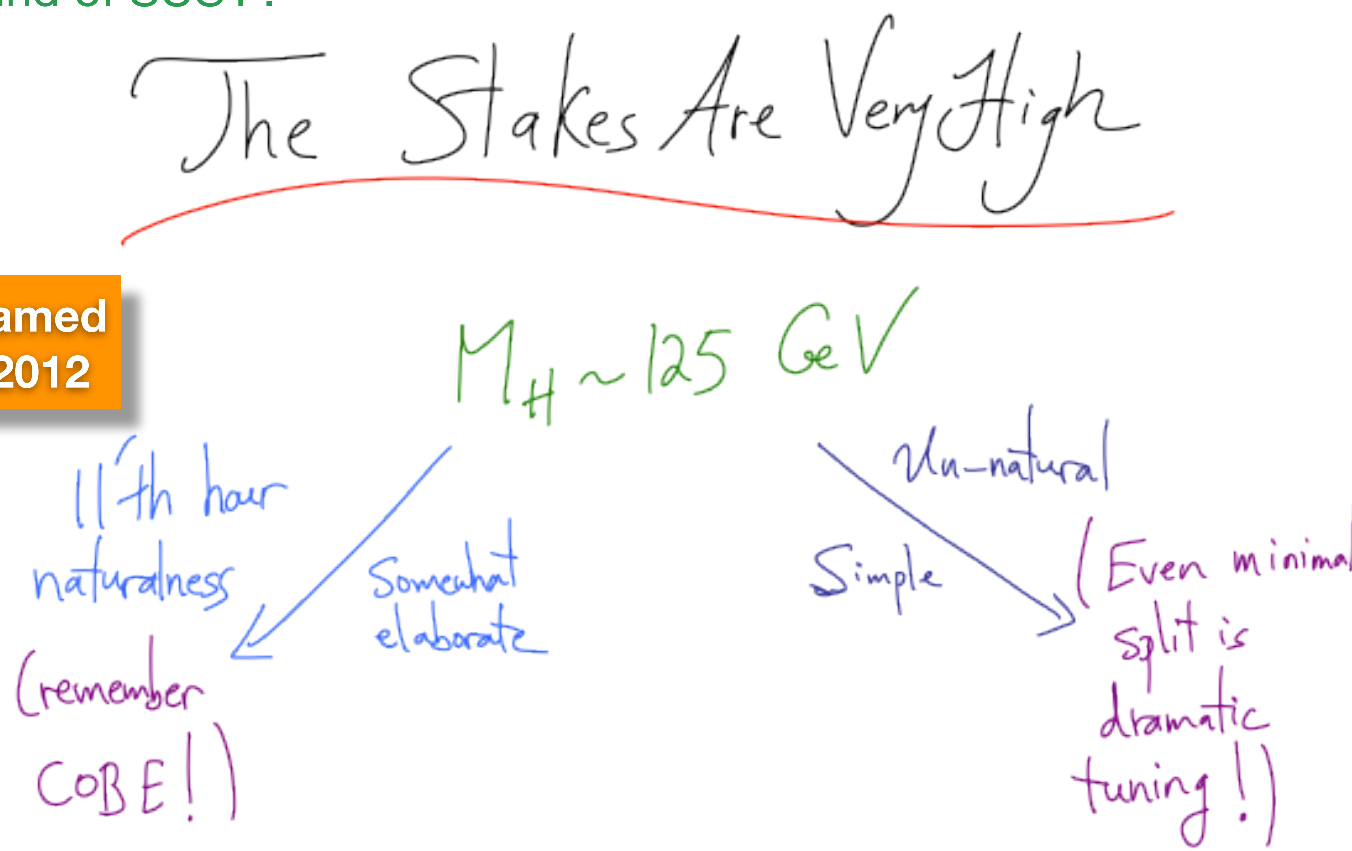


T. Rizzo (SLAC Summer Institute, 01-Aug-12)

We are at a SUSY Crossroad

- Light 125 GeV Higgs boson strongly prefers SUSY as the fundamental explanation of the EWSB mechanism (via soft SUSY-breaking terms and radiative corrections)
- But what kind of SUSY?

N. Arkani-Hamed SavasFest 2012



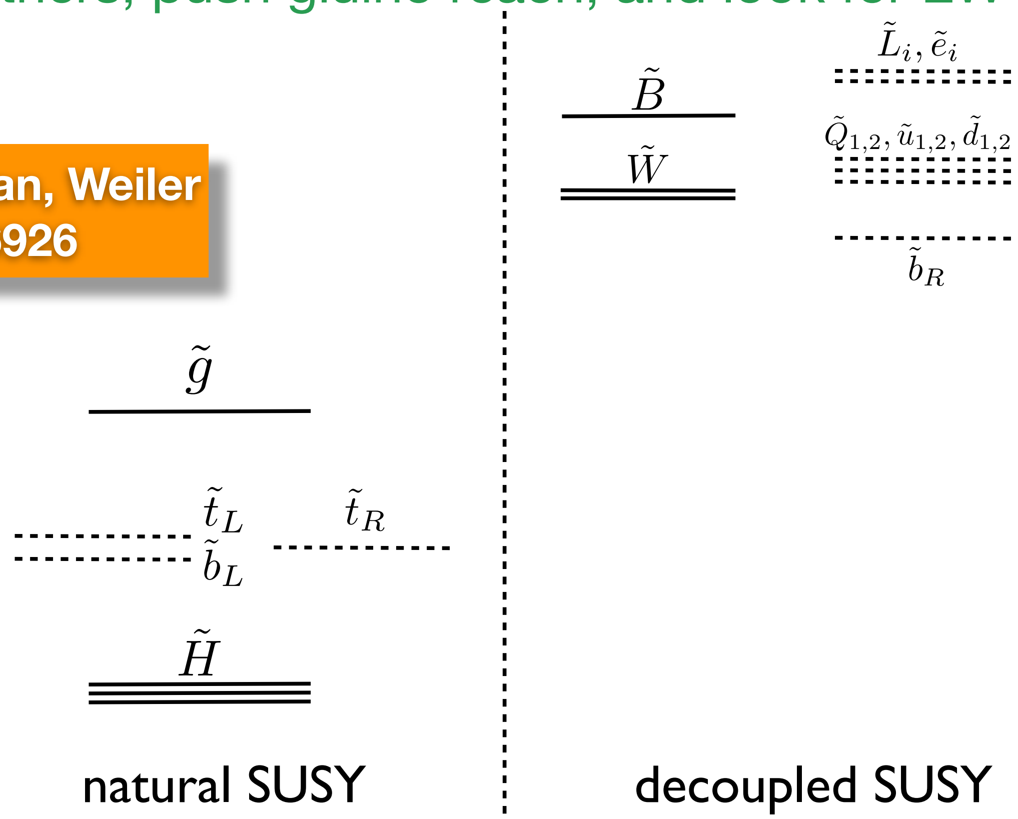
Implies: light stops/sbottom, reasonably light gluinos and charginos/neutralinos

Likely: long-lived particles, light neutralino, multi-TeV Z′, ...

Natural SUSY

- If SUSY is natural, we should find it soon:
  - And we most likely will find it by observing 3rd generation SUSY particles first!
- Requires shifting of the SUSY search paradigm: going for the third generation partners, push gluino reach, and look for EW boson partners

Papucci, Ruderman, Weiler
arXiv:1110.6926



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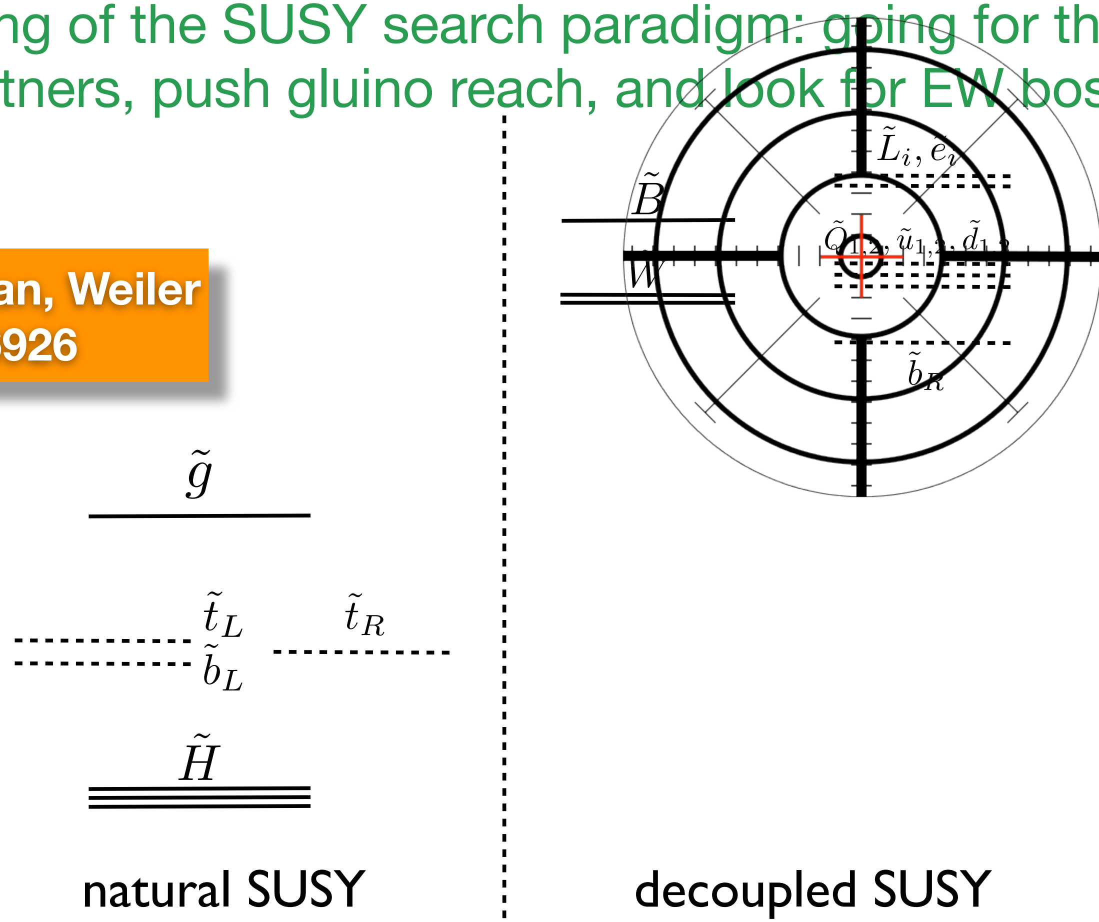

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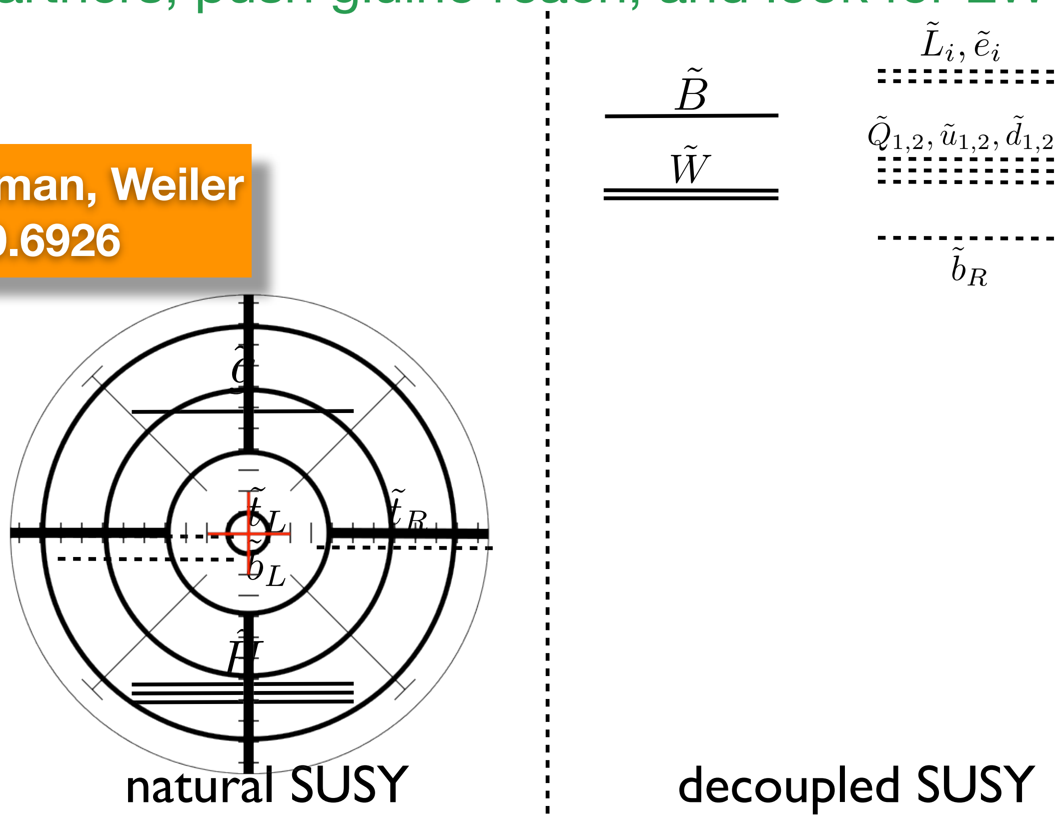
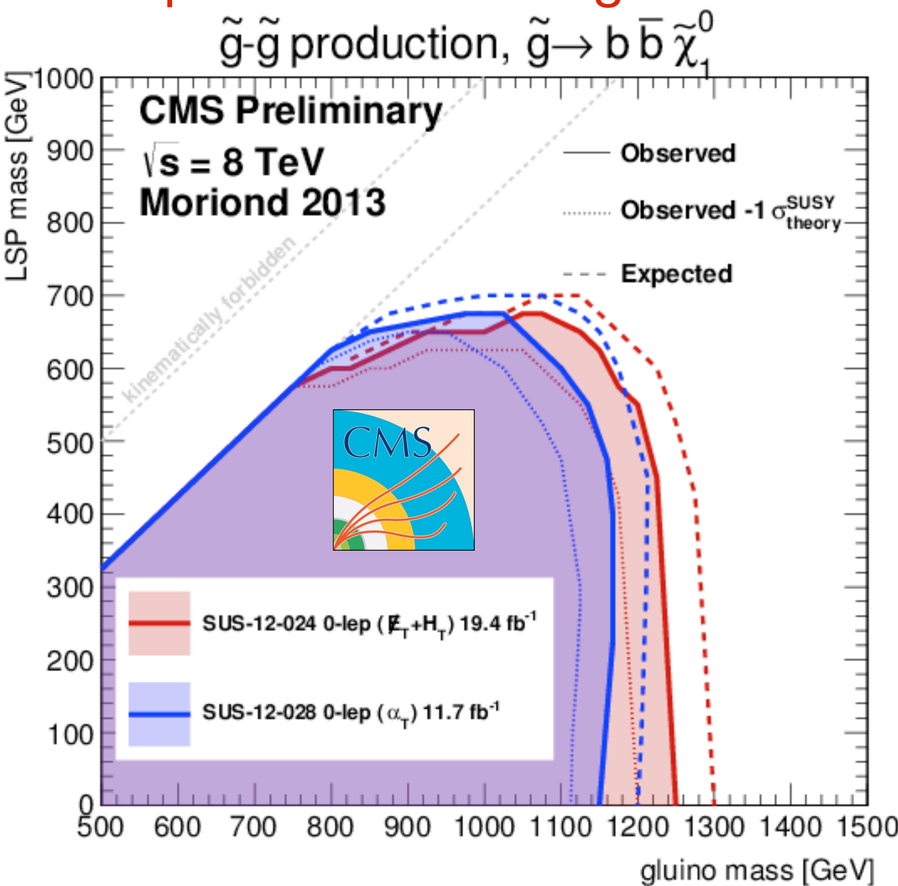
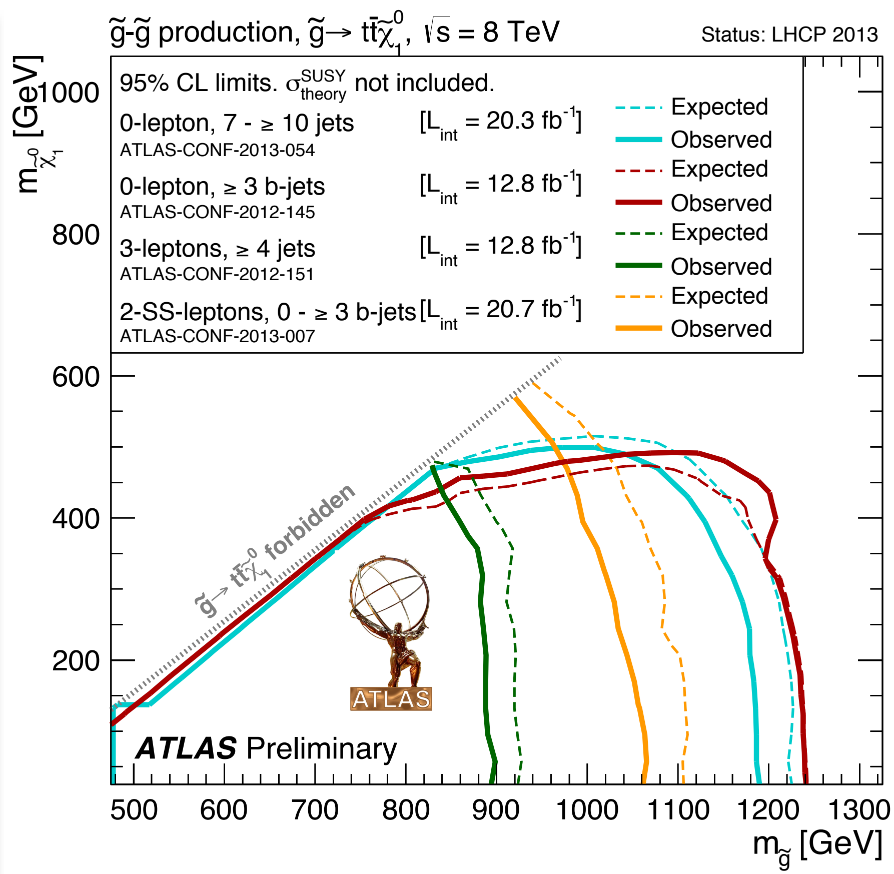


