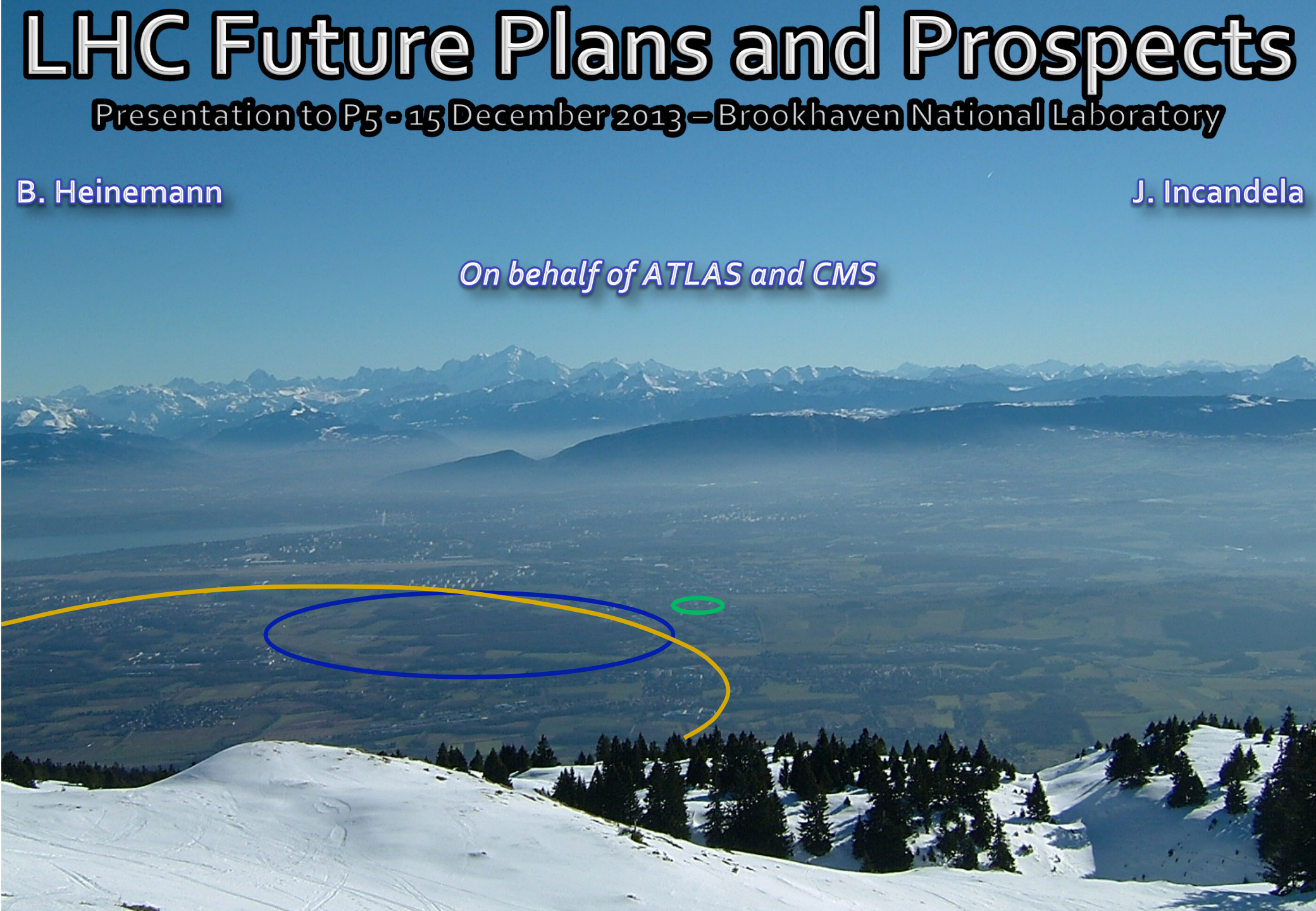
LHC Future Plans and Prospects

Presentation to P5 - 15 December 2013 – Brookhaven National Laboratory

B. Heinemann

J. Incandela

On behalf of ATLAS and CMS



Potential and Challenges of the HL-LHC Program

The Case for the HL-LHC in a Nutshell

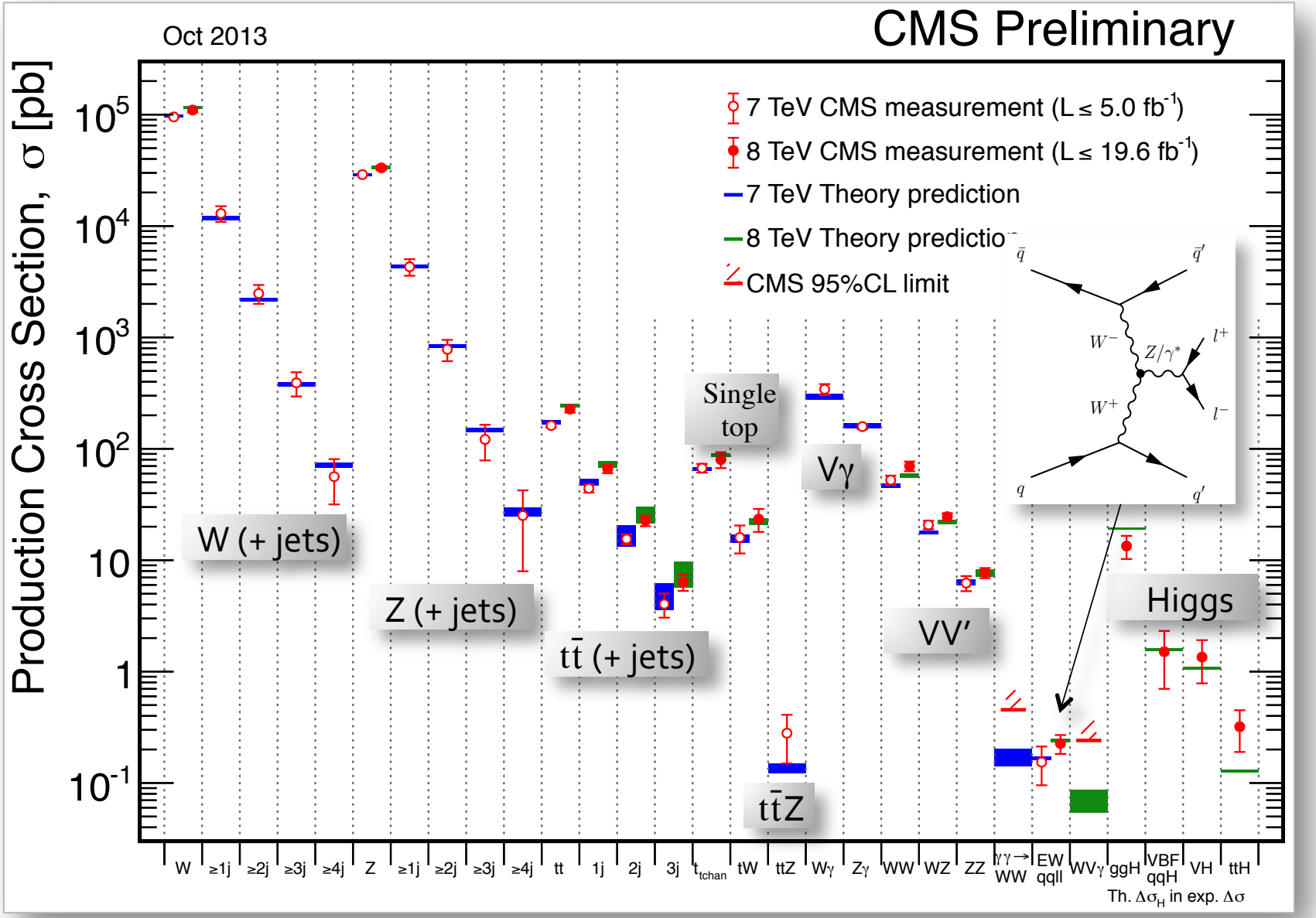
- Access to Physics: both known and unknown
  - Discovery potential at new mass scales
  - Discovery potential in rare, unusual processes
  - Complementarity
    - *Test models in phase space that's overlapping or complementary to other programs*

- Maintain US co-leadership in collider physics
  - US Involvement in collider physics spans generations
  - US has made large investments, critical contributions to ATLAS, CMS, LHC
    - *And in establishing itself as a trusted and reliable partner*
  - Success relies upon continued involvement of the US collider community

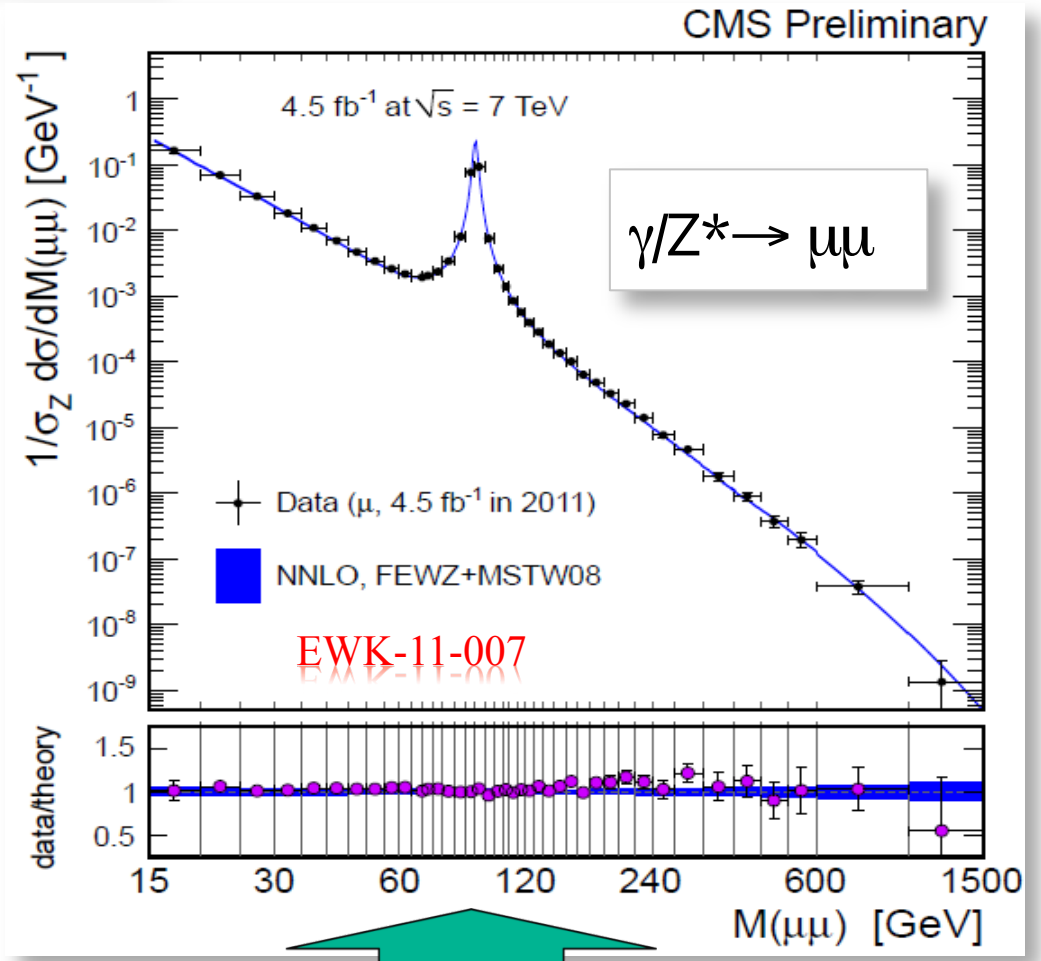
- Continuity, growth and regeneration of core competence
  - *Innovation of detectors and accelerator components, their construction and operation, data analysis across a broad array of physics topics*
    - Opportunities to train the next generation of collider physicists

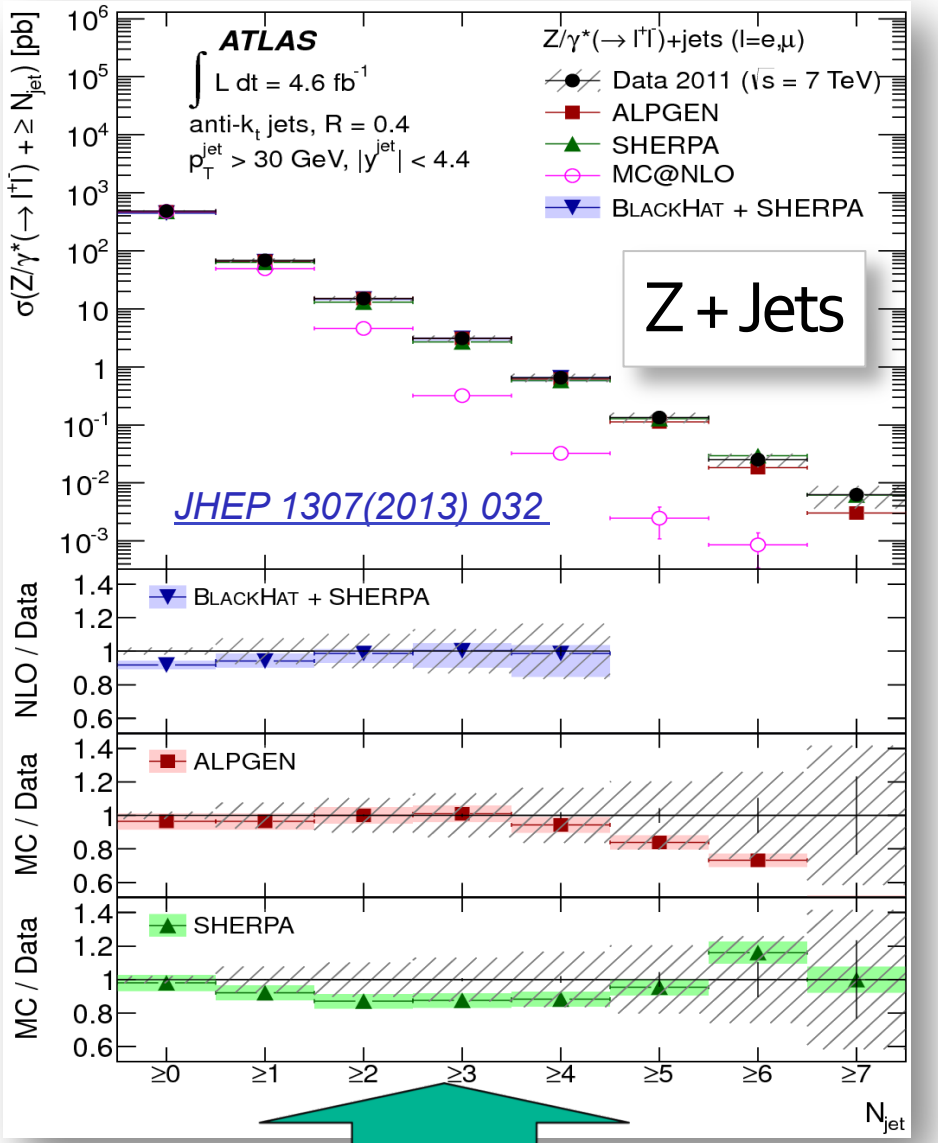
- It is the primary interest of a large portion of the US community

Run 1: Tackling ever rarer processes



with unprecedented reach and precision from early on…

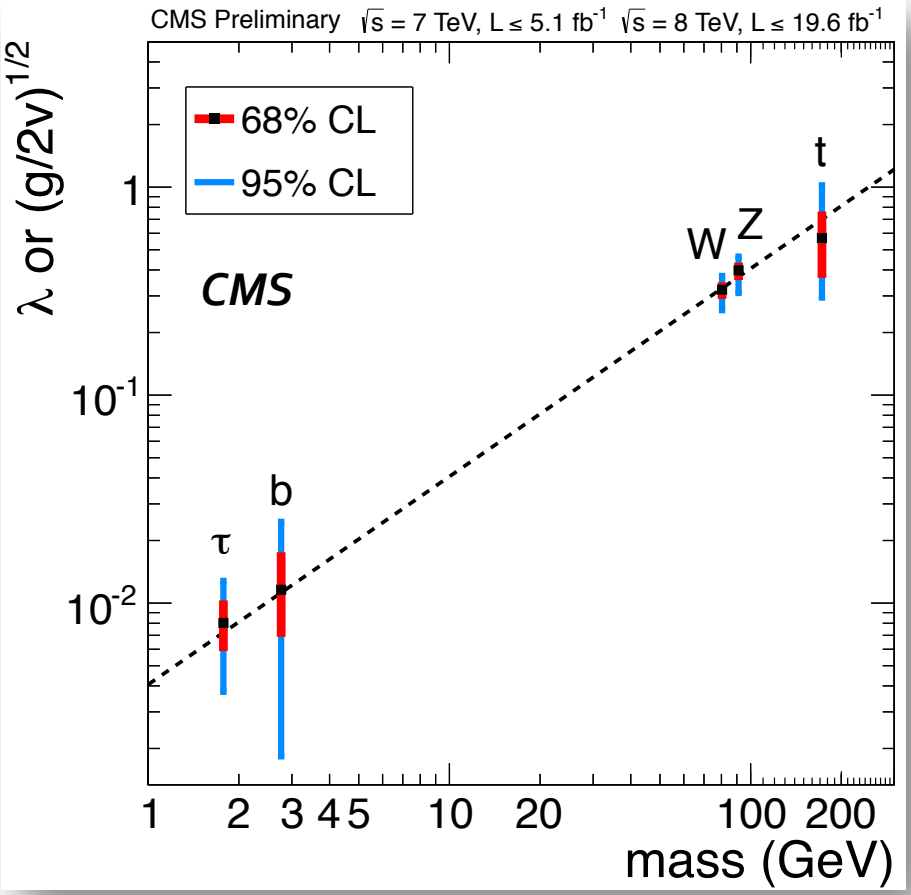


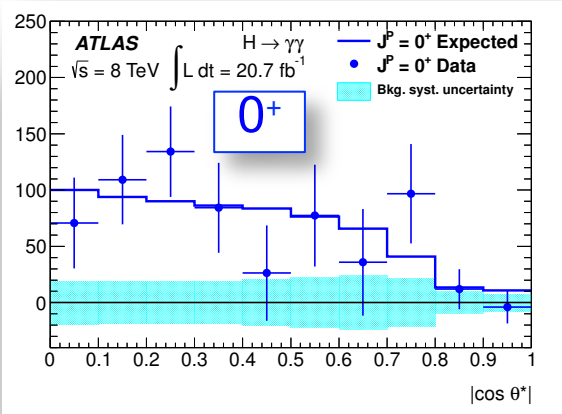


Differential Drell-Yan (DY) cross section: 2.5M μμ pairs (~15% of data) tests NNLO cross sections and PDFs over >8 orders !!

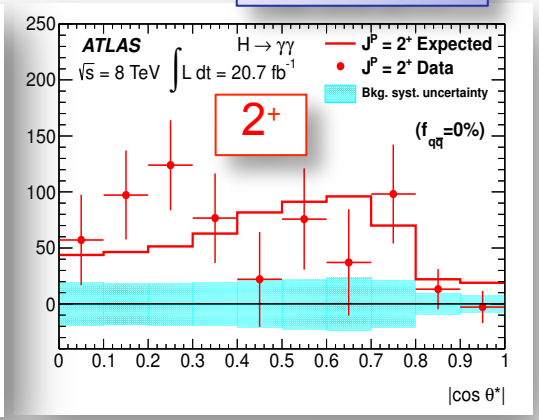
Z+jets compared to NLO and LO Matrix Element +Parton Shower MC's
Sakurai prize : Bern, Dixon, Kosower (Blackhat)

… and of course an early discovery



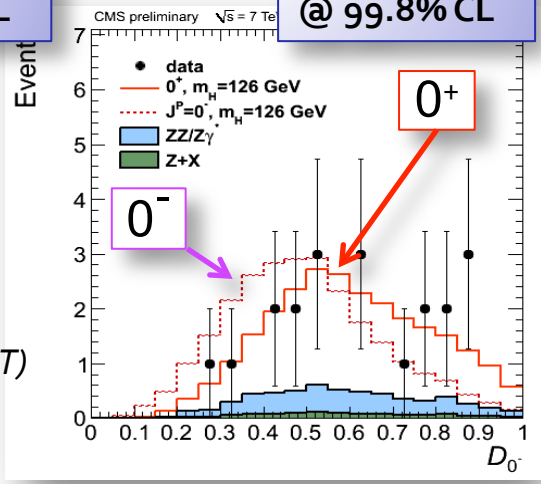


$2^{\pm}$ Excluded @ 99.9%



$1^{\pm}$ Excluded @ 99.9% CL

0^{-} Excluded @ 99.8% CL



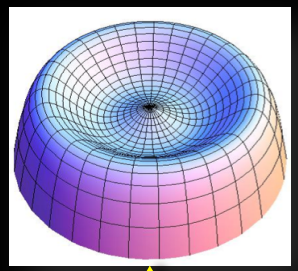
- $H \to \gamma\gamma$
  - Angle $\cos(\theta^*)$
    - sensitive to spin
- $H \to WW^* \to l\nu l\nu$
  - $\Delta\phi_{ll}$, M_{ll} ..
    - *Boosted-Decision-Tree (BDT)*
- $H \to ZZ^* \to 4l$:
  - M_{Z1},M_{Z2} and 5 angles
    - *BDT or Matrix-Element-based discriminant*

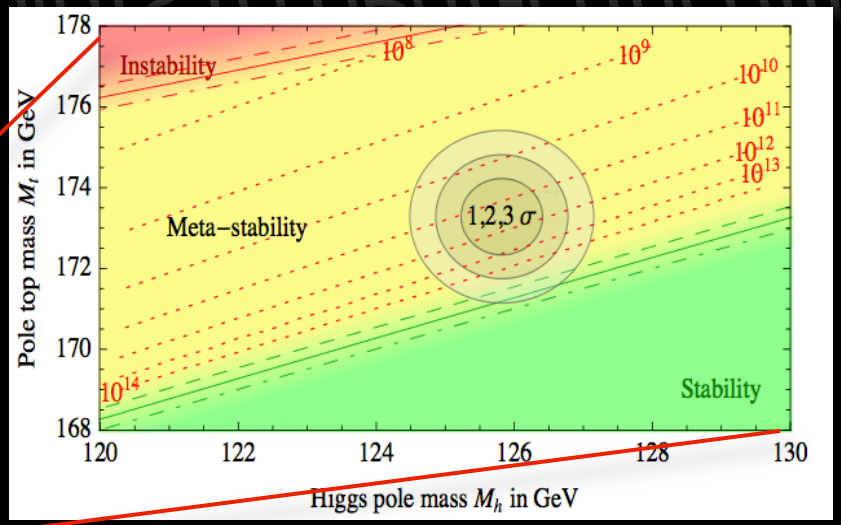
Properties compatible with SM Higgs expectations so far

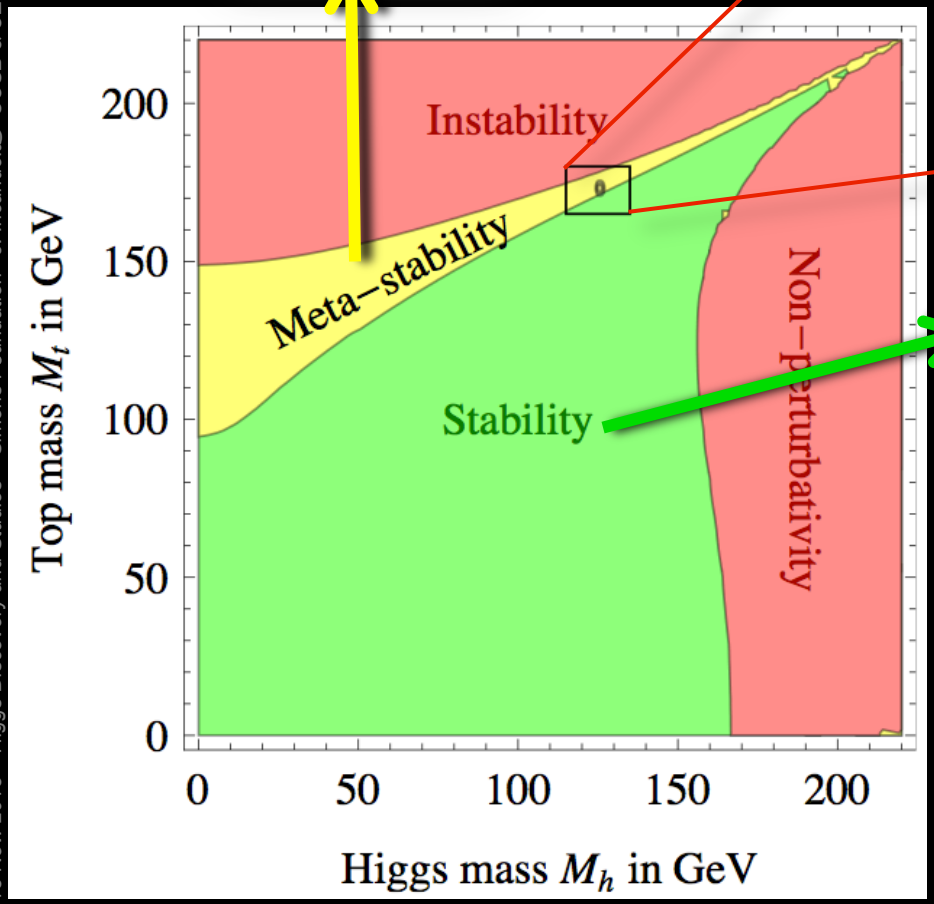
...but the mass points to near-criticality

