TRIUMF

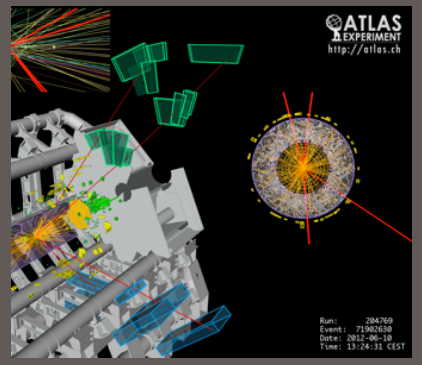
ATLAS EXPERIMENT

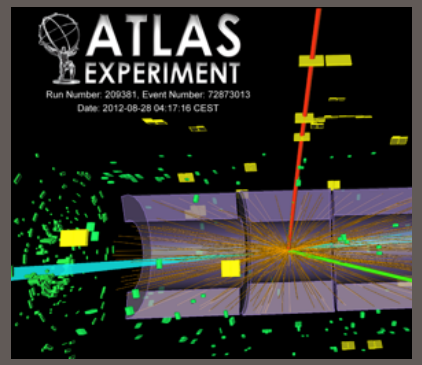
ATLAS results from LHC Run I

A new chart of the particle universe

Lake Louise Winter Institute 2014

Isabel TRIGGER | TRIUMF
for the ATLAS Collaboration

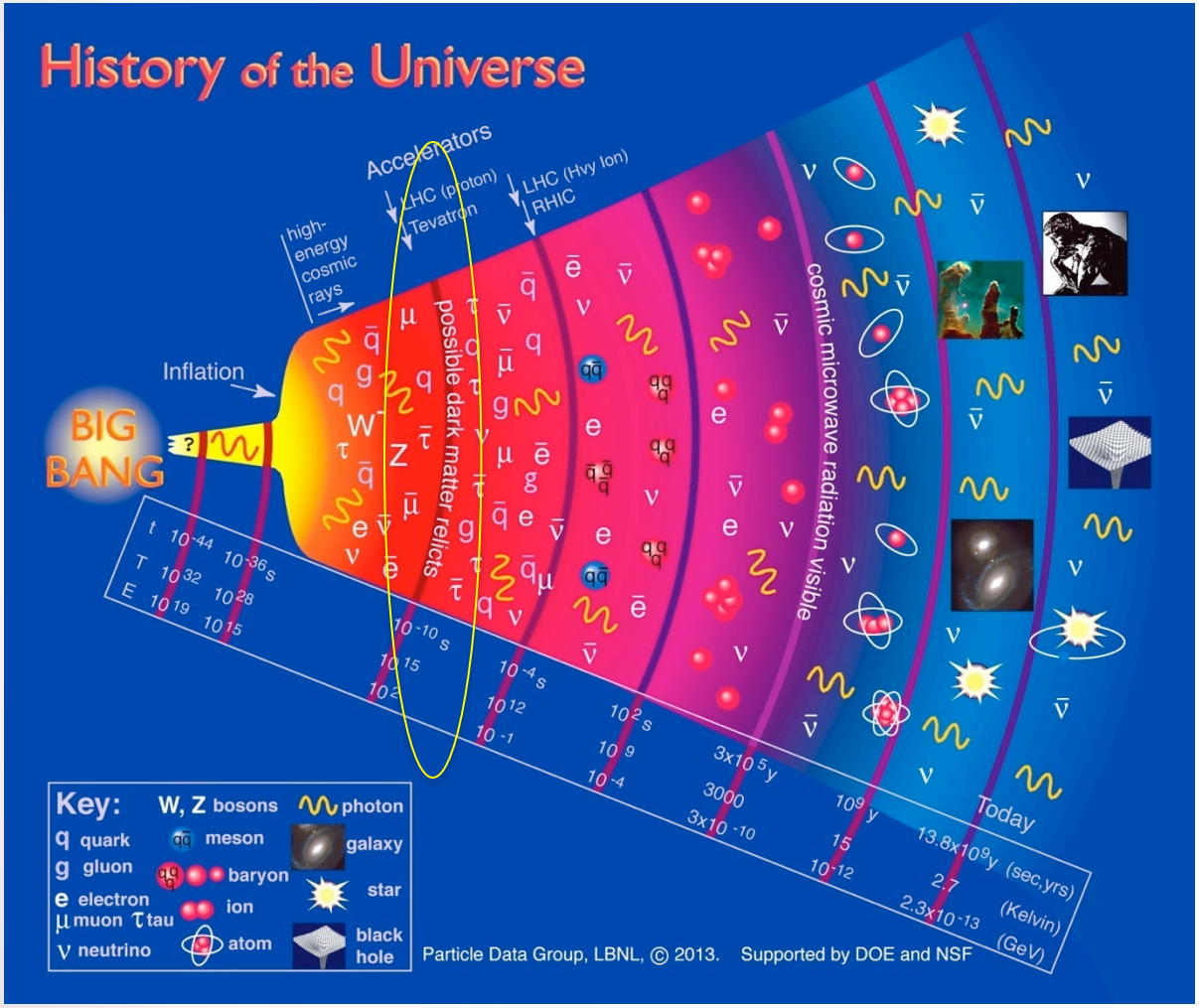




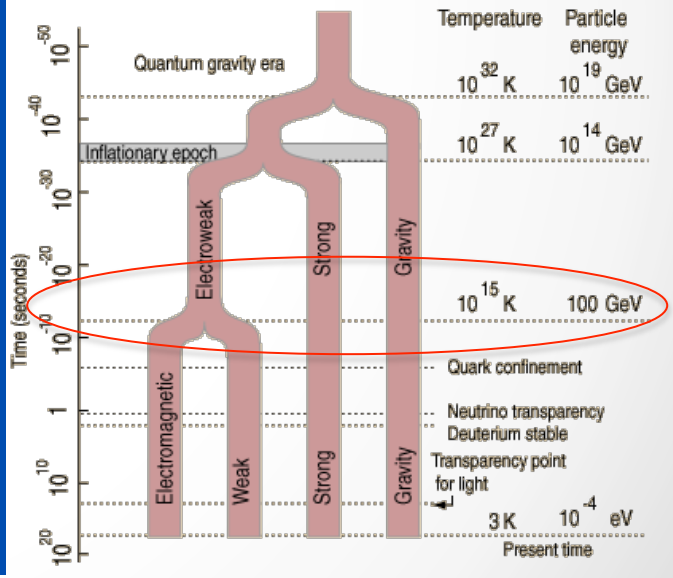
Overview

- Brief intro to LHC & ATLAS
- The Standard Model in the post-Higgs world
- What do we still (reasonably) hope to find?
- Selected highlights from past year (or so)