Gluino-Induced: Summary

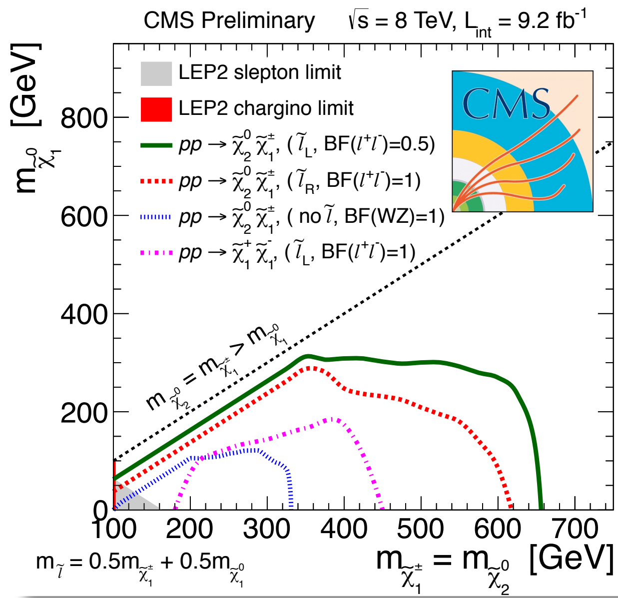
- Summary of current gluino-induced limits on sbottoms and stops
  - Pretty much reached the kinematic limit of ~1.3 TeV on gluino production for large fraction of the parameter space

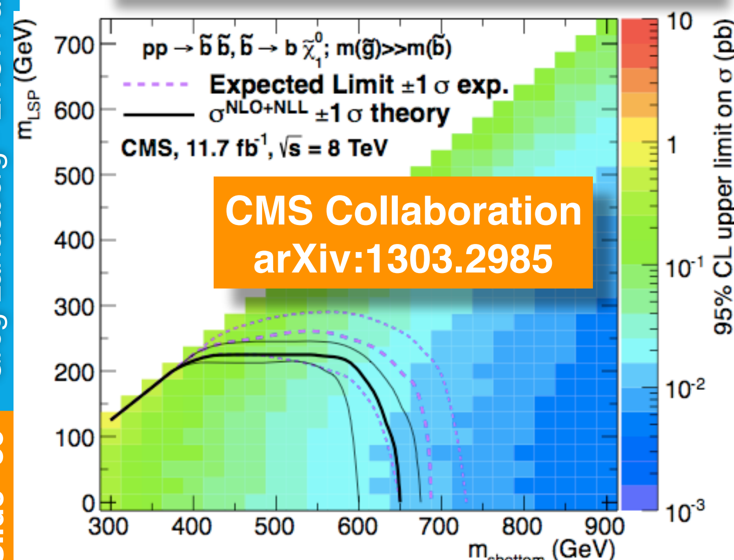


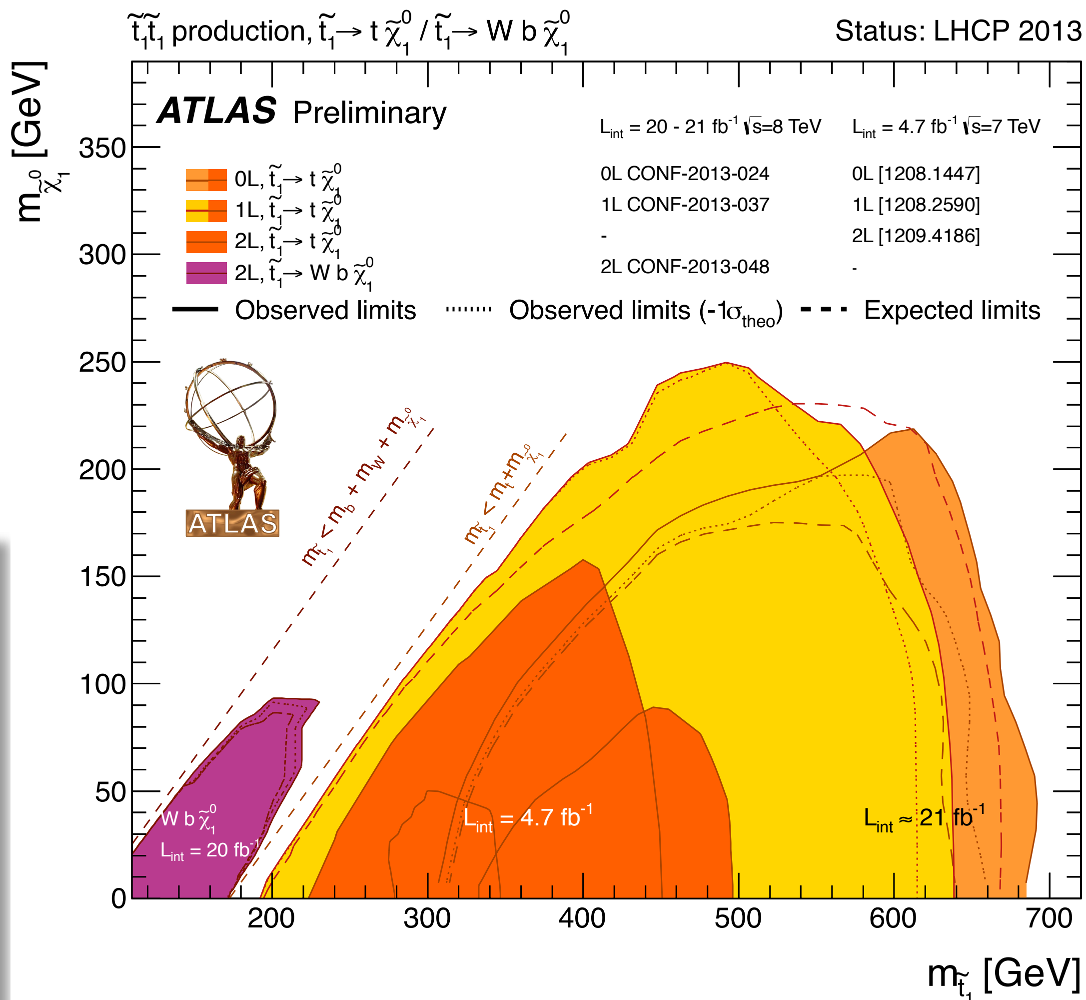


Greg Landsberg - LHC: Past, Present & Future - Strings 2013, Seoul

Direct EW/Sbottom/Stop Production







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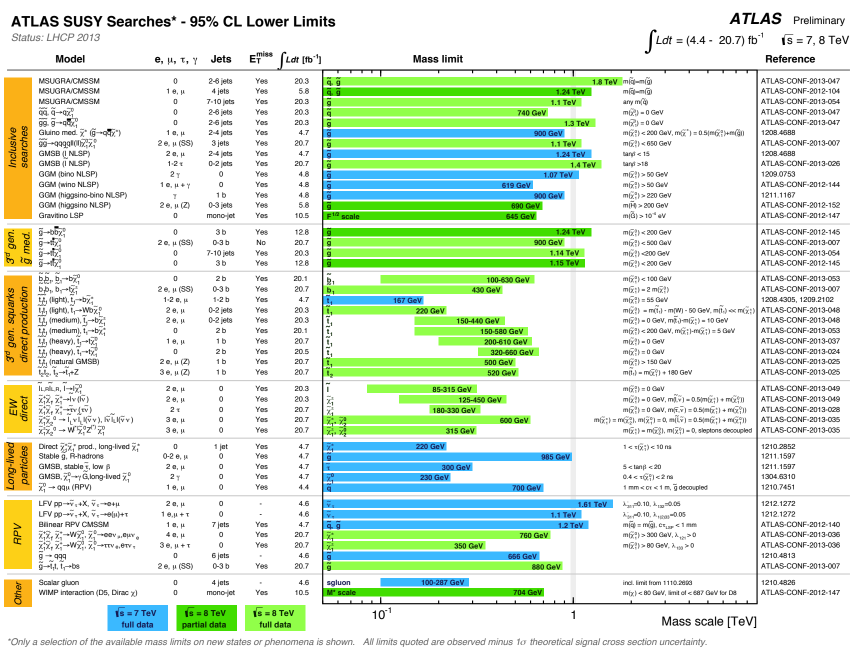
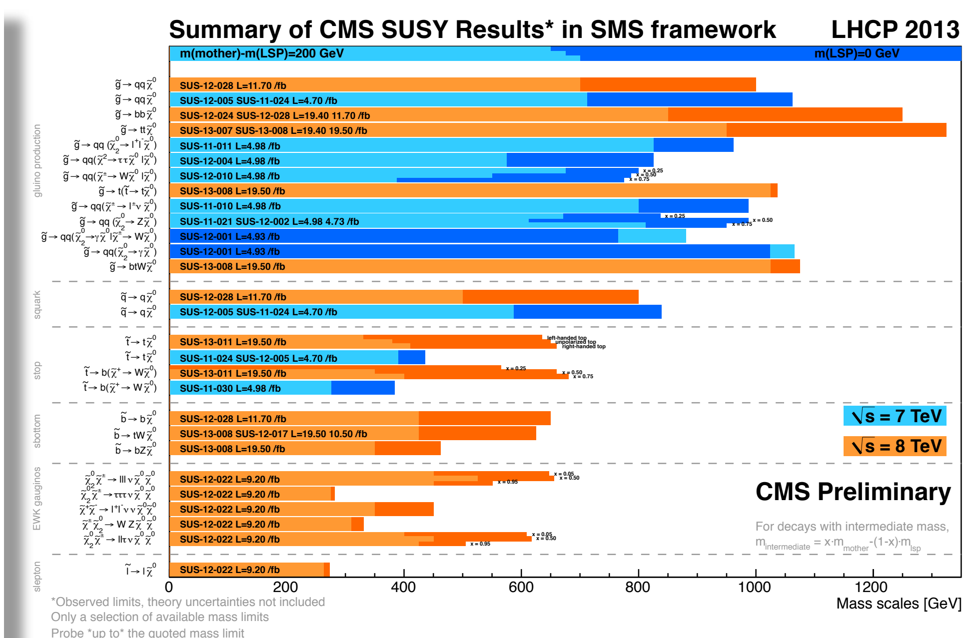
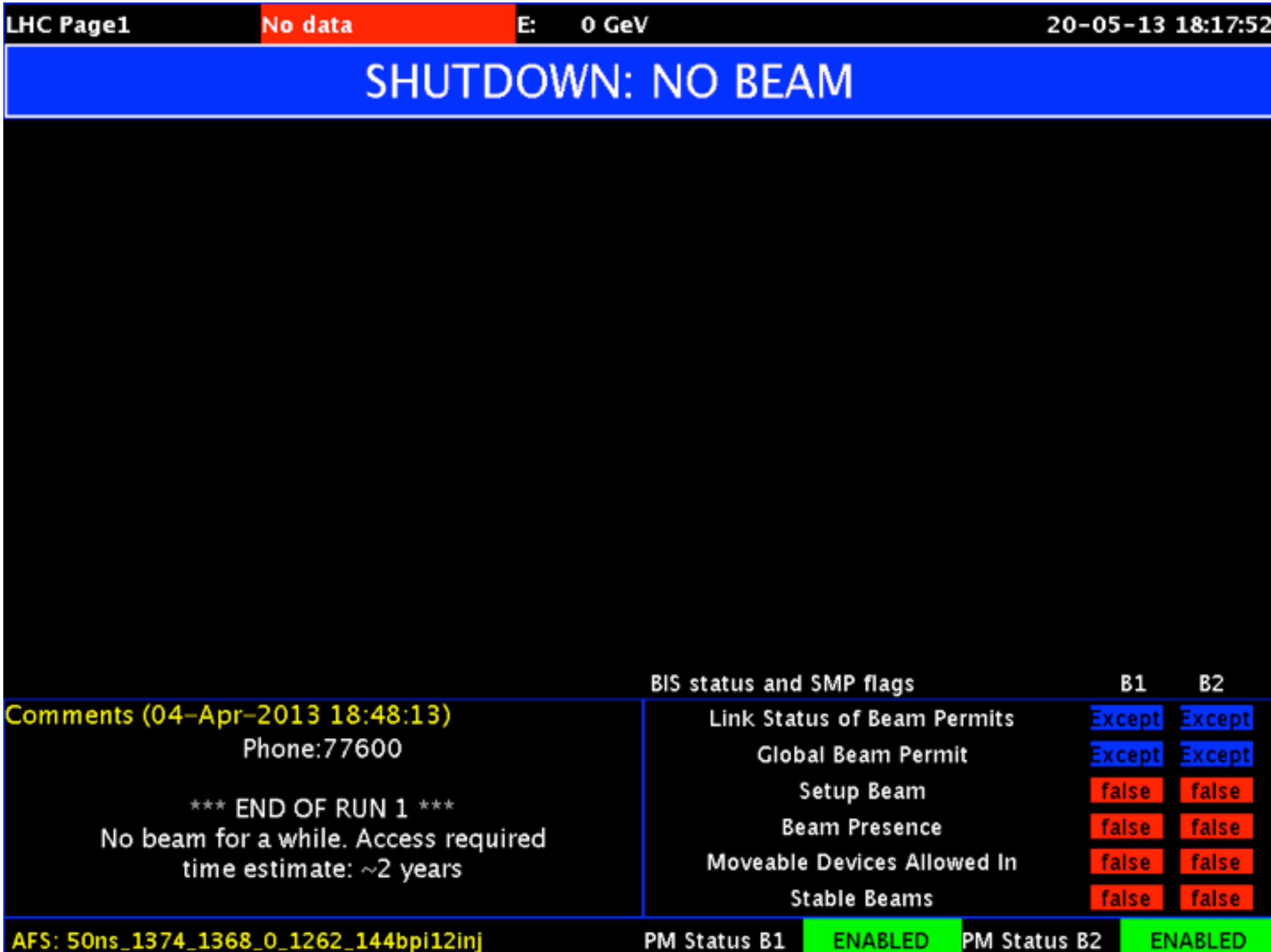
SUSY Grand Summary