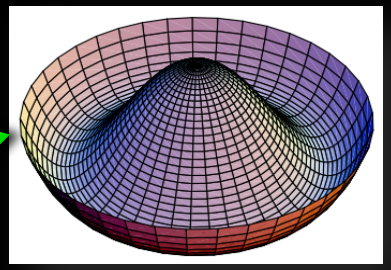
m_{top} ~ 173 GeV

m_H ~ 126 GeV









A. Strumia, Moriond EWK 2013

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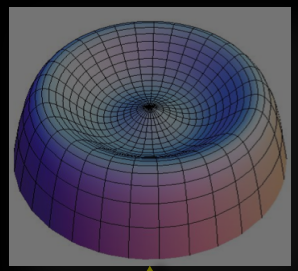
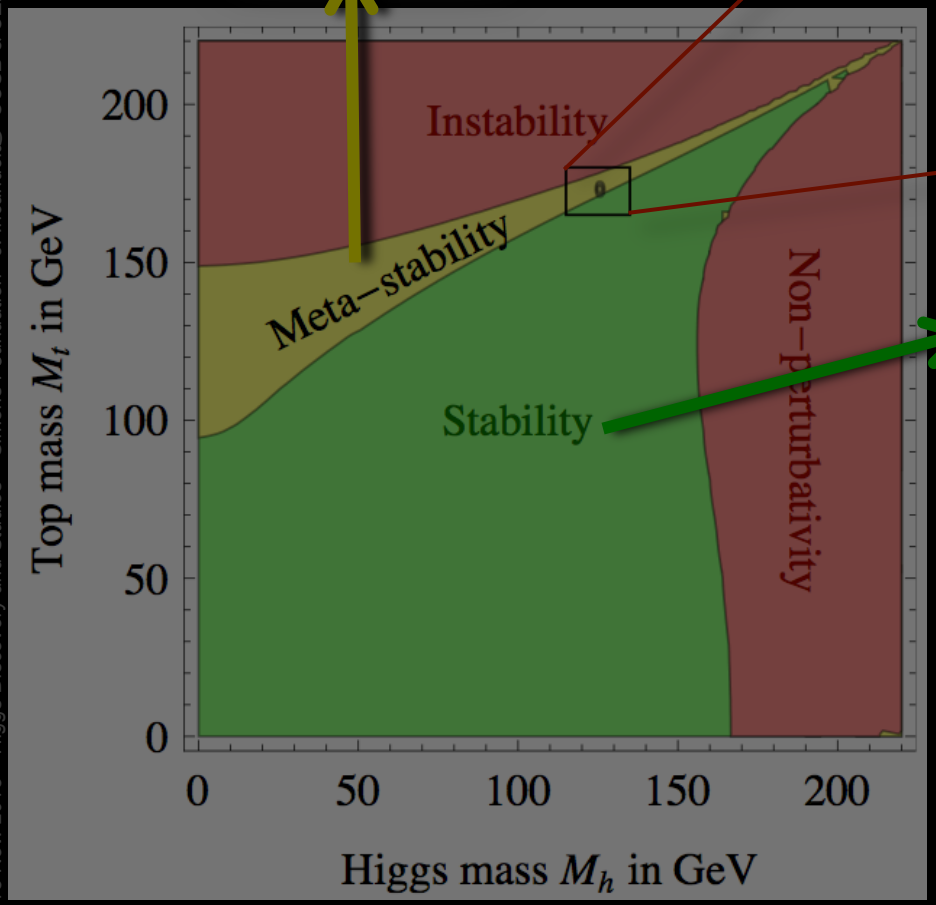
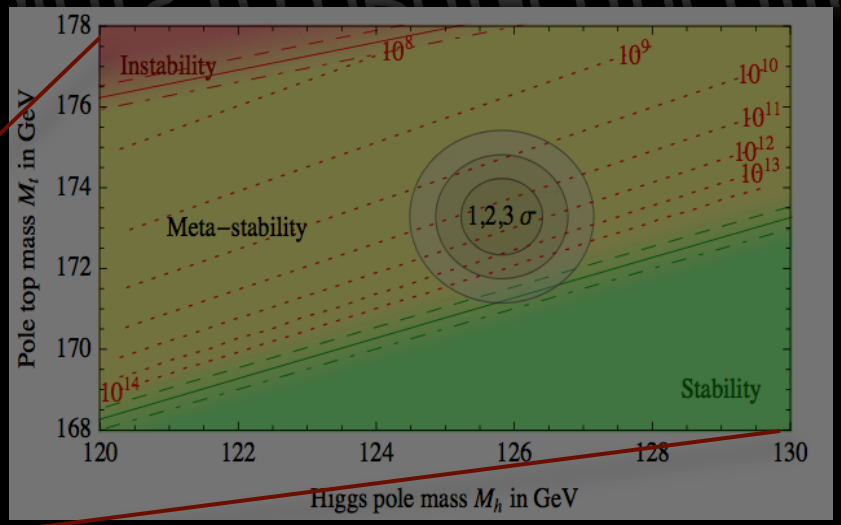
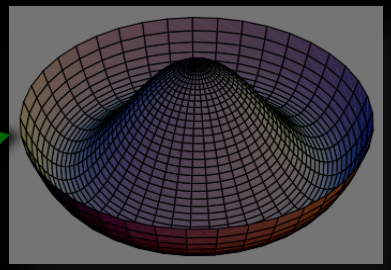


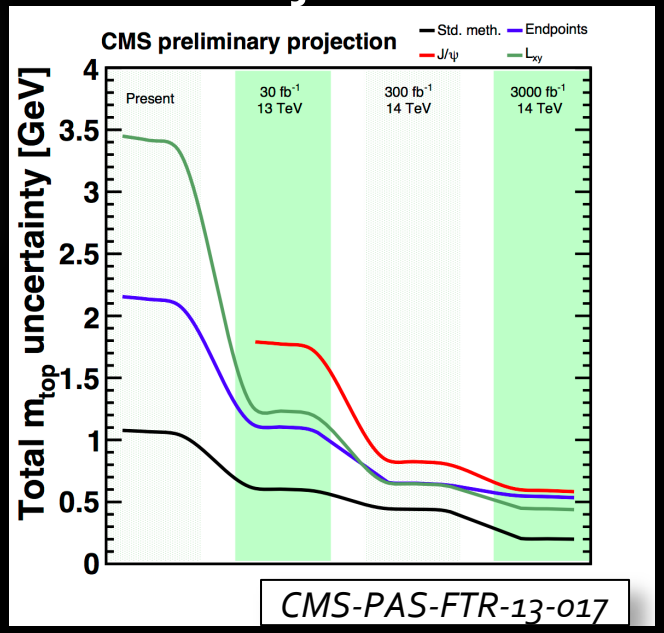






3 ab^{-1}	Per expt.
Δm_t	~200 MeV
Δm_H	<100 MeV
$\Delta \Gamma_H$	<100 MeV?

HL-LHC Projection



CMS-PAS-FTR-13-017

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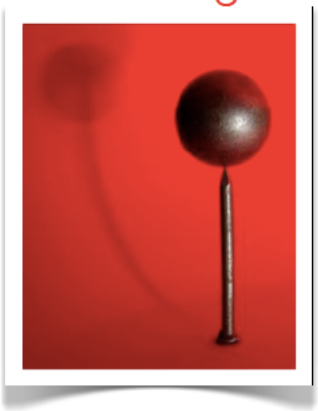
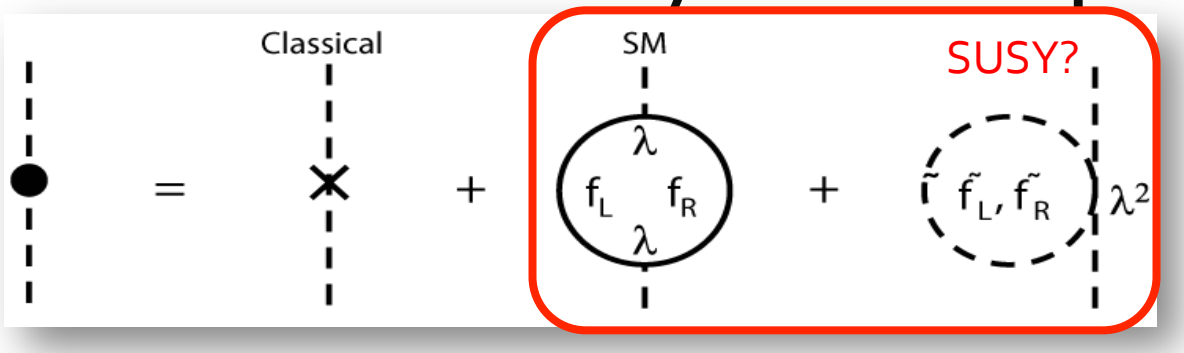
Post-discovery landscape

Fine-tuning?





- Higgs Discovery ⇒ Hierarchy problem no longer hypothetical
  - Corrections to the Higgs mass appear to want to be at the Planck scale
  - Is the universe incredibly fine-tuned?

- How do we resolve this issue?
  - SM partners especially 3rd generation & EWK Bosons ⇒ Naturalness
  - New phenomena related to the true Planck scale being much lower
  - …

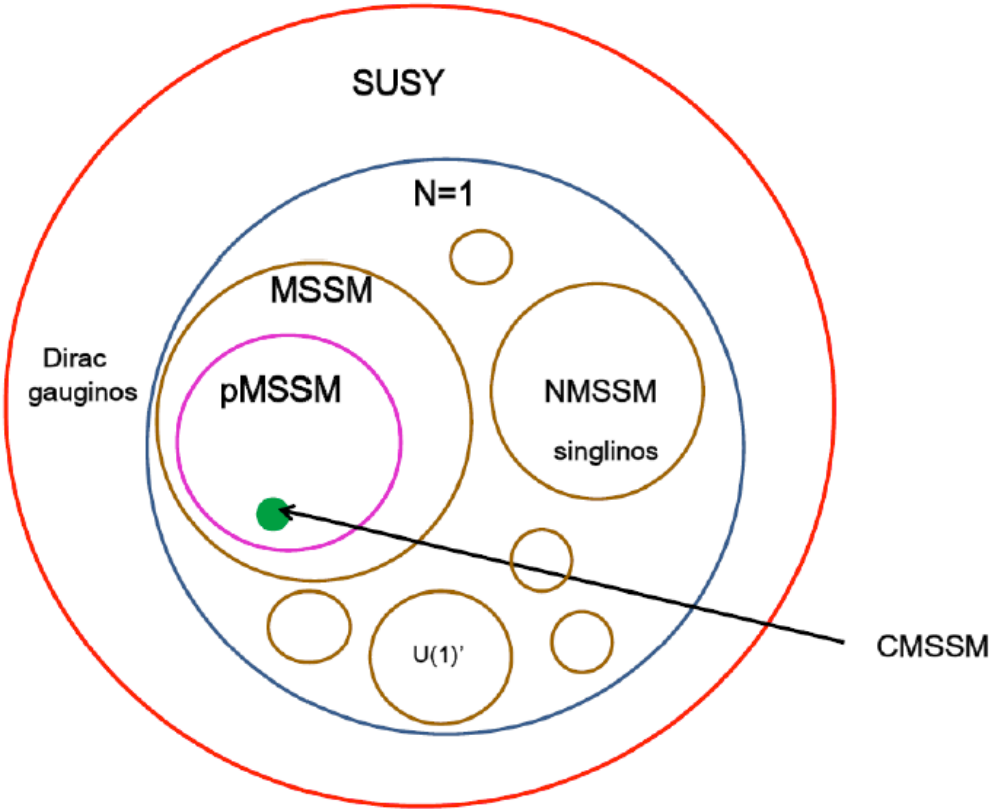
- These are experimentally testable at the LHC
  - e.g. naturalness even fine-tuning a bit requires partners at the TeV scale

SUSY

- Much uncovered phase space
  - *It could be at low mass but hidden*
  - *Or at higher mass but still natural*
- If something new is seen,
  - the LHC can provide insights into the underlying physics
    - *e.g. lifetimes of long-lived particles provide info about the SUSY scale**
- Until something new is seen
  - We'll expand the constraints
    - *We can potentially make a significant statement (albeit not 100% definitive) on naturalness*

More reasons to like SUSY

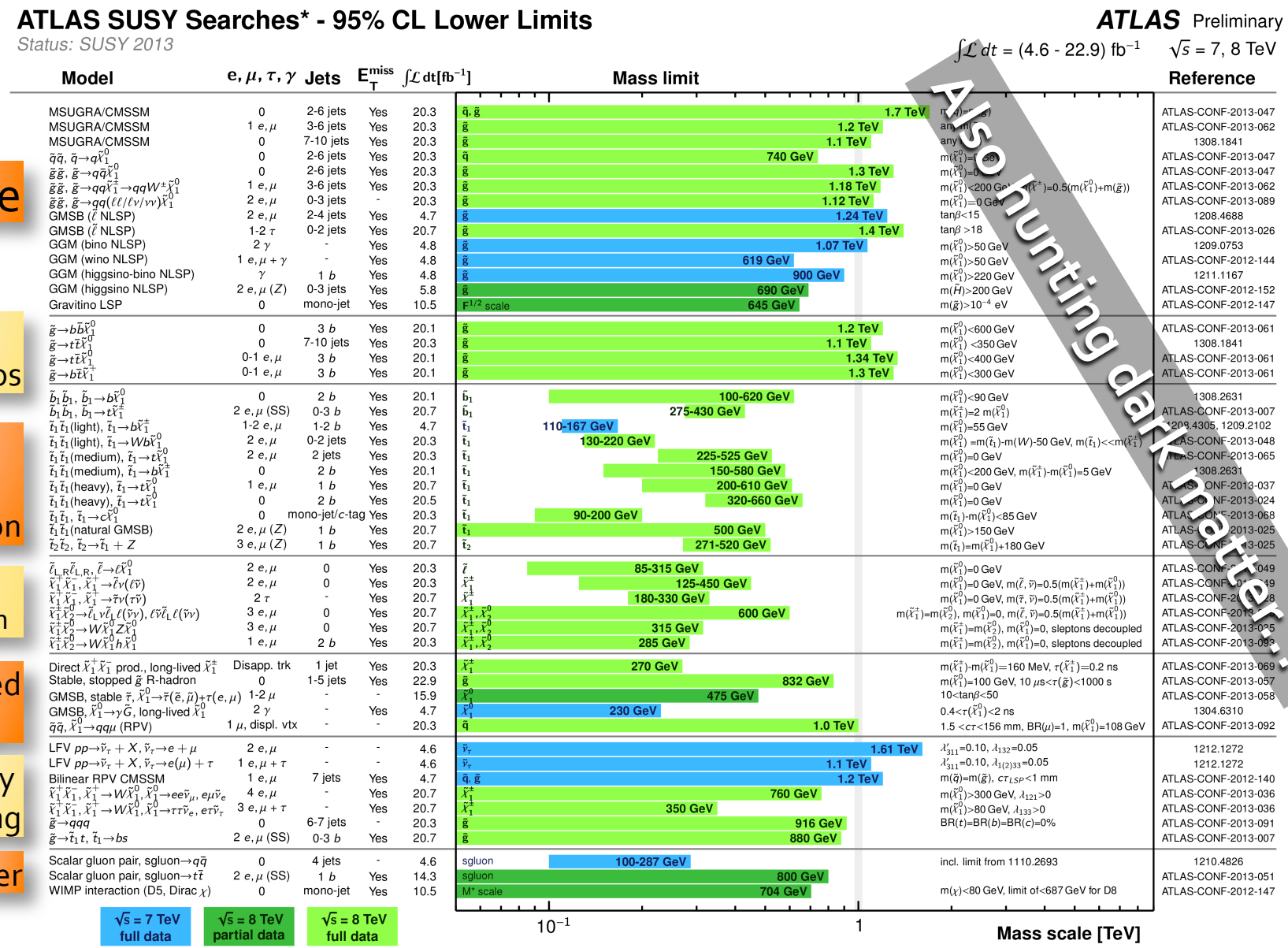
- ***Unifies couplings***
- ***Predicts SM-like Higgs m_h < 130 GeV***
- ***Dark matter candidates***
- ***Connects large Top mass to EWSB***



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

*N.Arkani-Hamed et al. arXiv:1212.6971v1

What is not seen is also important



Also hunting dark matter!

SUSY Search papers ~1000 citations per experiment

What is not seen is also important

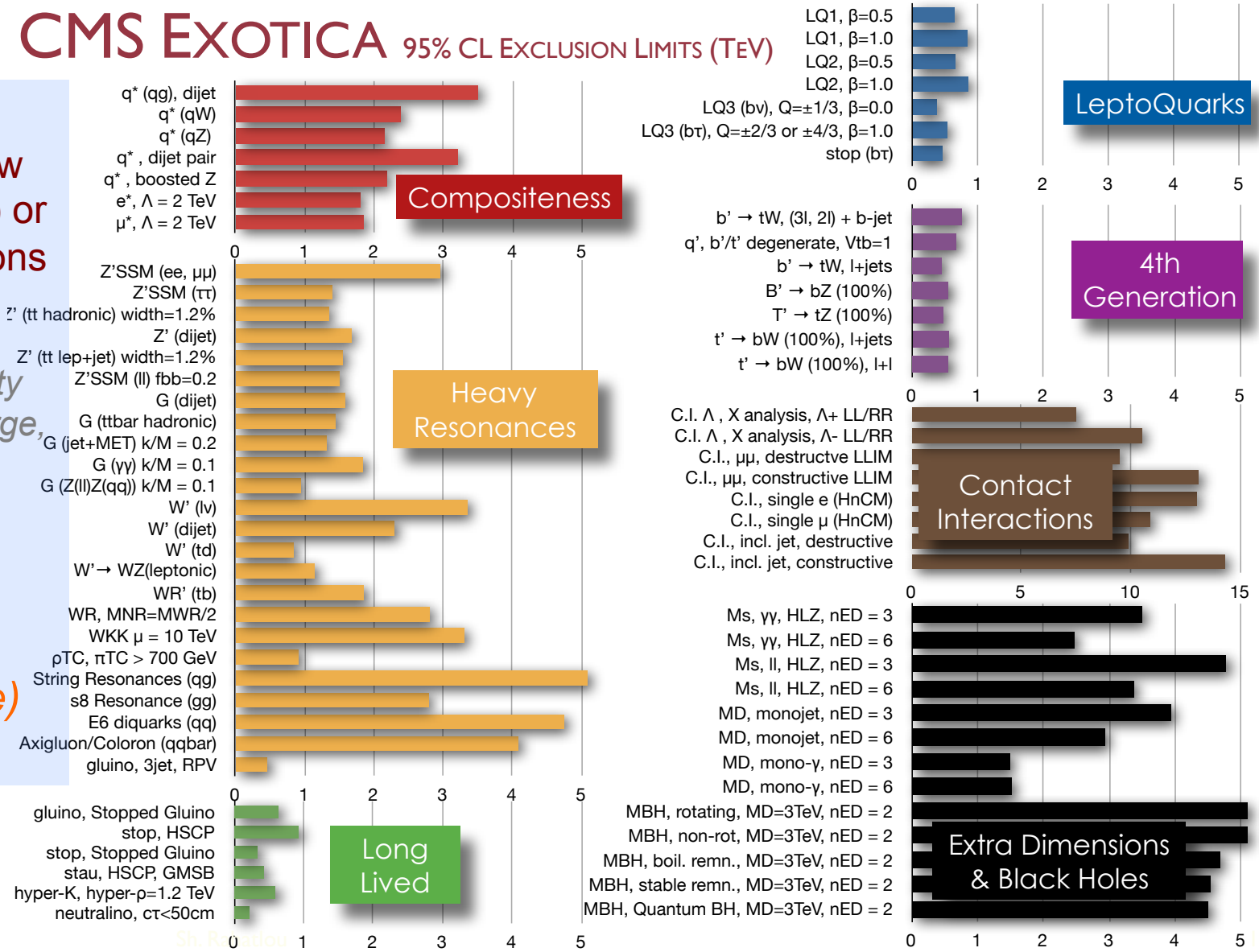
CMS Exotica 95% CL Exclusion Limits (TeV)

Many alternatives

- Characterized by new particles (like SUSY) or new spatial dimensions
  - *Little Higgs w/T Parity*
  - *Universal extra dimensions w/KK parity*
  - *Extra dimensions (Large, warped…)*
  - *Hidden Valleys*
  - *Split SUSY…*

The LHC can probe all of these models (and many yet-to-be)

Also Hunting dark matter… e.g. monojets



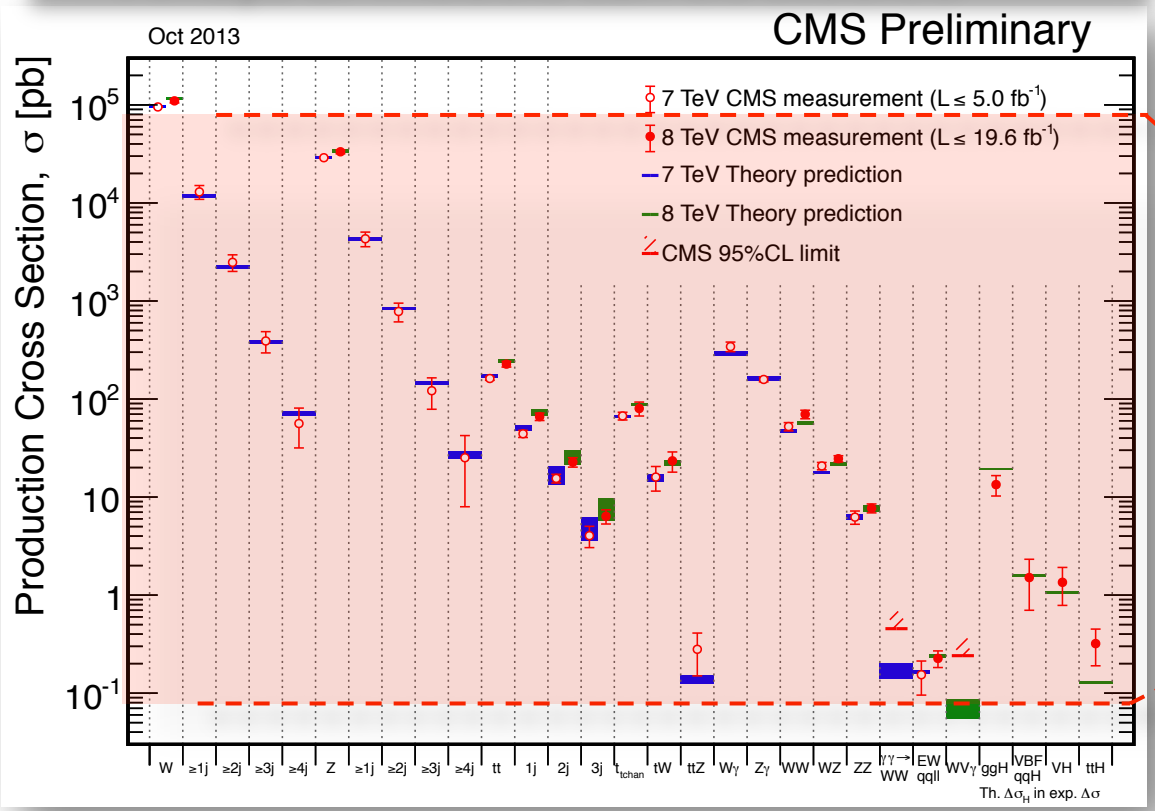
Exotica Search papers ~1000 citations per experiment

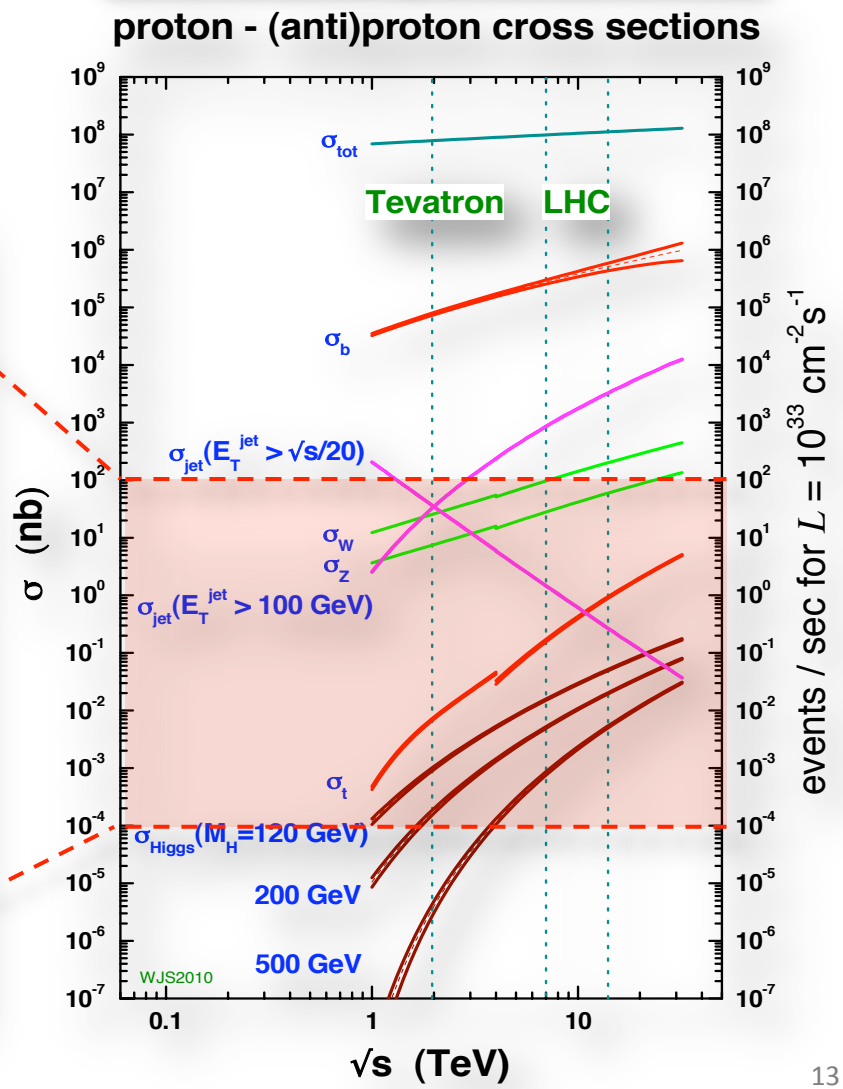
The LHC is an ideal tool for the current landscape

- Broad band, All-purpose capability
  - ~1 GeV to multi-TeV reach in E, mass
  - Few per mille to few per trillion in rates
- Arrays of models can be studied