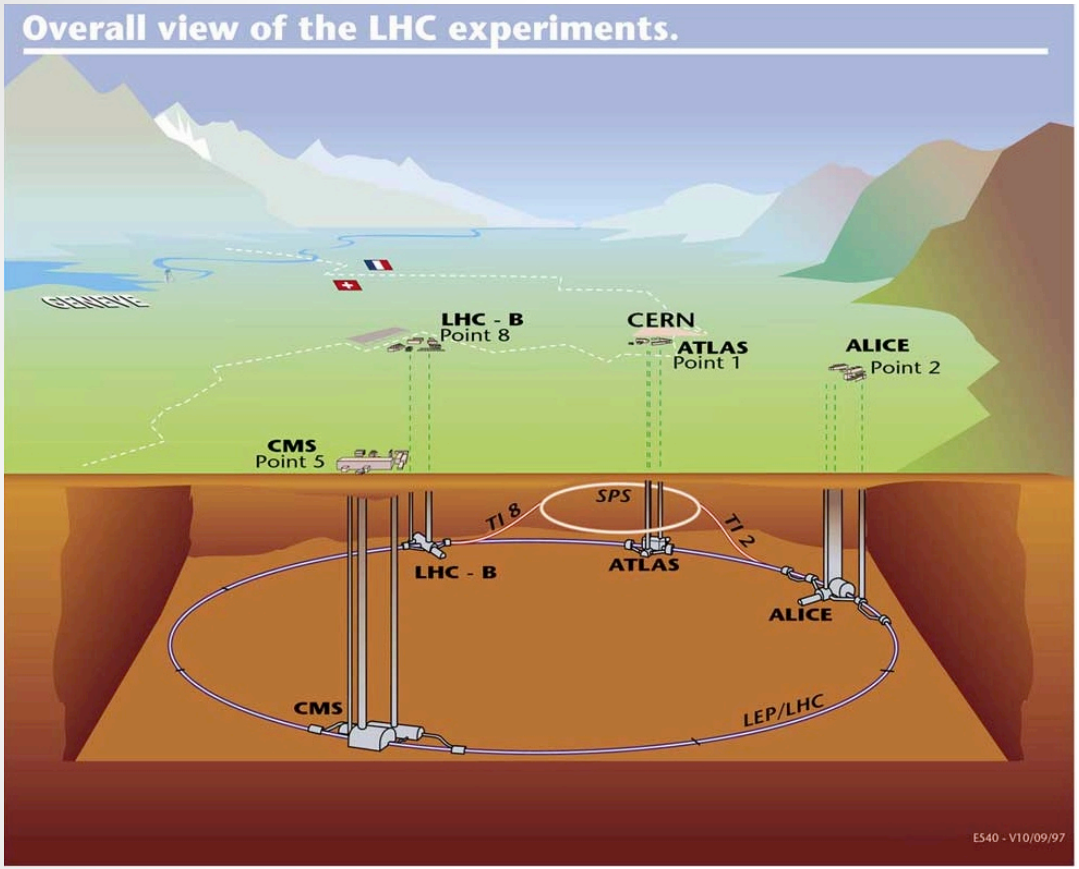
The Terascale: a Special Place

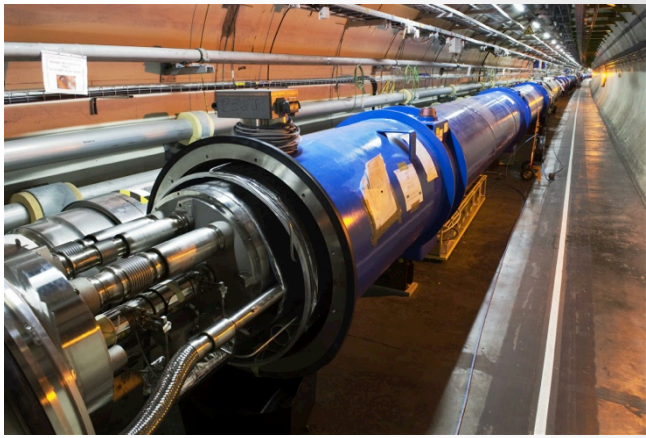


LHC is designed to probe EWSB scale around 100 GeV – few TeV



The Large Hadron Collider



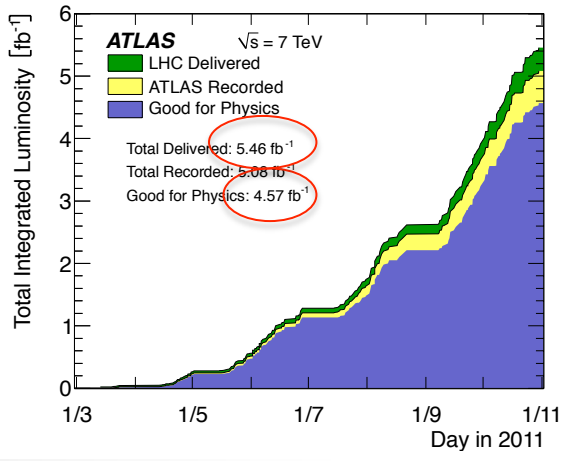


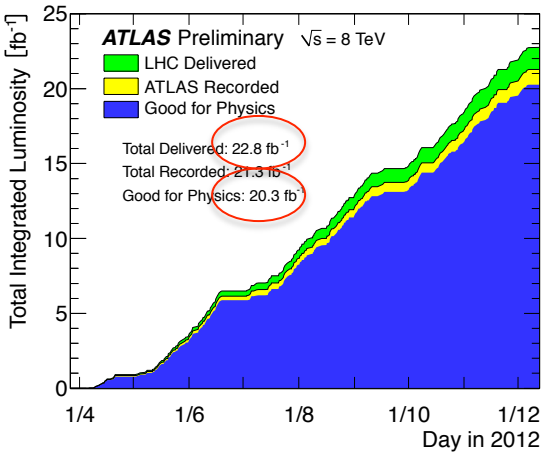
"hadrons" = p-p, p-Pb, Pb-Pb

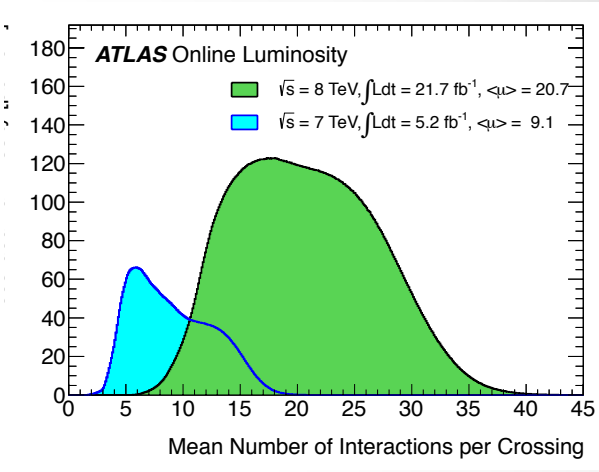
√s(pp): (main physics runs)
7 TeV in 2010-11
8 TeV in 2012
13 TeV+ from 2015

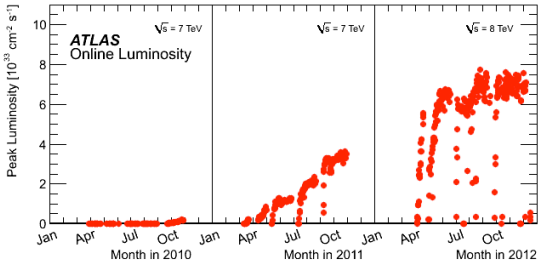
$\sqrt{s_{NN}}$=2.76 TeV Pb-Pb in 2011
$\sqrt{s_{NN}}$=5 TeV p-Pb in 2013

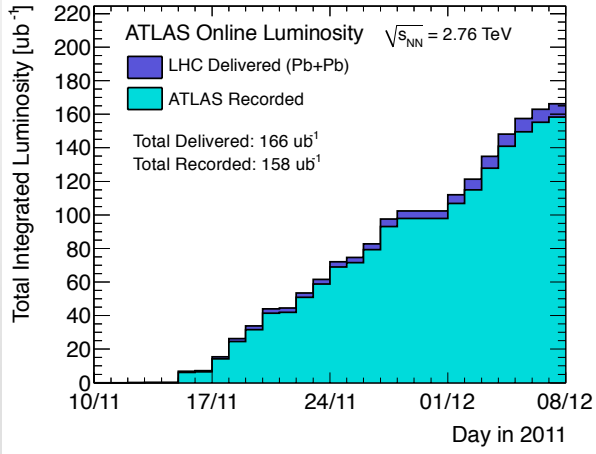
Integrating luminosity in 2010-2013

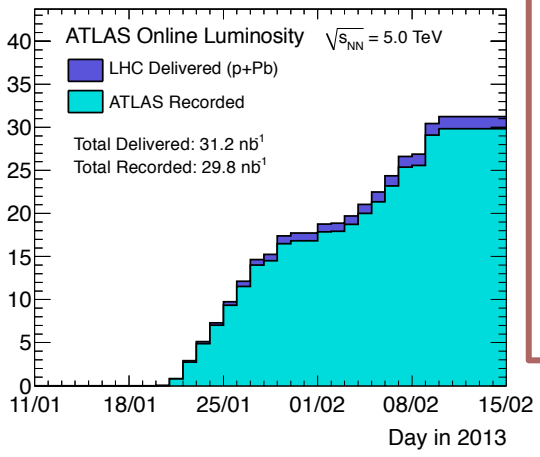












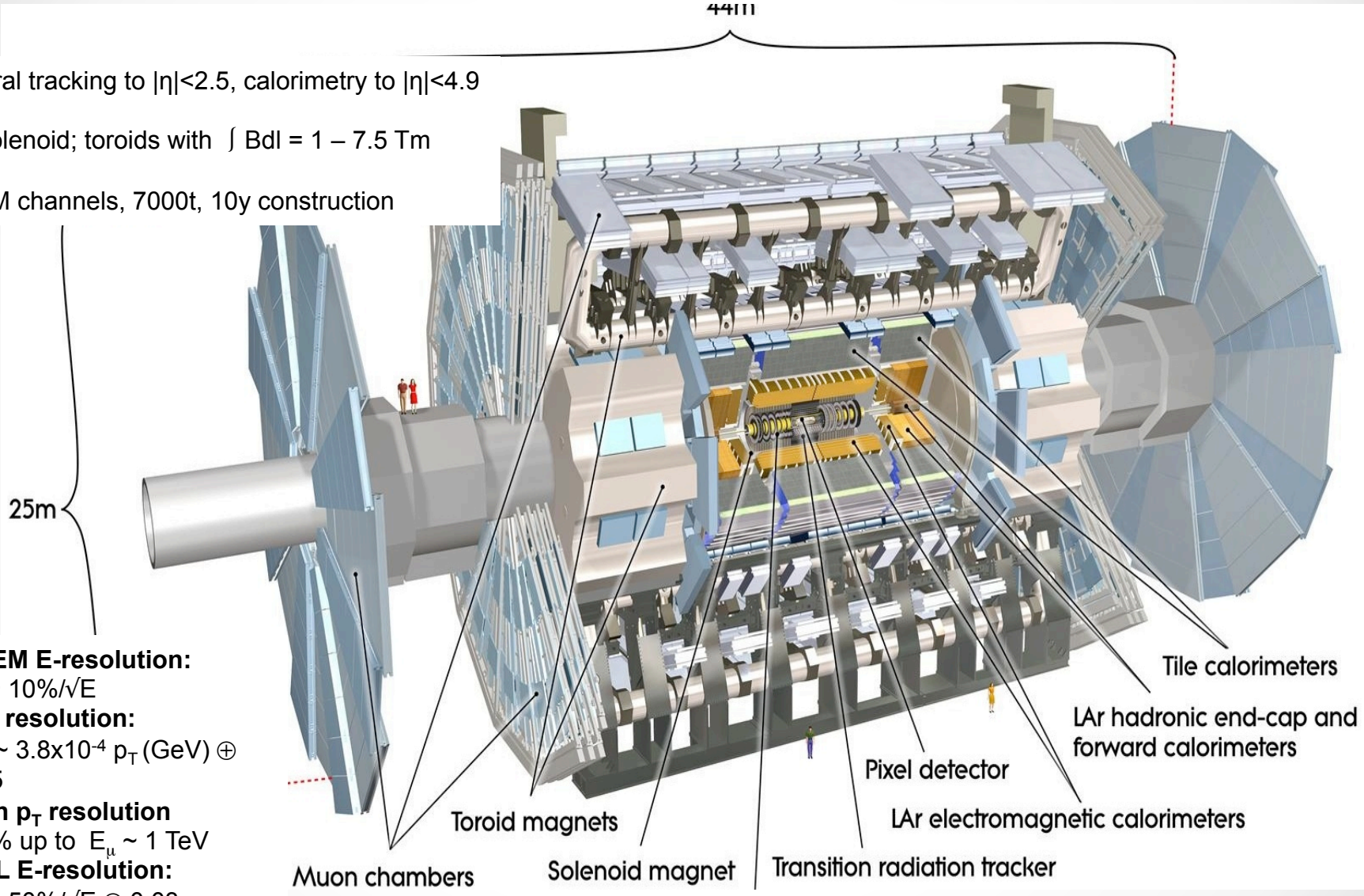
- $\mathcal{L}$(pp): 7 x 10^{33} $cm^{-2}s^{-1}$
- ~1400 bunches
- 50 ns separation
  - (tested 25 ns)
- >90% "good data" efficiency
  - (delivered data used for analysis)