- Closing in on the “natural” SUSY, but may be just short the reach
- Can we either find natural new physics or rule out naturalness as the guiding light to our quest for the origin of EWSB, dark matter, etc.?
- Very important to continue the quest for naturalness in SUSY and other BSM theories, which requires to explore the full energy potential of the LHC
- What would it take?





Long Shutdown One



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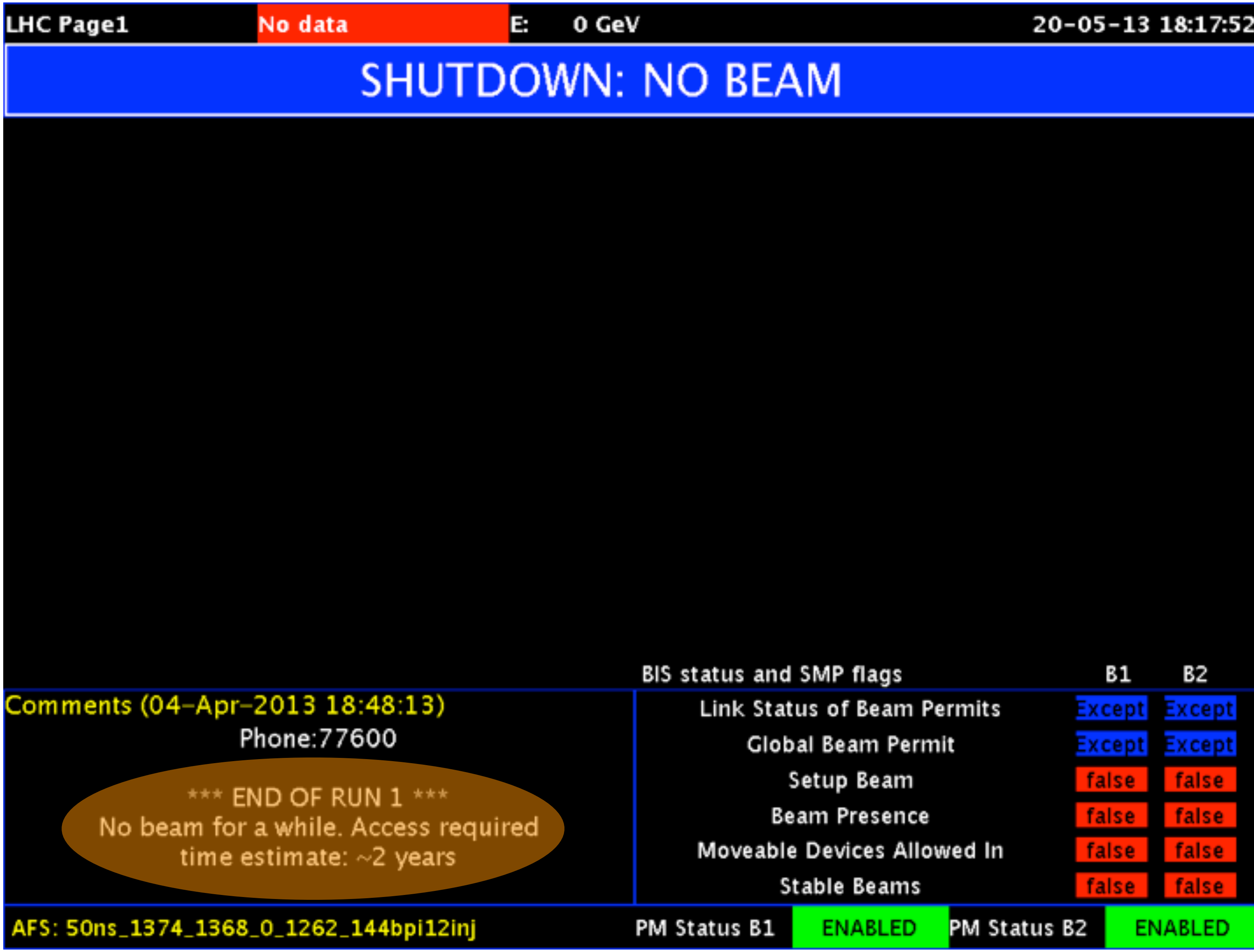

LS1 Consolidations

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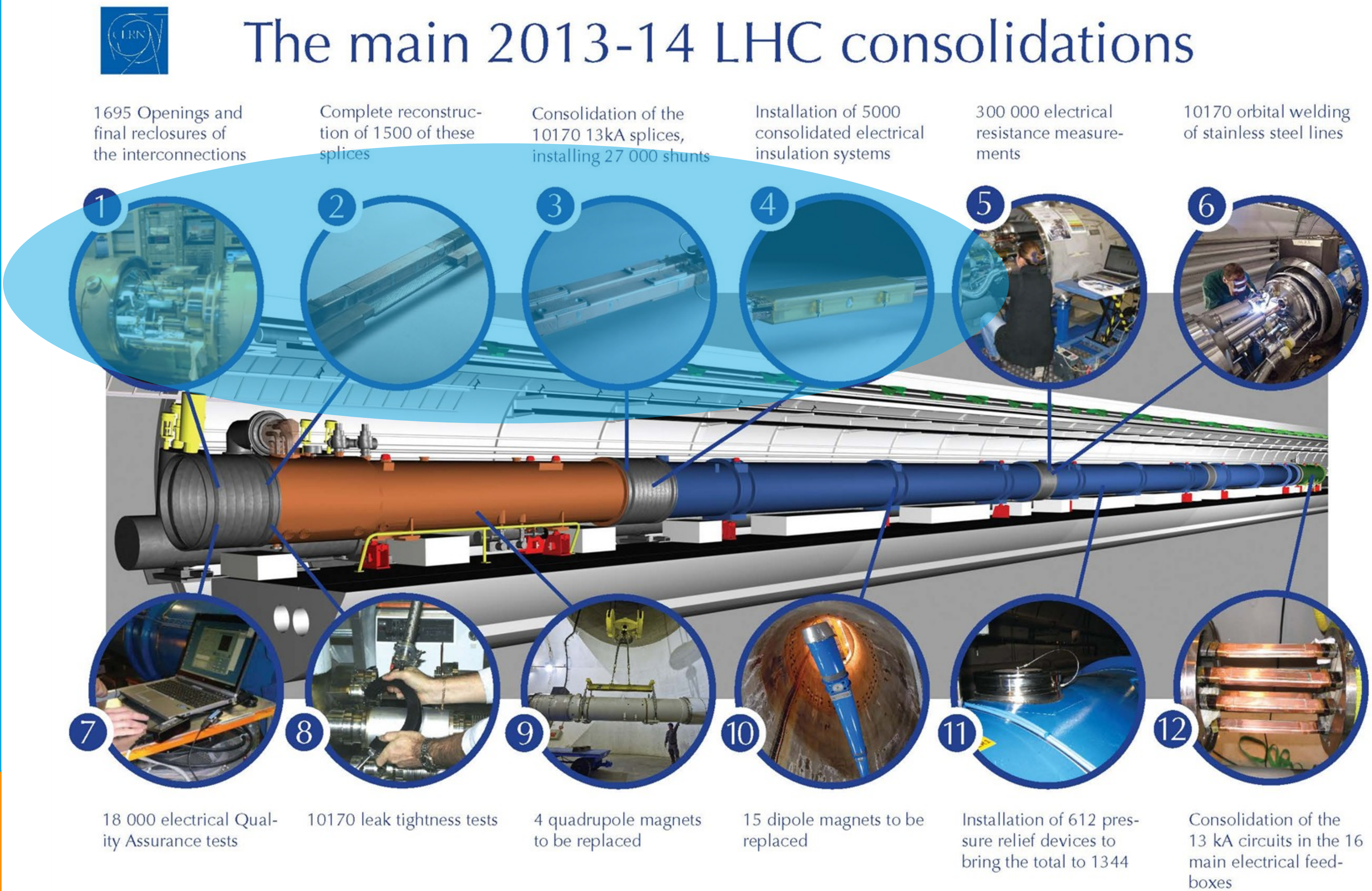
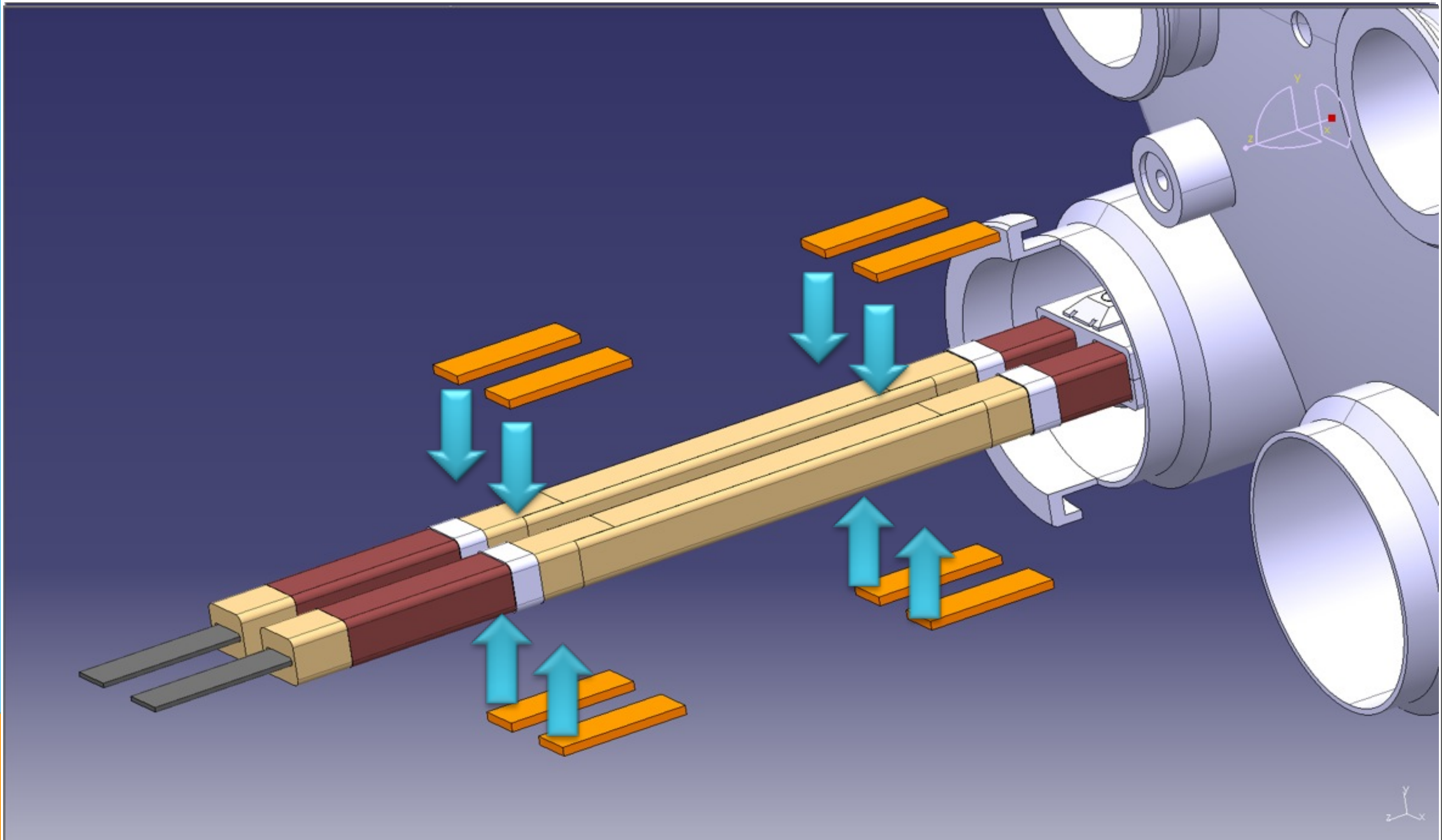
LS1 Consolidations