Precision over 6 orders

At a depth of 6 orders …

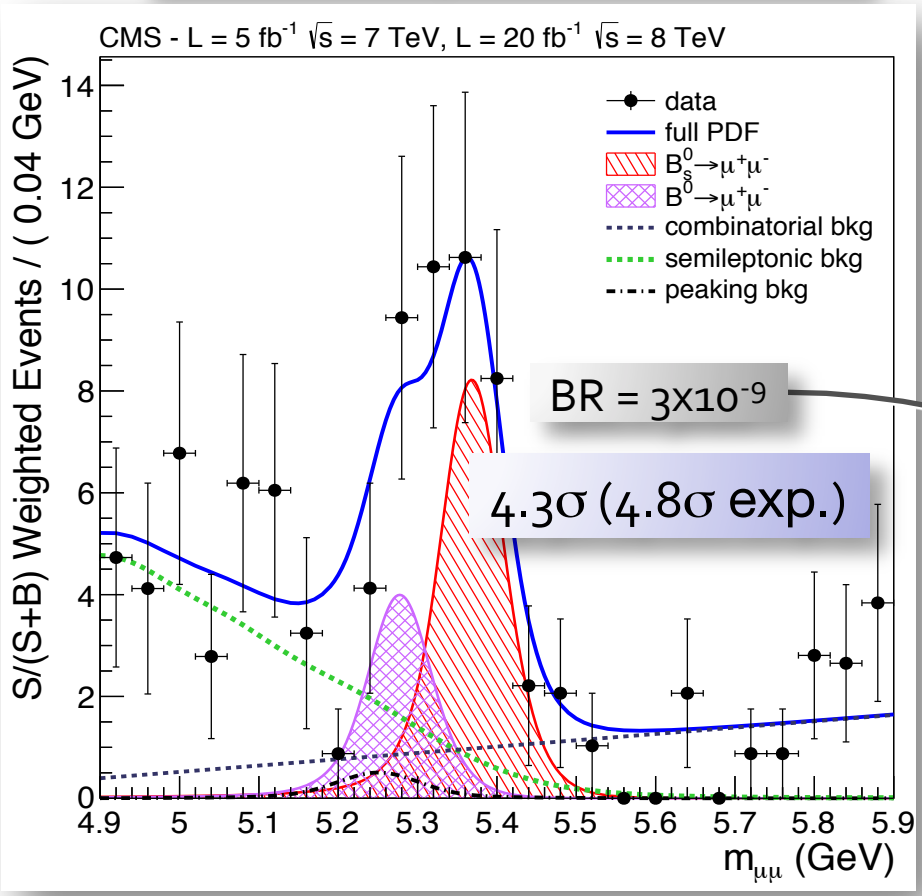


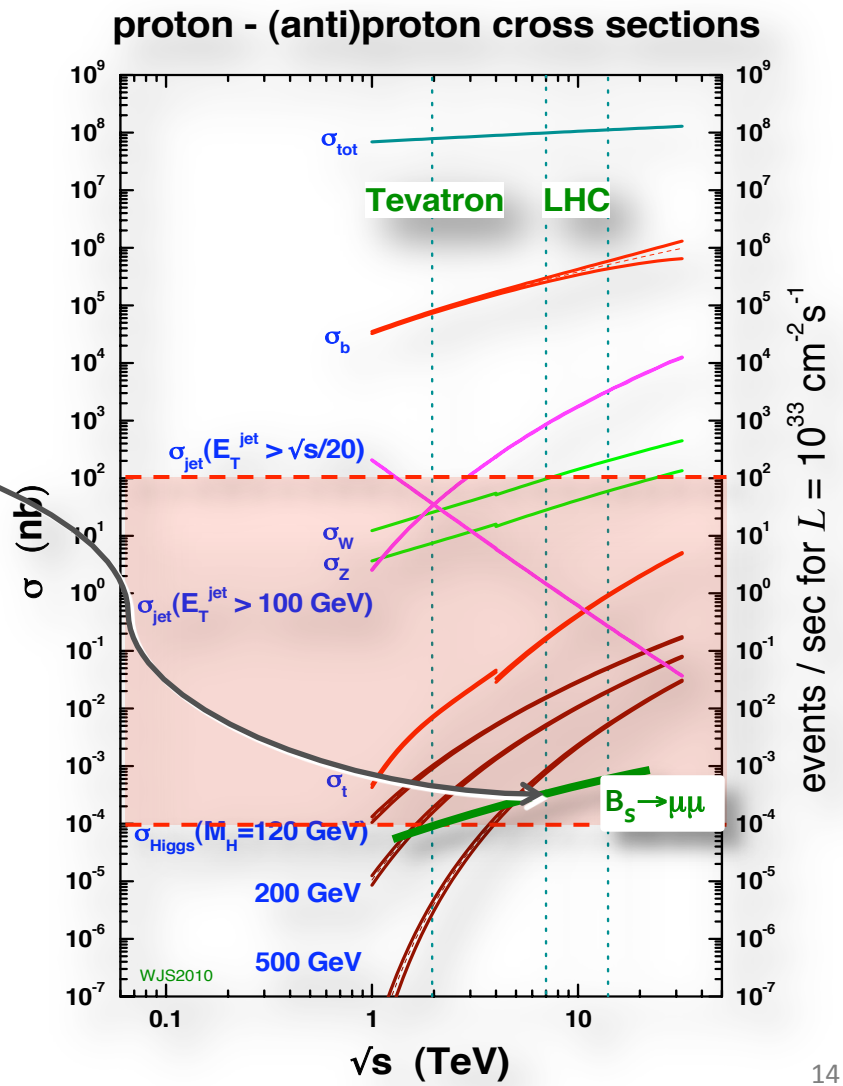


Adapted from a slide from Marumi Kado

access to rare processes…

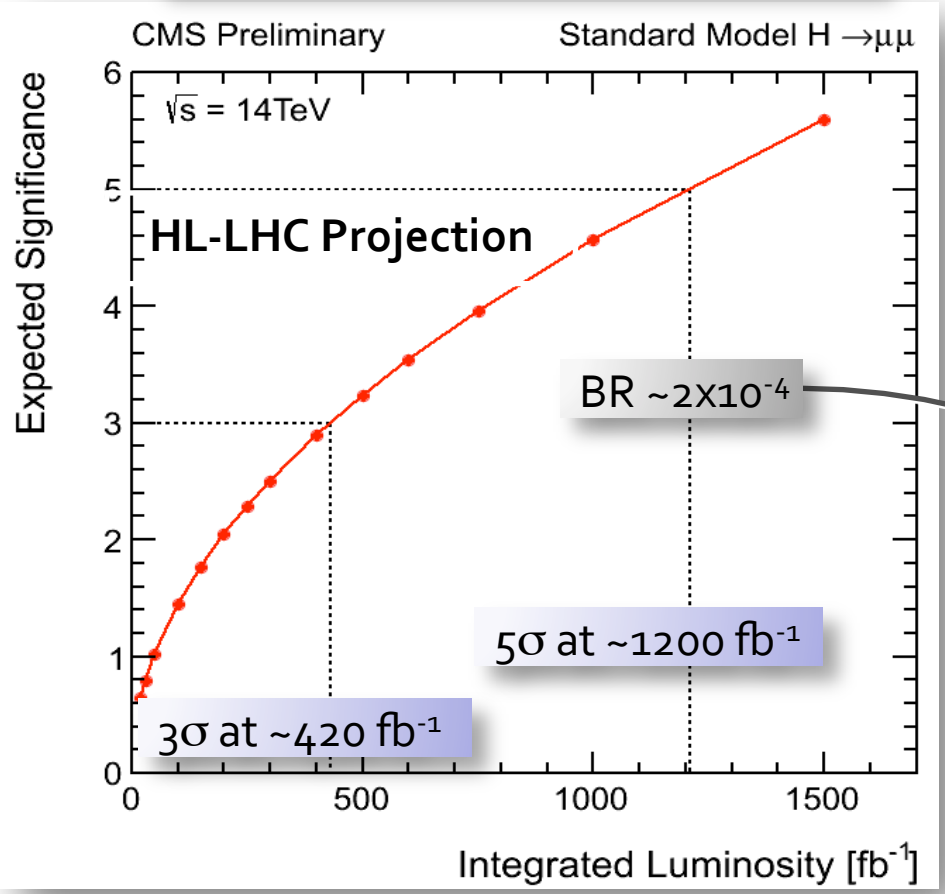
$B_s \rightarrow \mu\mu$

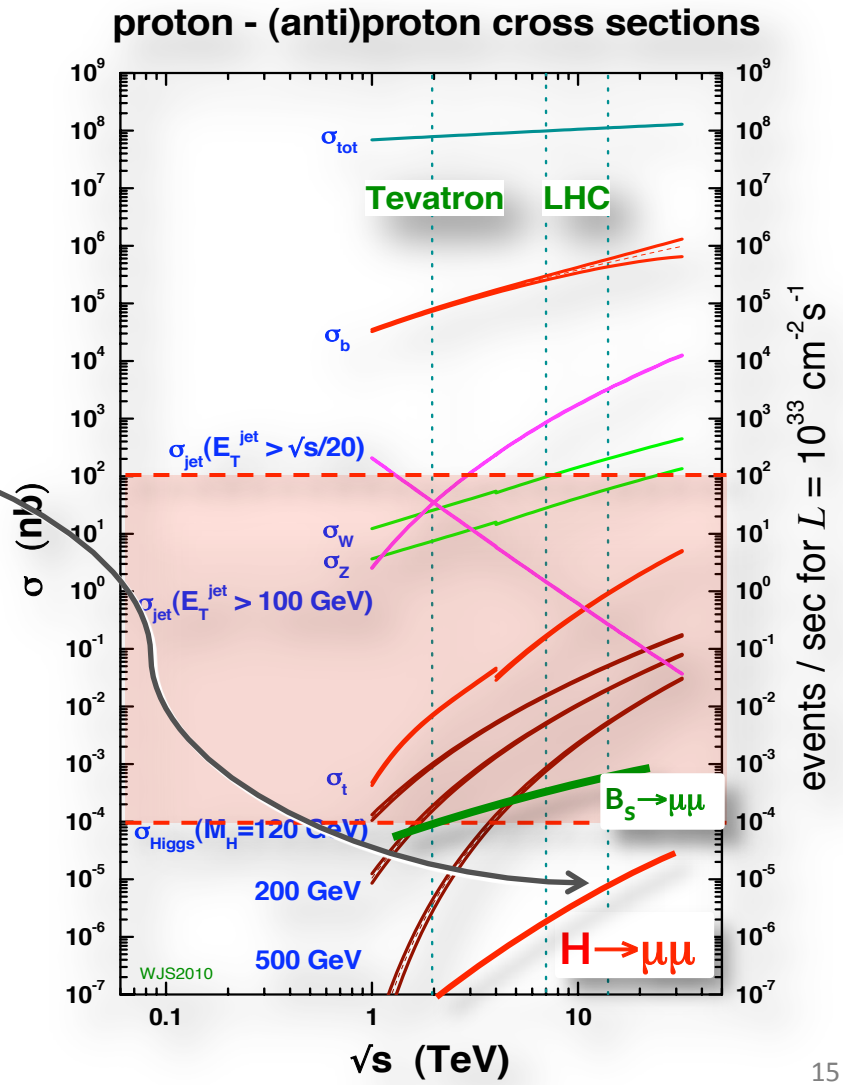




and rarer still…

H → μμ





ATLAS & CMS > 550 publications so far …

~All break new ground in one way or another

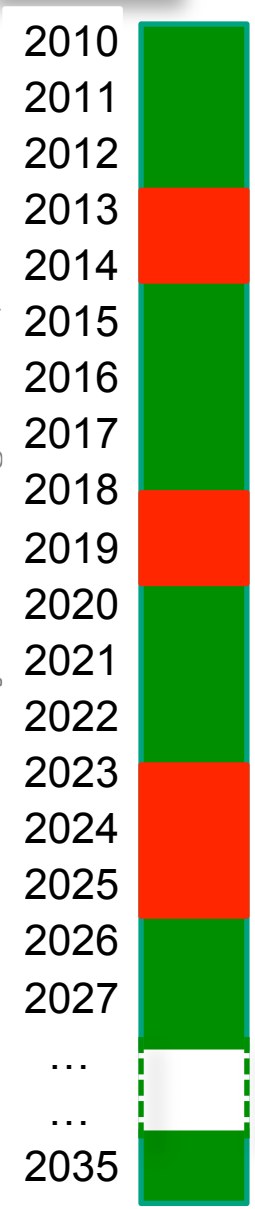
Higgs discovery papers: >2000 citations each (~100/month)

Extensive SUSY & Exotica Searches

Stunning Standard Model Results including measurements of key parameters and searches for anomalies

The LHC to HL-LHC Roadmap*

(updated by CERN: Dec. 2nd 2013)



Run 1: **$\sqrt{s}$=7-8 TeV**, **$\int$Ldt=25 fb^{-1}**, pileup **$\mu\approx$20**

$L^{peak}=0.7\times10^{34}$ cm^{-2}s^{-1}

LS1: **phase 0** upgrade

new

Run 2: **$\sqrt{s}\approx$13-14 TeV**, **$\int$Ldt$\approx$120 fb^{-1}**, pileup **$\mu\approx$43**

$L^{peak}=1.6\times10^{34}$ cm^{-2}s^{-1}

LS2: **phase 1** upgrade

Run 3: **$\sqrt{s}\approx$14 TeV, $\int$Ldt$\approx$350 fb^{-1}**, pileup **μ=50-80**

$L^{peak}\approx2\text{-}3\times10^{34}$ cm^{-2}s^{-1}

LS3: **phase 2** upgrade

HL-LHC: **$\sqrt{s}\approx$14 TeV, $\int$Ldt$\approx$3000 fb^{-1}**, pileup **$\mu\approx$140-200**

$L^{peak}=20\times10^{34}$ cm^{-2}s^{-1} leveled to $L^{peak}=(5\text{-}7.5)\times10^{34}$ cm^{-2}s^{-1}

** Consistent with the European Strategy recommendations as endorsed by the CERN Council*

LS="long shutdown"

LHC to HL-LHC: The next 2 orders of magnitude

≥300 fb^{-1} by 2023 √s=13+ TeV

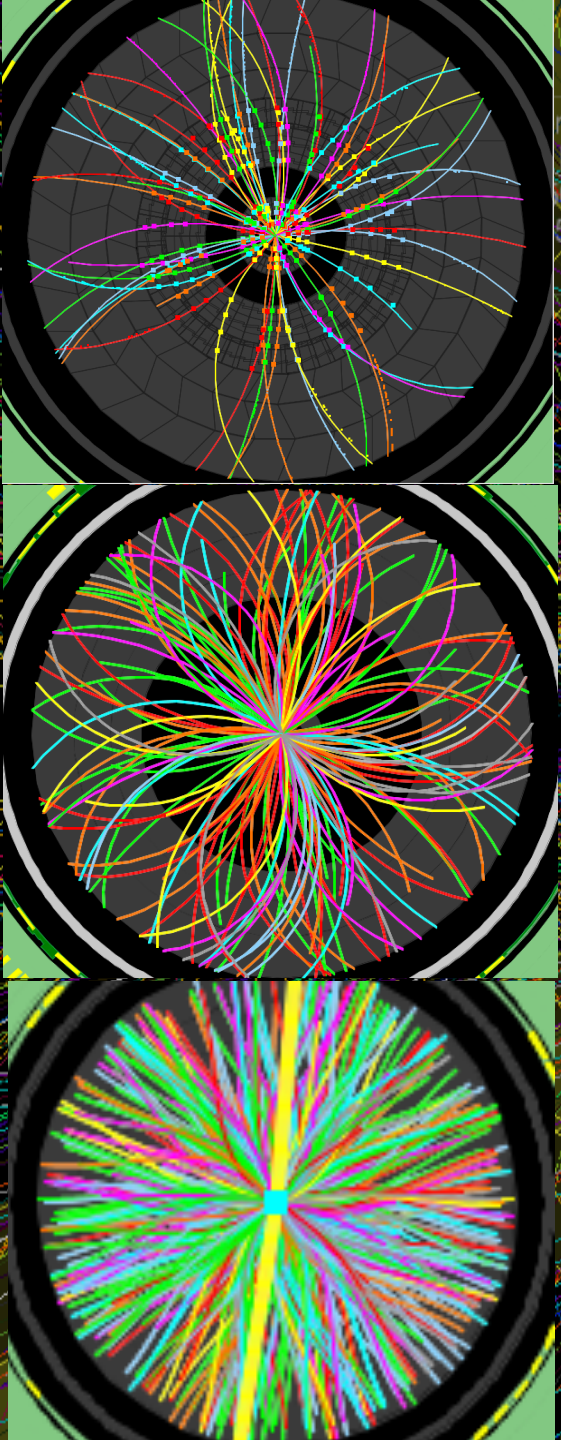
- Accessing a new scale
  - Over threshold for strongly produced new particles?
    - **Yes ⇒ Major breakthrough!**
    - No ⇒ Hunker down for a methodical hunt
  - Either case requires
    - Detailed understanding of the SM @ this √s, pile-up mitigation
- Exploring the SM
  - Ever more precise measurements and ever more rare processes
  - *Higgs, top, multi-bosons, heavy flavors, PDFs, Vector boson scattering…*

≥3000 fb^{-1} at √s=14+ TeV

- Precision studies
  - *Including any new particles found earlier*
    - *Couplings, Masses, J^{PC},*
      - *Higgs, top, W, X …*
- Steady extension of searches
  - *Continuing the methodical hunt*
    - Access higher masses with ∫Ldt
    - Rare processes, weakly produced states
- Targeted searches
  - New models
  - *Test/complement any discoveries*
    - *Including those made elsewhere*

Requires powerful detectors, DAQ, trigger, software, computing…

The pileup challenge



Events taken at random (filled) bunch crossings

2010

O(2) Pile-up events

150 ns inter-bunch spacing

2011

O(5-10) Pile-up events

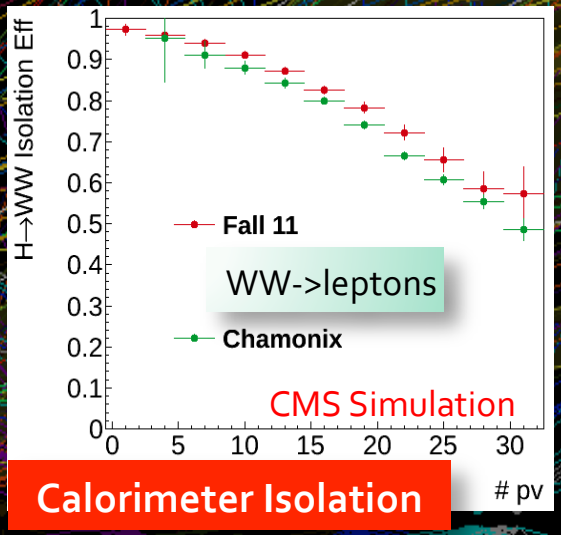
50-75 ns inter-bunch spacing

2012

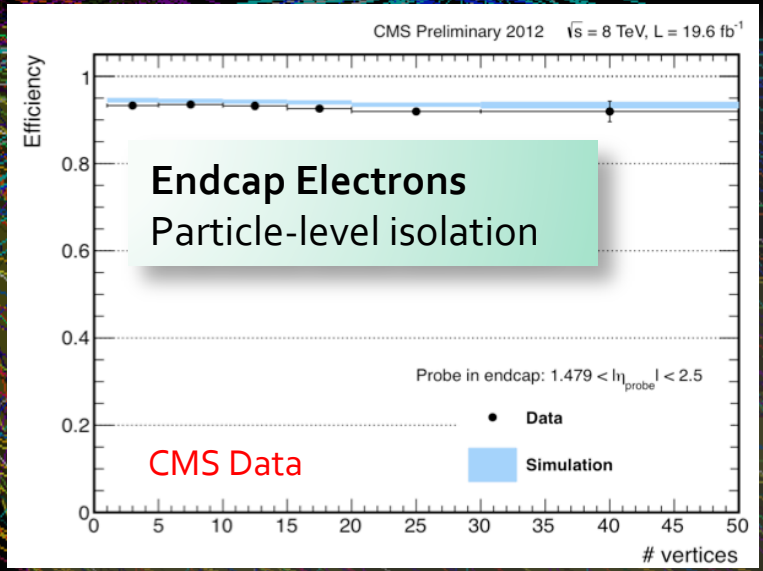
O(20-30) Pile-up events

50 ns inter-bunch spacing

Design value exceeded

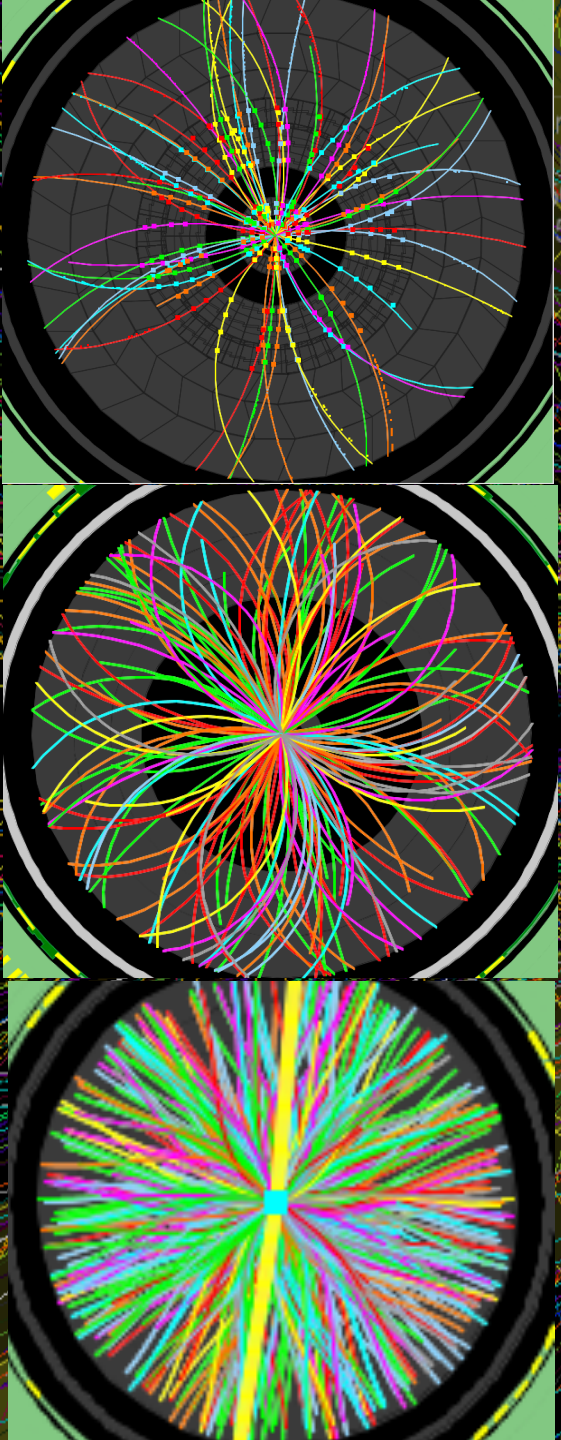


Calorimeter Isolation



Tracking is crucial

The pileup challenge



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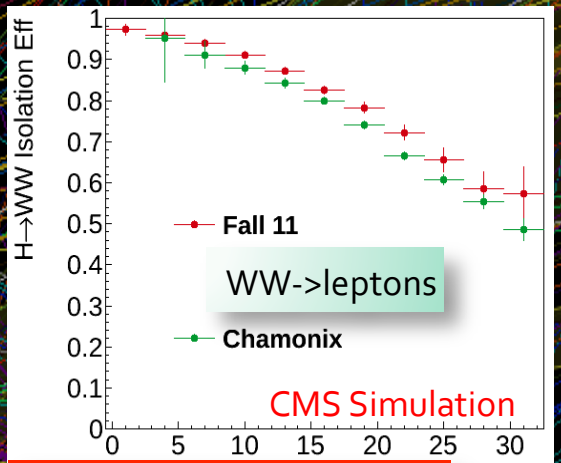

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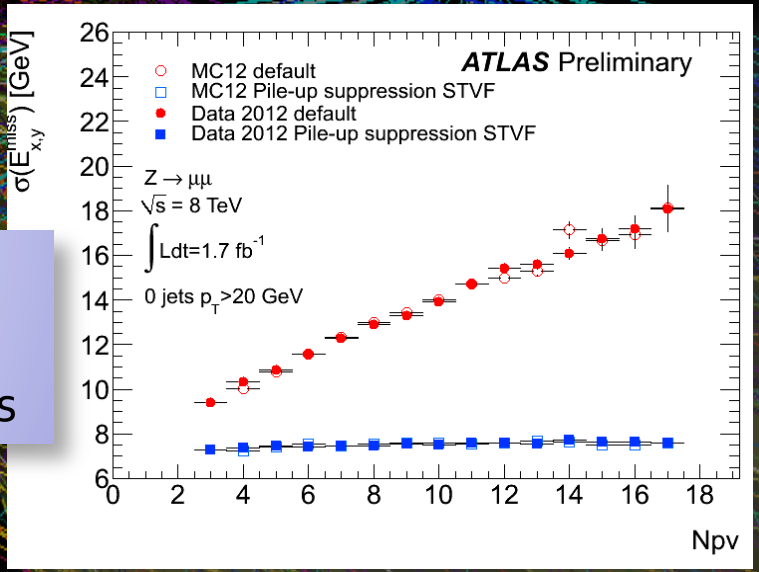
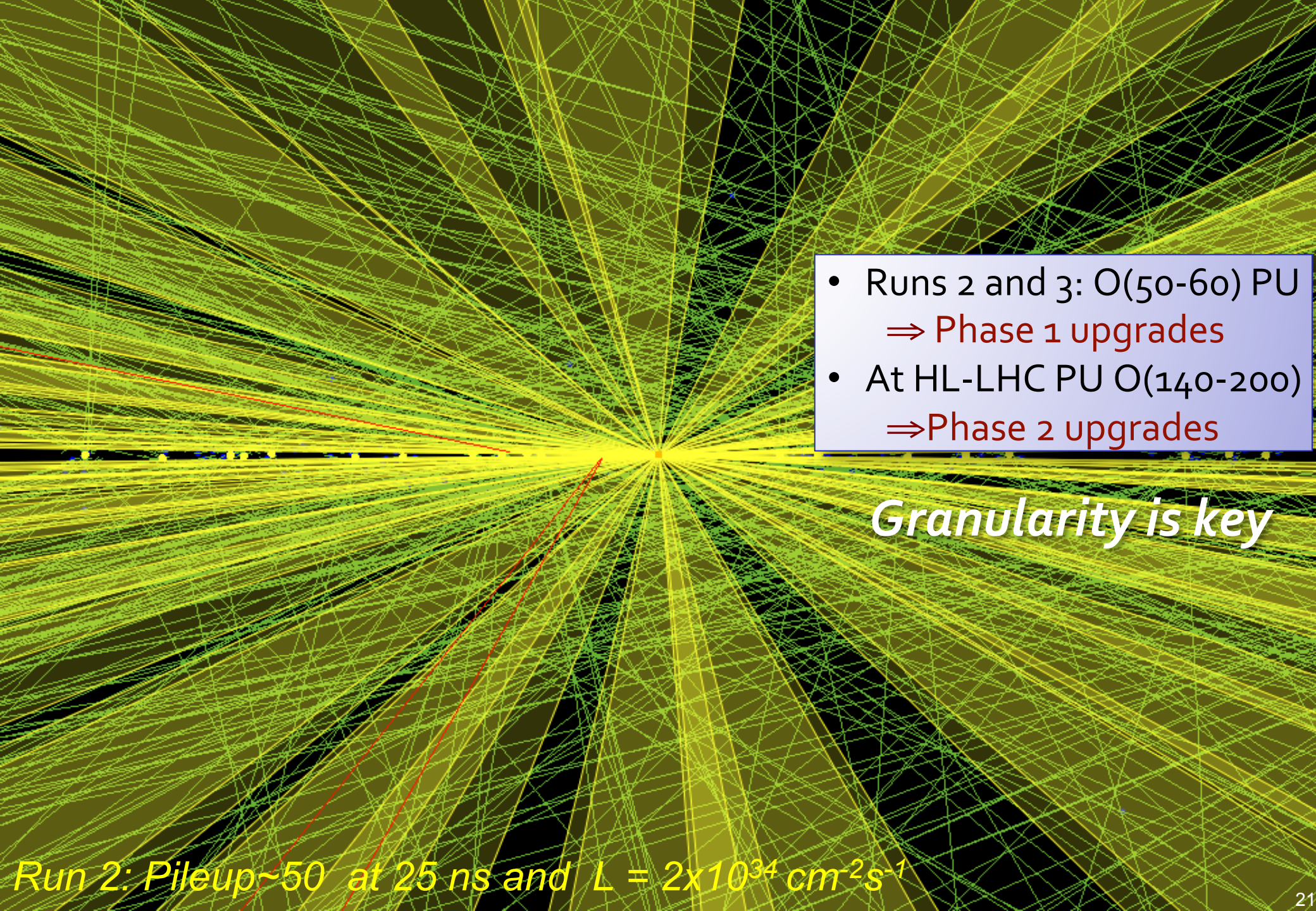


E_T^{miss} resolution **before/after** pile-up suppression w/tracks

Tracking is crucial

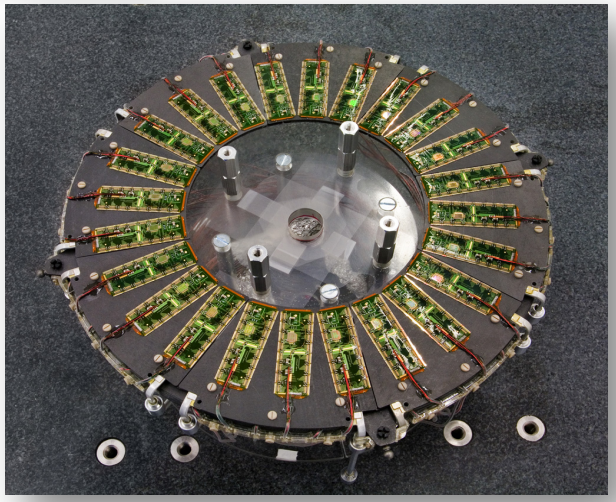


- Runs 2 and 3: O(50-60) PU
  ⇒ Phase 1 upgrades
- At HL-LHC PU O(140-200)
  ⇒Phase 2 upgrades