The ATLAS Detector

Central tracking to $|\eta|<2.5$, calorimetry to $|\eta|<4.9$

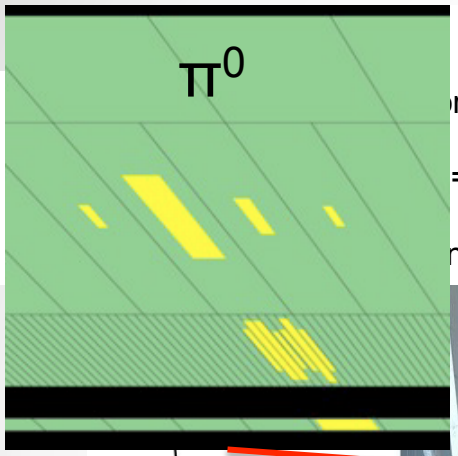
2T solenoid; toroids with $\int Bdl = 1 – 7.5$ Tm

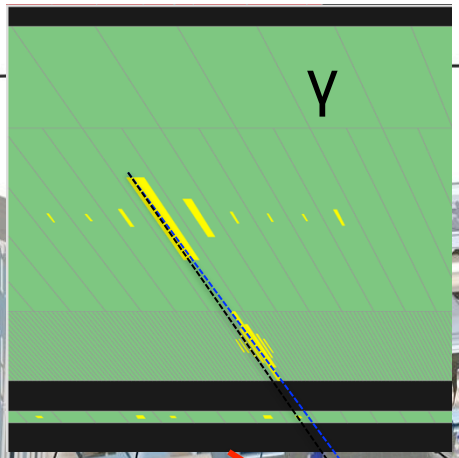
100 M channels, 7000t, 10y construction



LAr EM E-resolution:
$\sigma/E \sim 10\%/\sqrt{E}$
ID p_T resolution:
$\sigma/p_T \sim 3.8\times10^{-4}\, p_T\,(\text{GeV}) \oplus 0.015$
muon p_T resolution
< 10% up to $E_\mu \sim 1$ TeV
HCAL E-resolution:
$\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$

The ATLAS Detector



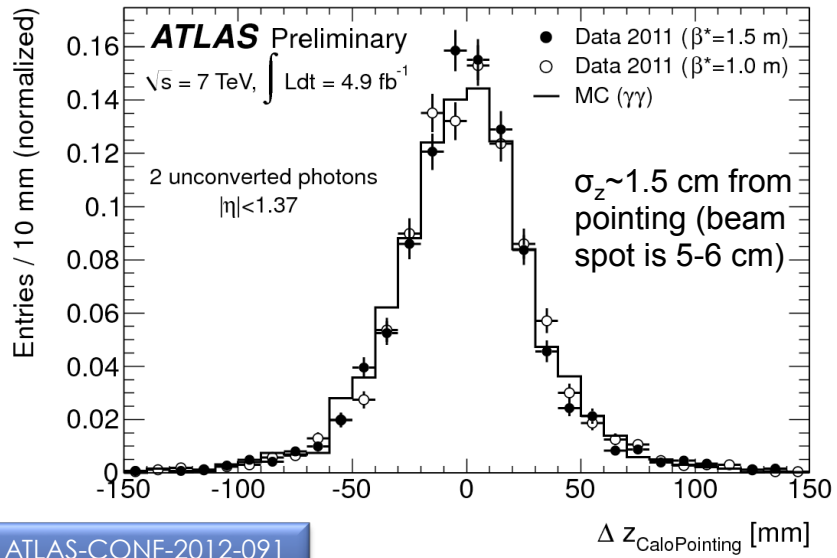


rimetry to |η|<4.9

= 1 – 7.5 Tm

nstruction

4 mm η-strips in first ECal layer allow good γ pointing

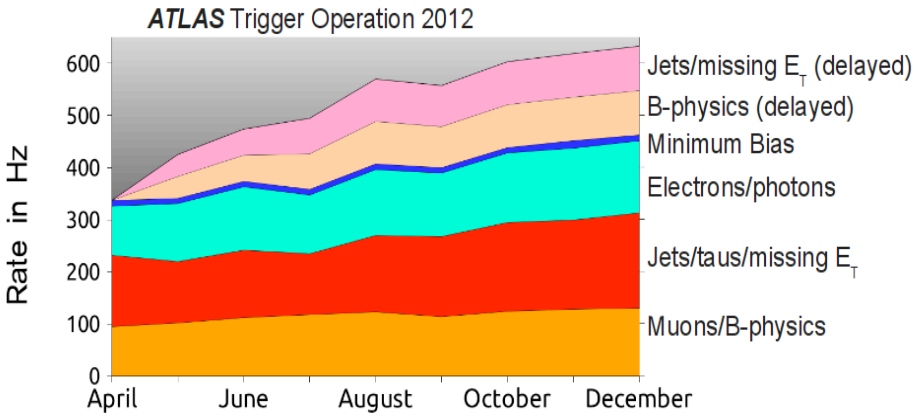


ATLAS-CONF-2012-091

Triggers & Physics Objects

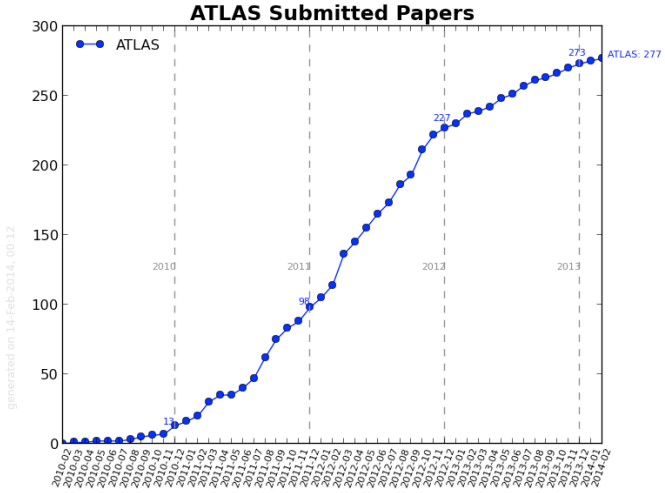
Lowest Unprescaled Trigger	2012 Threshold (GeV)
Inclusive μ	24
Inclusive e	24
2μ	13,13 or 18,8
2 e	12,12
2τ	29,20
2 γ	20,20
E_T^{miss}	80
Inclusive jet	360 (170 for 3j, 80 for 4j, 45 for 6j…)
… hundreds more with combos & prescales…	

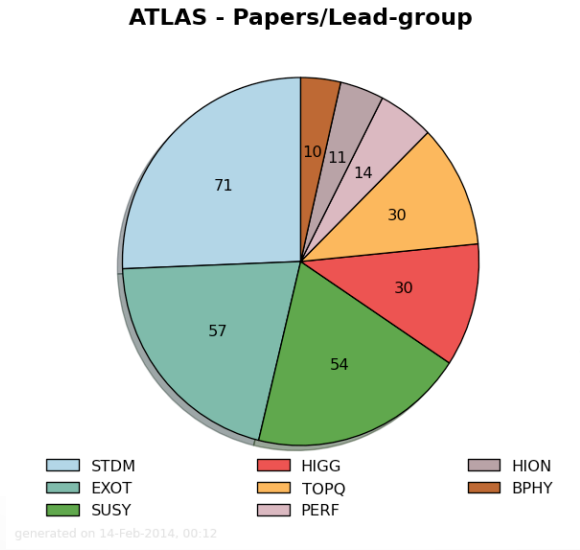
- Stable trigger menu in 2012
  - rather constant peak lumi
- Avg 2012 rate ~550 Hz
  - Prompt physics ~400 Hz
  - "Delayed" streams ~150 Hz
  - Peak Level-1 rate ~70kHz
  - Peak Output ~1 kHz

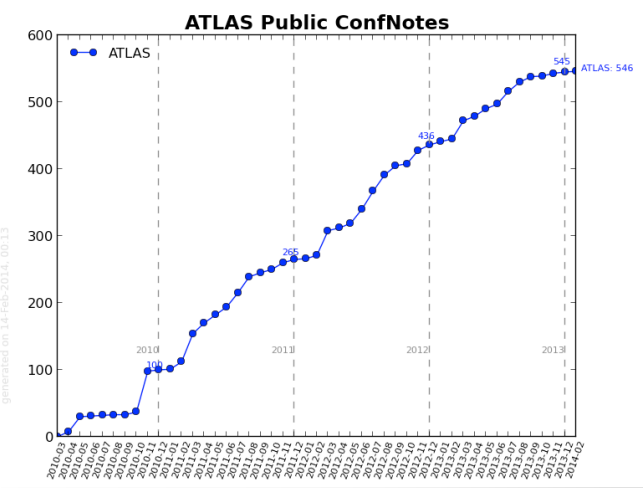


ATLAS Physics Results

- Publications:
  - Full ATLAS publication list available at: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/Publications
  - Last few months: – working to complete analyses with full Run 1 dataset ASAP and prepare for Run 2!
- At LLWI14:
  - 11 more talks and 3 posters