LHC Dipole Interconnects

✦ Welding, shunting, installation of spacer and shield



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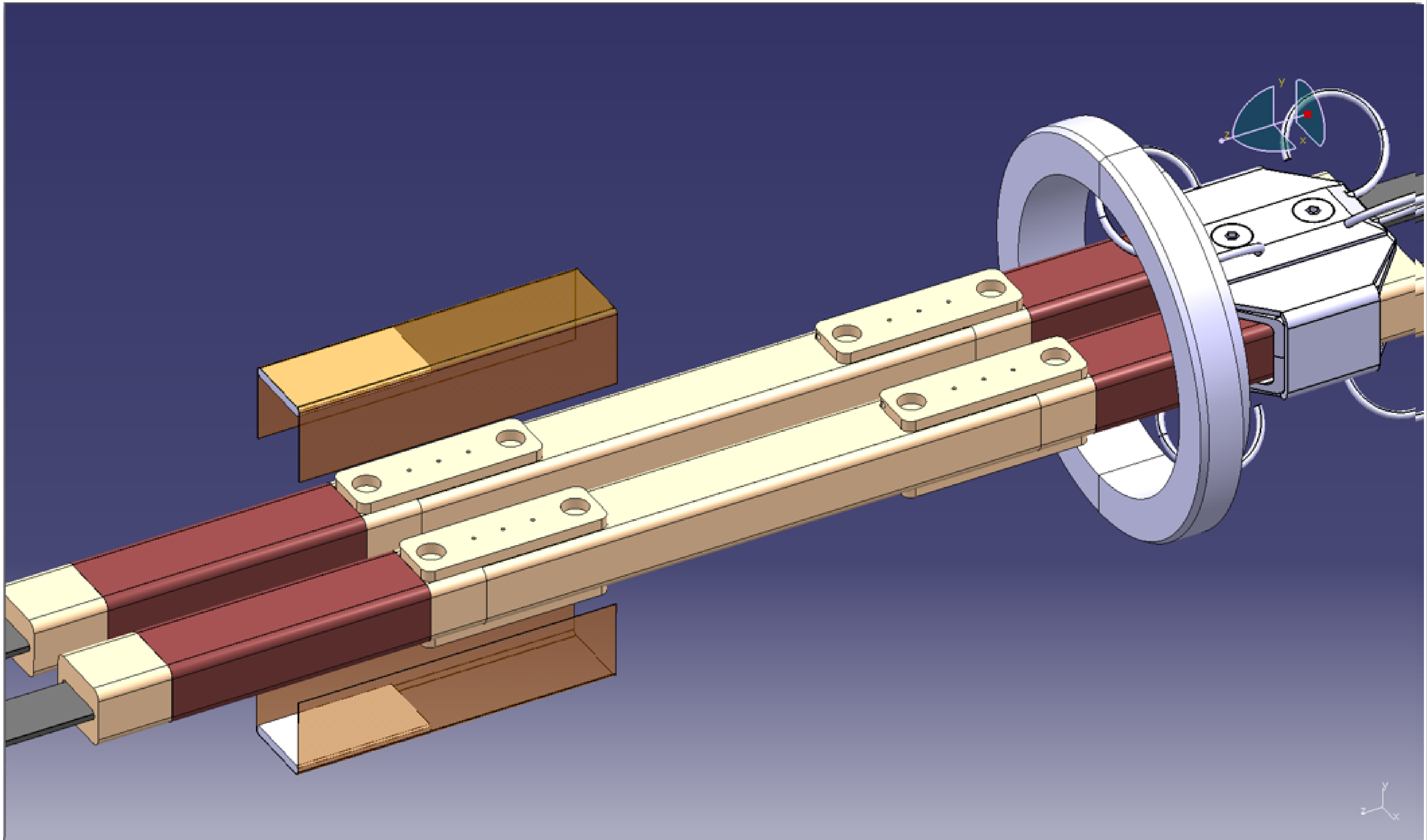

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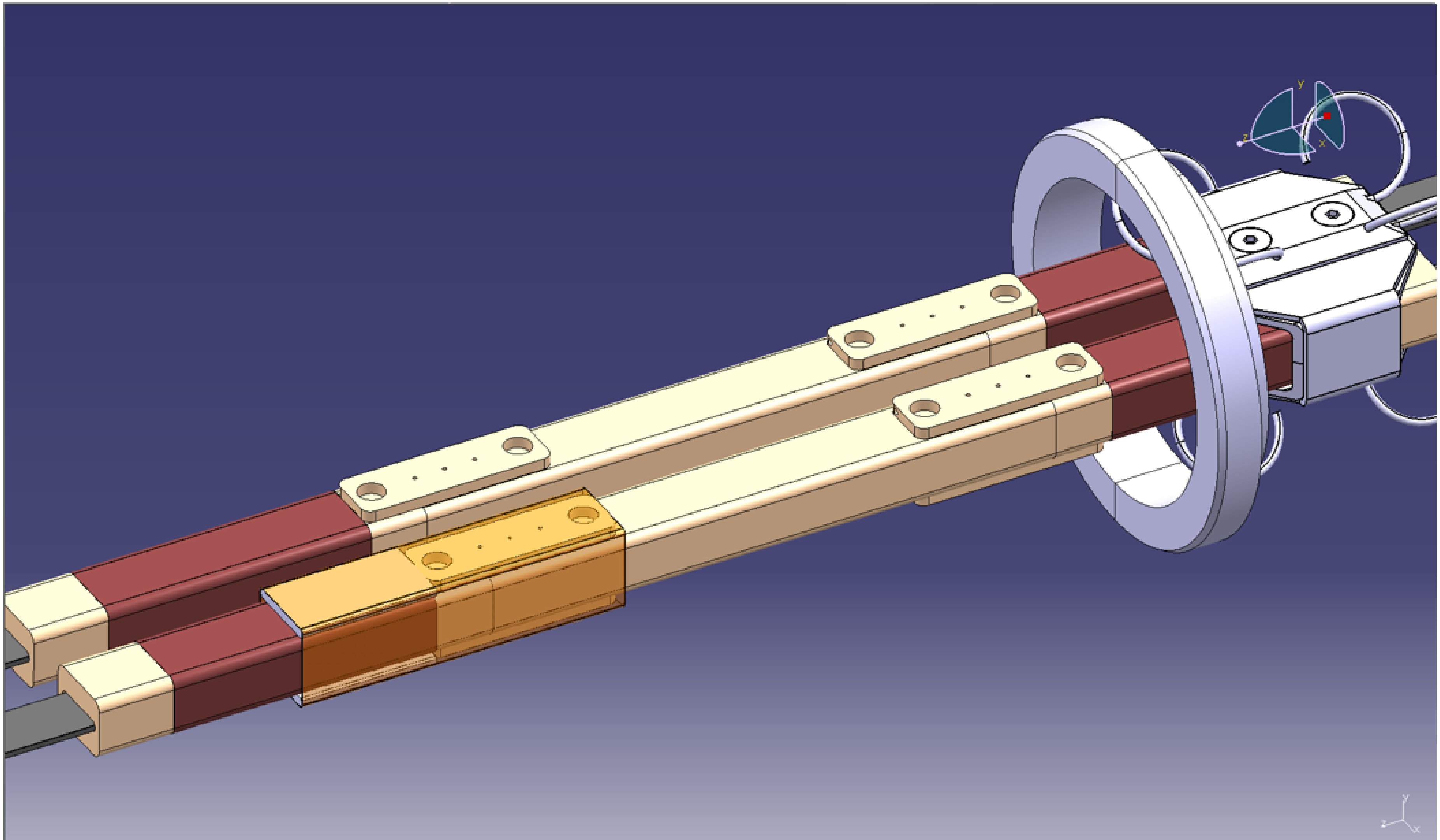

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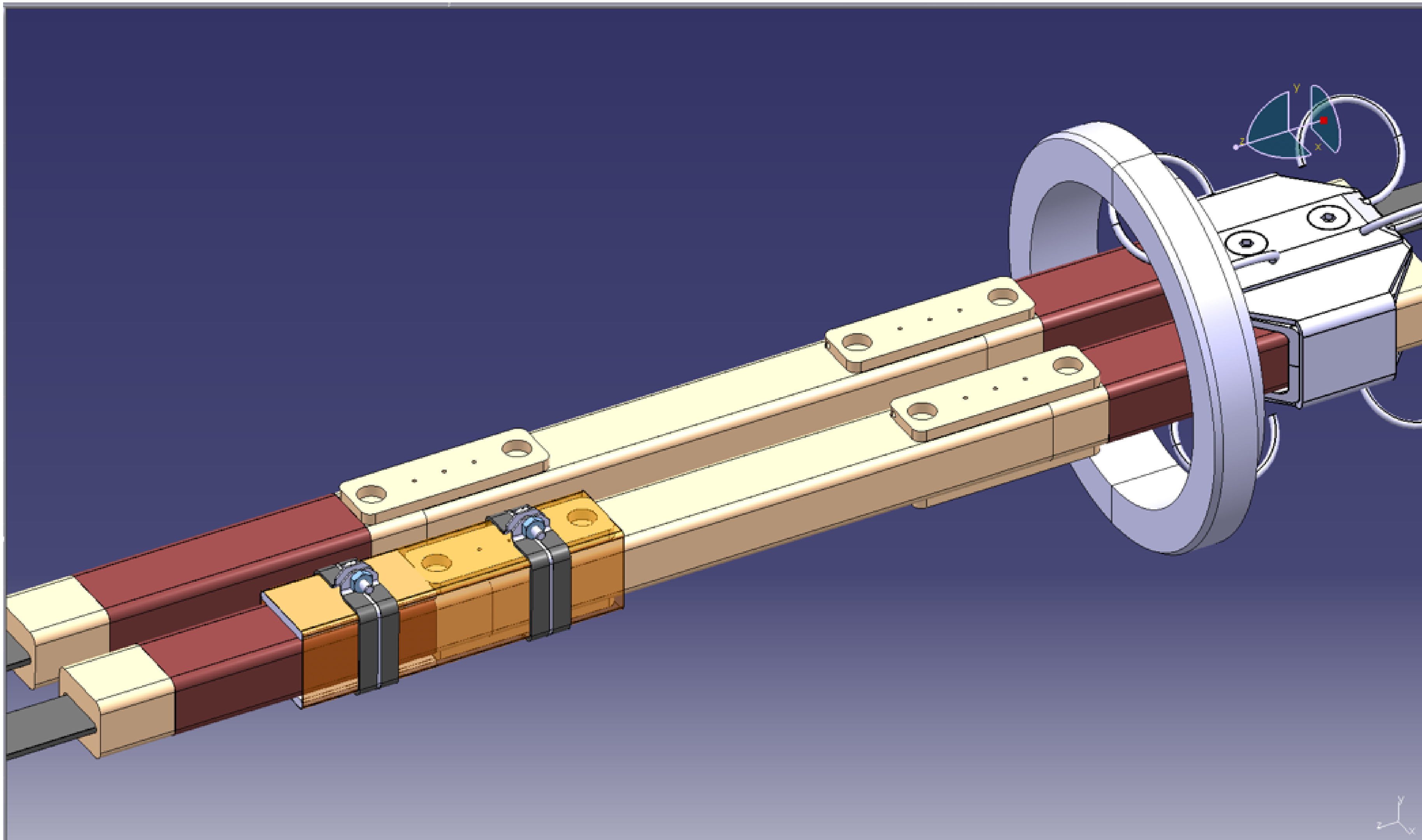

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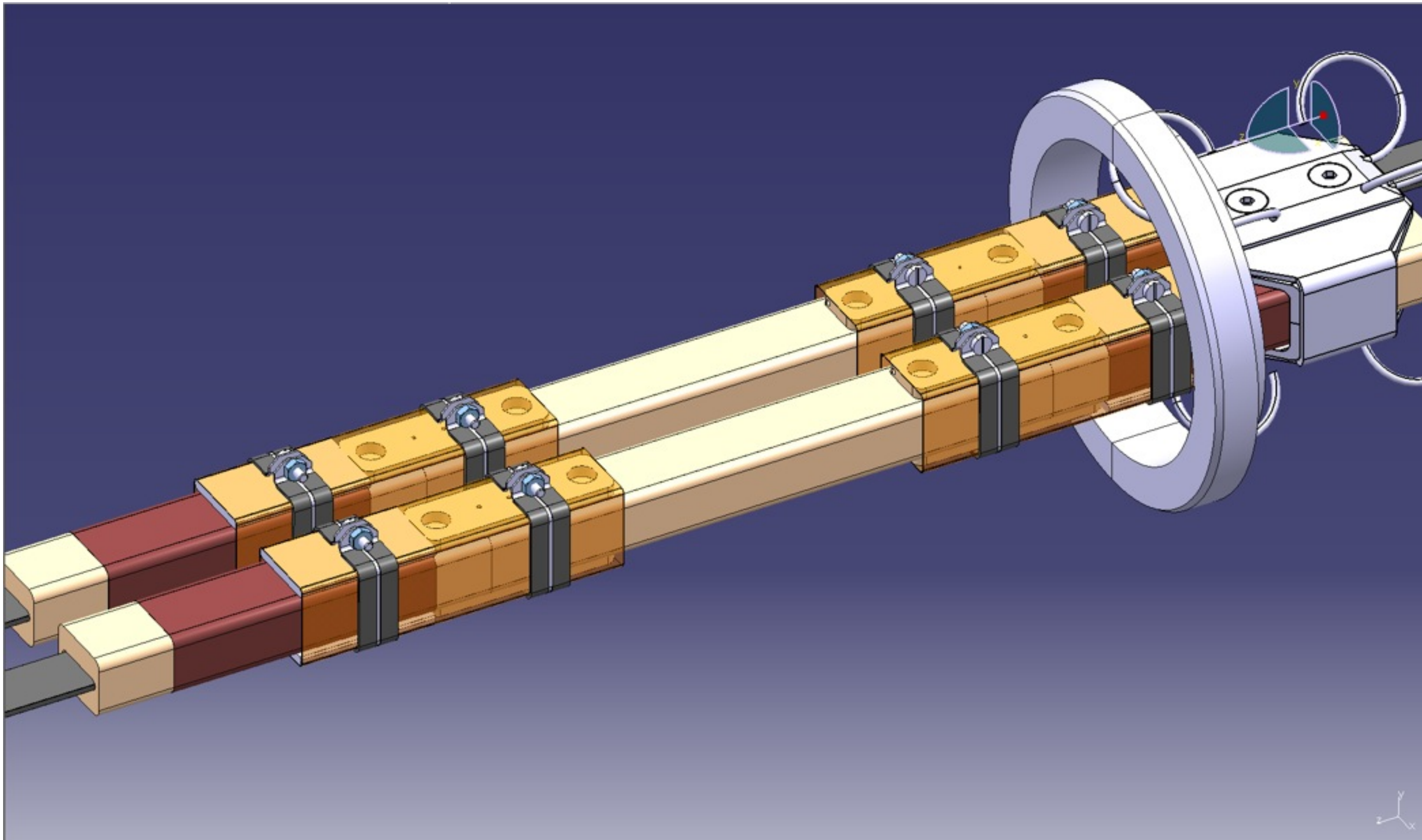