Granularity is key

Run 2: Pileup~50 at 25 ns and L = $2x10^{34}$ $cm^{-2}s^{-1}$

US Participation

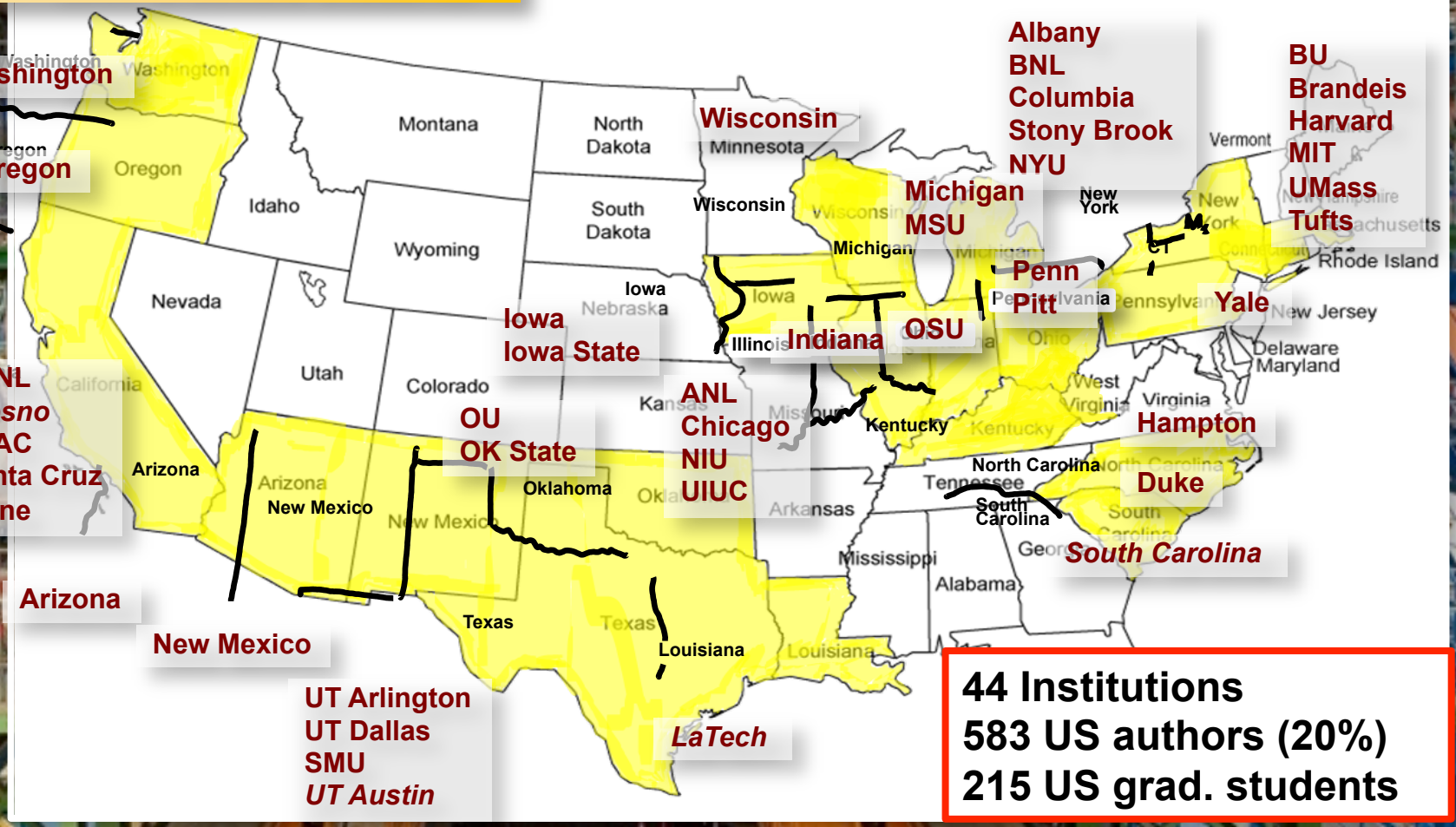


The first US groups joined ATLAS and CMS ≥20 years ago

- US is a leader or co-leader in many areas of both experiments
  - The US brings critical expertise, experience and resources
- After many years of hard work, the US is fully enmeshed,
  - An established and welcomed partner
- *Continued consistent and strong US contributions to ATLAS, CMS, LHC upgrades are crucial to the success of the LHC program and the vitality of the US HEP program*

ATLAS Collaboration

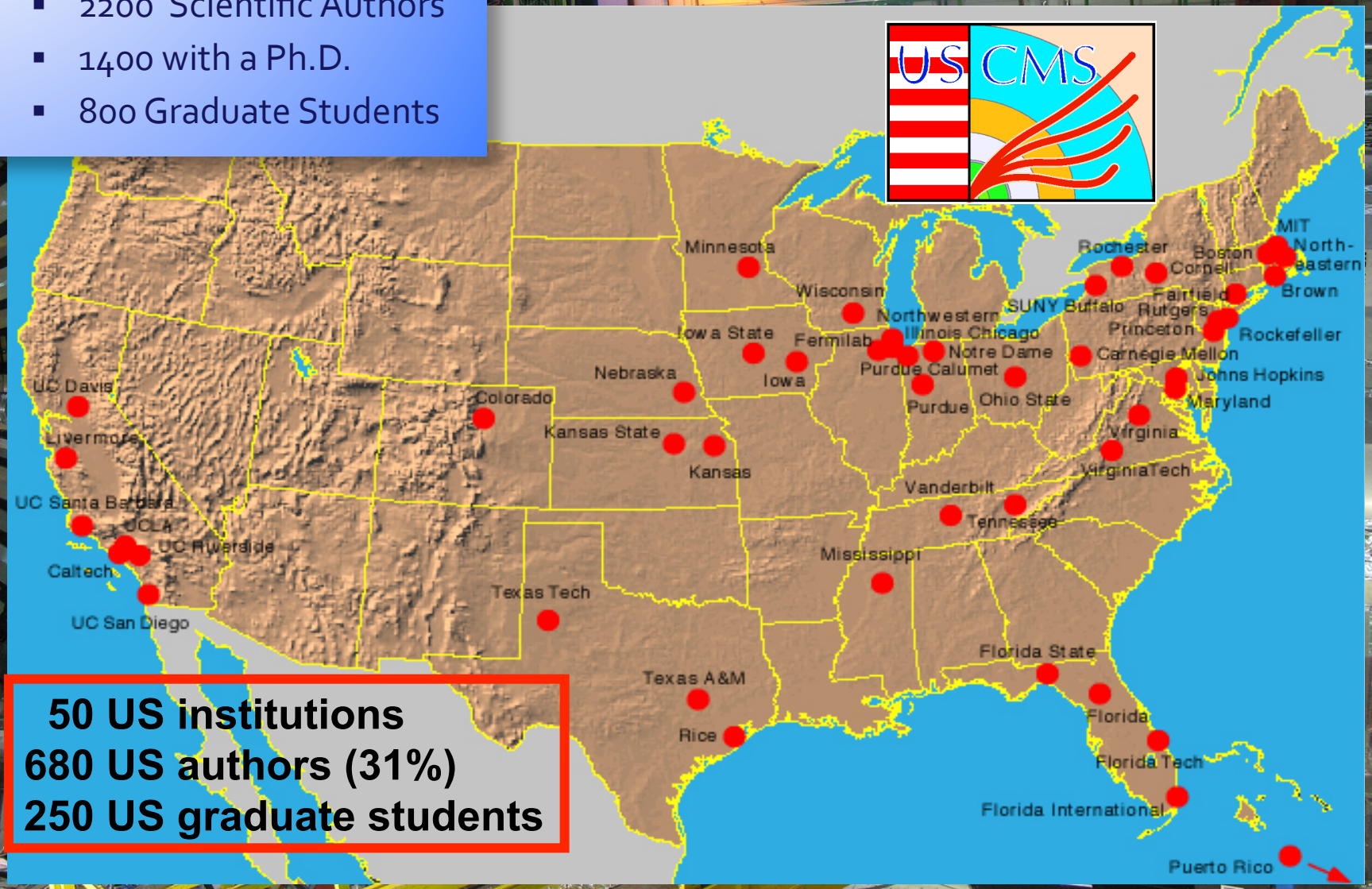
- ATLAS
  - 38 Countries
  - 177 Institutions
  - 3000 Scientific Authors
  - 1800 with a Ph.D
  - 1000 Graduate Students



44 Institutions
583 US authors (20%)
215 US grad. students

CMS Collaboration

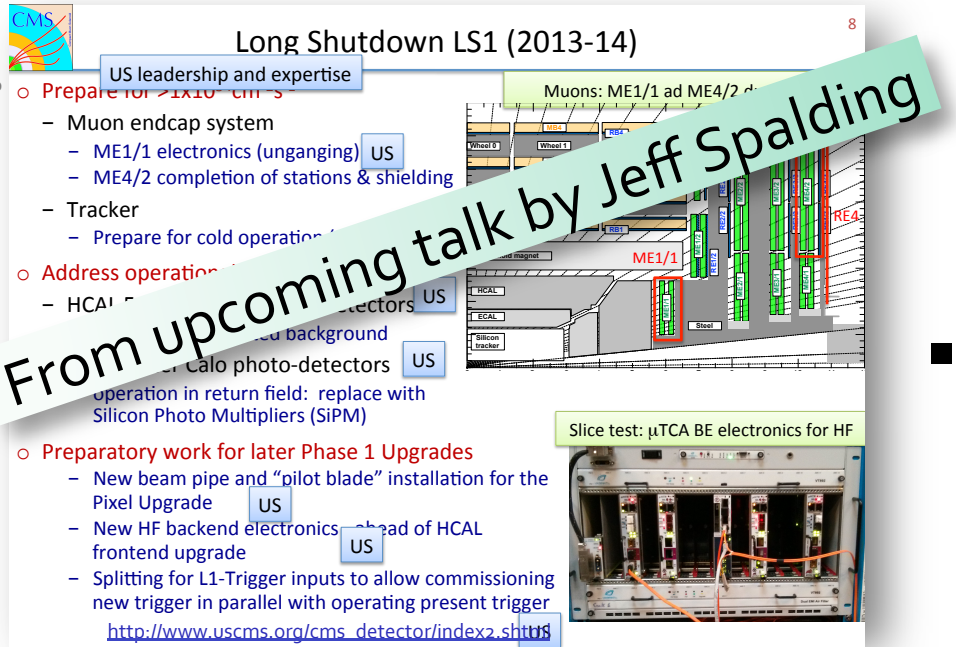
- CMS
  - 42 Countries
  - 190 Institutions
  - 2200 Scientific Authors
  - 1400 with a Ph.D.
  - 800 Graduate Students



50 US institutions
680 US authors (31%)
250 US graduate students

US in ATLAS & CMS

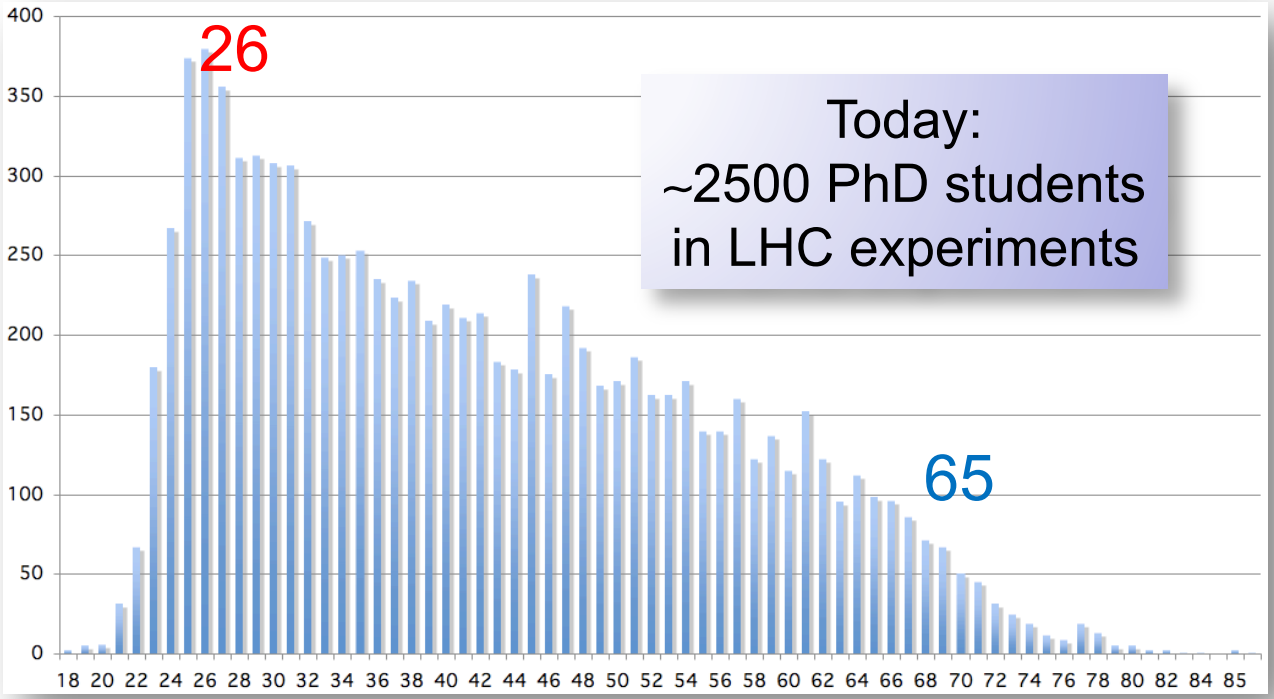
- Major hardware and operations contributions so far
  - *Run 1 construction*
  - *Long shutdown 1*
  - *Run 2 preparations*
  - *Phase 1 upgrades*
- Run 2 studies, designs, plans



- *Other major roles in both experiments*
  - *Trigger/DAQ, Offline, Computing*
    - *Software framework and ongoing development*
    - *Computing model and ongoing data operations*
    - *Triggers, datasets definitions, …*
- **Physics**
  - **Participation in leadership and high priority/high impact analyses!**
    - **Roughly 25-35% of physics conveners**

Attracting people to physics, technology, R&D

LHC Age Distribution Survey, March 2009



Today:
~2500 PhD students
in LHC experiments

>300 US PhD theses completed so far

- In just the past 2-3 years
- *Many more expected with Run 1 data*

Where do they go?
What do they offer?

Vast majority go to private sector

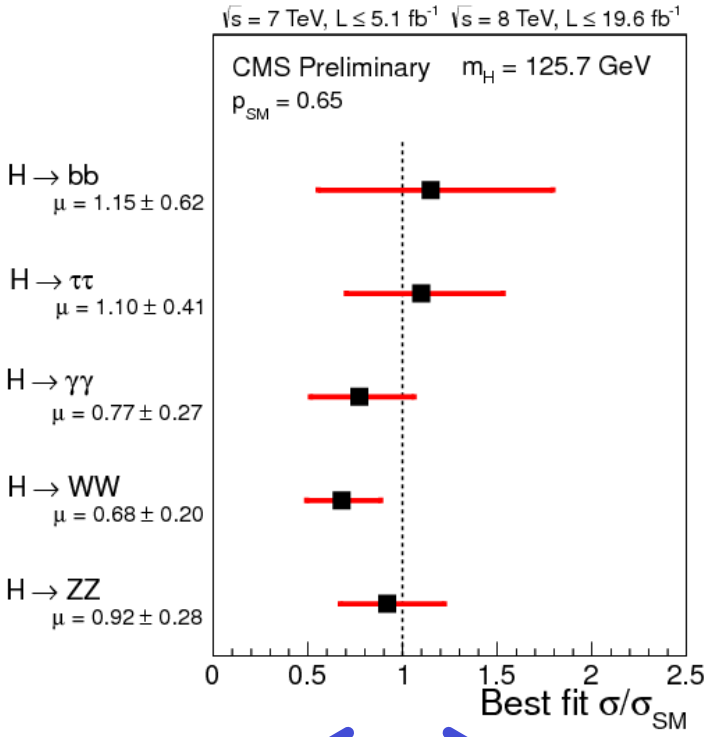
~ 2/3 to industry

- *Valuable expertise in many areas, …*
- *Experience working in a global collaboration*

Overview of Future LHC Physics and Detector Upgrades

Higgs Boson Coupling Measurements

Current Results on signal strength compared to SM



±50%

Observable number of Higgs events per LHC experiment

	Run-1	HL-LHC
H→4leptons	20	4,000
H→γγ	350	130,000
VBF H→ττ	50	20,000

Deviation of Higgs couplings from SM due to particles with M=1 TeV

Model	κ_V	κ_b	κ_γ
Singlet Mixing	$\sim 6\%$	$\sim 6\%$	$\sim 6\%$
2HDM	$\sim 1\%$	$\sim 10\%$	$\sim 1\%$
Decoupling MSSM	$\sim -0.0013\%$	$\sim 1.6\%$	$\sim -.4\%$
Composite	$\sim -3\%$	$\sim -(3-9)\%$	$\sim -9\%$
Top Partner	$\sim -2\%$	$\sim -2\%$	$\sim +1\%$

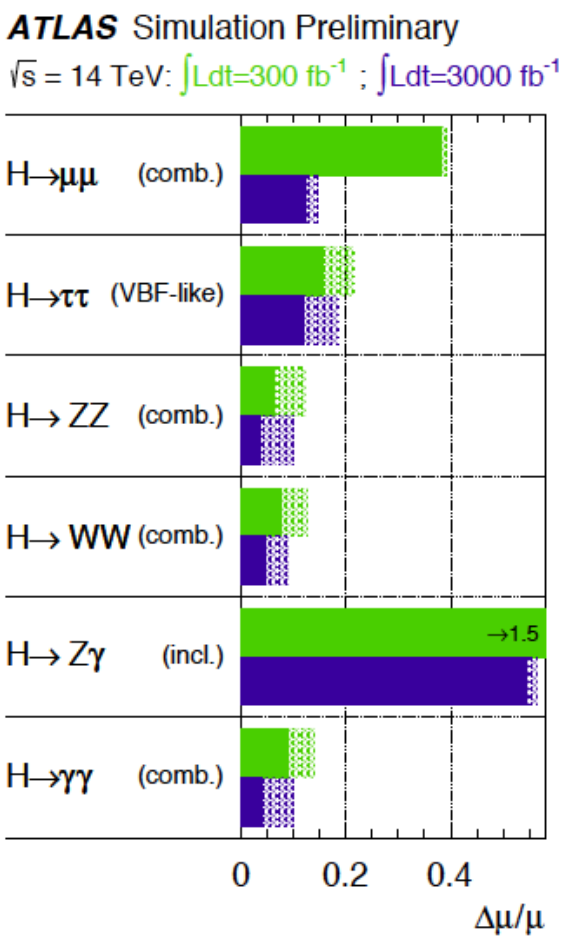
Higgs Snowmass report (arXiv:1310.8361)

- Run 1 precision on σ/σ_{SM} about 20-50% (10-25% on couplings)
- HL-LHC will increase Higgs dataset dramatically
- Need coupling precision of ~3% to probe TeV particles in loops

Higgs Boson Coupling Measurements

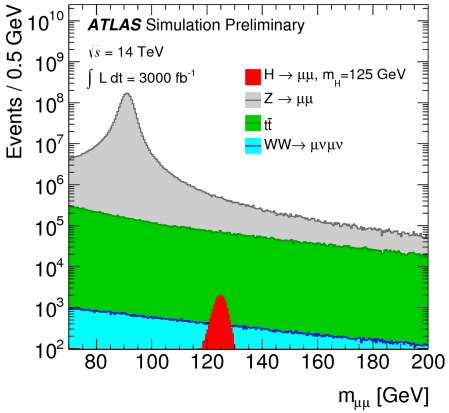
Relative precision on Higgs cross section

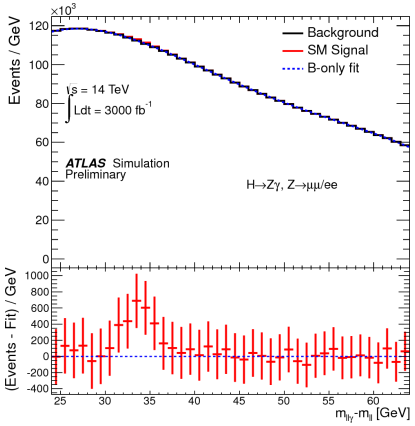
ATLAS-PHYS-PUB-2013-014



Access to rare decays:

- H→μμ: How does it couple to 2nd generation?
- H→Zγ: Is there new physics in loops?





CMS projections for coupling precision (*arXiv:1307.7135*)

L (fb^{-1})	κ_γ	κ_W	κ_Z	κ_g	κ_b	κ_t	κ_τ	$\kappa_{Z\gamma}$	$\kappa_{\mu\mu}$	BR_{SM}
300	[5, 7]	[4, 6]	[4, 6]	[6, 8]	[10, 13]	[14, 15]	[6, 8]	[41, 41]	[23, 23]	[14, 18]
3000	[2, 5]	[2, 5]	[2, 4]	[3, 5]	[4, 7]	[7, 10]	[2, 5]	[10, 12]	[8, 8]	[7, 11]

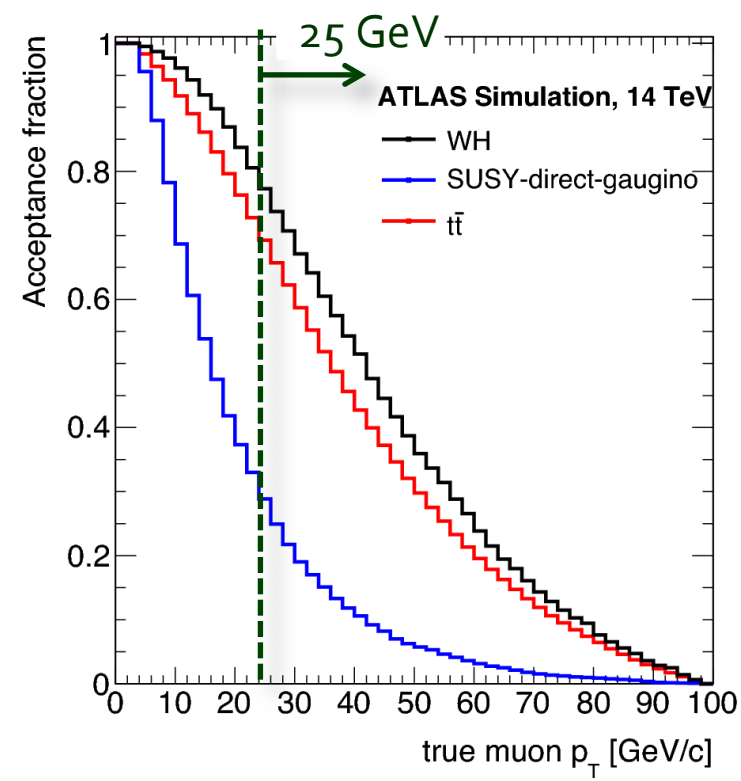
HL-LHC will enable precision Higgs physics:

- probe most couplings with 2-8% precision
  - factor ~3 improvement compared to 300 fb^{-1} LHC
- Access to important rare decays

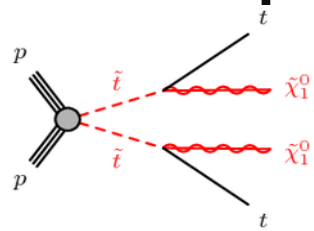
Need for Upgrade to Trigger System

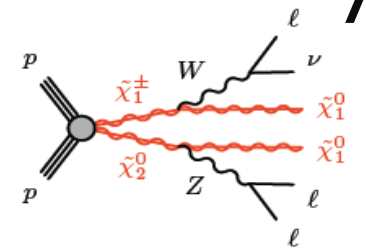
- **Triggering is a major challenge at hadron colliders**
  - Several upgrades already earlier (now and for phase-1) to improve trigger rejection against QCD background
    - $\sigma(H \rightarrow WW \rightarrow l\nu l\nu)/\sigma(pp \rightarrow X) = 1/10^{12}$
- **L1 trigger requirements to keep electroweak scale physics**
  - Maintain e and μ triggers at p_T~25 GeV
  - Maintain τ triggers at L1
  - …
- **Major changes to L1 required for HL-LHC**
  - Increase L1 trigger rate to 500-1000 kHz for HL-LHC
    - Requires upgrades to FE electronics for subsystems
  - Track trigger at L1
    - Different strategies from CMS and ATLAS
  - Upgrades to Muon System
    - Improve p_T resolution and background rejection

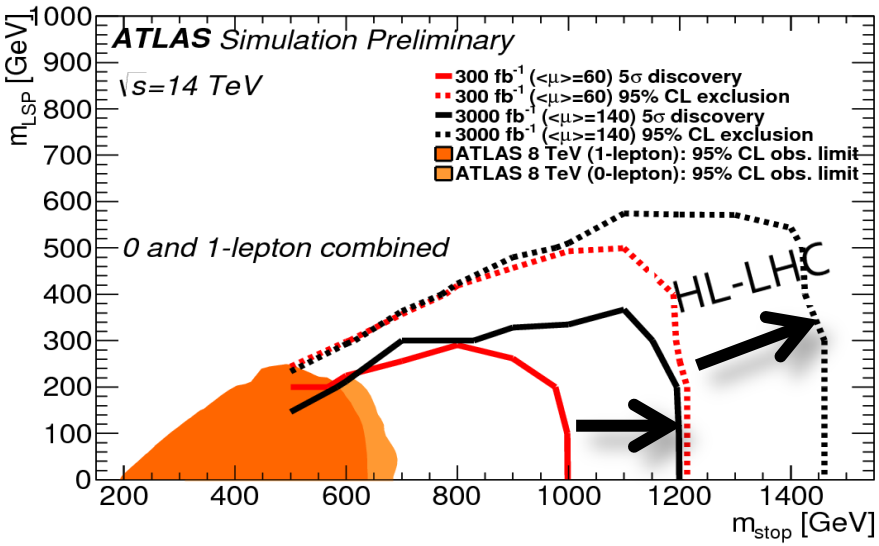
Rates (Hz)		
	Run-2	**HL-LHC**
collision	40×10^6	40×10^6
L0/L1 trigger	10^5	$(0.5\text{-}1.0) \times 10^6$
to disk	10^3	$\sim 10^4$

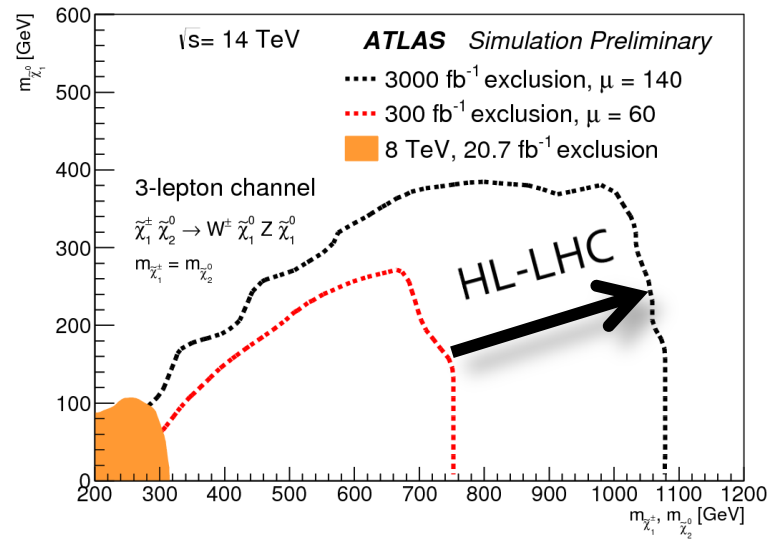


Future Prospects for SUSY Discovery









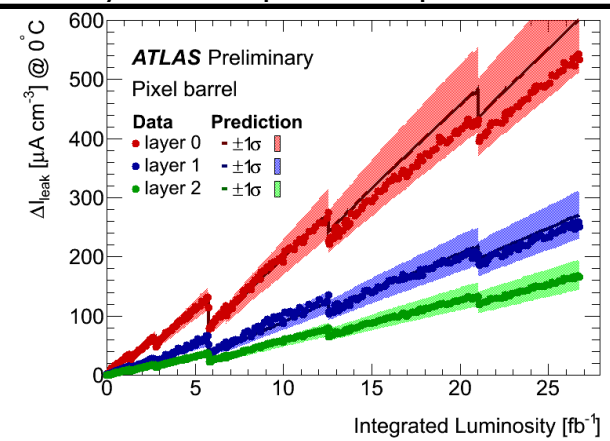
- **HL-LHC enables characterization of any new particles found in runs 2 and 3**
- **HL-LHC significantly extends discovery reach**
  - Probe stop masses up to M~1.5 TeV
  - Probe chargino/neutralino masses up to M~1 TeV
  - Probe gluino masses well beyond 2 TeV