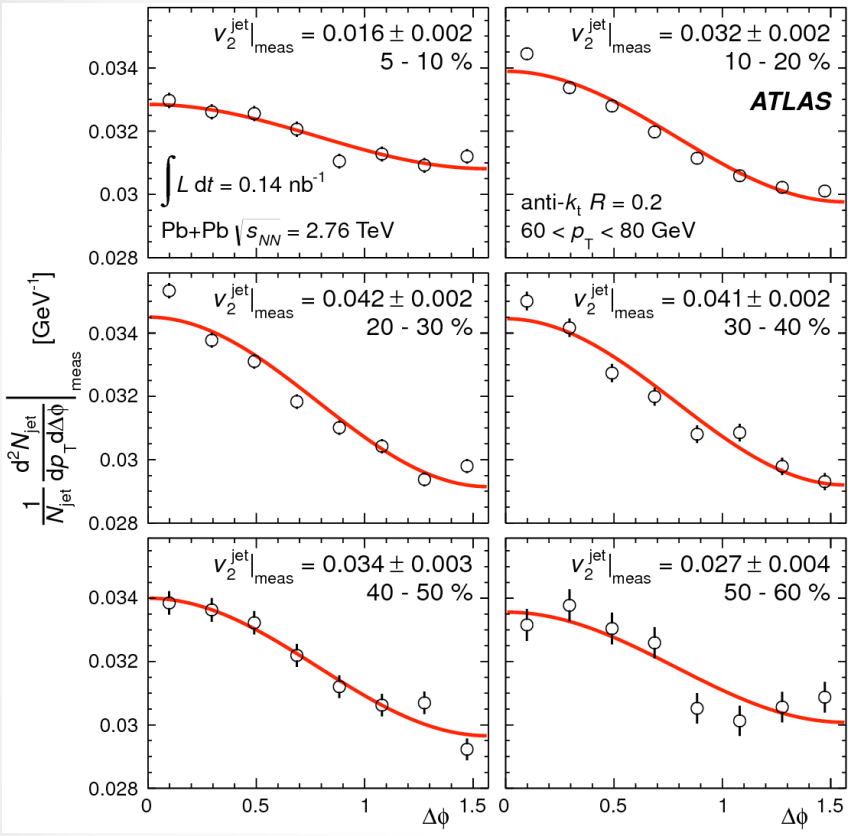






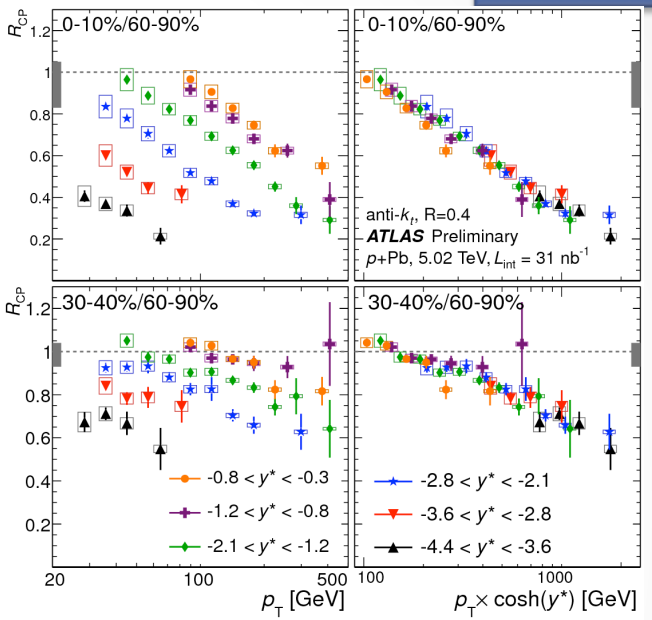
Heavy Ion Results

Phys. Rev. Lett 111, 152301 (2013)

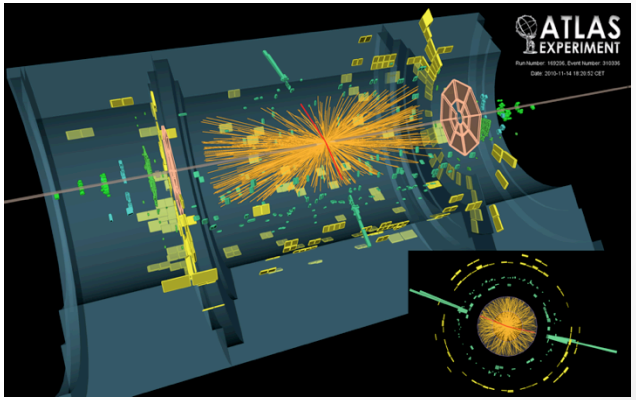


Azimuthal angle dependence of inclusive jet yields in Pb-Pb for 6 centrality ranges (curves are fits); v_2^{jet} measures single jet suppression as function of Δϕ

ATLAS-CONF-2013-105

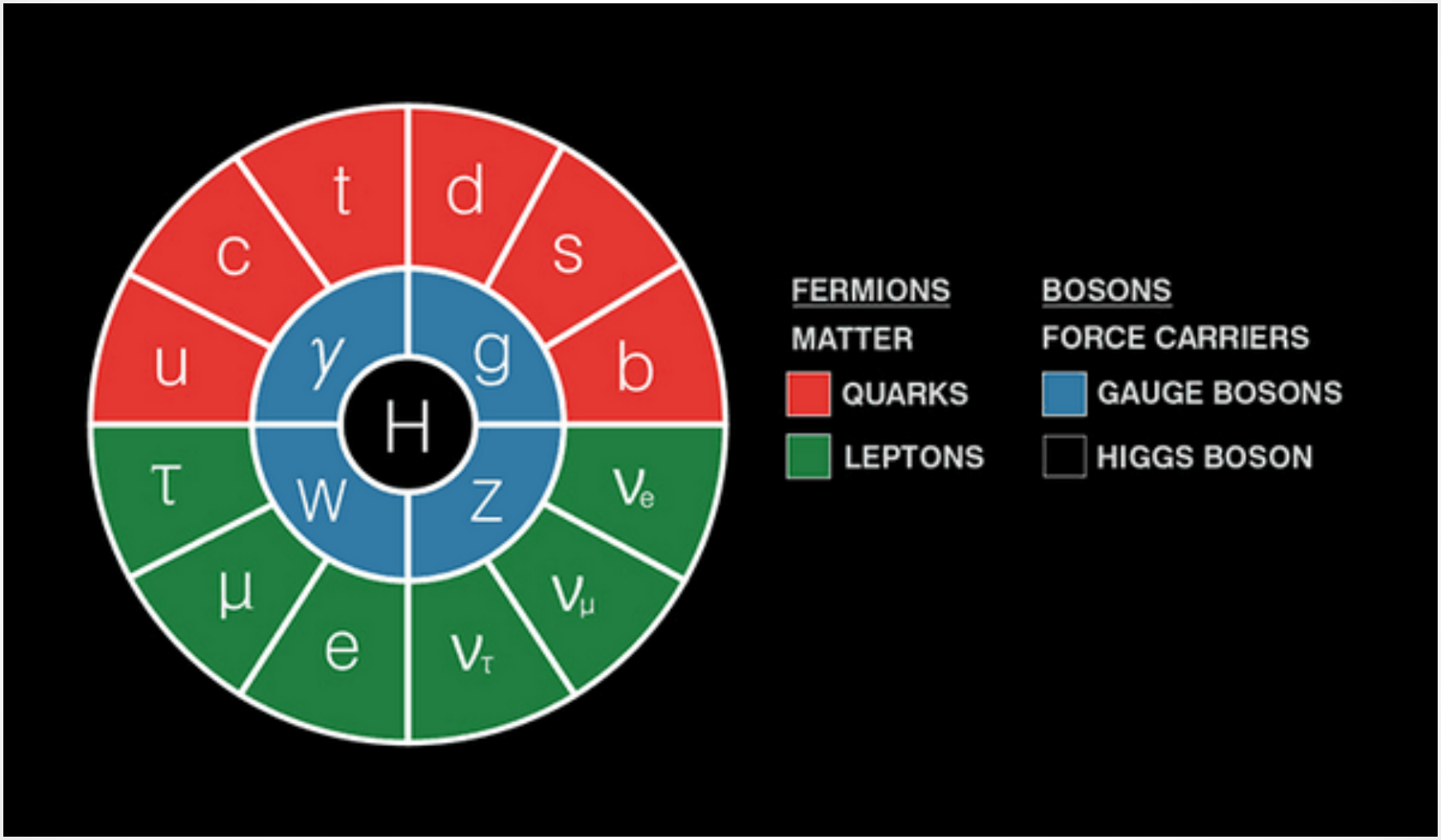


pPb: jet suppression enhanced in central collisions
Mechanism seems E_{jet}-dependent



Z➔ee candidate in Pb-Pb (m_{ee}=104 GeV)