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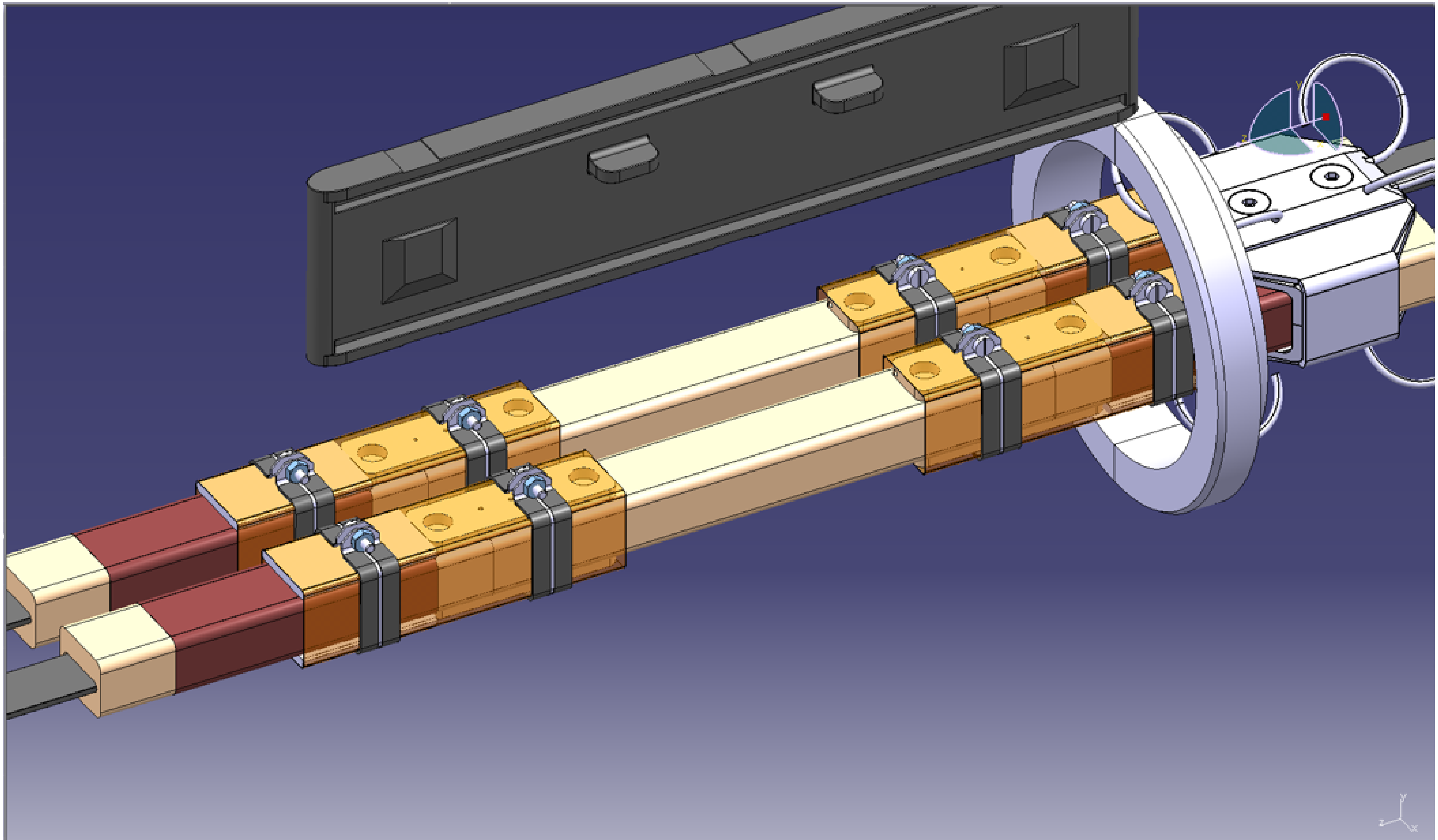

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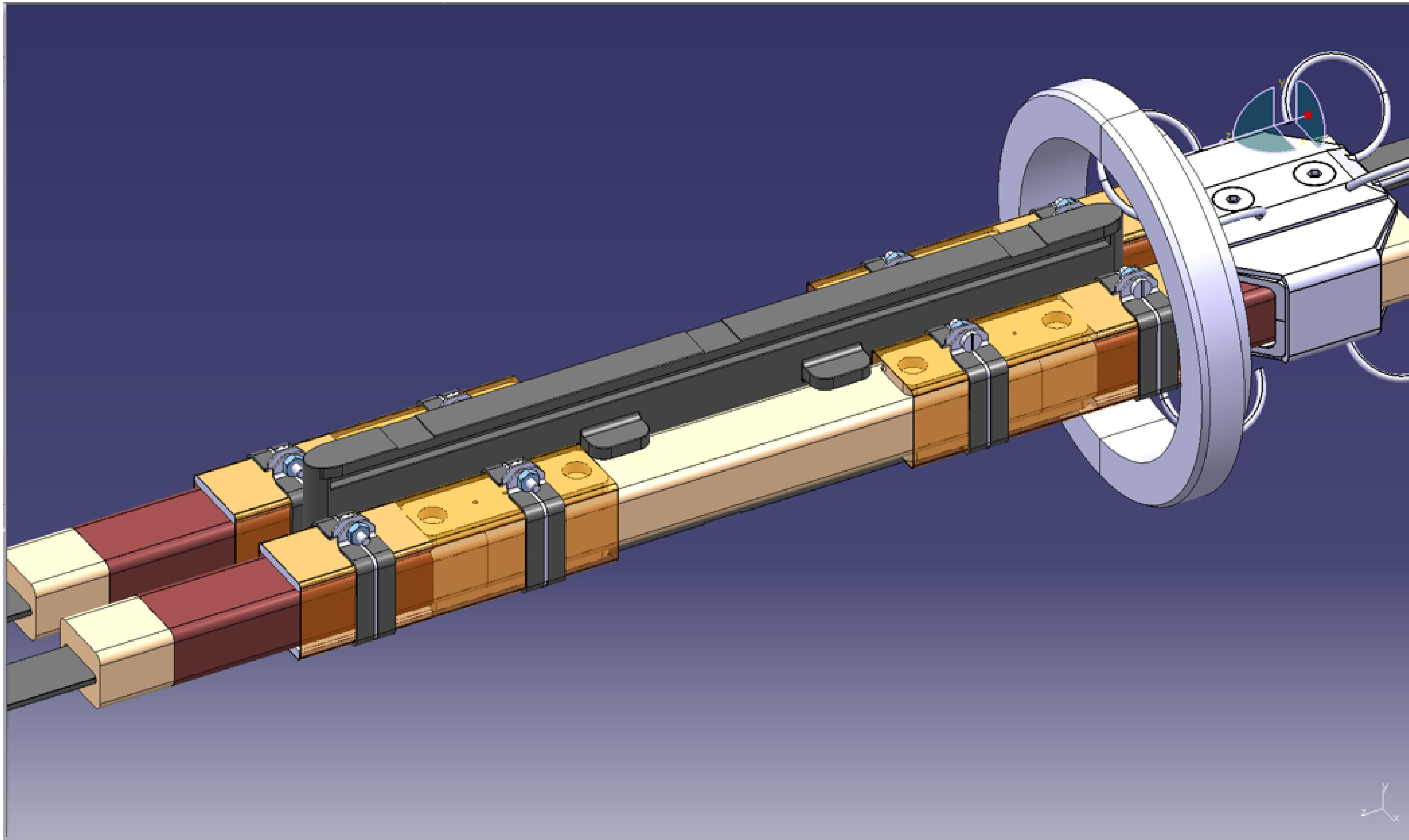

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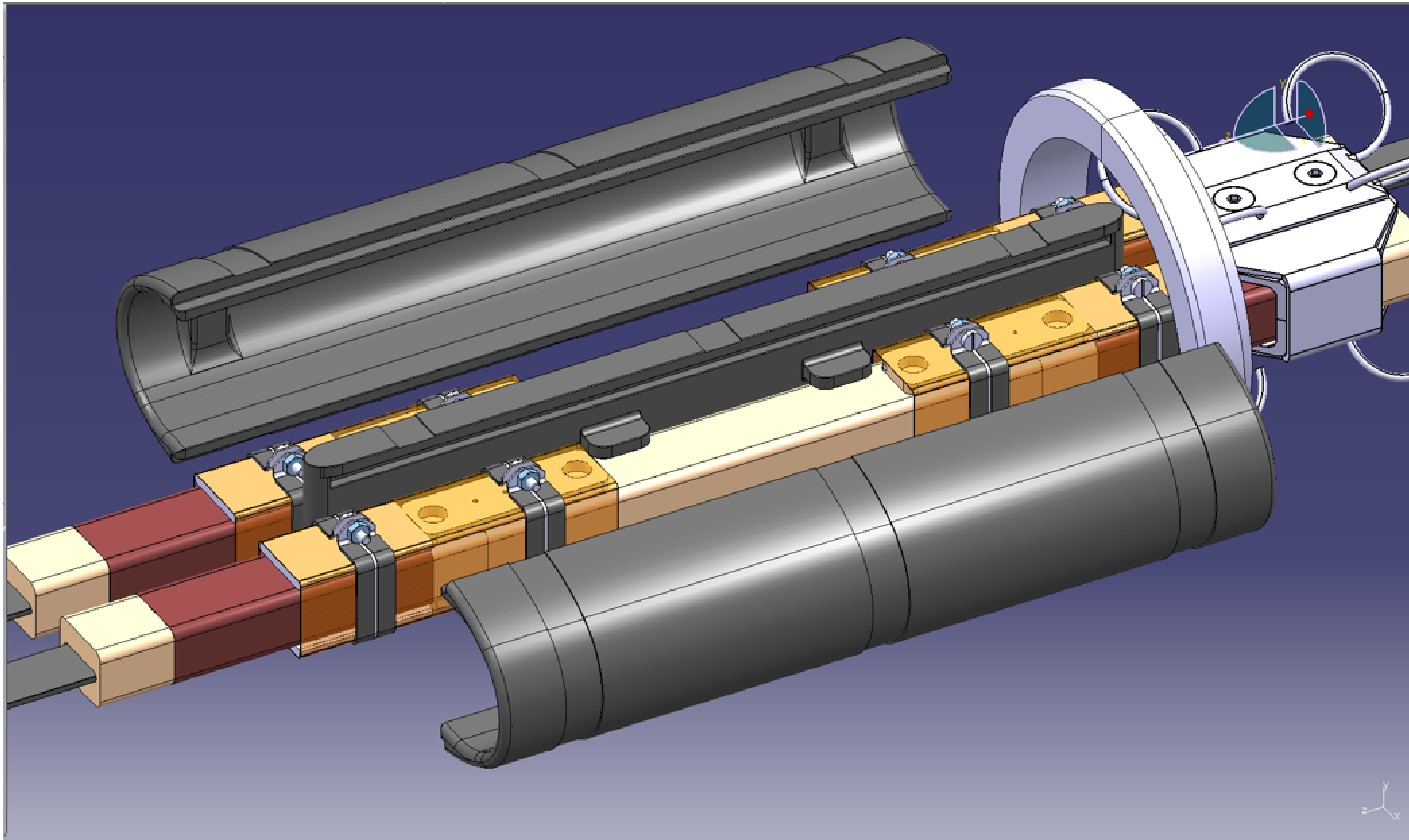

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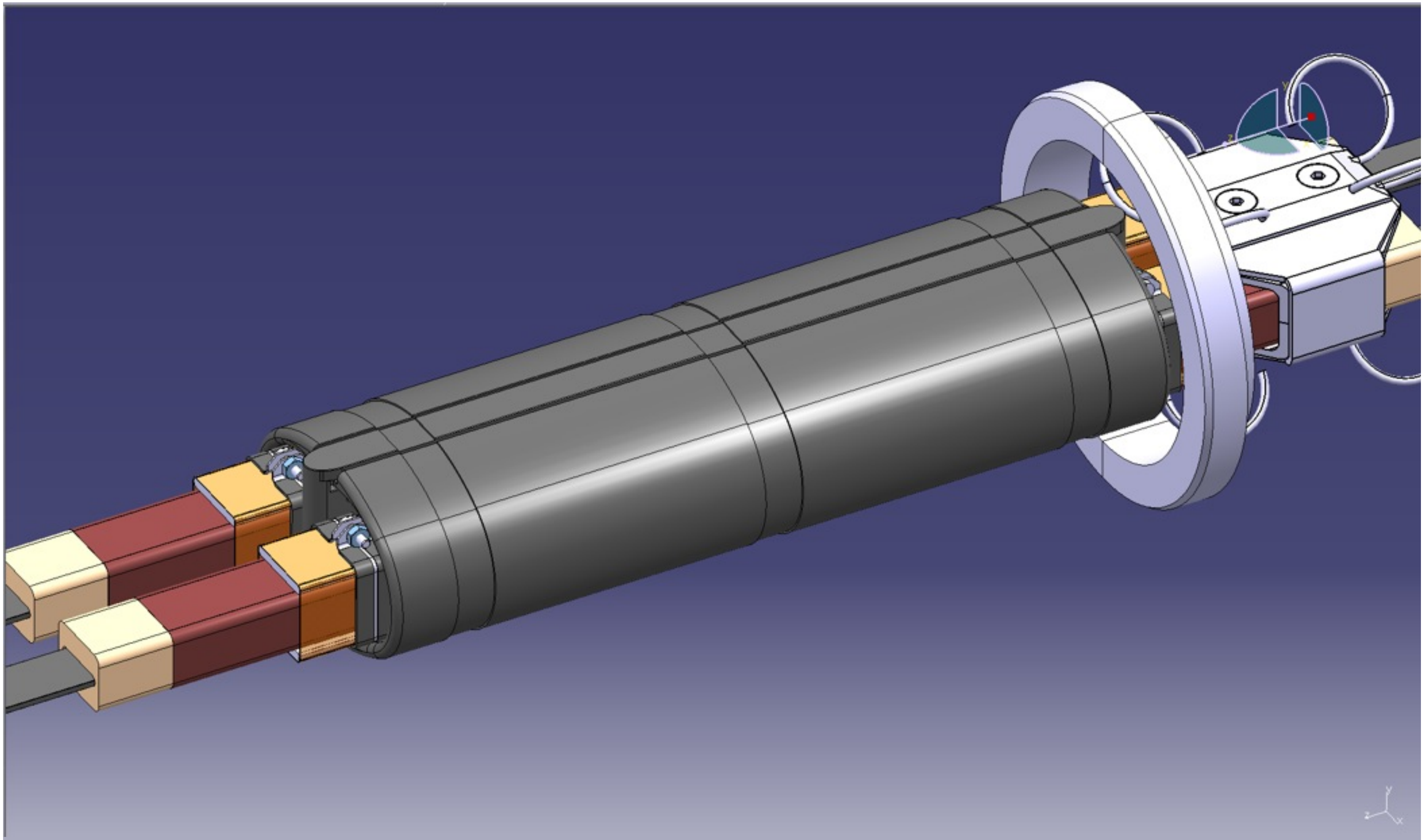