CMS-PAS-FTR-13-014
ATLAS-PHYS-PUB-2013-011

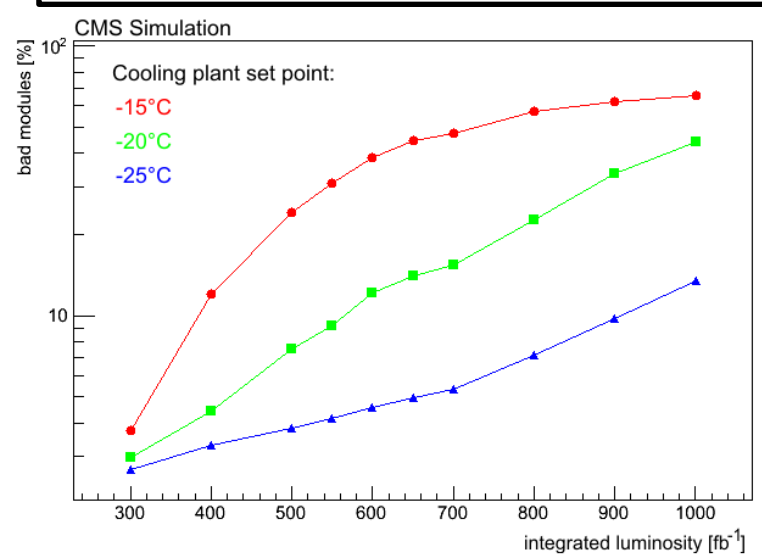
Need for New Tracking Detectors

- **Radiation damage**
  - Increased leakage current
    - Measurements consistent with predictions
  - Cannot operate large fractions of inner detector layers beyond ~500 fb^{-1}
- **Occupancy at 140-200 pileup events** >6 times higher than design
  - Readout inefficiencies due to limited bandwidth
  - Granularity of current trackers not high enough for robust pattern recognition
- **Coverage** limited to |η|<2.5
  - Extending coverage desirable for pileup jet rejection
- Improve **momentum resolution**
  - Benefits e.g. H→μμ search

Observed leakage current in ATLAS Pixel layers compared to prediction

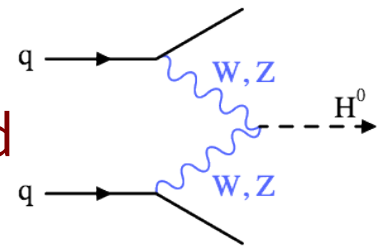


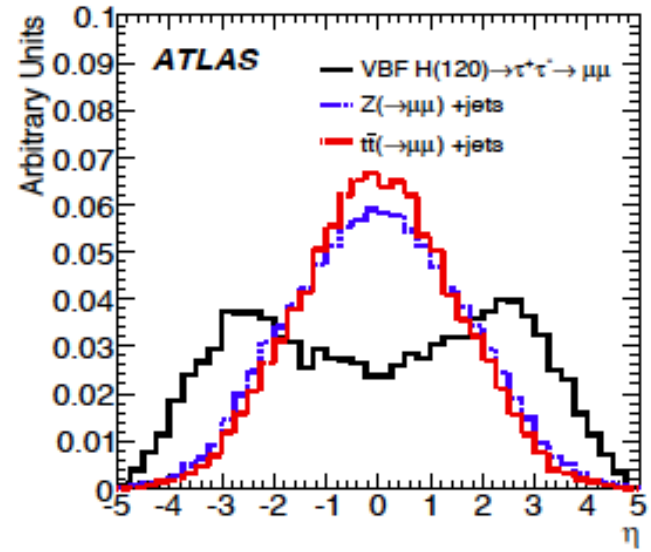
CMS Tracker: significant fraction inoperable beyond 500 fb^{-1} for 20°C

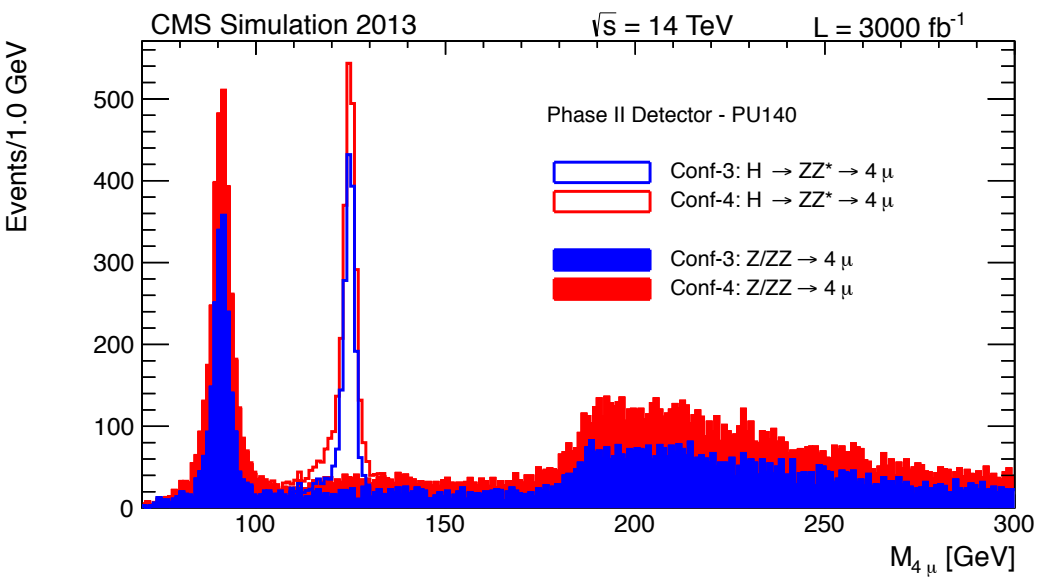


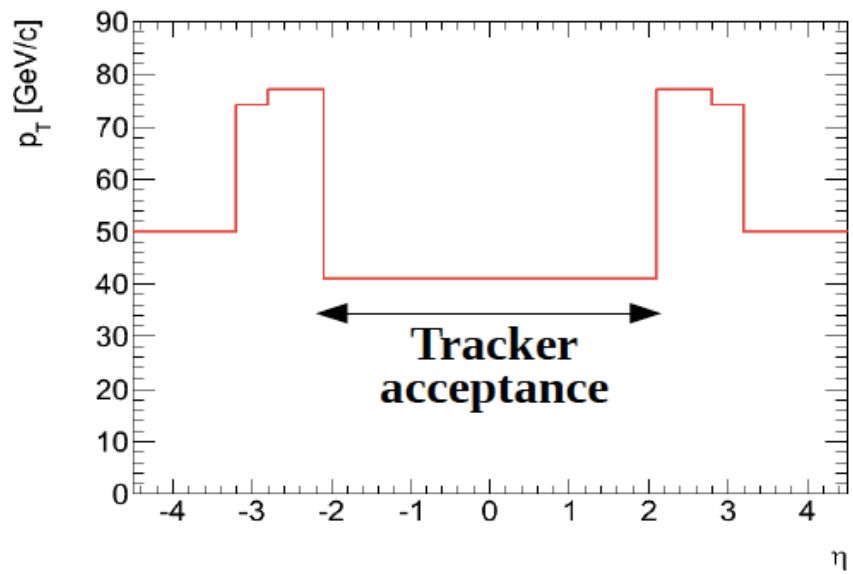
Extended Tracker Coverage

- Extend tracking to |η|>2.5
  - Allows lowering of p_T threshold for forward jets
    - Improves VBF-jet tagging
  - Increase acceptance e.g. for H→4l by ~45%



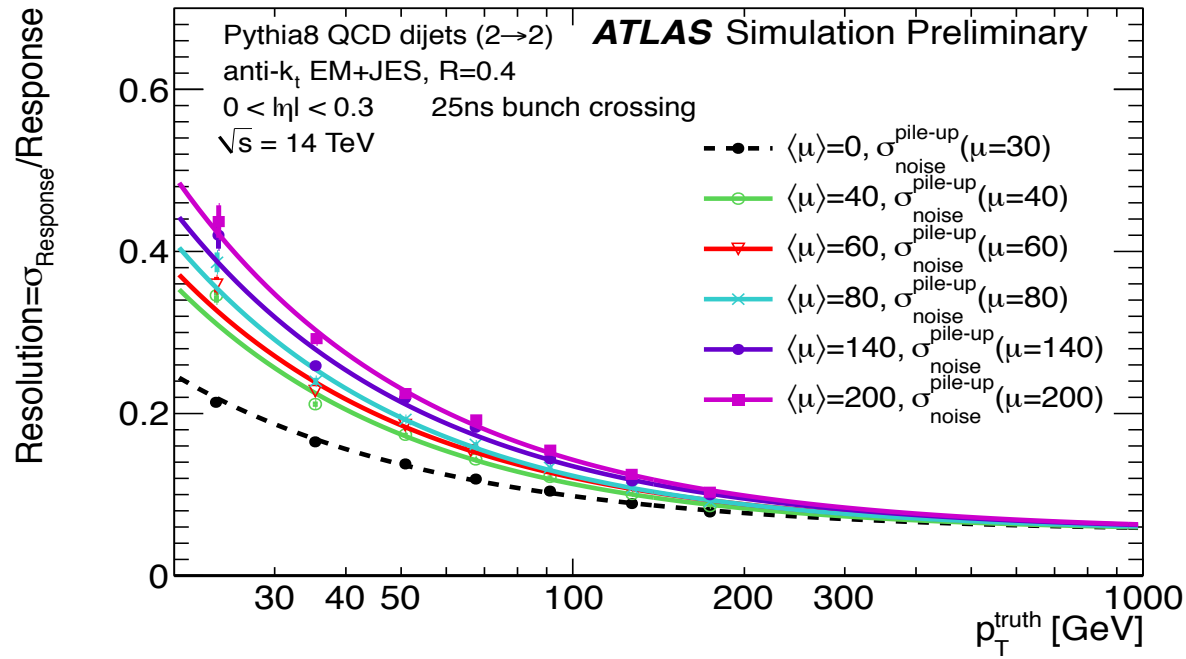




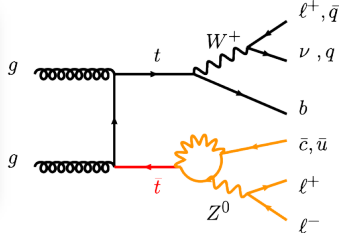


Calorimetry: Jets and E_t^{miss} at high pileup

- **Good Jet and E_T^{miss} resolution needed for Higgs and SUSY program, e.g.**
  - H->bb sensitive to $\sigma(E_{jet})$
  - SUSY sensitive to $\sigma(E_T^{miss})$
- **Requires**
  - Hermetic calorimeters
  - Efficient tracking
    - Pileup rejection
    - Particle flow



- **Studies with current calorimeter at high pileup**:
  - Resolution degrades moderately with increasing pileup
  - Performance still sufficient if current calorimeter and performance can be maintained
- **Requires replacement of endcap or forward calorimeters**



Rare decays, e.g. of the top quark

- **HL-LHC will yield 5x10^8 observable $t\bar{t}$ events per experiment**
- **In SM top quark decays to Wb nearly 100%**
  - Observing decays to other modes clear sign of new physics
  - Interesting range starts at ~10^{-4}
- **HL-LHC will probe ~10^{-5}**

Branching ratios of top decays in new physics models
From snowmass top group report (arXiv:1311.2028)

Process	SM	2HDM(FV)	2HDM(FC)	MSSM	RPV	RS
$t \to Zu$	7×10^{-17}	–	–	$\leq 10^{-7}$	$\leq 10^{-6}$	–
$t \to Zc$	1×10^{-14}	$\leq 10^{-6}$	$\leq 10^{-10}$	$\leq 10^{-7}$	$\leq 10^{-6}$	$\leq 10^{-5}$
$t \to gu$	4×10^{-14}	–	–	$\leq 10^{-7}$	$\leq 10^{-6}$	–
$t \to gc$	5×10^{-12}	$\leq 10^{-4}$	$\leq 10^{-8}$	$\leq 10^{-7}$	$\leq 10^{-6}$	$\leq 10^{-10}$
$t \to \gamma u$	4×10^{-16}	–	–	$\leq 10^{-8}$	$\leq 10^{-9}$	–
$t \to \gamma c$	5×10^{-14}	$\leq 10^{-7}$	$\leq 10^{-9}$	$\leq 10^{-8}$	$\leq 10^{-9}$	$\leq 10^{-9}$
$t \to hu$	2×10^{-17}	6×10^{-6}	–	$\leq 10^{-5}$	$\leq 10^{-9}$	–
$t \to hc$	3×10^{-15}	2×10^{-3}	$\leq 10^{-5}$	$\leq 10^{-5}$	$\leq 10^{-9}$	$\leq 10^{-4}$

95% CL upper limits expected per experiment

Decay mode	BR limit at 95% CL
$t \to q\gamma$	1.3×10^{-5}
$t \to qZ$	4.1×10^{-5}
$t \to cZ$	1.0×10^{-5}
$t \to cH$	1.4×10^{-4}

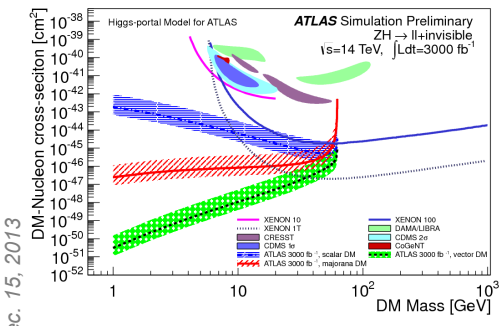
CMS-PAS-FTR-13-016
ATLAS-PHYS-PUB-2013-007
ATLAS-PHYS-PUB-2013-012

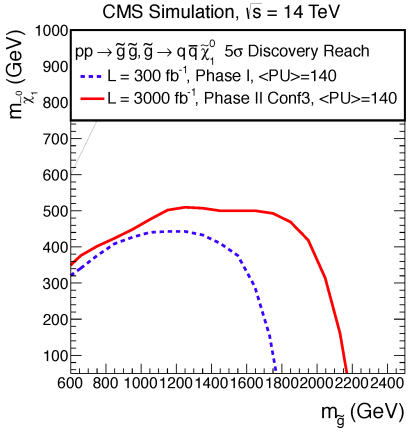
From Physics to Detector Requirements

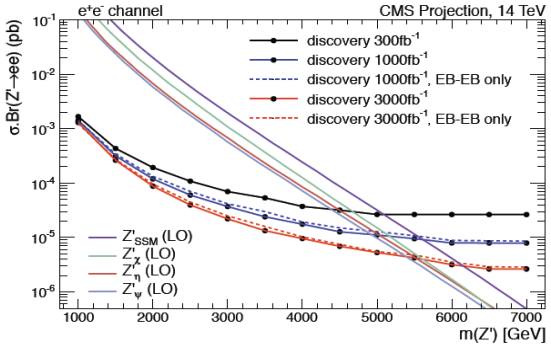
Needed	H->WW	H->4l	H->ττ	H->bb	VBS	SUSY stop	SUSY 3l	top	Extra Dim.	Primary Upgrade need
Low p_T leptons	✓	✓	✓		✓	✓	✓	✓		Trigger (L1 rate)+ electronics+ muon system upgrades
Tau's			✓				✓			Trigger upgrade (L1+HLT)+ track trigger
b-jet tag				✓		✓		✓	✓	Low mass precision tracker
Jet energy resolution				✓				✓	✓	Good calorimeter + efficient tracker (for particle flow)
Forward jets	✓	✓	✓		✓					Fwd. calorimeter+tracker
E_T^{miss} resolution	✓					✓	✓	✓	✓	Hermetic calorimeter + efficient tracking
High lepton acc.		✓					✓			Fwd. tracking + fwd. calorimeter

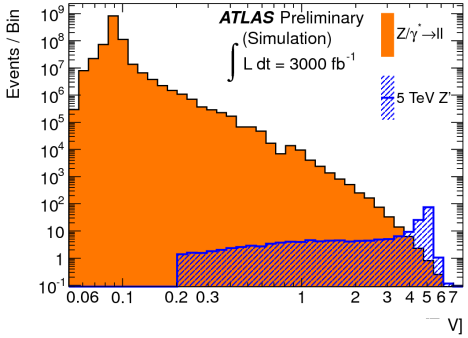
- **Higgs analysis alone require significant upgrades to detectors**
  - Maintain sensitivity similar to run-1 at high pileup expected for HL-LHC
- **All these upgrades also benefit a huge variety of other analyses**

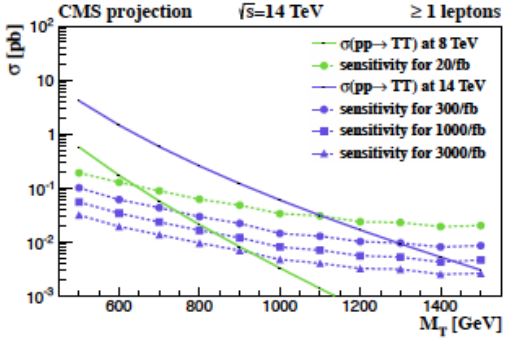
And so much more HL-LHC physics…

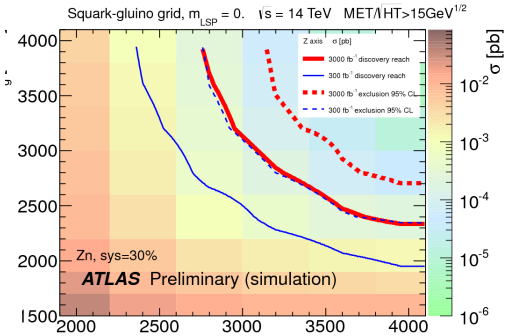


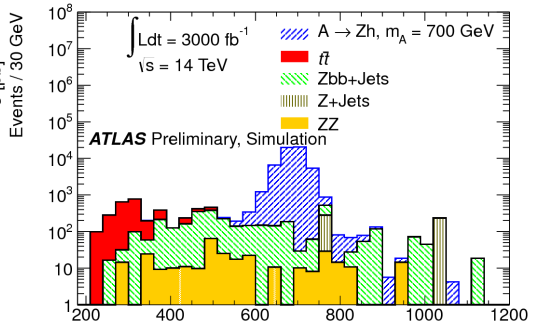


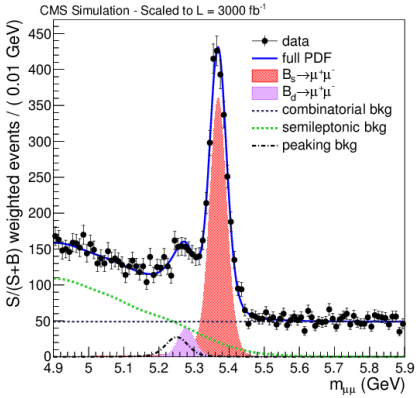


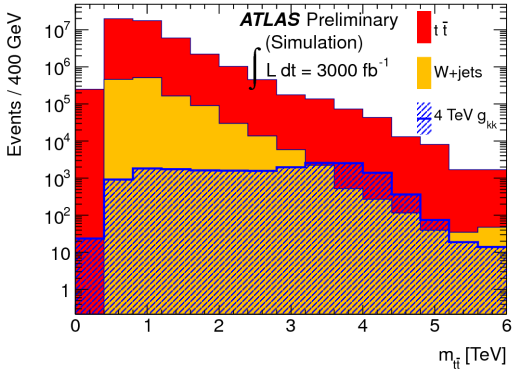


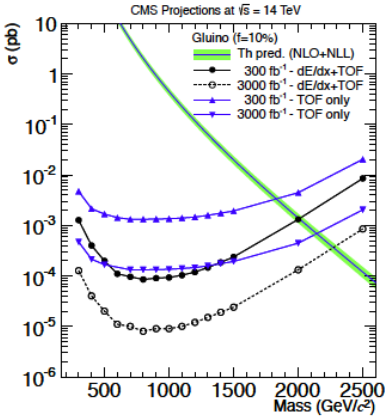


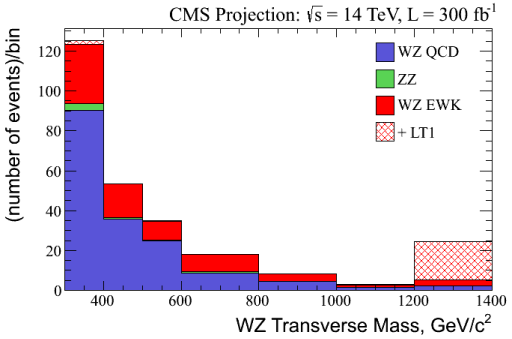


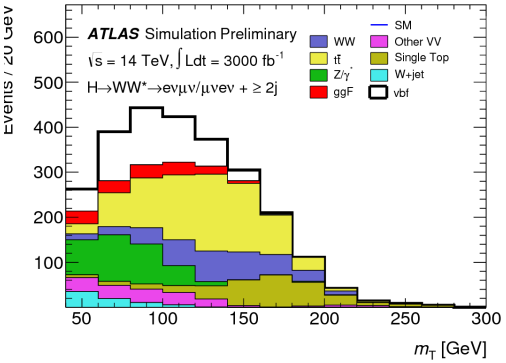












Summary and Conclusions I

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  - Why is there a low-mass Higgs boson in Nature? Is the electroweak scale natural? Are there new particles at TeV scale that explain the electroweak scale?
- **LHC directly probes TeV scale and will dramatically improve sensitivity during Runs 2, 3, and HL-LHC at 13-14 TeV**
  - Indirectly probe TeV scale particles via precision measurements and rare decay searches
    - Higgs coupling precision will improve by an order of magnitude
    - Rare decays of Higgs boson, top quark, …
  - Directly search for TeV scale particles
    - Searches for new types of fermions or bosons (e.g. SUSY, Extra Dim., …)
    - Search for the unexpected, Nature may have surprises for us!

Summary and Conclusions II

- **HL-LHC requires a significant new investment**
  - Upgrades to LHC, injectors, and ATLAS and CMS detectors needed
    - Powerful detectors needed to fully exploit LHC luminosity
    - Diverse set of detector requirements based on physics goals
    - Technology choices still under study => need to converge by ~2016

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Major Physics is guaranteed at HL-LHC!

The End

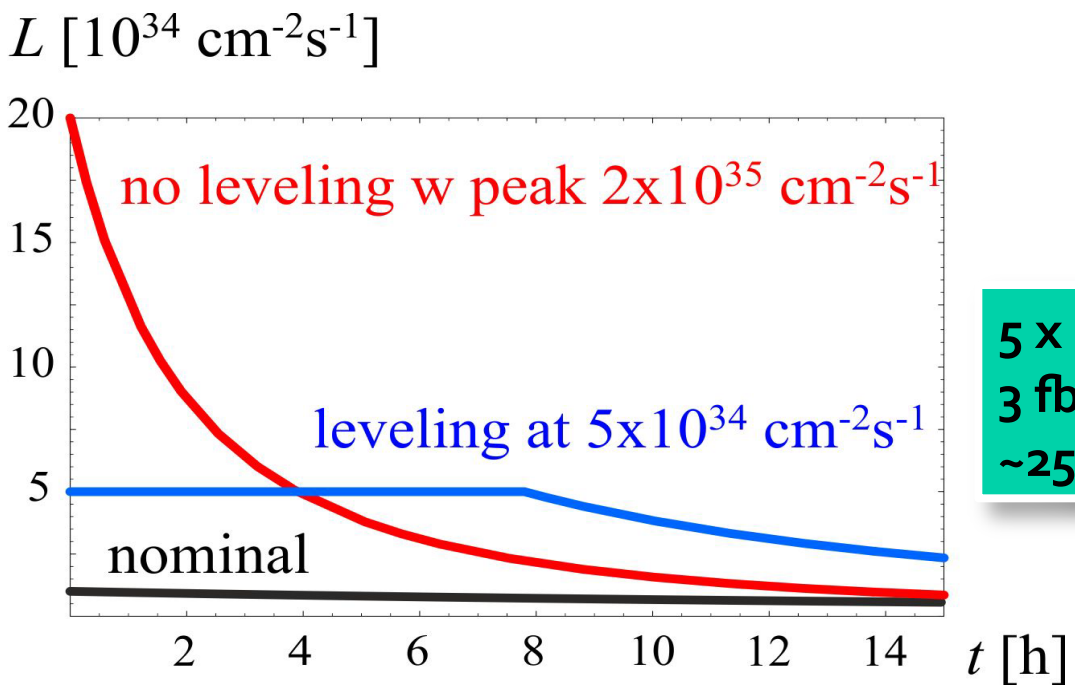
Backup Slides

LHC Schedule beyond LS1

LHC schedule approved by CERN management and LHC experiments spokespersons and technical coordinators Monday 2nd December 2013

HL-LHC

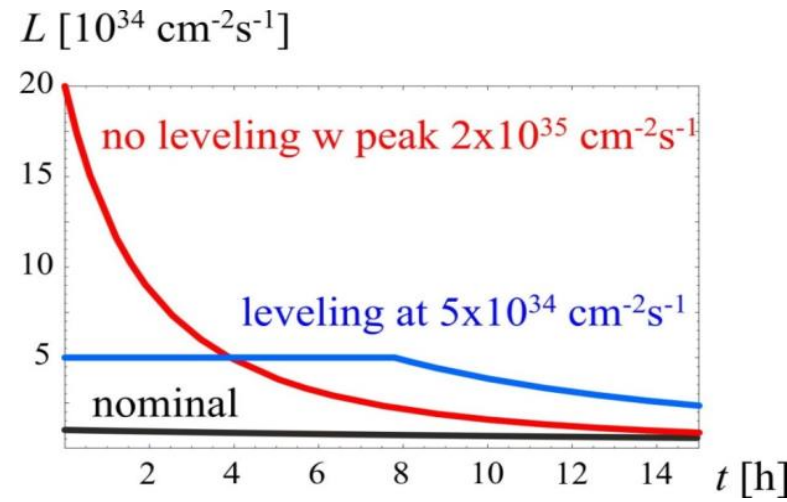
- 3000 fb^{-1} delivered in the order of 10 years
- High "virtual" luminosity with levelling anticipated
- Challenging demands on the injector complex
  - major upgrades foreseen (Linac 4, Booster 2GeV, PS and SPS)



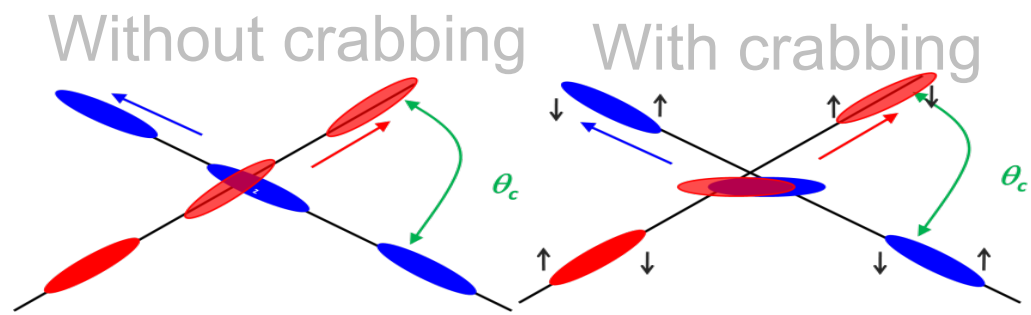
5 x 10^{34} $cm^{-2}s^{-1}$ levelled luminosity
3 fb^{-1} per day
~250 fb^{-1} /year

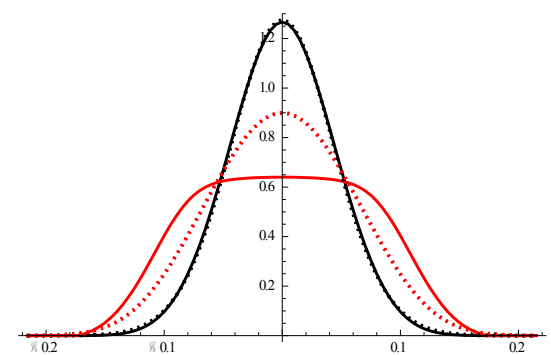
HL-LHC Collision Region

- Luminosity leveling reduces pileup in experiments
  - 5×10^{34} cm^{-2}s^{-1} corresponds to ~140 pileup interactions
  - Exact amount of pileup tolerable by experiments still under discussion
    - Can experiments tolerate 200? Or more?