The Final Piece in the Standard Model

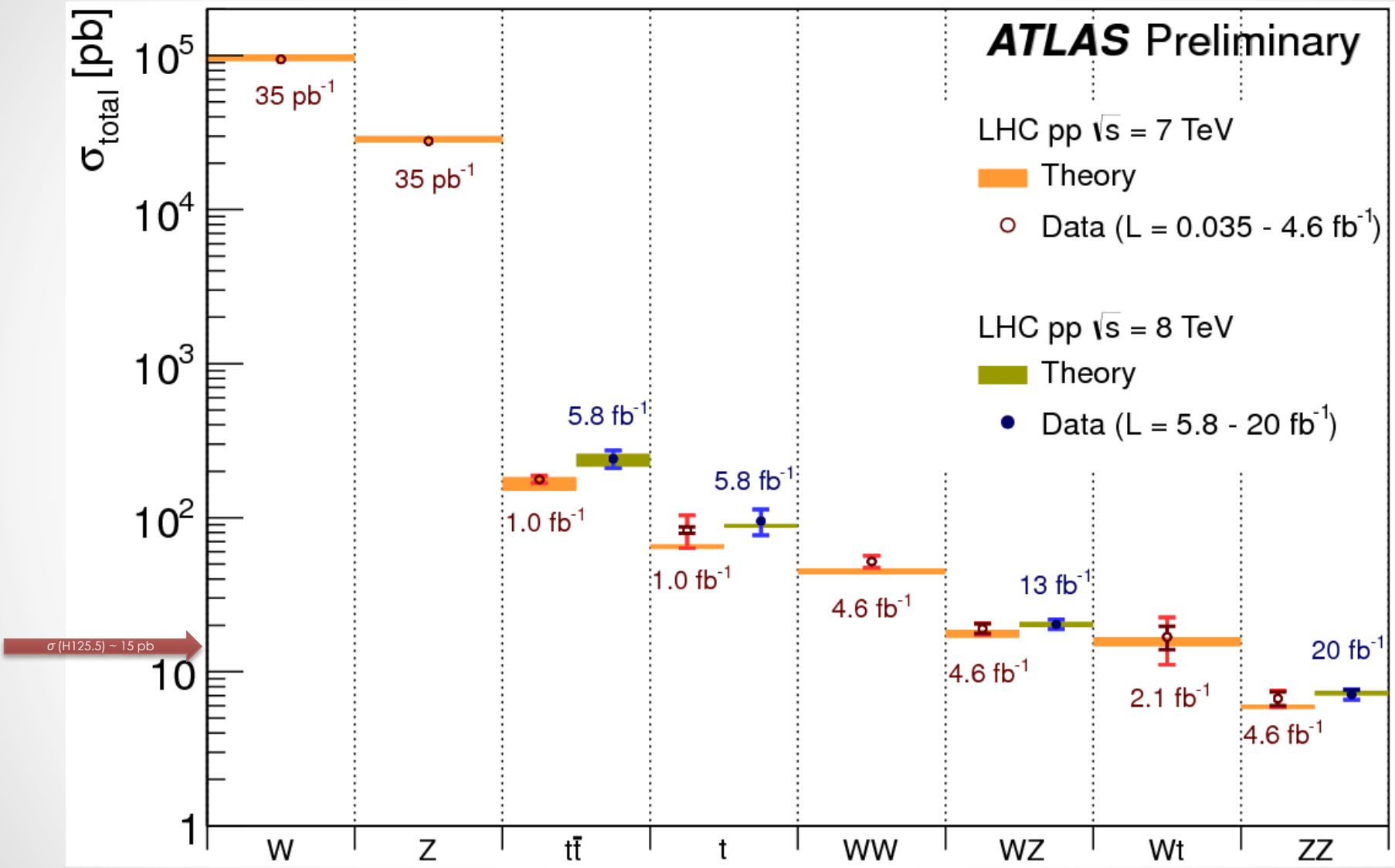


Standard Model Highlights

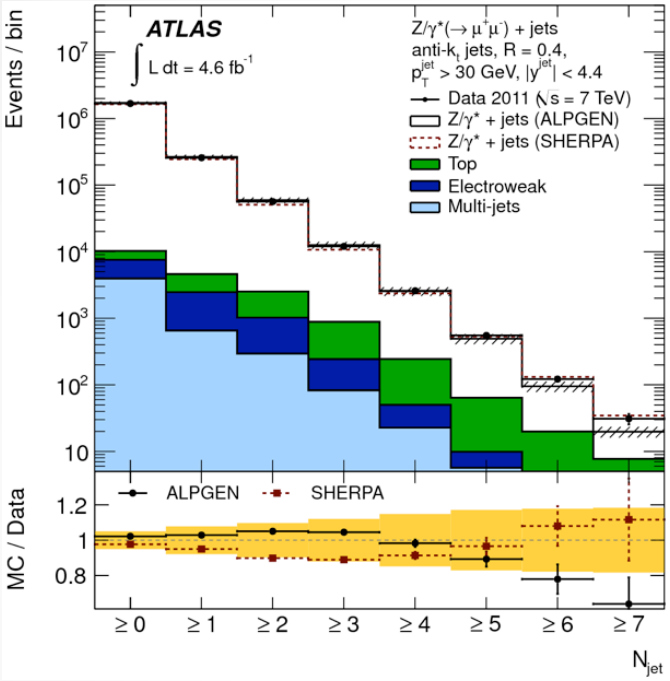
- LHC allows wealth of precision measurements on W, Z, top that have never been possible before
  - *after* selections: 100M W➔ $\ell\nu$, 10M Z➔$\ell\ell$, 400k tt➔ℓX, hundreds of H(125)
- Probe perturbative QCD at electroweak scale
- Measure electroweak processes at electroweak scale

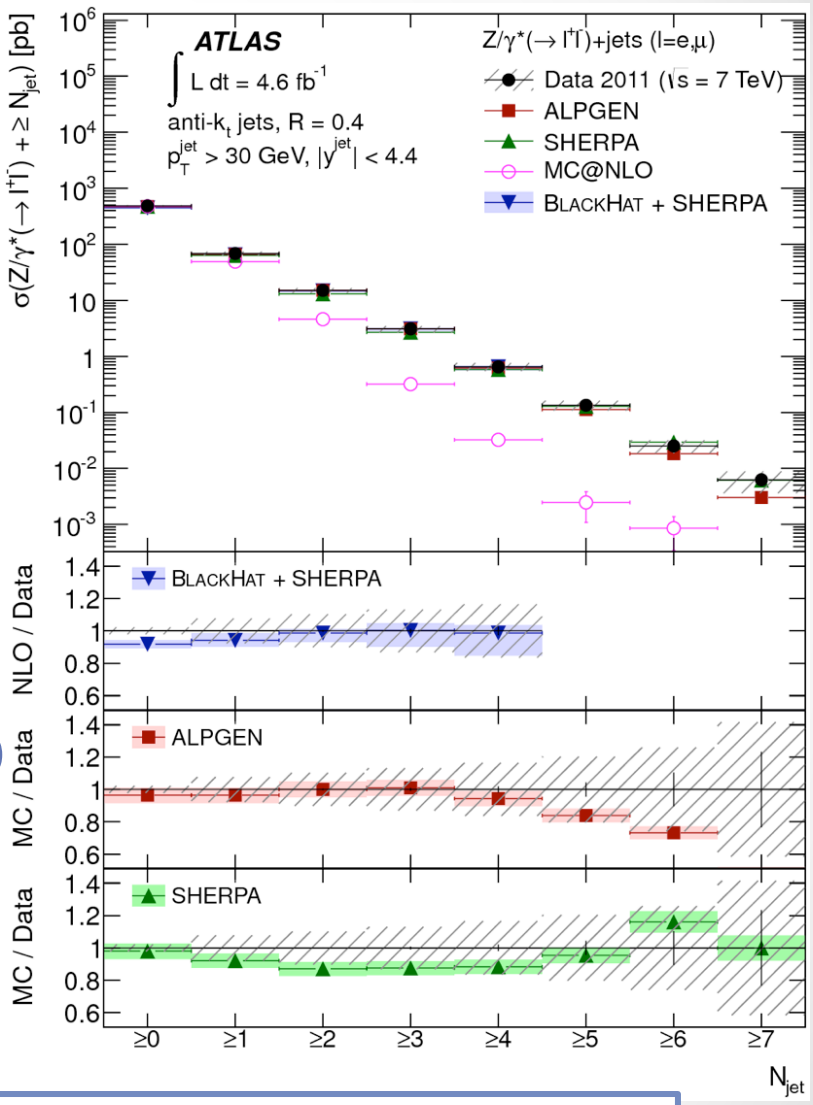
- Standard Model / QCD results at LLWI14:
  - Zdenek Hubacek ***Recent QCD results from ATLAS***
  - Rodger Mantifel ***Measurements of vector bosons plus jet productions with the ATLAS detector***
  - Stefano Camarda ***ATLAS tunes of Pythia8 and Powheg and PDF sensitivity of prompt photon and di-jet measurements*** (Poster)

ATLAS Standard Model Results



Vector bosons in association with jets: example Z+jets





- W/Z+jets probes *perturbative* QCD
- Exquisite test of NLO (in pQCD) fixed-order predictions & LO ME + PS MC

JHEP07(2013)032

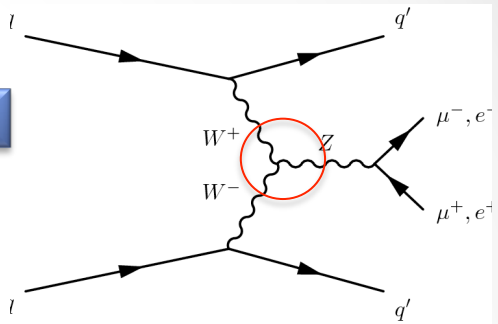
Also: W+b: JHEP 06 (2013) 084, W+c – see R.Mantifel talk

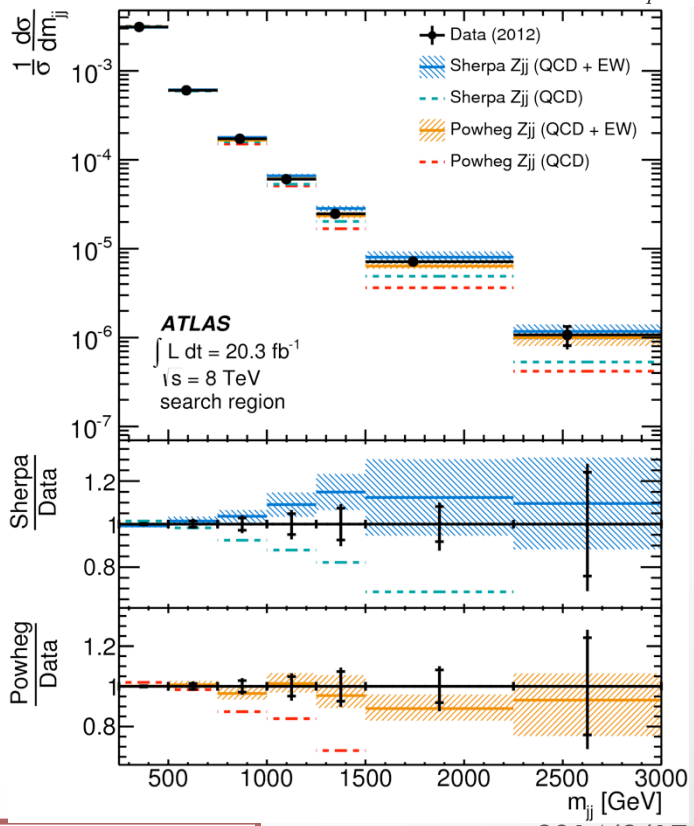
Electroweak production of dijets in association with a Z boson

New!