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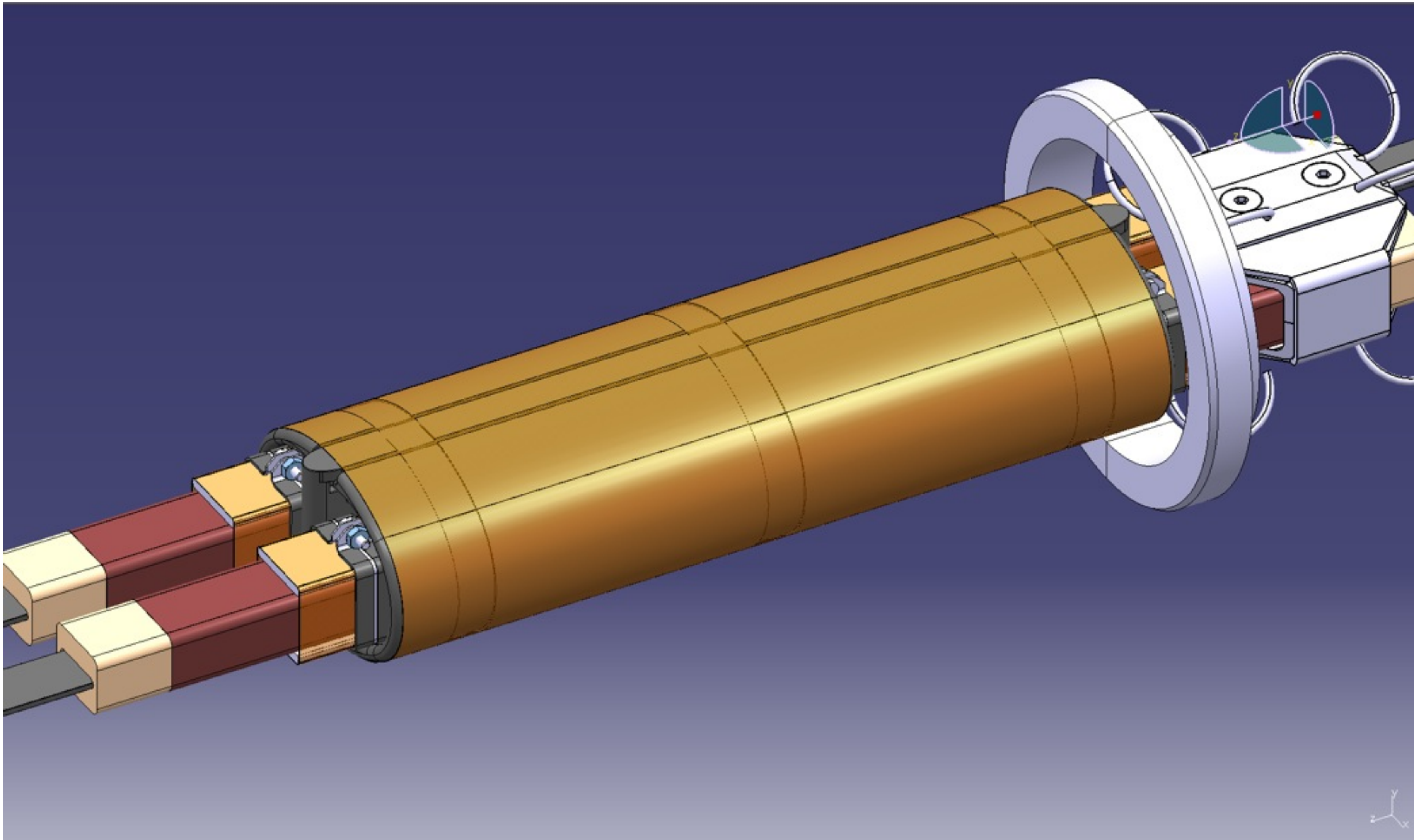

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The Ten-Year Plan

	J	F	M	A	M	J	J	A	S	O	N	D
2011		1	2	3	4	5	6	7	8	9	IONS	
2012			1	2	3	4	5	6	7	8	9	
2013	IONS	IONS	LS1 - SPLICE CONSOLIDATION									
2014												
2015	RECOM	RECOM	RAMP-UP	1	2	SCRUB 25 ns	3	4	5	6	IONS	
2016		RAMP-UP	1	2					7	8	IONS	
2017		RAMP-UP	1	2	3	4	5	6	7	8	IONS	
2018	LS2 (LIU UPGRADE: LINAC4, BOOSTER, PS, SP											
2019	RECOM	RECOM	RAMP-UP	1	2	3	4	5	6	7	IONS	
2020		RAMP-UP								8	IONS	
2021		RAMP-UP	1	2	3	4	5	6	7	8	IONS	
2022	HL-LHC UPGRADE											

LS1

PHYSICS AT 6.5/7 TeV

LS2 – Injector upgrade

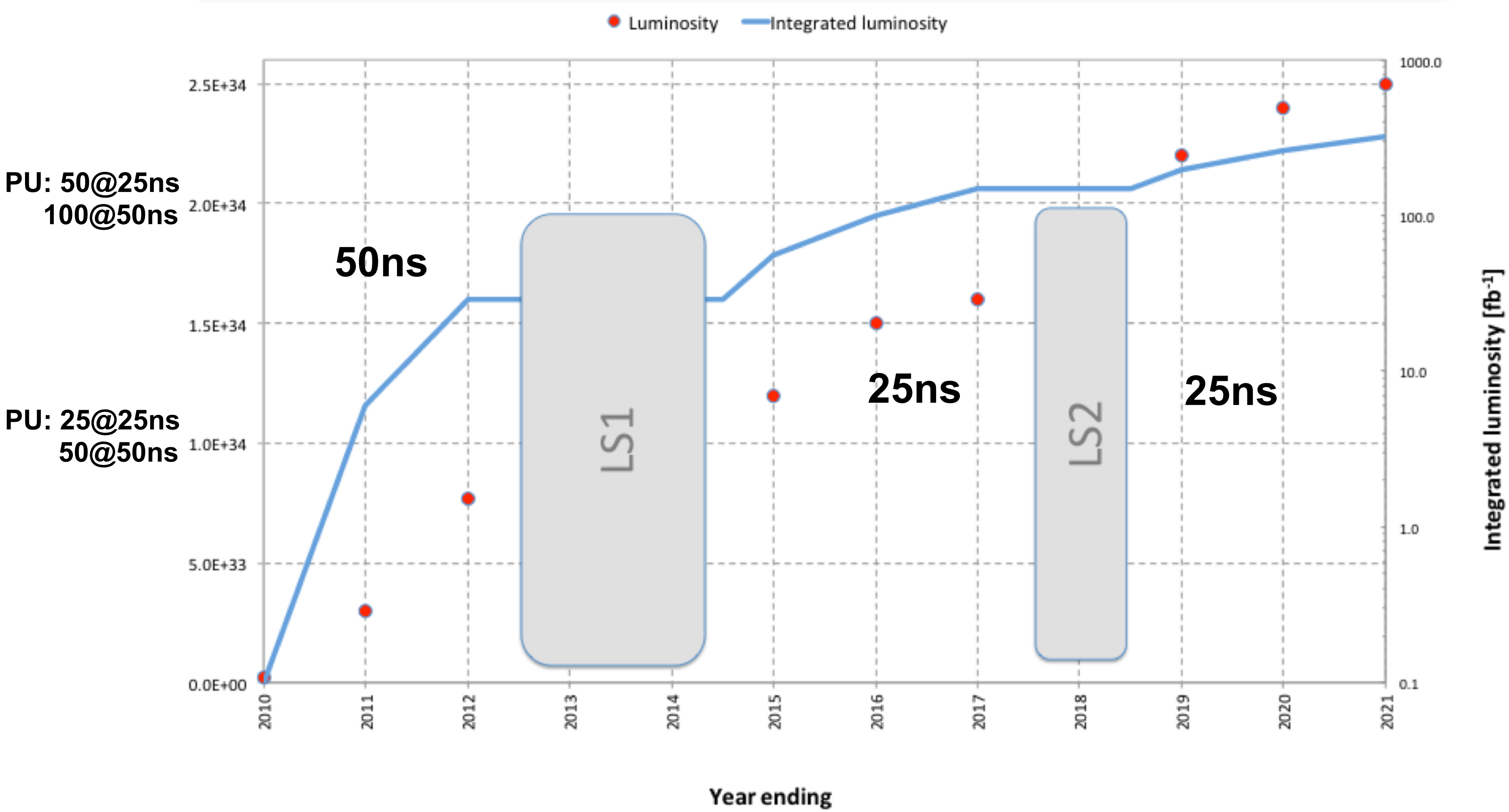
“ULTIMATE” PHYSICS (~2.4 x 10^{34} $cm^{-2}s^{-1}$)

LS3 – HL-LHC upgrade

- Technical stop or shutdown
- Proton physics
- Ion Physics
- Recommissioning
- Intensity ramp-up

Luminosity vs. Time

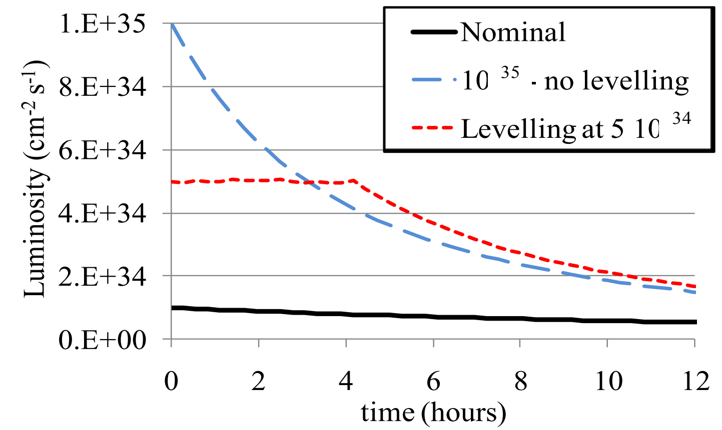
From Mike Lamont, CMS Upgrade Workshop, January 17, 2013



- 2013-2022: 300-400/fb by 2022
- 2023-2033: HL-LHC upgrade with leveling at ~5x10^{34} cm^{-2}s^{-1}?

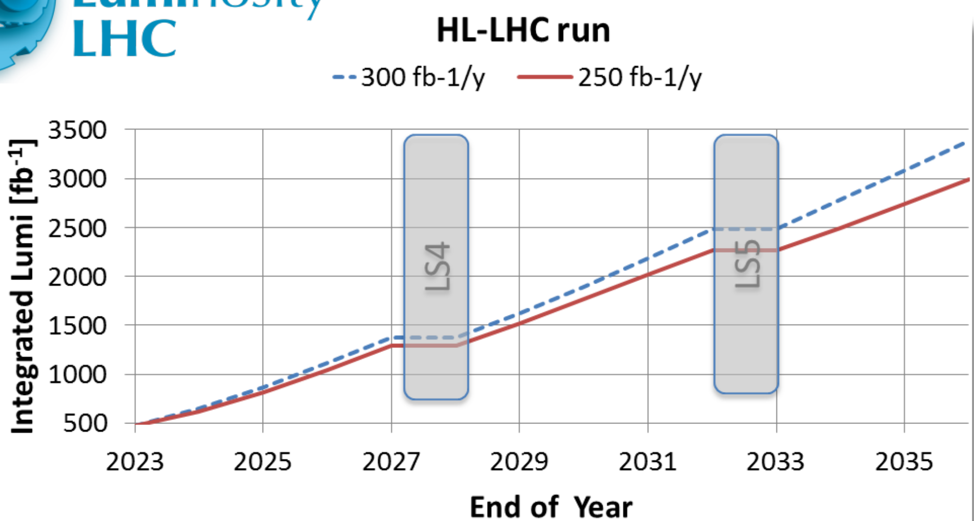
HL-LHC: Need for an Upgrade

- By 2022, several machine elements will need to be replaced, including triplets
- In addition, the LHC luminosity will saturate by then and doubling time becomes too long
- Detectors will suffer significant radiation damage
- Time to upgrade to reach $L = 10^{35}$ $cm^{-2}s^{-1}$ (but run with the luminosity leveling at $5x10^{34}$ $cm^{-2}s^{-1}$)



Parameter	Nom. 25 ns	Target 25 ns	Target 50 ns
N_b [10^{11}]	1.15	2.0	**3.3**
n_b	2808	2808	1404
I [A]	0.56	**1.02**	0.84
θc [μrad]	300	475	445
β* [m]	0.55	**0.15**	**0.15**
ε_n [μm]	3.75	**2.5**	**2.0**
ε_s [eV s]	2.5	2.5	2.5
IBS h [h]	111	25	**17**
IBS l[h]	65	21	**16**
Piwinski	0.68	2.5	2.5
F red.fact.	0.81	0.37	0.37
b-b/IP[10^{-3}]	3.1	3.9	**5**
L_{peak}	1	7.4	8.4
Crabbing	no	**yes**	**yes**
$L_{peak\ virtual}$	1	20	22.7
Pileup $L_{lev}=5L_0$	19	95	190
Eff.† 150 days	=	0.62	0.61