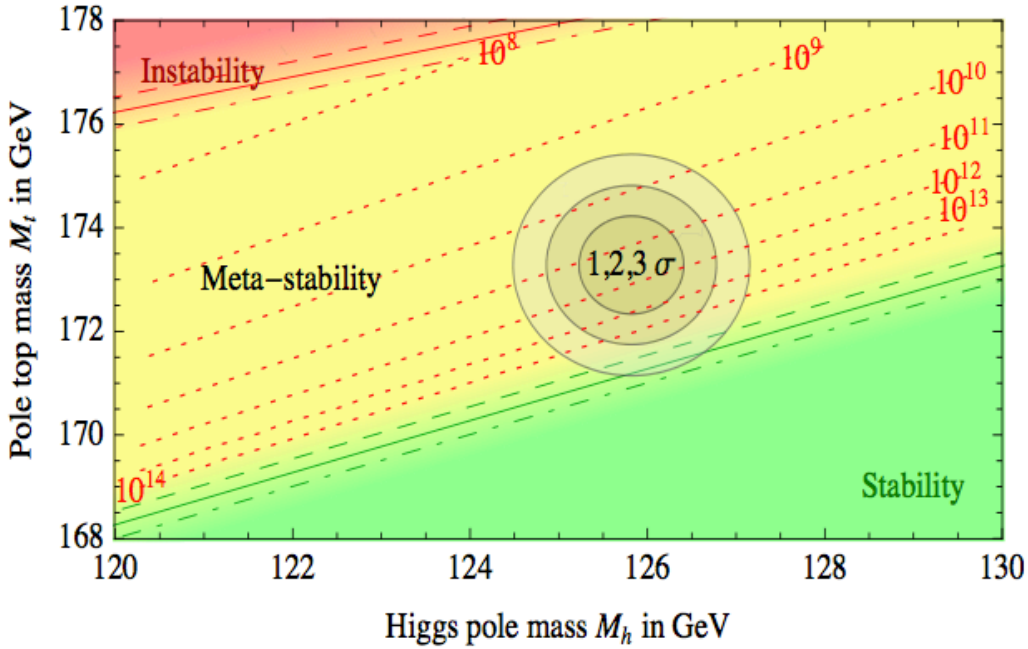


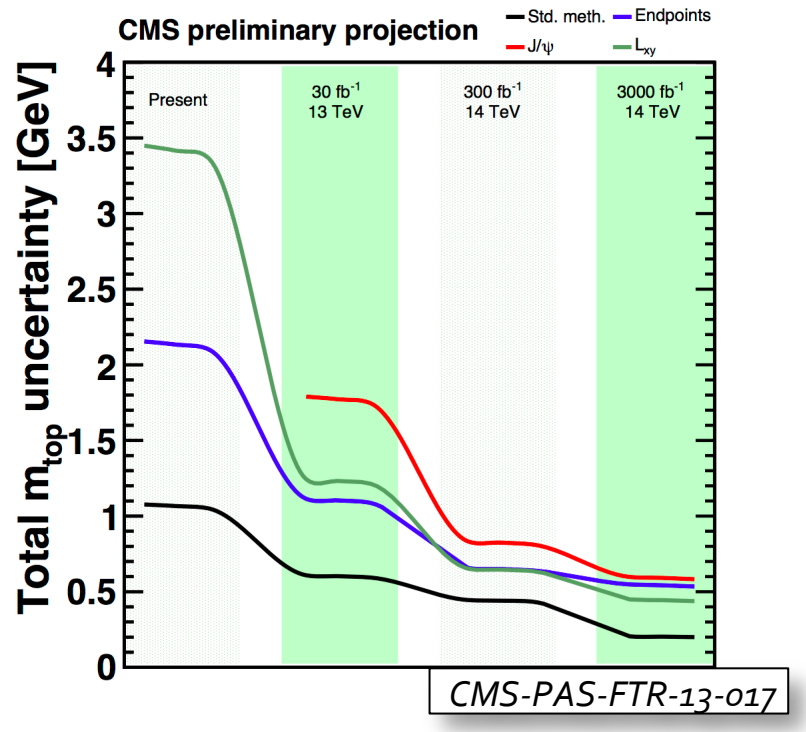
- Introduce crab cavities rotate beams to increase fraction of collisions per bunch
- Shape of luminous region still under discussion
  - Try to minimize peak vertex density





Precision Mass Measurements

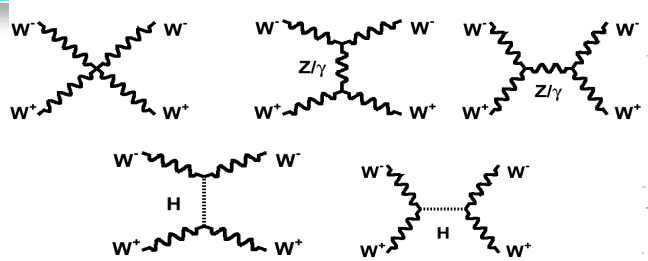




CMS-PAS-FTR-13-017

- Precision measurements of Higgs, top and W mass
  - Understand if measurements are fully consistent within EWK SM
  - How stable is the Universe?
- Expect from HL-LHC
  - $\Delta m_H \approx 50$ MeV, $\Delta m_{top} \approx 200$ MeV, $\Delta m_W \sim 6$ MeV

How do bosons interact with each other?



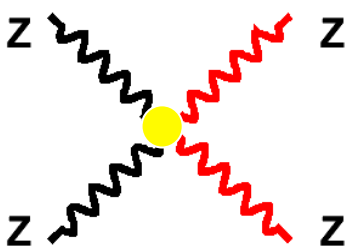
$$A \approx g^2 \frac{E^2}{M_W^2}$$

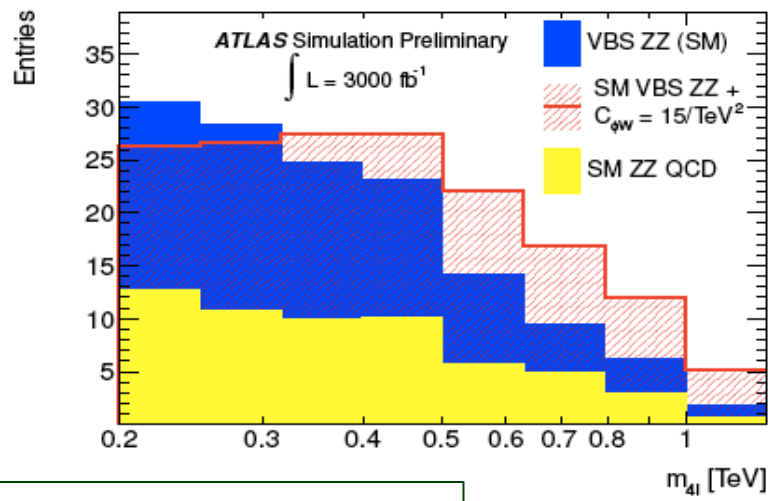
$$A \approx -g^2 \frac{E^2}{M_W^2}$$

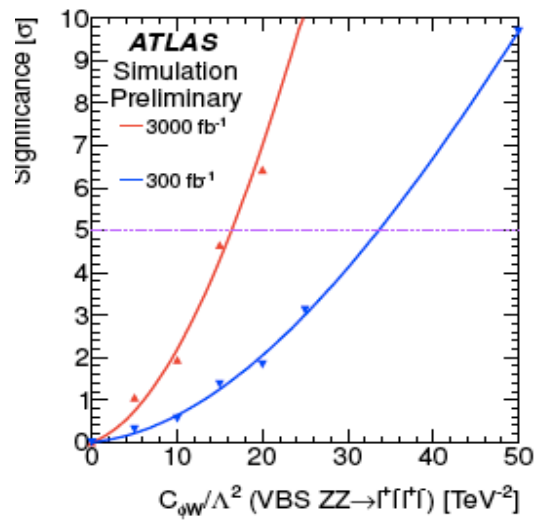
Terms which grow with energy cancel for E >> M_H

This cancellation requires M_H < 800 GeV

- In SM there is an exact cancellation between terms for longitudinal vector boson scattering
  - Without presence of Higgs it grows faster than total x-section
- LHC allows for the first time study of quartic gauge boson couplings



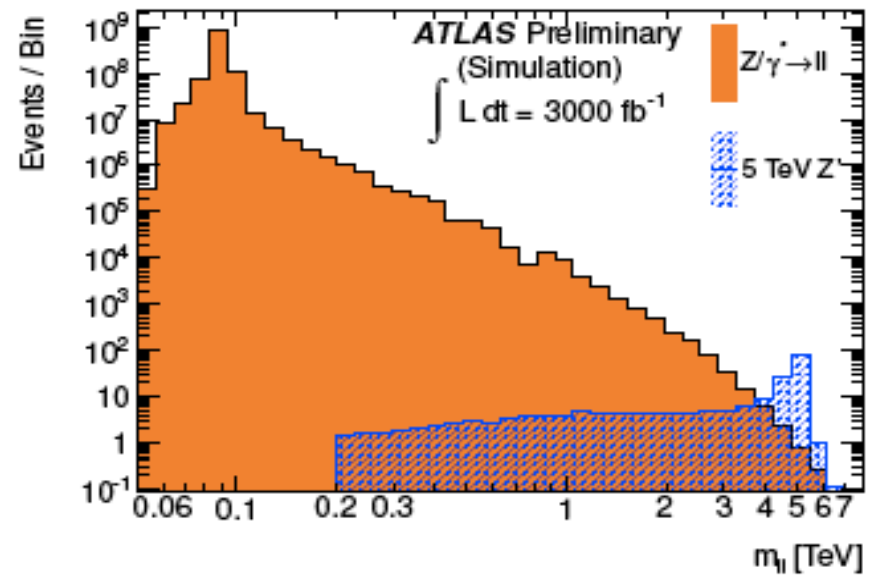


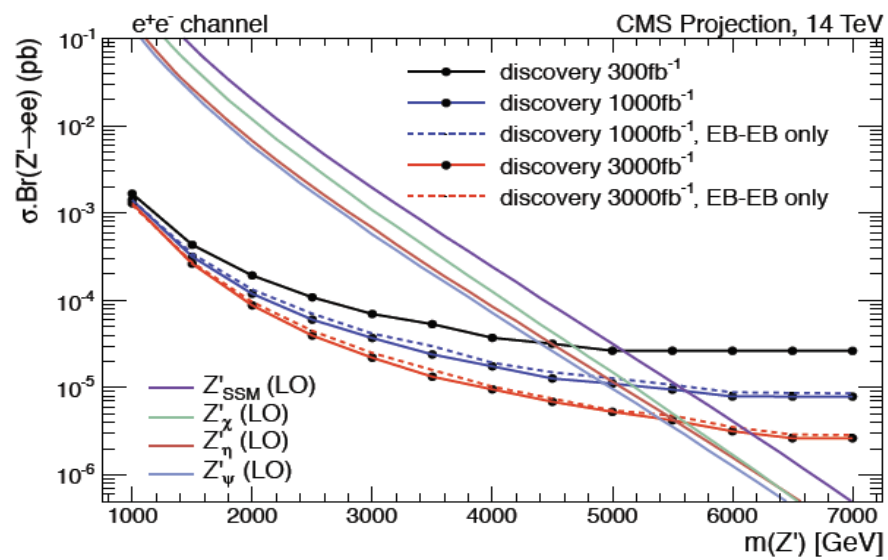


ATLAS-PHYS-PUB-2013-006, CMS-PAS-FTR-13-06

Dilepton resonances: limit and discovery

- Current limits are on σxBR are ~0.3 fb
  - Exclude Z'_{SSM} up to ~3 TeV
- Expect to improve by a factor of ~100 with HL-LHC
  - Discover Z'_{SSM} up to masses of 6.4 TeV



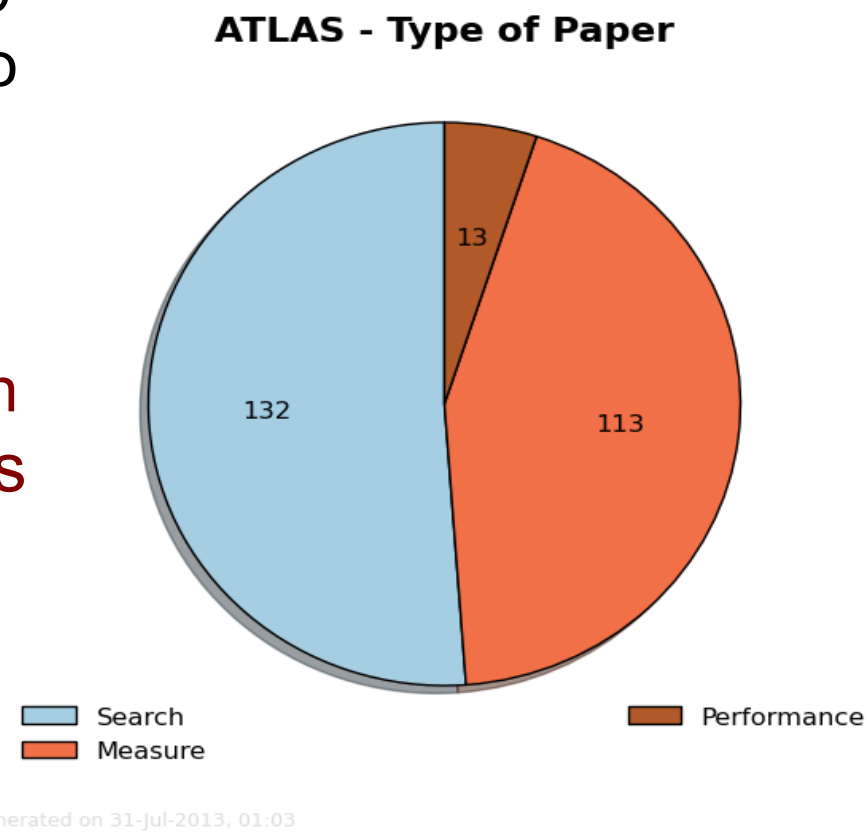


5 σ discovery of:		
	Z'_{SSM} ee	Z'_{SSM} μμ
300 fb^{-1}	5.1 TeV	5.2 TeV
3000 fb^{-1}	6.2 TeV	6.4 TeV

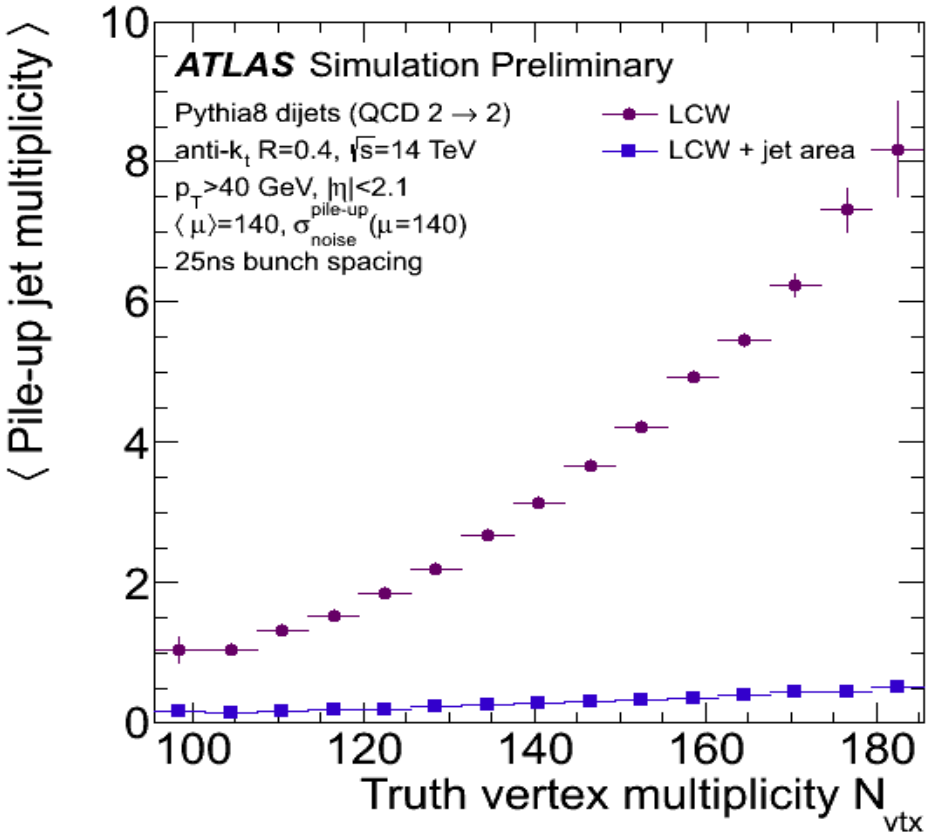
arXiv:1307.7135, ATLAS-PHYS-PUB-2013-007

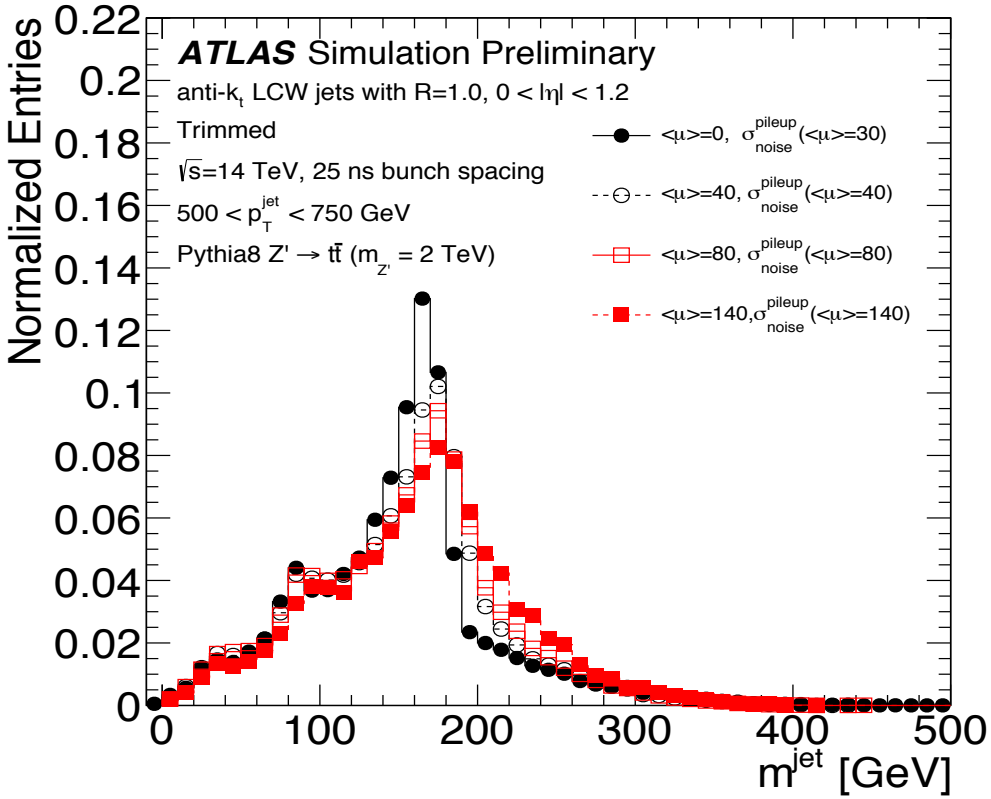
Run-1 Publications

- ATLAS and CMS have published >550 papers based on run-1 collision data to date
  - Split about 50/50 between searches and measurements
  - Expect >100 more per experiment on run-1 data as 7 and 8 TeV analyses finish…
  - Behind every paper there is a PhD thesis!
    - Often more than one…
- Huge interest in the field
  - Higgs observation papers have ~2000 citations each
    - they are merely 1.5 years old!



Jet counting and substructure at high pileup

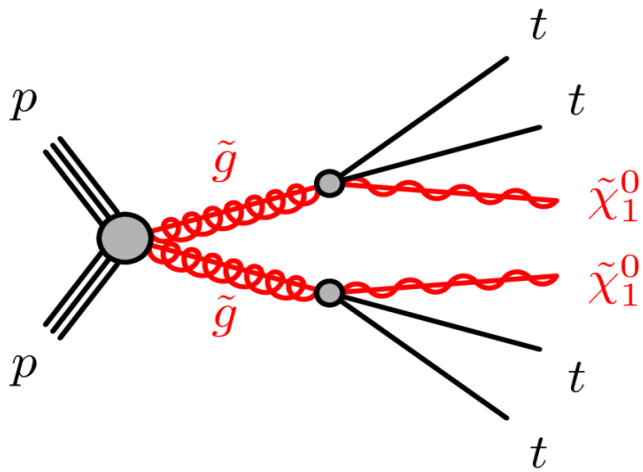




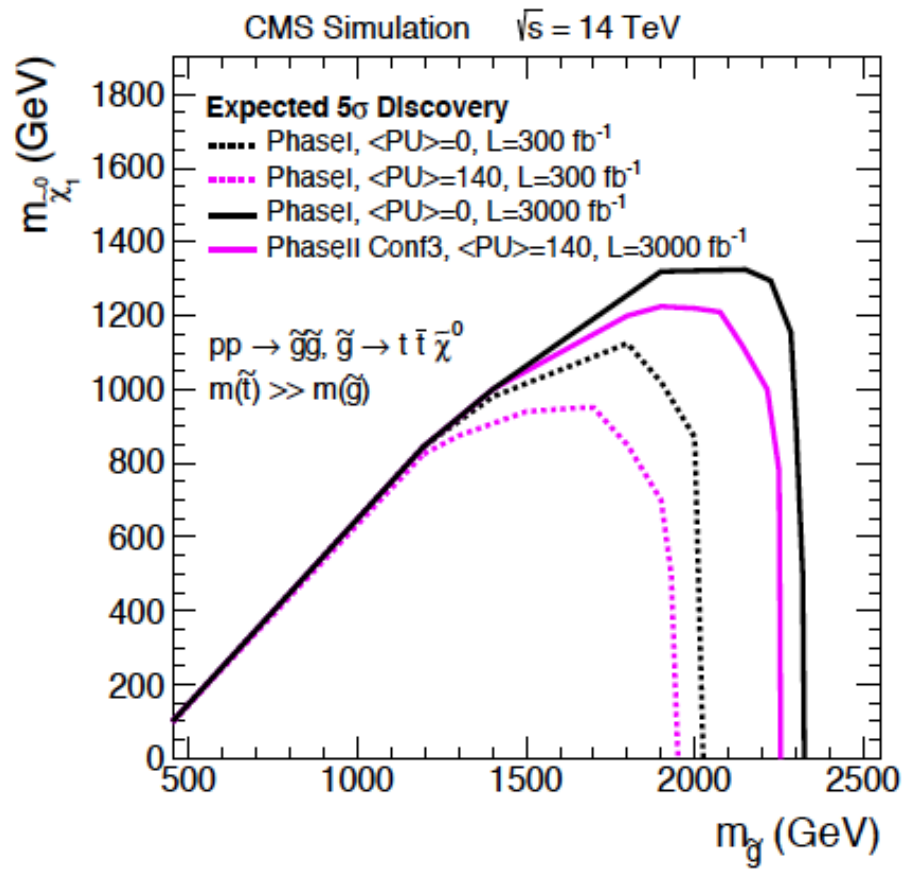
- Jet multiplicity is controlled with clever pileup suppression techniques
- Jet substructure can still be resolved thanks to “trimming” techniques
  - Important for searches with boosted massive objets (e.g. top, W, H)

B. Heinemann and J. Incandela

Gluino reach if decay via top

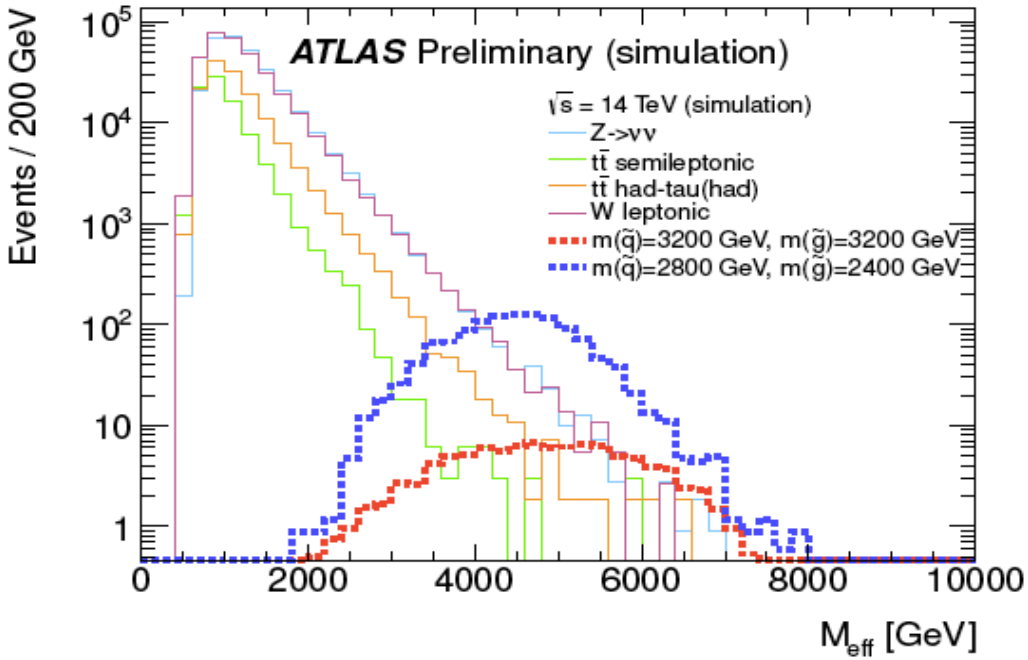


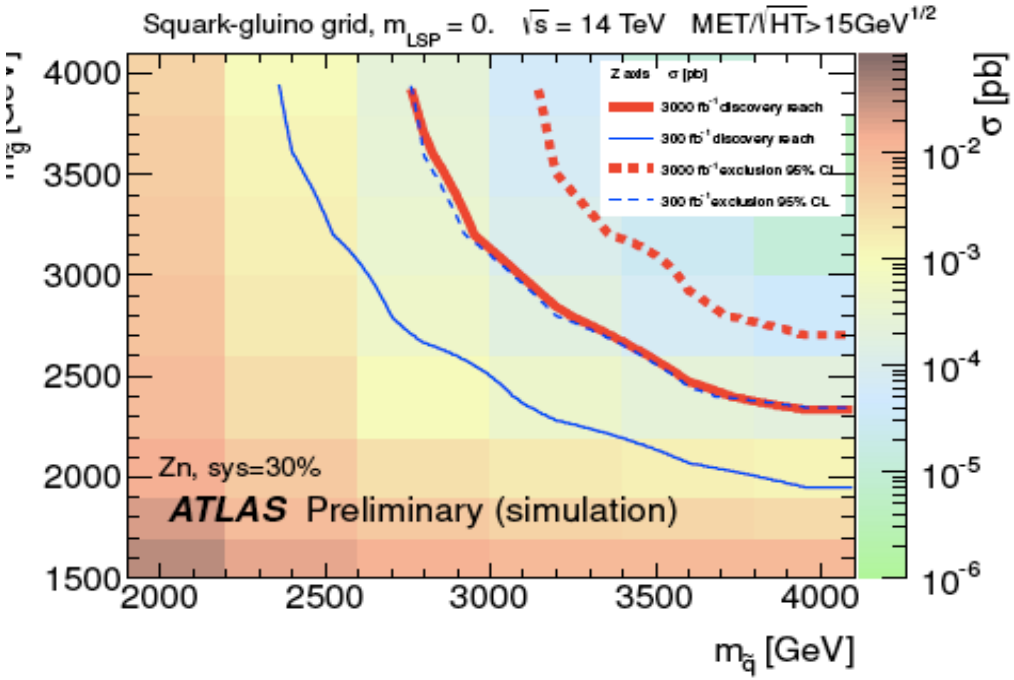
CMS-PAS-FTR-13-014



- With 3000 fb^{-1} will reach about 2.2 TeV in gluino mass both in top-decay signature

Generic Squarks and Gluinos



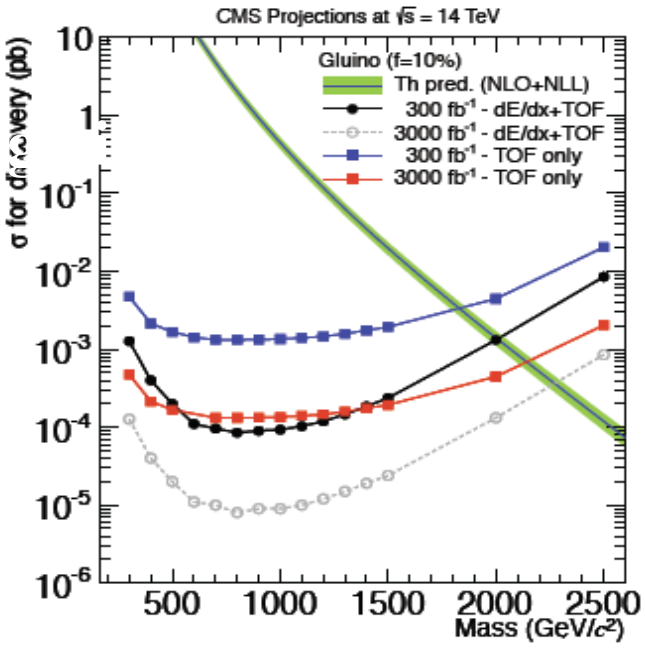


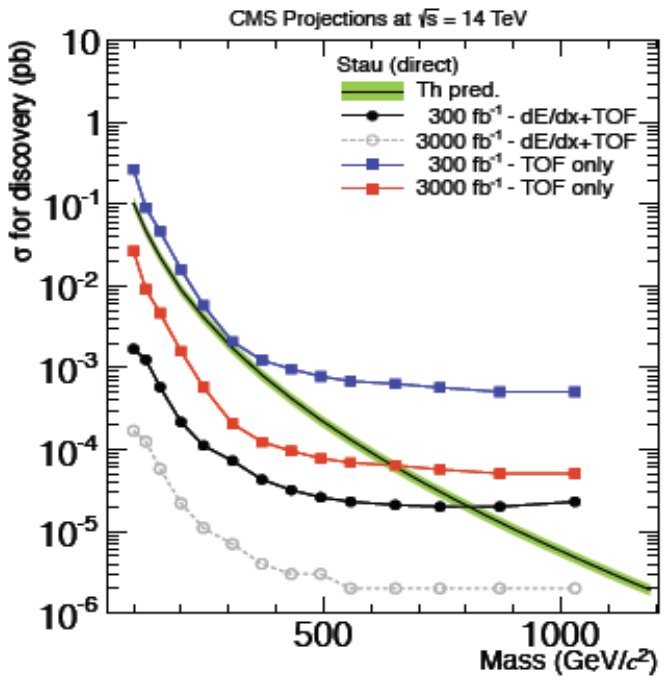
- Search for large E_T^{miss} and large M_{eff}
- Current limit ~1.2 TeV at 95% CL:
  - Will be extended to 2.3 (2.7) TeV with LHC (HL-LHC) if we don't discover it
- Discovery potential extended by 400 GeV with HL-LHC

ATLAS-PHYS-PUB-2013-007, CMS-PAS-FTR-13-014

Metastable Gluinos and Staus

- Metastable sparticles occur in many scenarios of new physics
  - E.g. Split-SUSY gluino, GMSB stau, ….