- Challenging measurement, calculation also challenging (interference)
- Closely related to Higgs VBF production
- Sensitive to TGCs (time-like momentum transfer, completely different form factors from the diboson space-like measurements)
- Inclusive Zjj production in "search" region fit to extract 5 σ observation of electroweak Zjj fiducial cross section:
  - $\sigma = 54.7 \pm 4.6(\text{stat})\ ^{+9.8}_{-10.4}(\text{syst}) \pm 1.5(\text{lumi})$ fb
  - $\sigma_{\text{theory}} = 46.1 \pm 0.2(\text{stat})\ ^{+0.3}_{-0.2}(\text{scale}) \pm 0.8(\text{PDF})\ ^{+0.4}_{-0.5}(\text{model})$ fb

arXiv:1401.7610

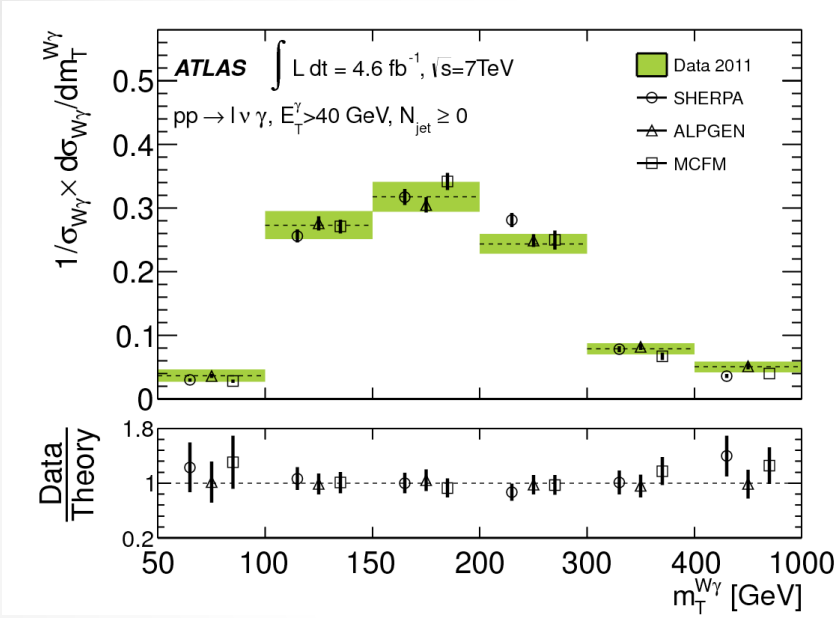




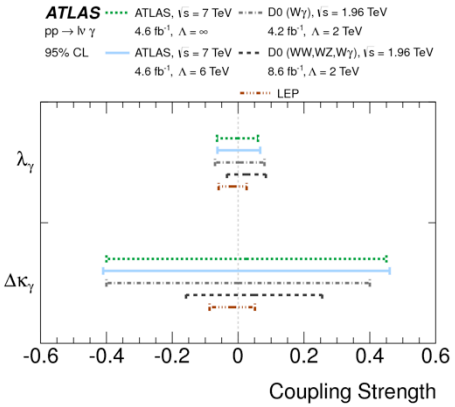
See R.Mantifel talk for details

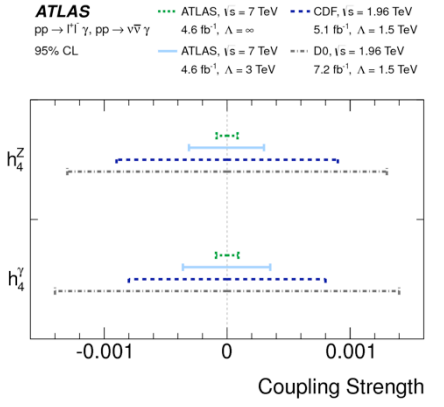
Diboson and TGC measurements: Wγ and Zγ production

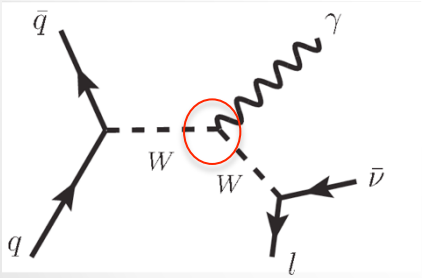
Phys. Rev. D 87, 112003 (2013)



- Test MC predictions for QCD at EW scale
- Measure WW γ gauge couplings, limits on ZZ γ, Z γ γ etc.
- Also search for narrow W γ, Z γ resonances







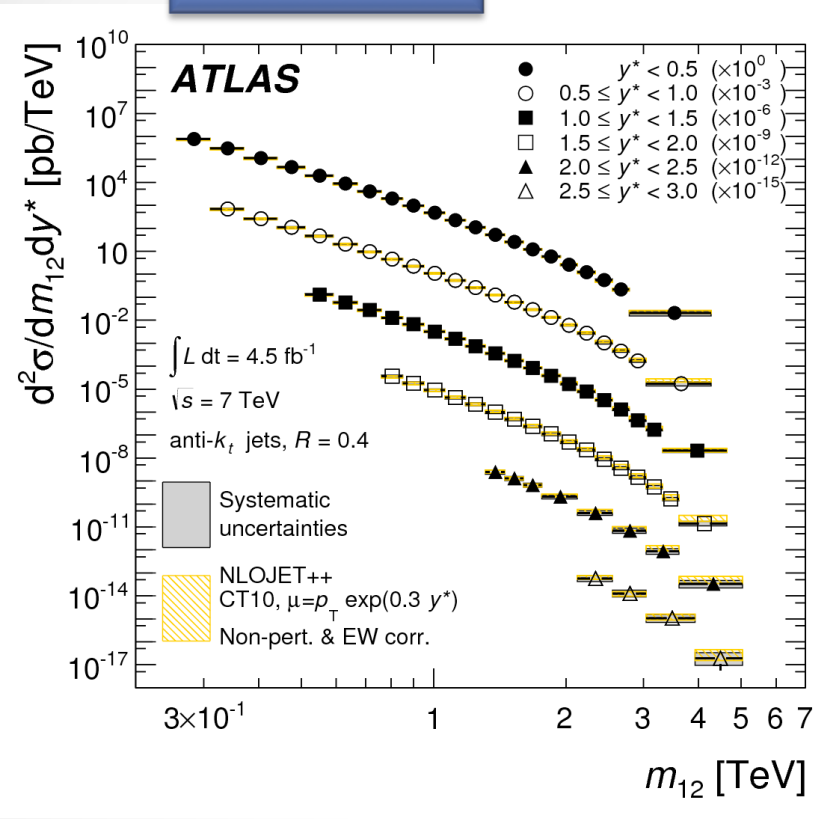
$$\mathcal{L}_{WW\gamma} = -ie\left\{(W^{\dagger}_{\mu\nu}W^{\mu}A^{\nu} - W^{\dagger}_{\mu}A_{\nu}W^{\mu\nu}) + \kappa W^{\dagger}_{\mu}W_{\nu}F^{\mu\nu} + \frac{\lambda}{M_W^2}W^{\dagger}_{\lambda\mu}W^{\mu}_{\nu}F^{\nu\lambda} + \tilde{\kappa}W^{\dagger}_{\mu}W_{\nu}\tilde{F}^{\mu\nu} + \frac{\tilde{\lambda}}{M_W^2}W^{\dagger}_{\lambda\mu}W^{\mu}_{\nu}\tilde{F}^{\nu\lambda}\right\} \quad (2.1)$$

Here A^{μ} and W^{μ} are the photon and W^{-} fields, respectively, $W_{\mu\nu}=\partial_{\mu}W_{\nu}-\partial_{\nu}W_{\mu}$, $F_{\mu\nu}=\partial_{\mu}A_{\nu}-\partial_{\nu}A_{\mu}$, and $\tilde{F}_{\mu\nu}=\frac{1}{2}\epsilon_{\mu\nu\rho\sigma}F^{\rho\sigma}$. e is the charge of the proton, and M_W represents the W-boson mass.

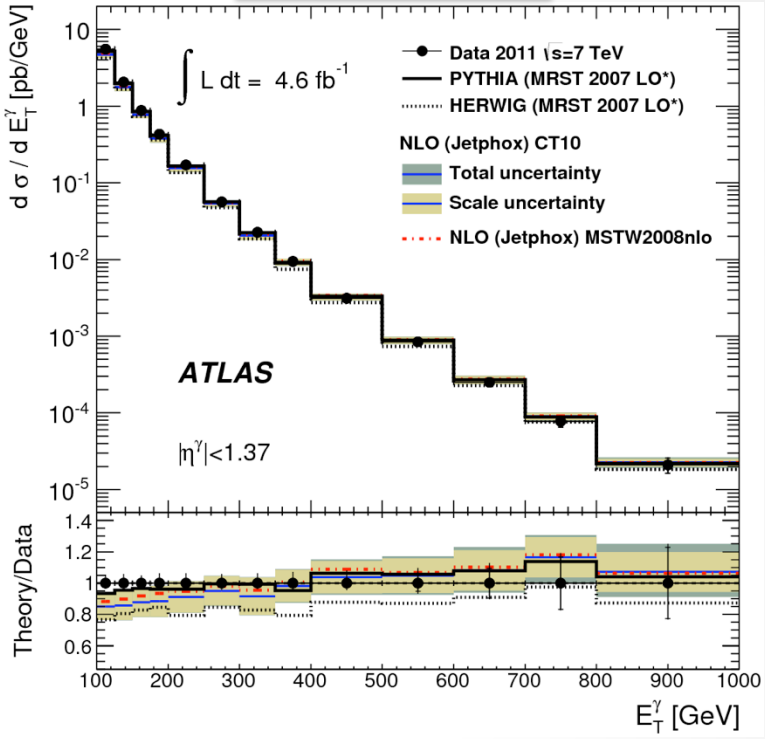
Similar results for
ZZ: *JHEP03(2013)128*
WW: *Phys. Rev. D 87, 112001 (2013)*
WZ: *Eur. Phys. J. C (2012) 72:2173*