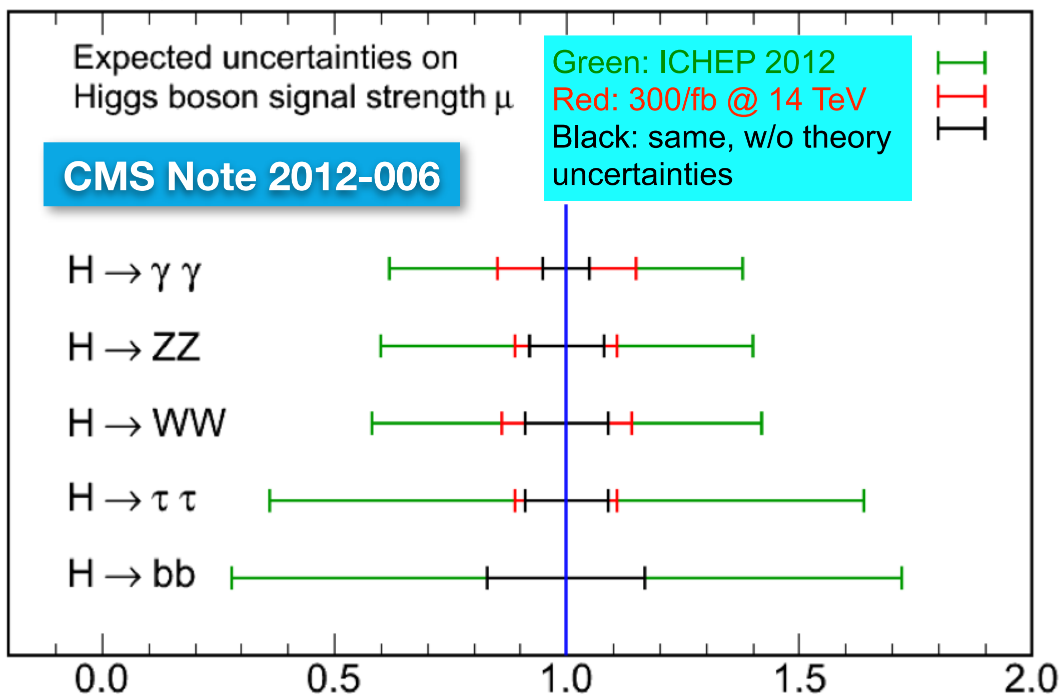
baseline

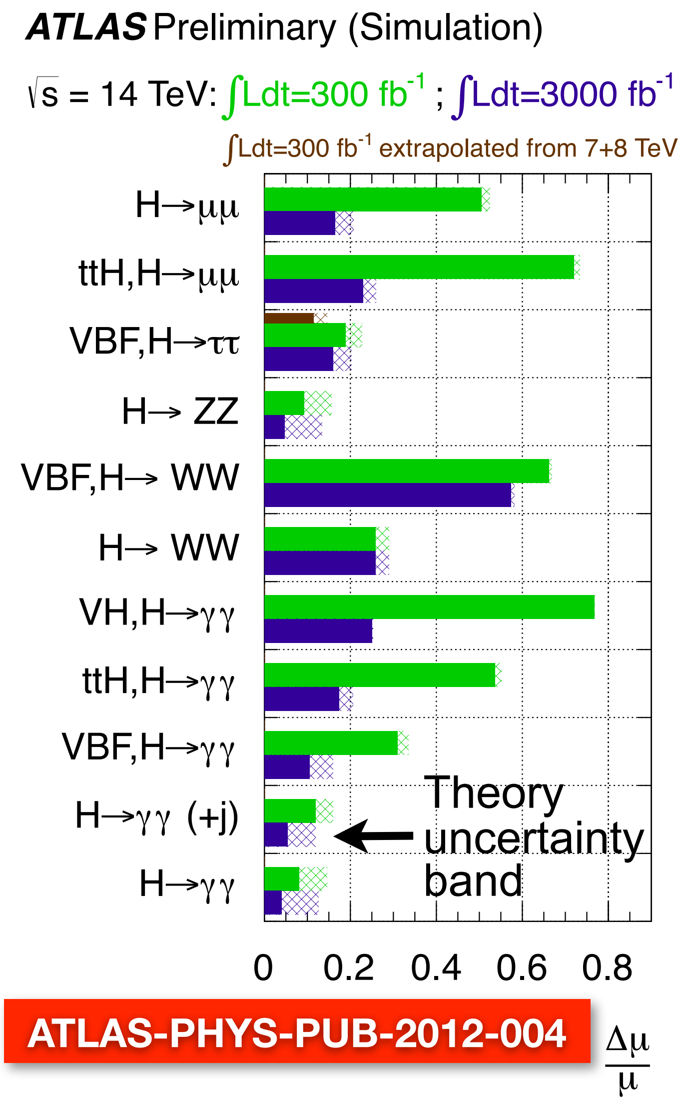


Higgs Signal Strength

- 15% precision has been already achieved in the combination
- 10-15% precision per channel is achievable w/ 300/fb
  - Effect of theory uncertainties is mostly important in the H(γγ) and H(ZZ) channels

CMS Projection





Couplings: Where are we Now?

- 2013: couplings consistent with the SM within 1σ
  - Typical uncertainty: 15% (κ_V) – 40% (κ_F)
- Crucial to improve this precision to ~5% level or better
  - Many BSM Higgs scenarios predict coupling modification at that level

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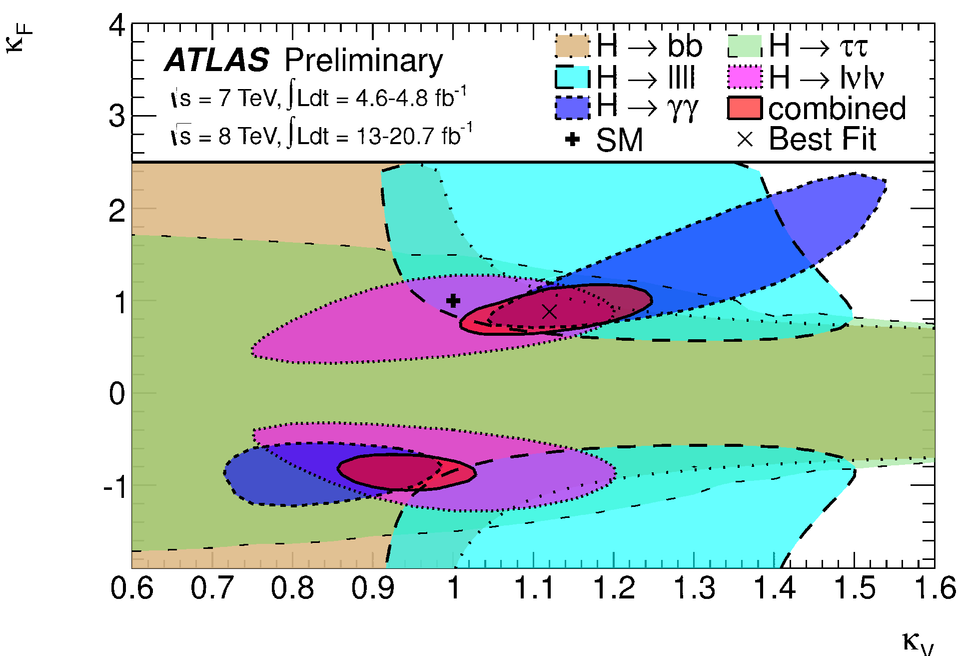
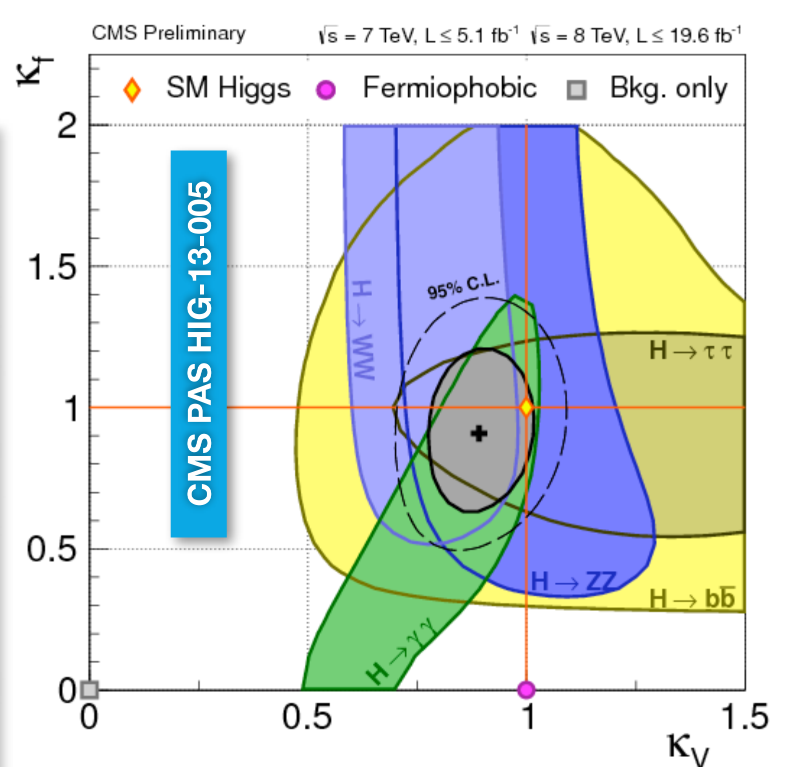
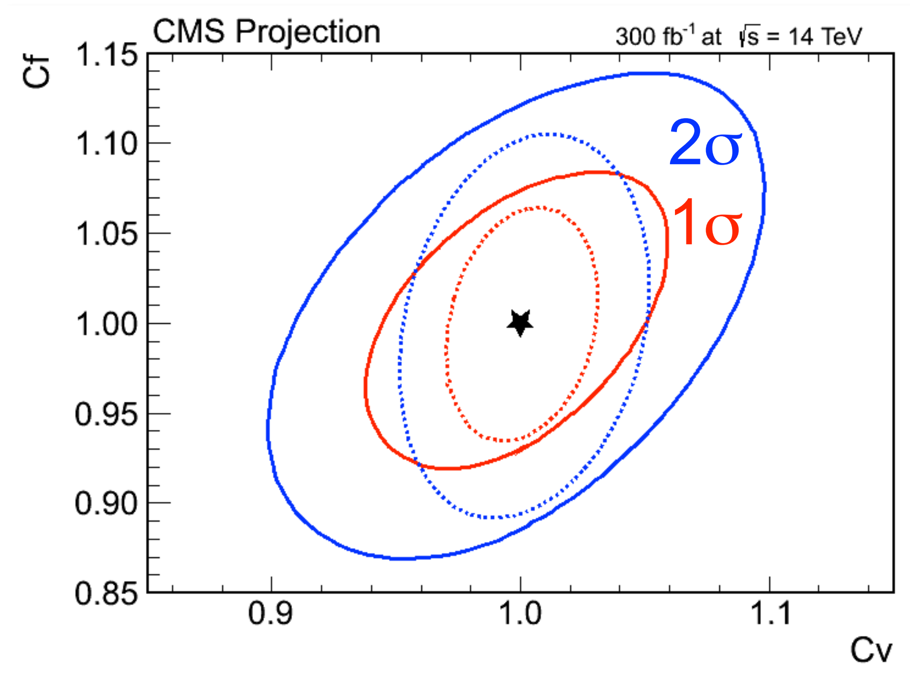


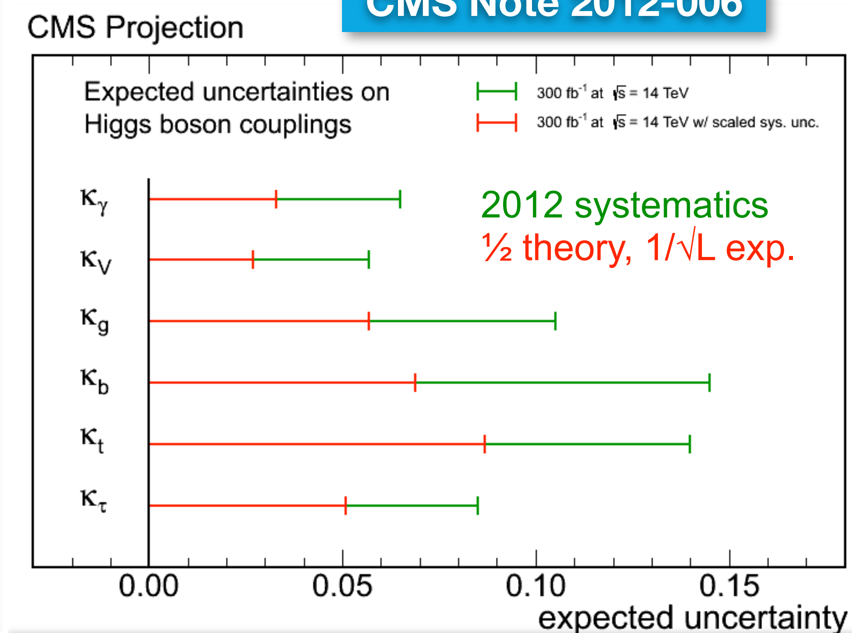


Couplings at the LHC-14

- Projections up to ~300/fb (~2022) are reasonably straightforward
- Two scenarios considered in CMS:
  - Scenario 1: same systematics as in 2012 - pessimistic
  - Scenario 2: theory systematics are halved; the rest scale as $1/\sqrt{L}$ – somewhat optimistic



CMS Note 2012-006



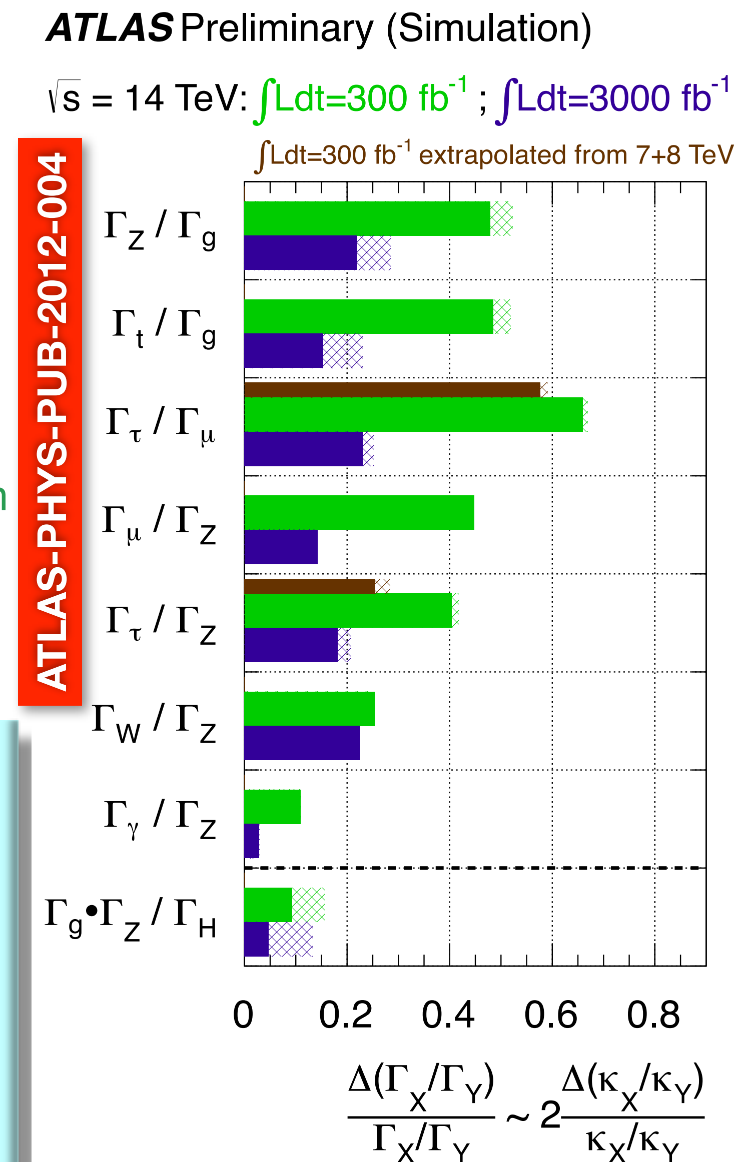
Solid: nominal; dashed: no theory systematics

Couplings: Beyond 300 fb^{-1}

- Projections further out are subject of large uncertainties
  - The exact detector configurations & even the technology are not quite known yet
  - The running conditions have not been defined yet
  - Theoretical progress in the next decade is hard to gauge
- Still, in an optimistic "Scenario 2" the HL-LHC would allow to do precision Higgs physics with individual couplings measured up to 1-3% precision
- Also: searches for exotic/invisible Higgs decay as a window on new physics

CMS Note 2012-006

Coupling	Uncertainty (%) 300 fb^{-1} Scenario 1	300 fb^{-1} Scenario 2	3000 fb^{-1} Scenario 1	3000 fb^{-1} Scenario 2
κ_γ	6.5	5.1	5.4	1.5
κ_V	5.7	2.7	4.5	1.0
κ_g	11	5.7	7.5	2.7
κ_b	15	6.9	11	2.7
κ_t	14	8.7	8.0	3.9
κ_τ	8.5	5.1	5.4	2.0