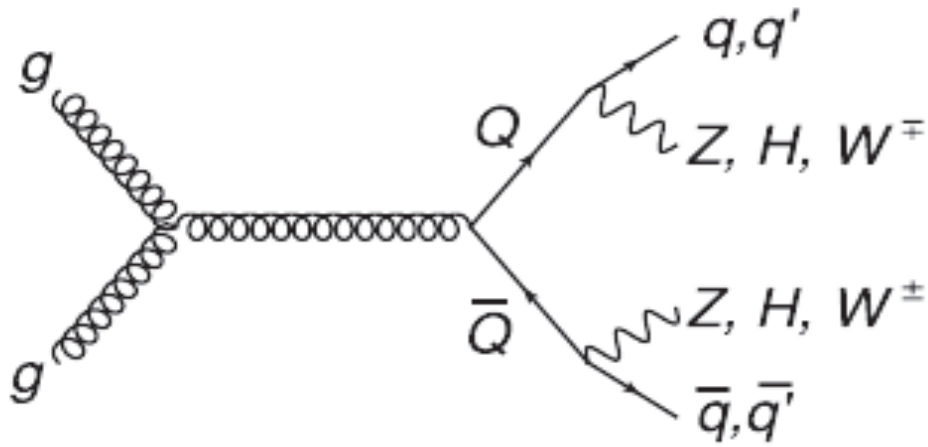


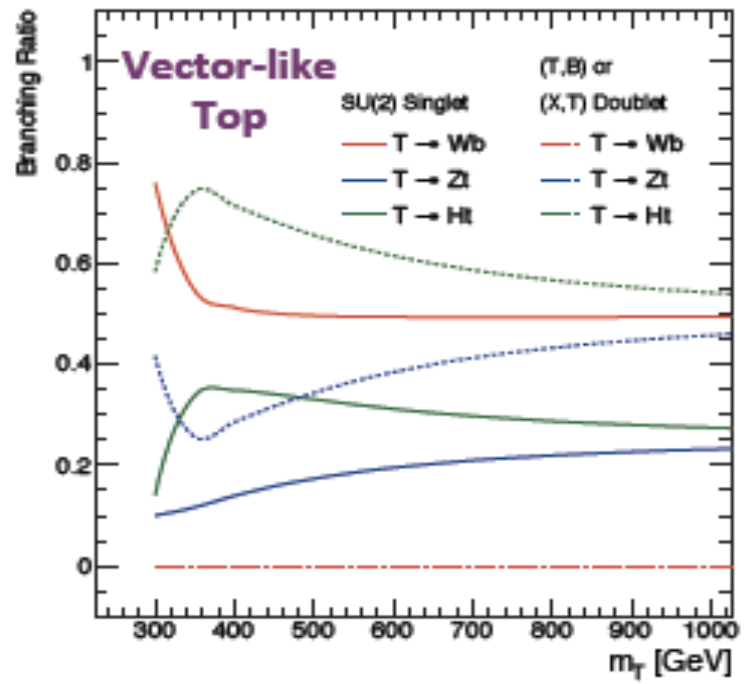


	$M(\tilde{g})$ [TeV]	$M(\tilde{\tau})$ [TeV]
Run-1 data 95% CL limit	>1.0	0.27
300 fb^{-1} 5σ discovery	1.8-2.0	~0.8
3000 fb^{-1} 5σ discovery	2.1-2.3	~1.2

arXiv:1307.7135

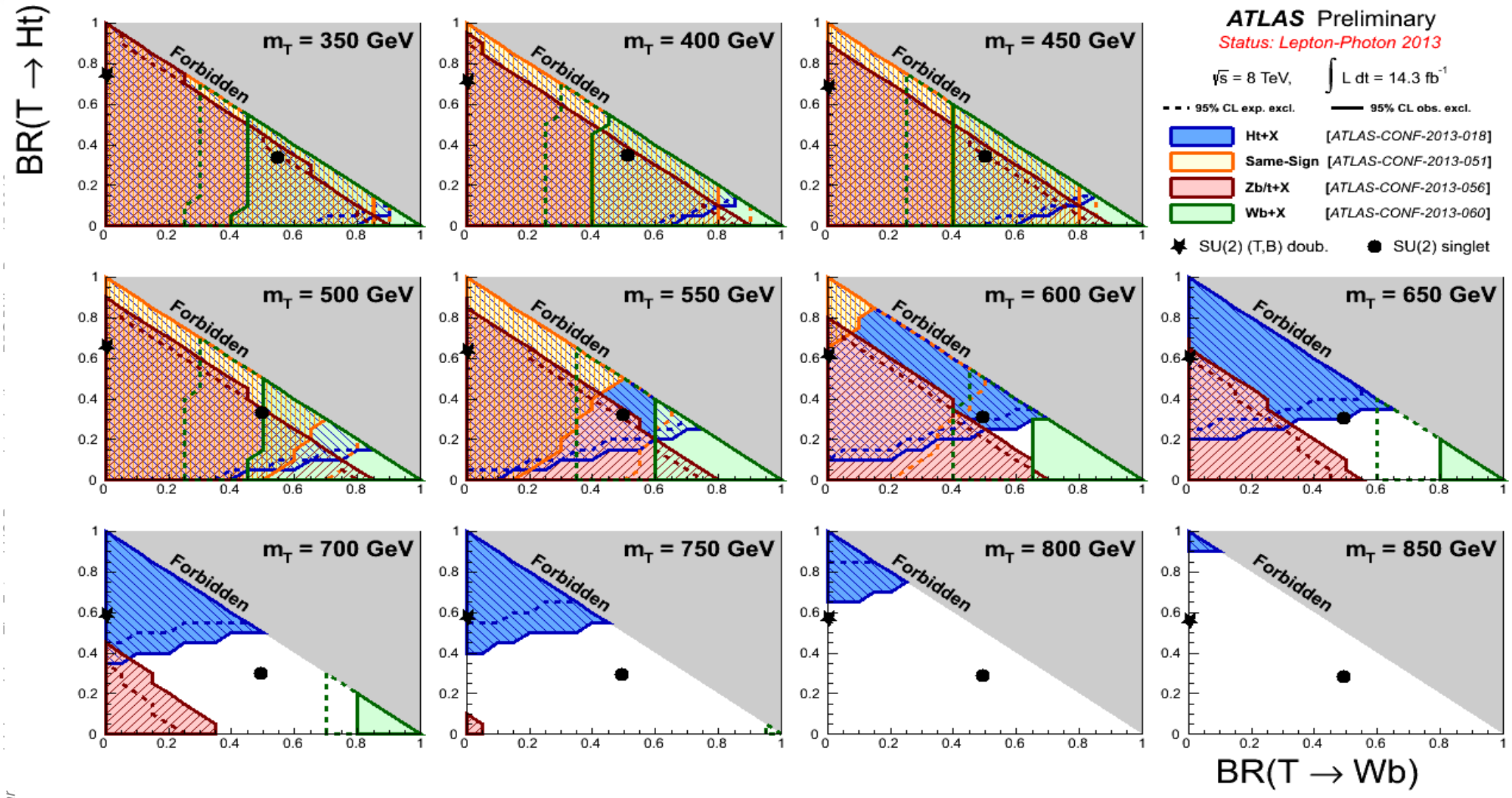
Vector-like Top Quarks





- Colored spin-1/2 fermions
  - transform the same for left- and right-handed under EW gauge group
- Provide alternative solution to little hierarchy problem
- Appear in many BSM models, e.g.
  - Little Higgs, Extra Dimensions,…

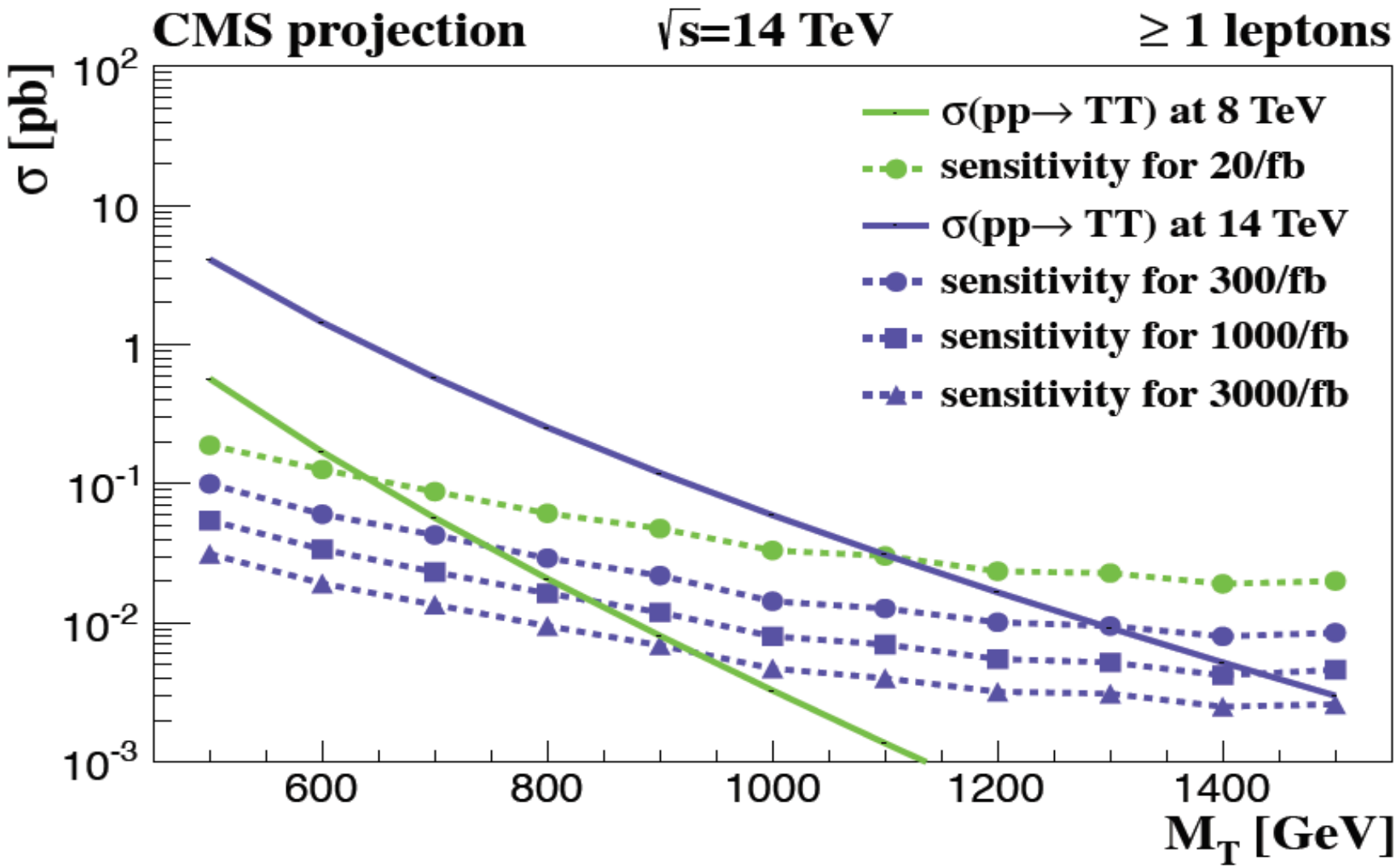
Vector-like Top: Run-1 Data



Currently probing up to about 600-800 GeV

B. Heinemar

Vector-like Top: future



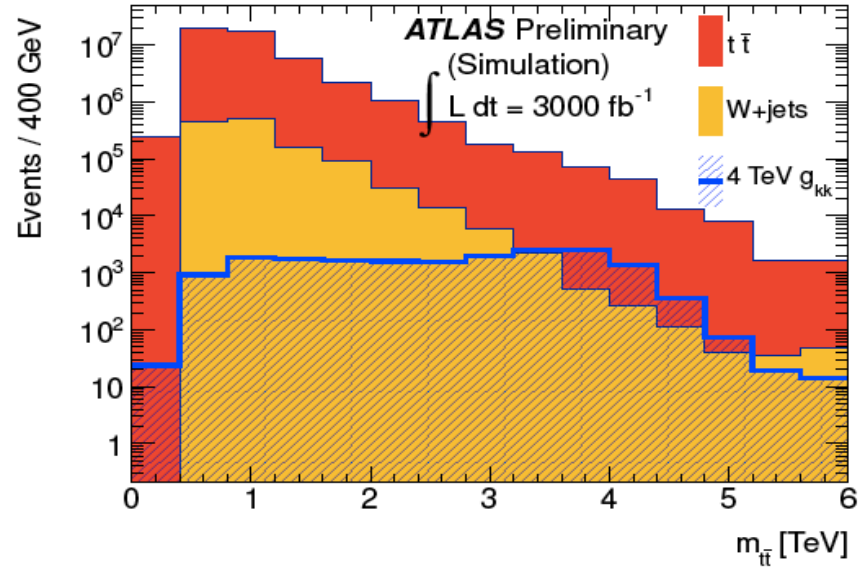
- Probe >1.5 TeV with 3000 fb^{-1}

arXiv:1307.7135

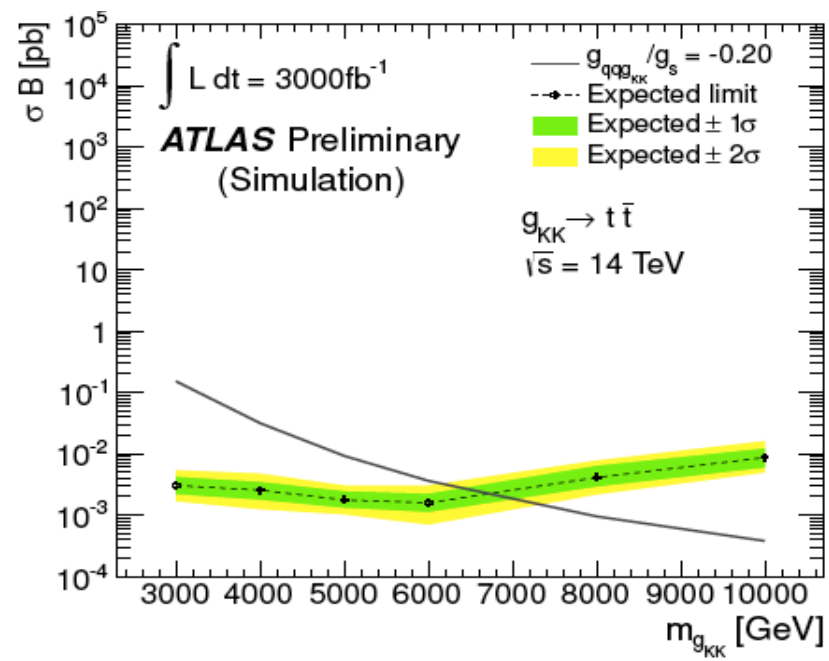
Ditop resonances: limits

- Current limits are on σxBR are ~0.1 pb
  - Expect to improve by a factor of ~100 with HL-LHC
  - Probe KK gluons up to masses of ~6.7 TeV

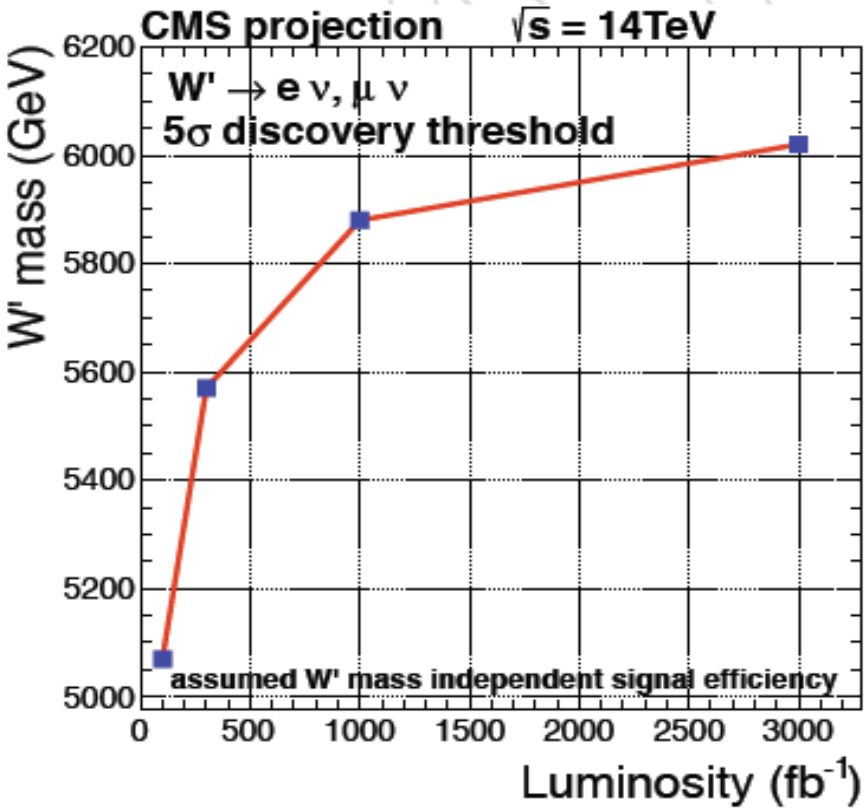
ATLAS-PHYS-PUB-2013-007

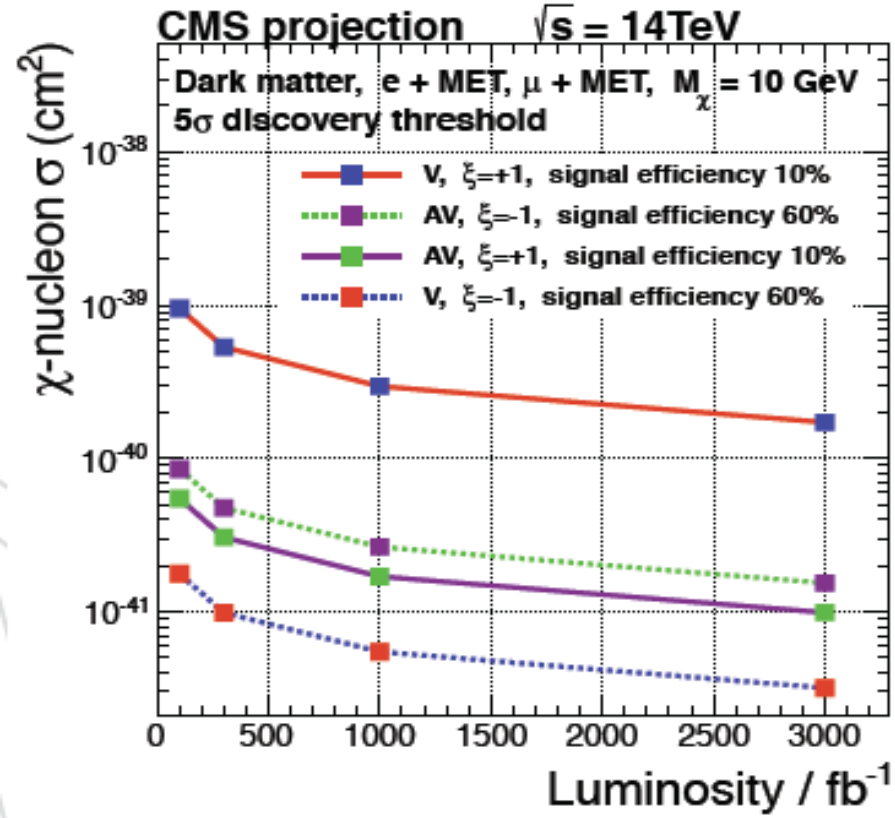


95% CL limits on:		
	Z′ (TeV)	g_{KK} (TeV)
Run-1 data	1.8	2.0
300 fb^{-1}	3.3	4.3
3000 fb^{-1}	5.5	6.7



Monoleptons: W' and Dark Matter

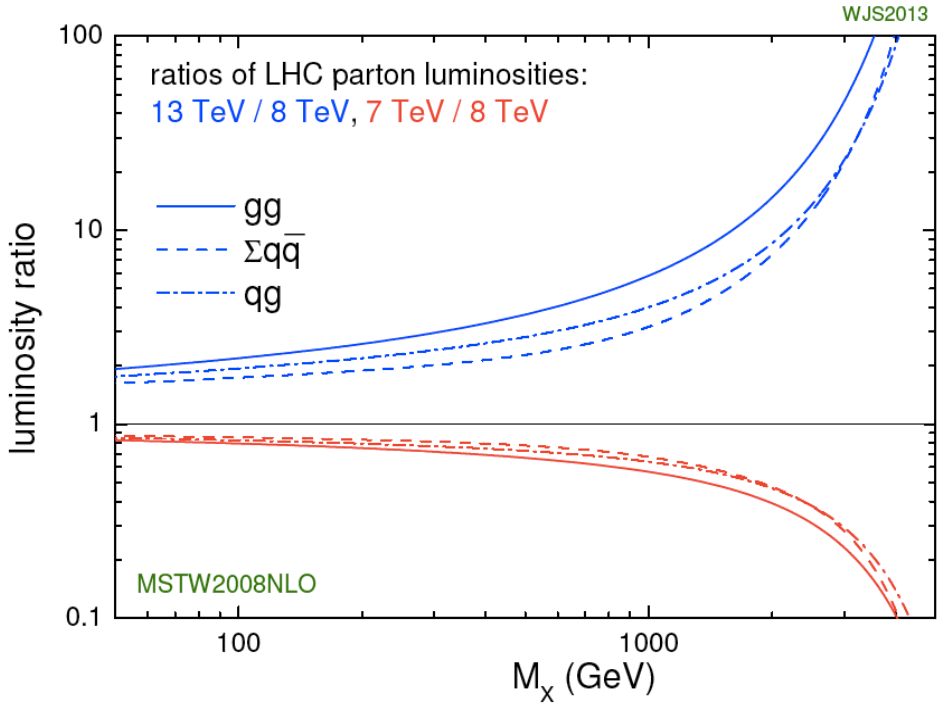


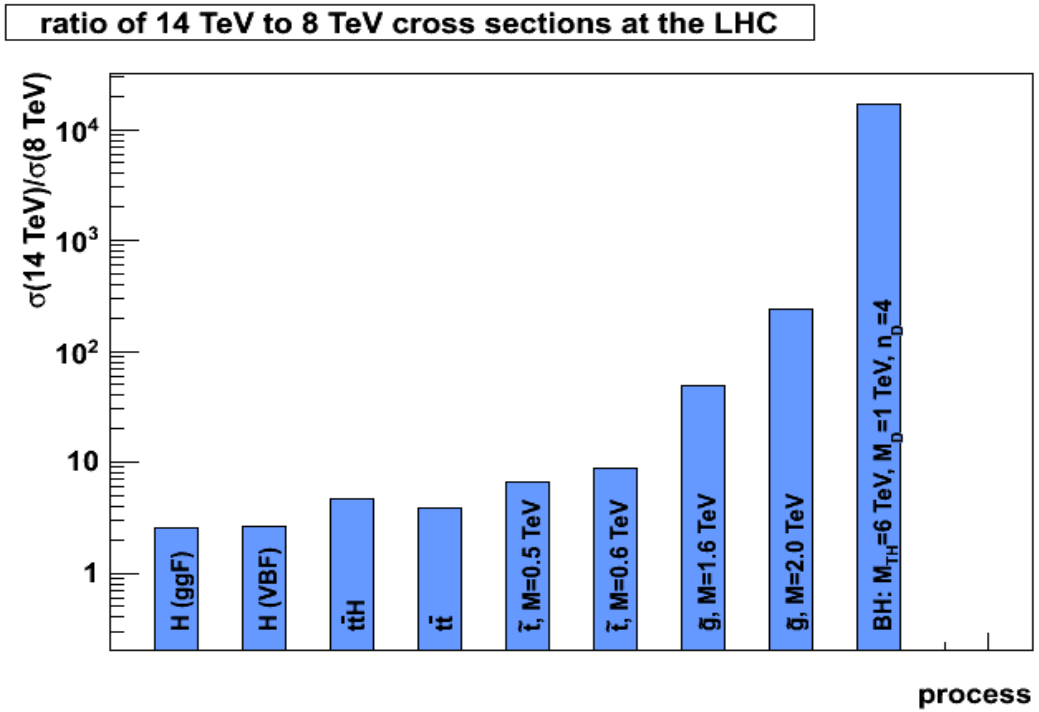


- W' discovery potential increased to 6 TeV for 3 ab^{-1}
- Also probe dark matter cross section:
  - Improvement from 300 fb^{-1} to 3000 fb^{-1}: factor 3-5

arXiv:1307.7135

Run-2 vs Run-1 Cross Sections





- Increase in cross section by factor ~10 for M~2 TeV

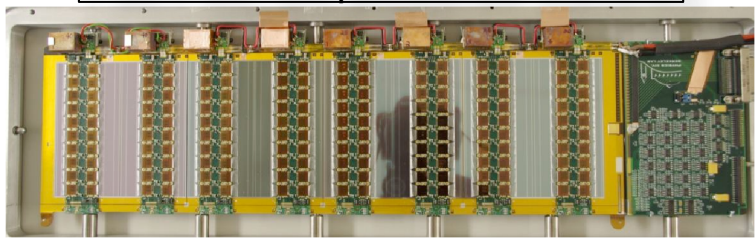
Detector Upgrades: Next Steps

- Current Status:
  - Letter of Intent from ATLAS published in Spring 2013: http://cds.cern.ch/record/1502664
  - CMS: technical proposal being prepared for Fall 2014
  - Physics case was evaluated carefully in past two years
- Towards **technical design reports** during 2015-2017:
  - ECFA set up workshop: theory, LHC and all 4 experiments
    - Oct. 2014 workshop: http://indico.cern.ch/conferenceDisplay.py?confId=252045
    - Identified synergies between various experiment
  - Critical now to make final design choices for detectors
    - Much R&D ongoing, particularly to prove technologies and/or to reduce cost, e.g.
      - RD53 collaboration on 65nm technology for IC joint by CMS and ATLAS
      - Use of MAPs for pixel and/or strip trackers
      - …
    - Many essential developments are lead by US or have strong US involvement
      - Important for the CMS and ATLAS collaborations
  - Funding R&D now is critical to reduce cost and/or improve detector capabilities