Dijet, inclusive jets and inclusive photons

arXiv:1312.3524



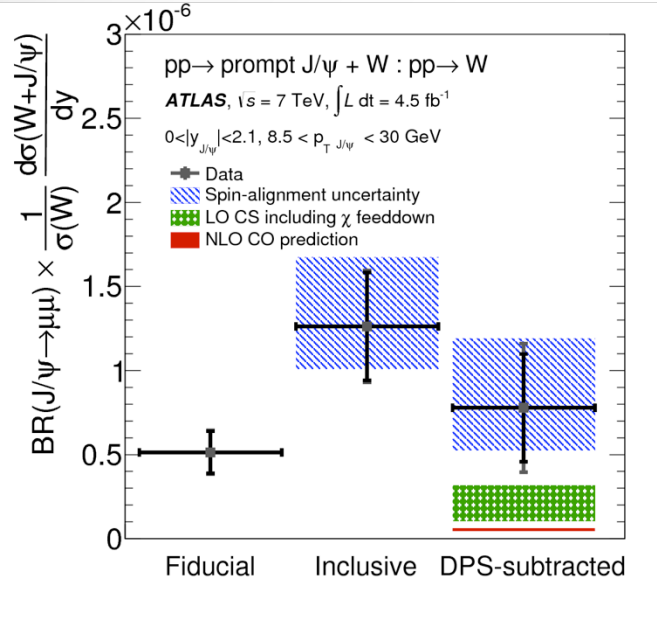
arXiv:1311.1440



- Double-differential dijet and inclusive photon measurements (dijet mass and rapidity separation) compared to NLO MC predictions
- Sensitive to different PDFs

See Z.Hubacek talk for details

Flavour Physics Highlights



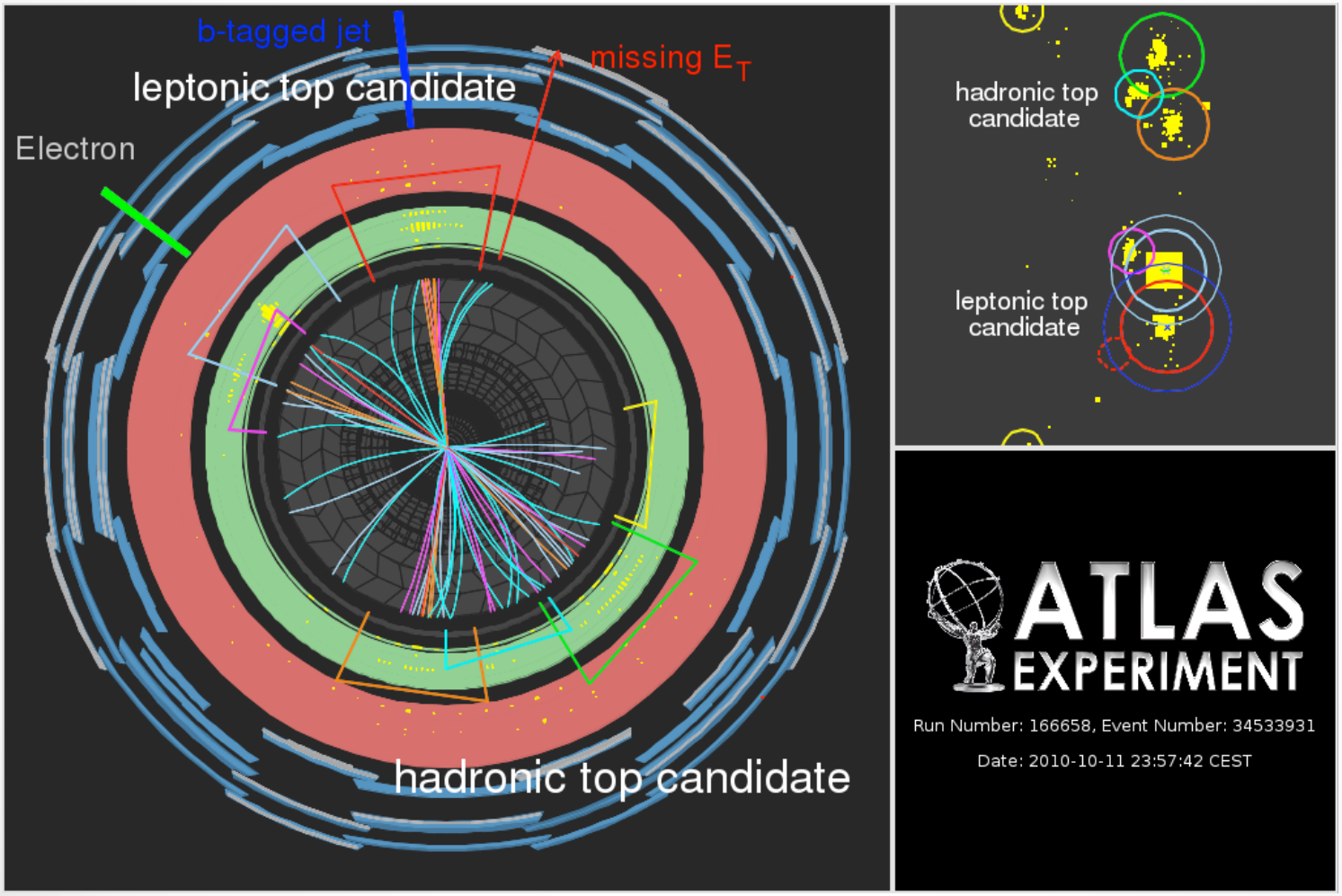
arXiv:1401.2831

- Production of charmonium with W probes QCD at perturbative / non-perturbative boundary
- Can distinguish colour-octet, colour-singlet production
- Sensitive to double-parton scattering (W, J/ψ from different interactions)

- Complementary to LHCb, B-factories
- B-physics talks at LLWI14:
  - Dongliang Zhang ***Study of the Λ_b decay properties with the ATLAS experiment***

Top results

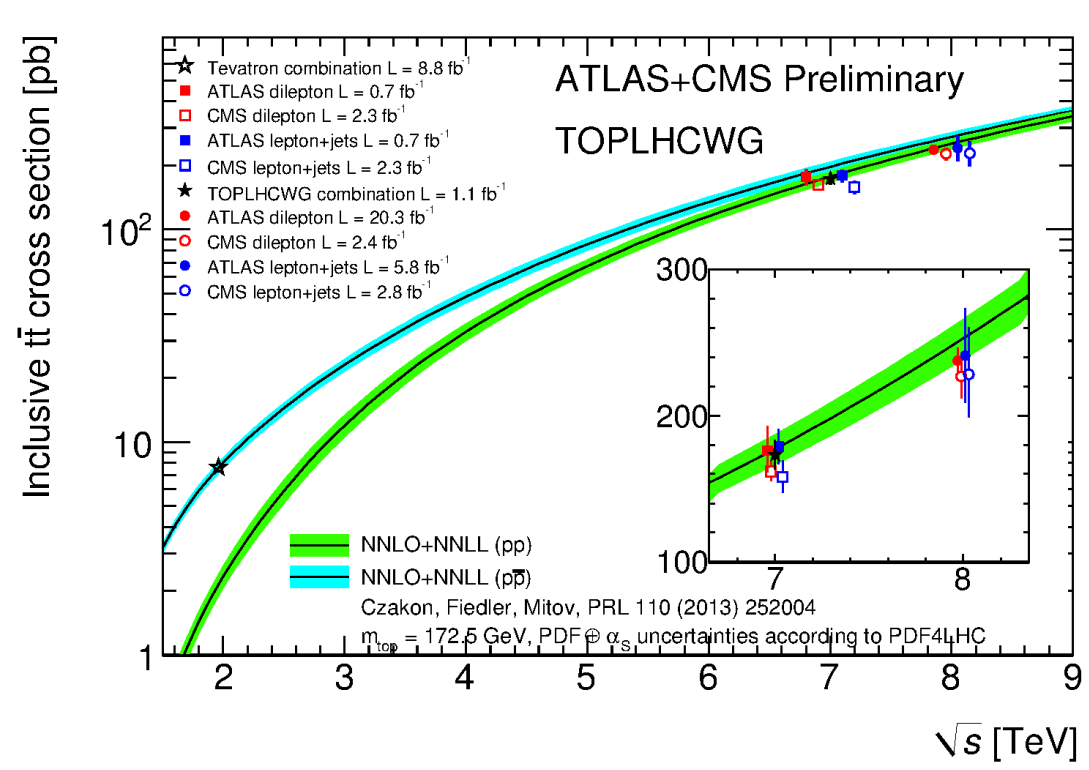
- Top quarks at LLWI14:
  - Tom McCarthy ***Precision measurements of the top quark with the ATLAS detector***



Top pair production

New!