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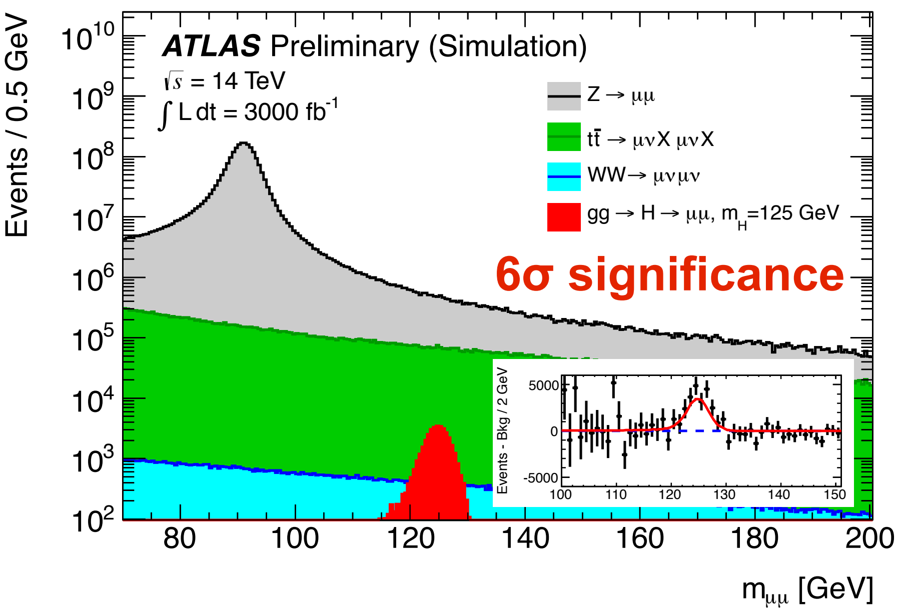
Beyond 300 fb^{-1}: More

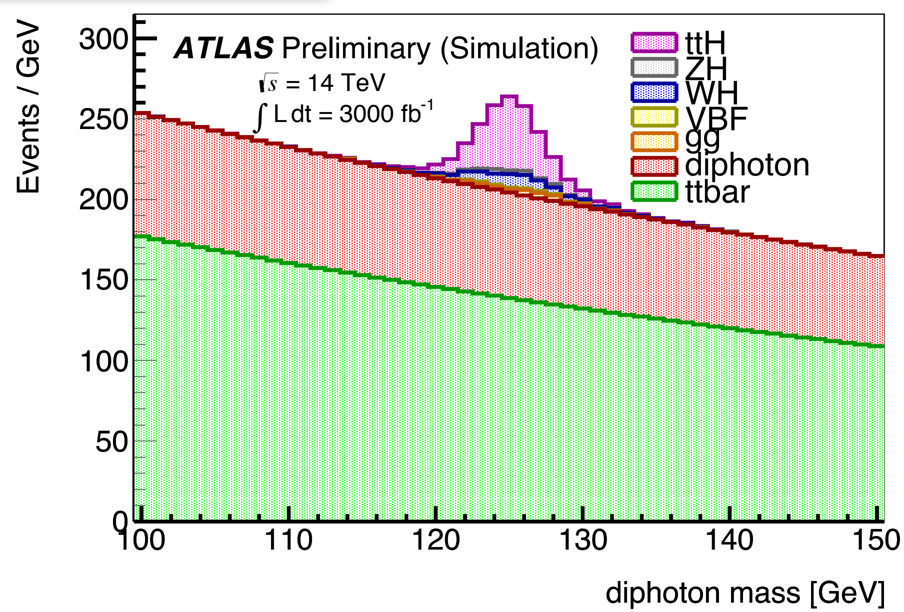
- Need to go significantly beyond 300 fb^{-1} to study Higgs couplings to the muons and top quarks
  - Muon is the second-generation fermion: are the Higgs couplings flavor-universal?
    - Muons offer a possibly unique measurement (charm tagging is hard!)
  - Are couplings to the up- and down-type quarks have the same structure?

$H \rightarrow \mu\mu$

ATLAS-PHYS-PUB-2012-004

$t\bar{t}H(\gamma\gamma)$





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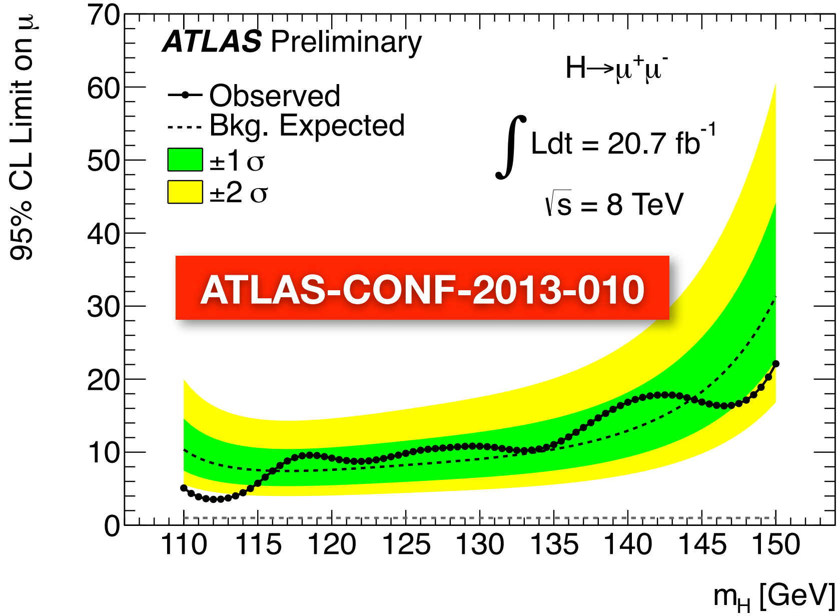
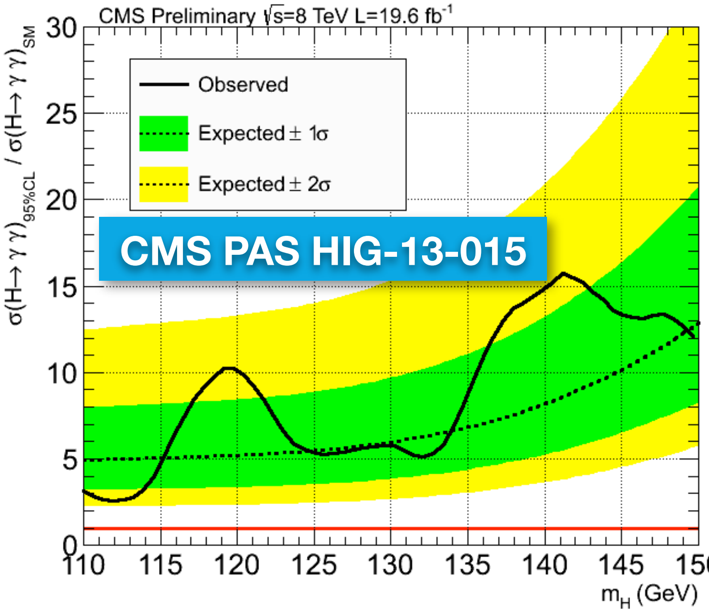
First 8 TeV studies are already under way!

$H \rightarrow \mu\mu$



$ttH(\gamma\gamma)$



Strong Case for the HL-LHC

- There are unique measurements, which require to go far beyond 300 fb^{-1}:
  - Establishing H($\mu\mu$) decay at >5σ significance and measurement of the H$\mu\mu$ coupling to ~15% level
  - Measurement of the Higgs self-coupling (cross section for HH production is only 33 fb @ 14 TeV)
  - Observing how the VV scattering amplitudes unitarize in the presence of the Higgs boson
    - Are there other s-channel resonances involved?
- Higgs is not the only case for the HL-LHC
  - Finding massive new physics or ruling out broad class of "natural" new physics model and demonstrating that SM is fine tuned
  - Answering the major question if we have entered the "desert" and there are no new weakly or strongly interacting states below a few TeV
  - Probing higher energy scales via precision measurements

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SUSY beyond LHC-14

- If we find new physics (e.g., SUSY) at the LHC-14, we will need to measure masses and decay rates precisely to shed light on:
  - Gaugino mass unification
  - Squark/slepton unification
  - SUSY flavor and CP violation
  - Baryogenesis
  - Neutrinos and leptogenesis
  - String compactification
  - …
- If SUSY is not found at the LHC-14, how far should we push?
  - Important to test naturalness to the limit
  - Need to go up to ~1 TeV for stops and sbottoms
  - Also target chargino-neutralino pair production up to high masses
    - The latter is not possible at any of the foreseen e^+e^- colliders

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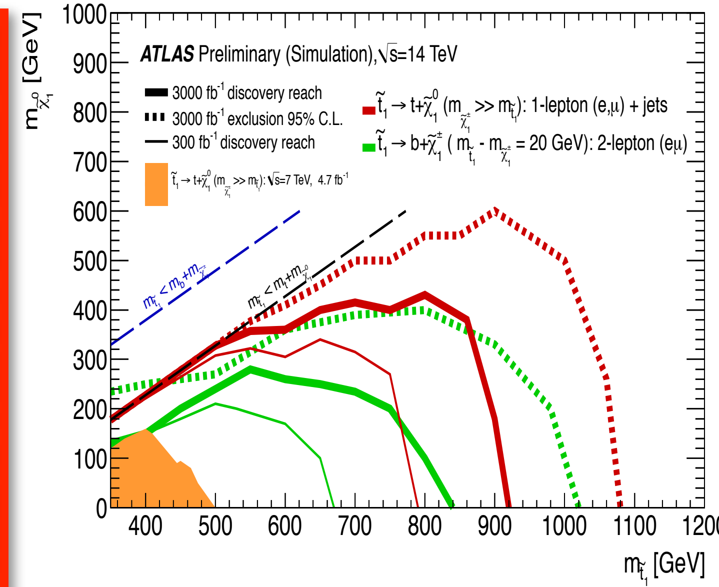
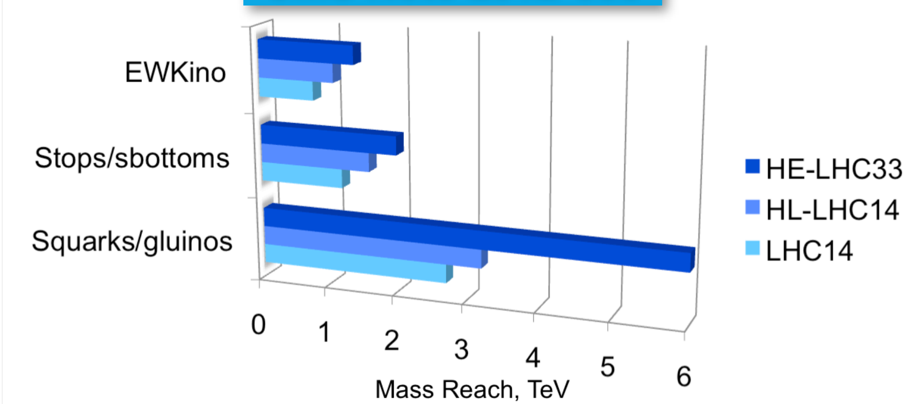


CMS Note 2012-006



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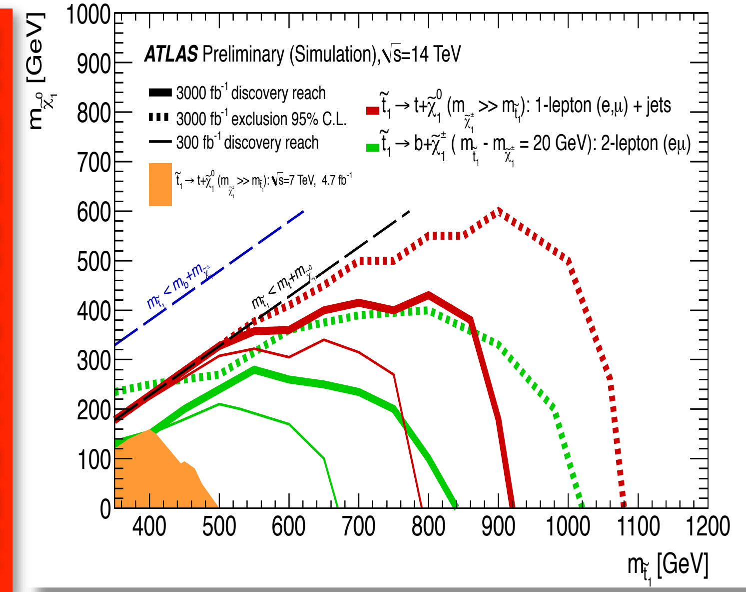

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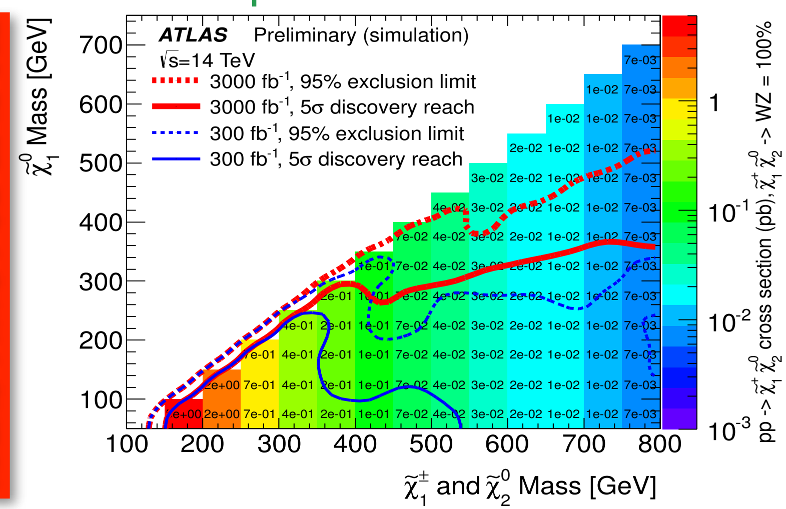

Greg Landsberg - LHC: Past, Present & Future - Strings 2013, Seoul

Conclusions

- The LHC is the most successful and amazing particle accelerator built so far
- The first three years of spectacular performance of the machine and the detectors brought in the first major discovery and a whole new program of precision measurements and searches
- The LHC is taking a short break till 2015 to come back at the ~13 TeV energy to explore the Terascale with a full potential
- Running beyond 2022 with much x10 higher integrated luminosity (HL-LHC) will be needed for detailed studies of the Higgs sector and any new physics to be found beforehand
- The LHC is a very young machine, and it has a 20+ year long exciting program ahead, which is what we need to fully explore the properties and the consequences of the new particle the LHC has delivered so far!

감사합니다 !