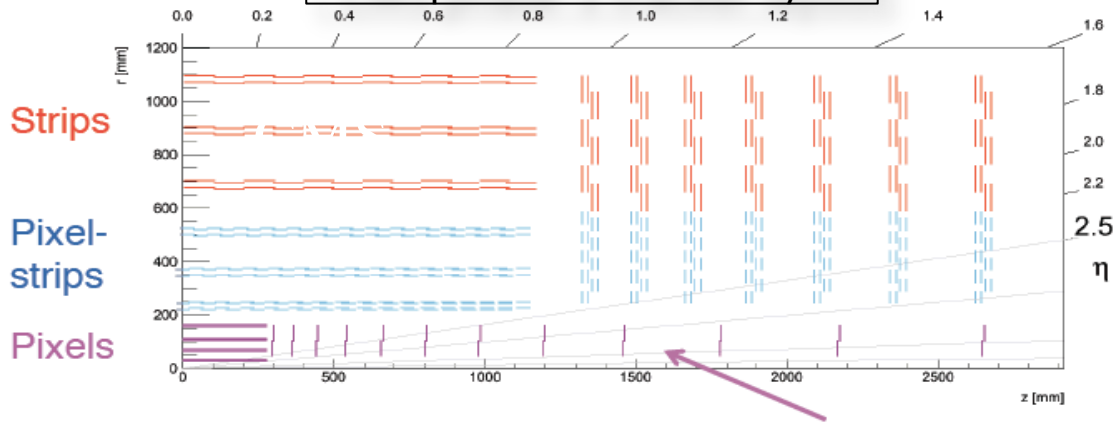
Phase-2 Tracking Detectors

- Strawman designs available from both CMS and ATLAS
  - 4-5 pixel barrel layers
    - with increased granularity in most inner layers
  - 5-6 strip barrel layers
    - Much shorter strips in inner layers
    - CMS also envisages "pixel-strips"
  - Extend coverage to |η|=4.0 e.g. by adding many pixel disks
    - Reconstruct which vertex a forward jet came from to mitigate pileup
  - Improved momentum resolution
    - Important for H→μμ and H->ZZ

SCT DC-DC powered stavelet

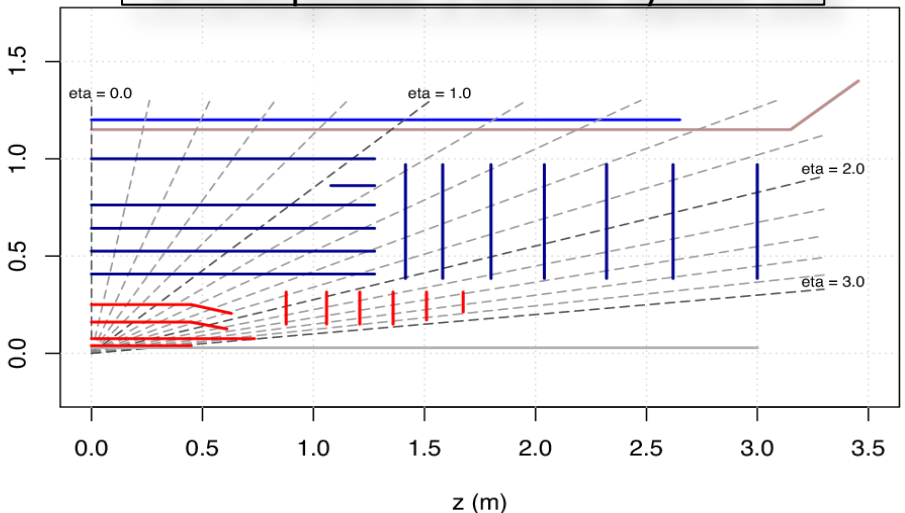


CMS phase-2 tracker layout



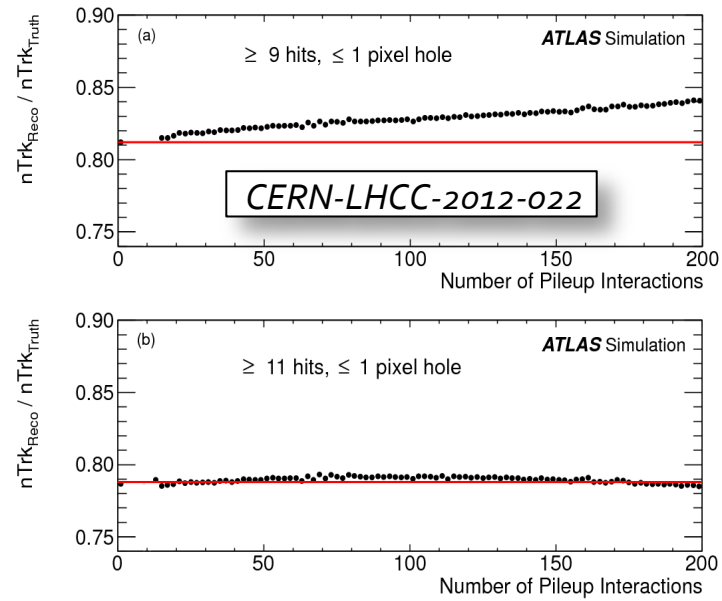
Possible tracker layout with forward pixel disks

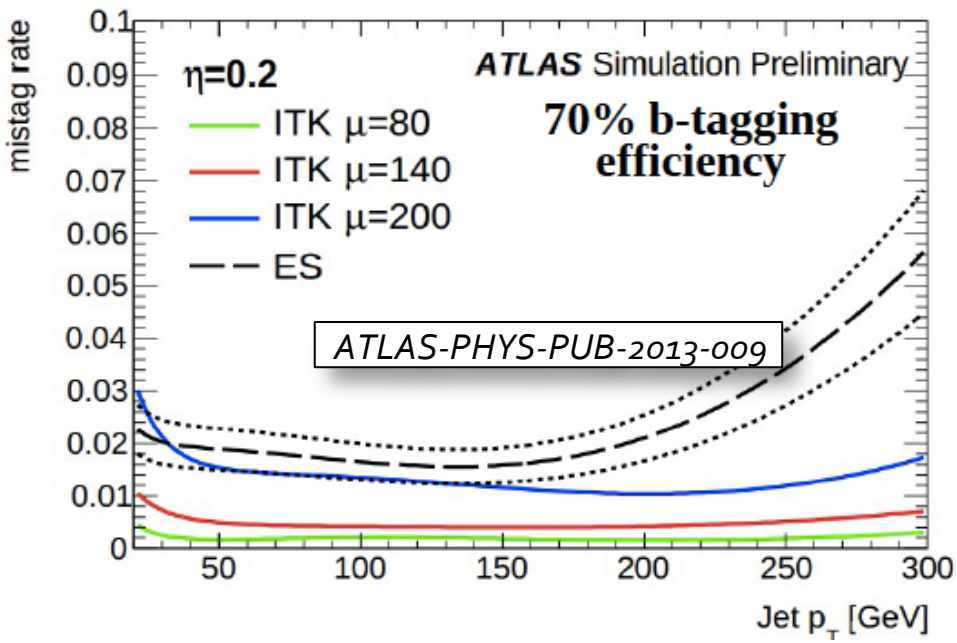
ATLAS phase-2 tracker layout: LoI

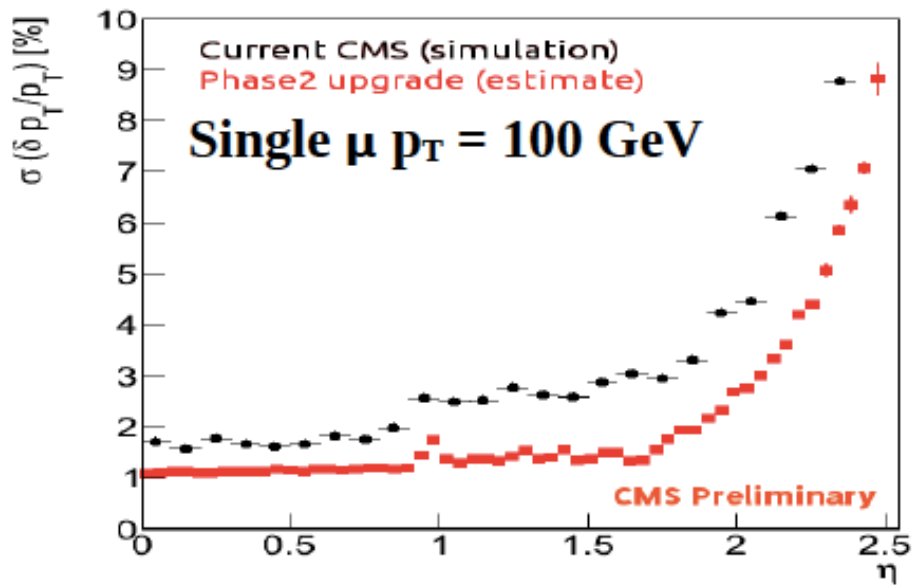


Tracking Performance

- Performance of trackers evaluated with full simulation
  - Track fake rate under control if sufficient hits on track required
  - Improved momentum resolution
  - B-tagging performance improved compared to current detector







More options for part 1

SUSY is not ruled out, it just may be more complicated…

Fayet 1975

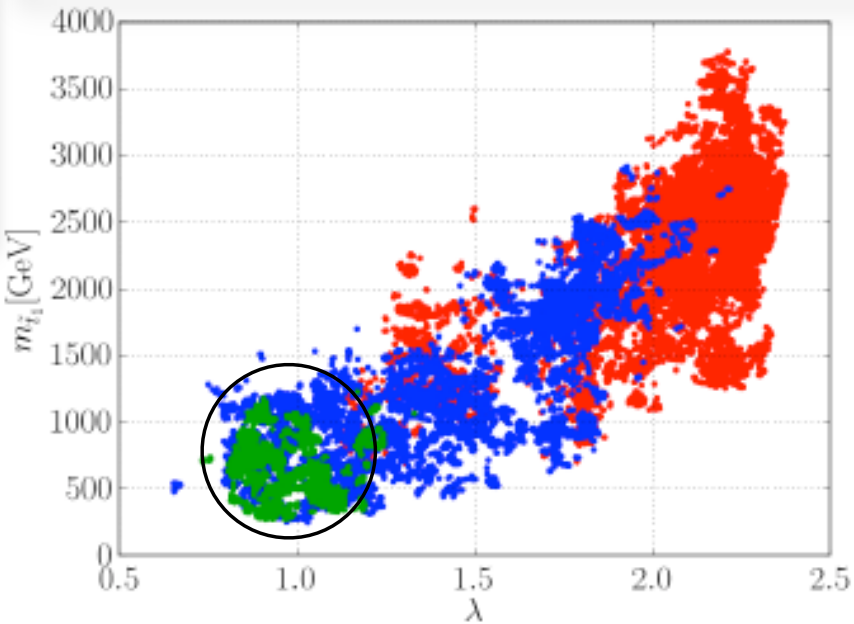
Two independent reasons to consider it:

1. Add an extra contribution to $m_{hh}^2 = m_Z^2 c_{2\beta}^2 + \Delta_t^2 + \lambda^2 v^2 s_{2\beta}^2$ thus allowing for lighter stops
2. Alleviates fine tuning in v for $\lambda \gtrsim 1$ and moderate $\tan\beta$

$$\frac{dv^2}{dm_{H_u}^2}|_{NMSSM} \approx \frac{\kappa}{\lambda^3}\cot 2\beta \quad \text{versus} \quad \frac{dv^2}{dm_{H_u}^2}|_{MSSM} \approx \frac{4}{g^2}$$

NMSSM example
(cf Talk by R. Barbieri)*

Stops, naturalness potentially within reach



green points have better than 5% "combined" fine-tuning and $\Lambda_{mess} = 20\ TeV$ in the scale invariant NMSSM

$$m_{\tilde{t}_1} < 1.2\ TeV$$
$$m_{\tilde{g}} < 3\ TeV$$

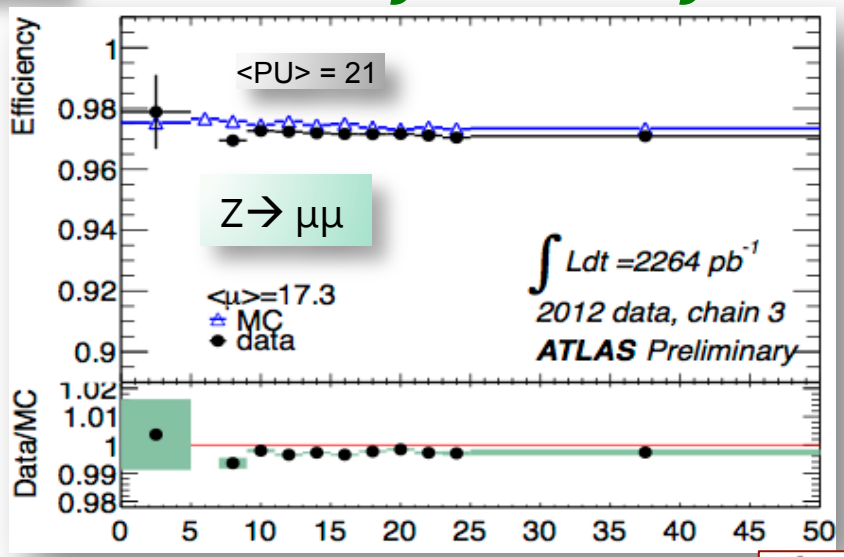
Gherghetta et al 2012

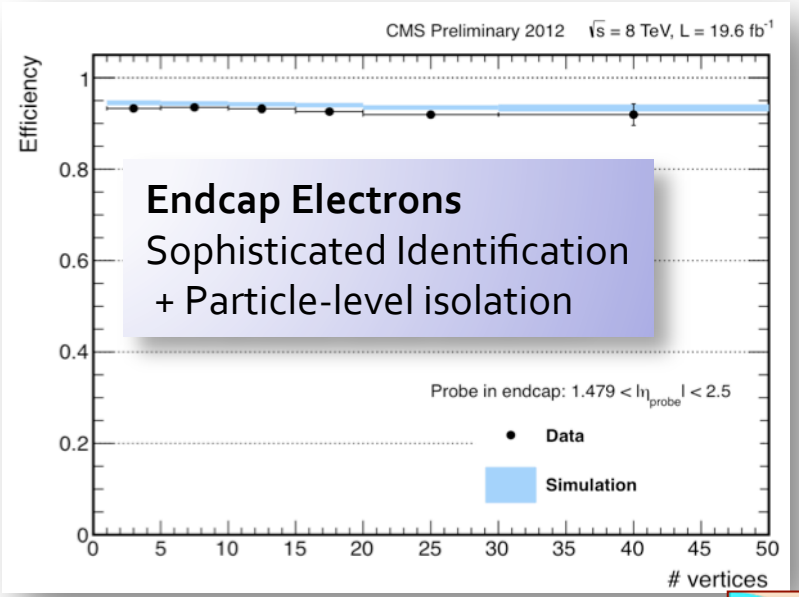
*R. Barbieri: https://indico.cern.ch/conferenceDisplay.py?confId=239571

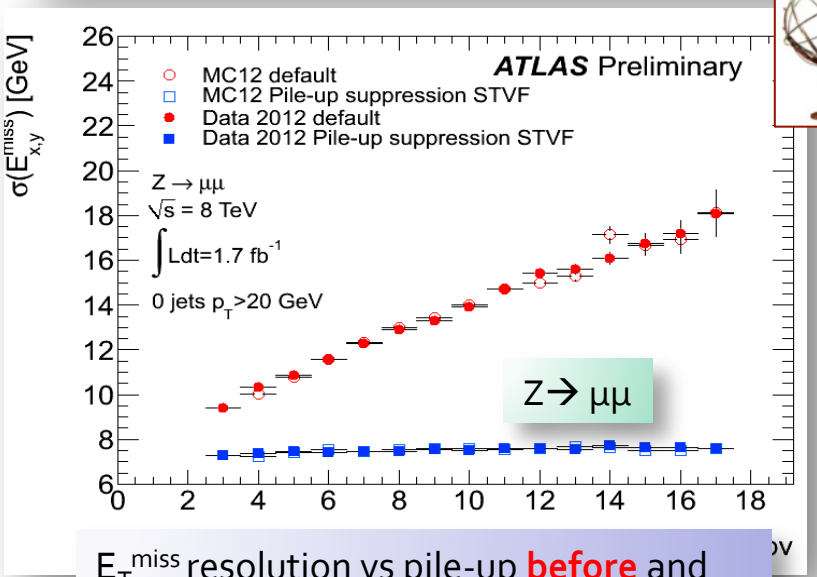
Taking control of PileUp:

Granularity is the key

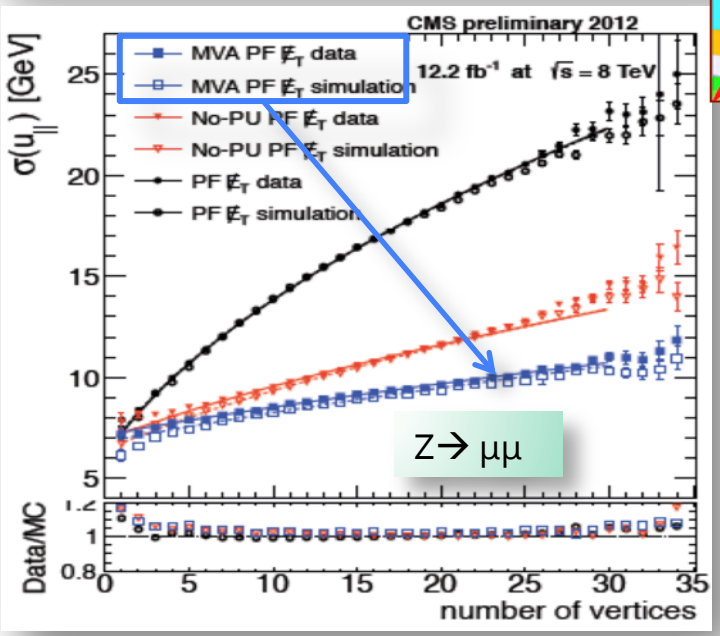
May-June 2012







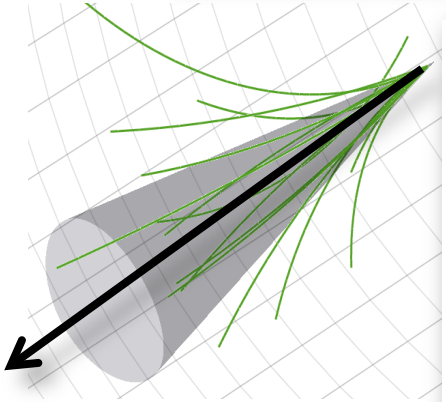
E_T^{miss} resolution vs pile-up **before** and **after** pile-up suppression using tracks



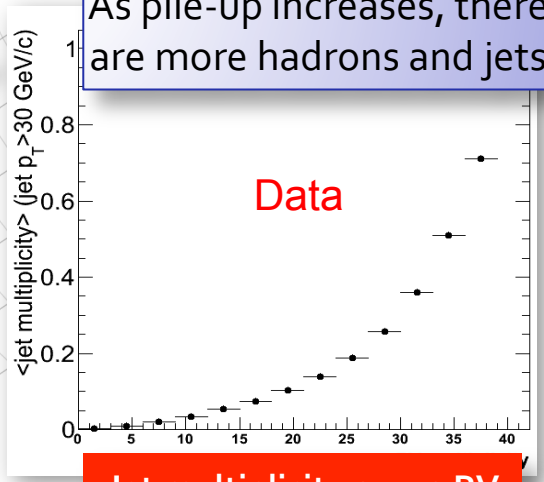
E_T^{miss} : PFlow and MVA regression

The impact of pileup

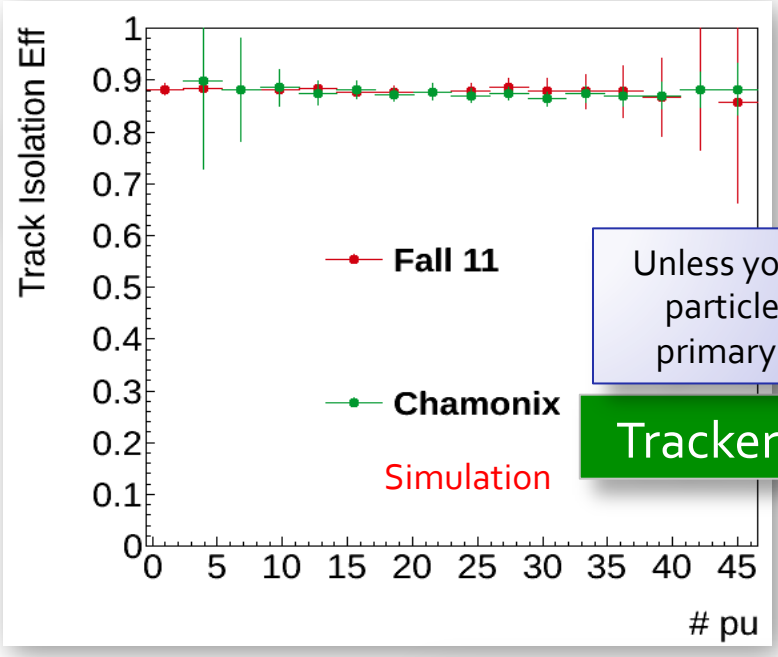
To avoid 'fakes' require e, μ, τ, γ to be 'isolated' in a conical region



As pile-up increases, there are more hadrons and jets



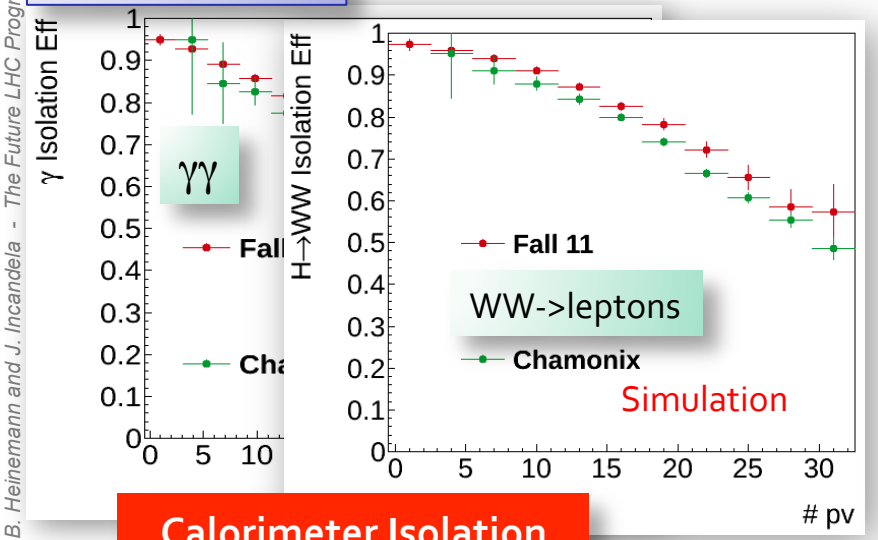
Jet multiplicity 0 – 40 PV



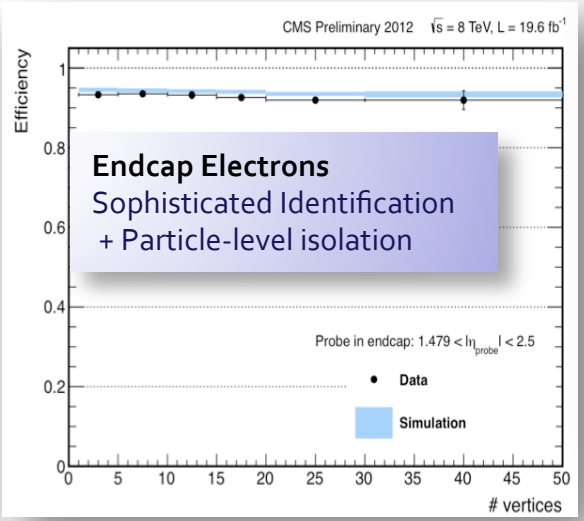
Unless you can trace particles to their primary collisions

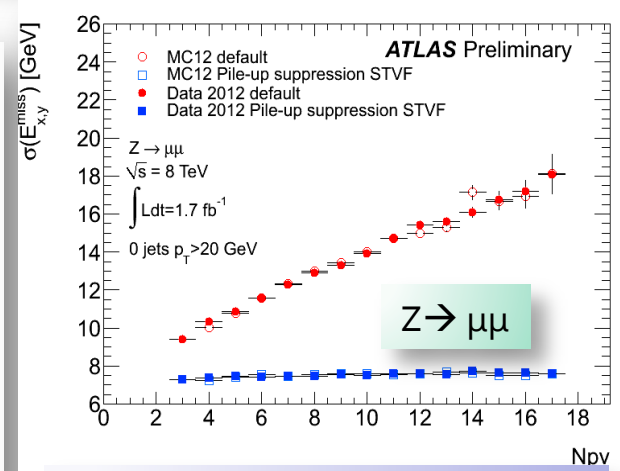
Tracker isolation

It's harder to be isolated



Calorimeter Isolation





E_T^{miss} resolution **before/after** pile-up suppression using tracks

US Contributions to CMS in Run 1

- Original CMS Construction project
  - DOE & NSF contributed $167M towards construction
    - Magnet ($23M)
    - Full Hadron Calorimeter ($41M)
    - Full Endcap Muon system ($41M)
    - Full Forward Pixels ($12M)
    - Tracker: Outer Barrel, End Caps
      - Module assembly 110 m2 ($9M)
    - Electromagnetic Calorimeter ($14M)
    - Trigger and DAQ ($15M)
- Commissioning and Operations
  - US Led subsystems
    - Hadron Calorimeter
    - Endcap Muons
      - Including current improvement program
    - Forward pixels
    - Trigger
  - Systems with critical US participation
    - Data Acquisition
    - Silicon Strip Tracker
    - Electromagnetic Calorimeter

http://www.uscms.org/cms_detector/index2.shtml