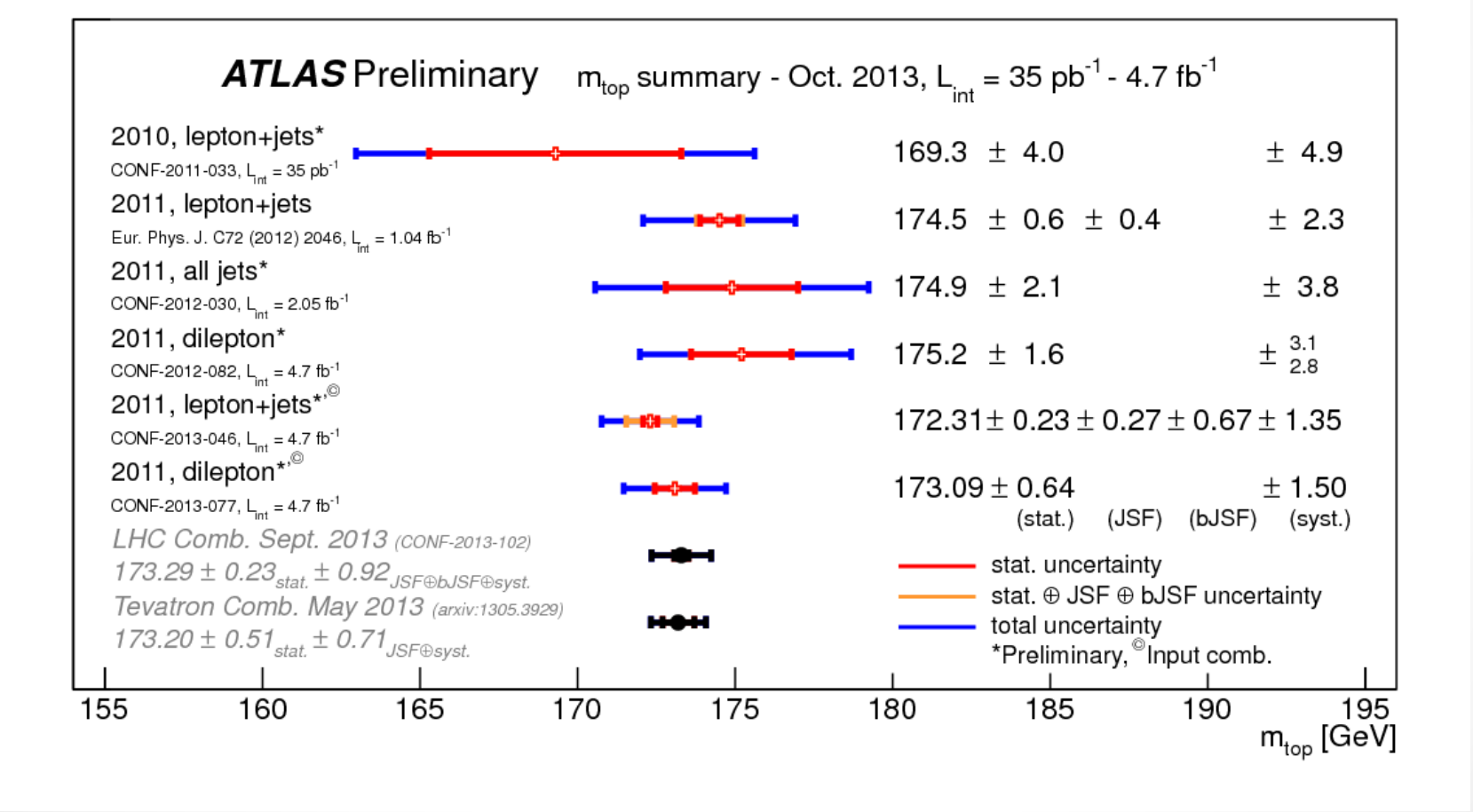
ATLAS-CONF-2013-097



- New dilepton ($e\mu$) result with 20.3 fb^{-1} at 8 TeV has 4.8% uncertainty
  - Dominated by luminosity & beam energy
- Consistent with QCD @ NNLO

Top Quark Mass

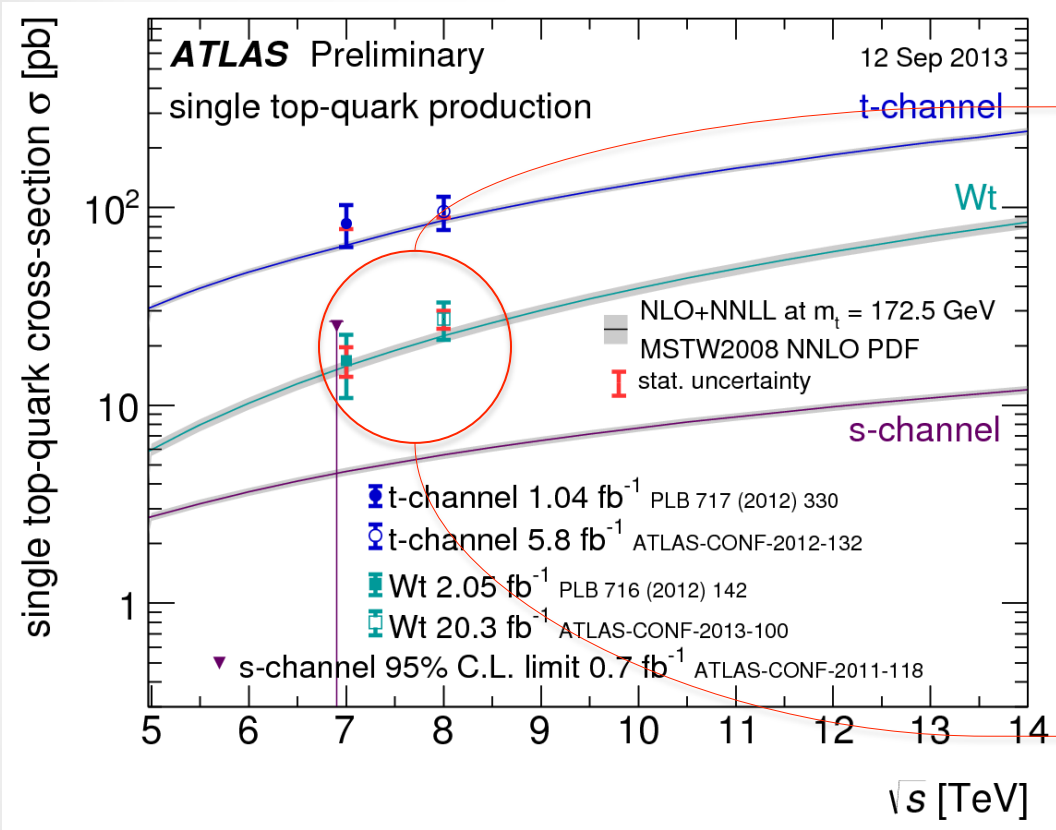
ATLAS-CONF-2013-102 (ATLAS/CMS combo)

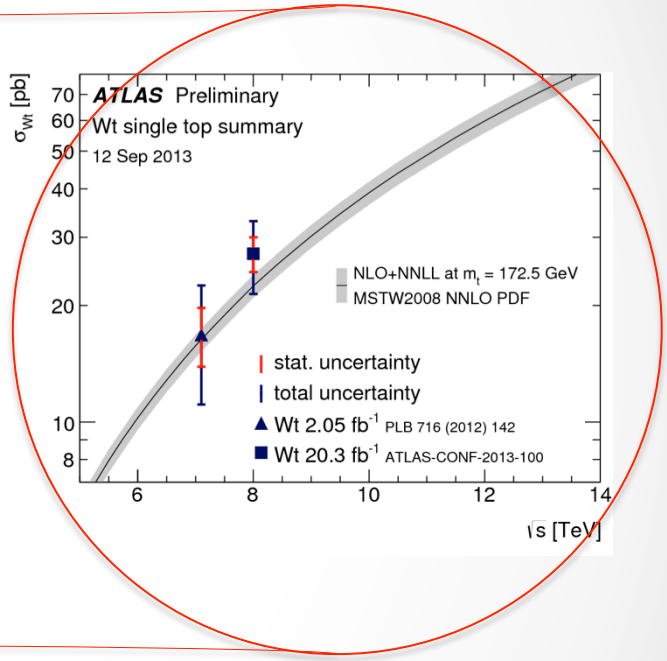


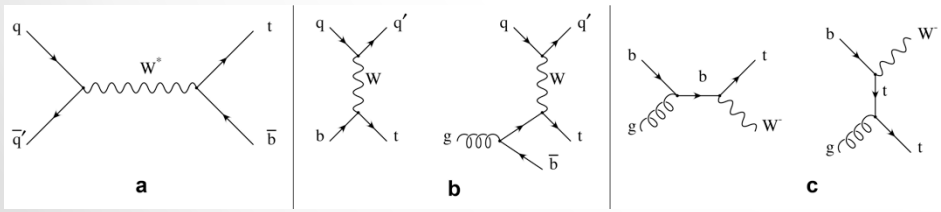
Total uncertainty of 0.95 GeV – or 0.5% – most precisely measured quark mass

Single Top (electroweak top production)

ATLAS-CONF-2013-100



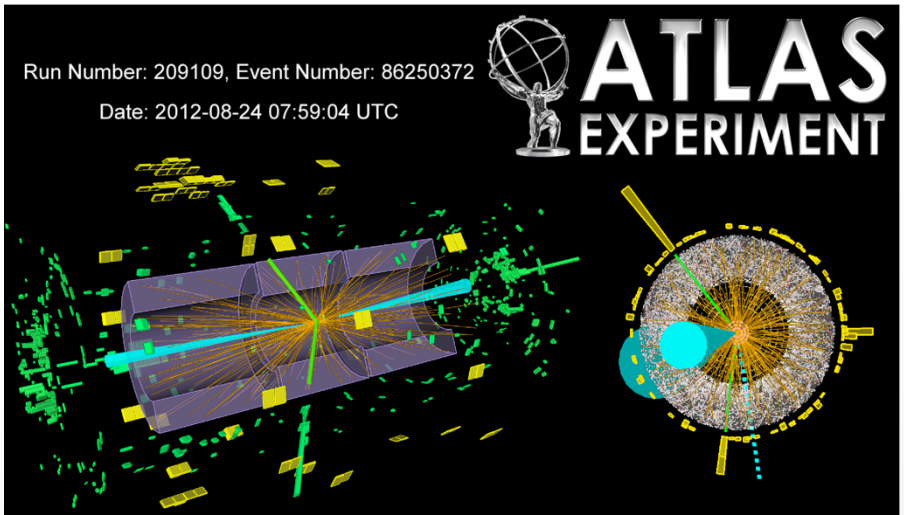




Full data set analysis for Wt, s- and t-channel updates still in progress… stay tuned

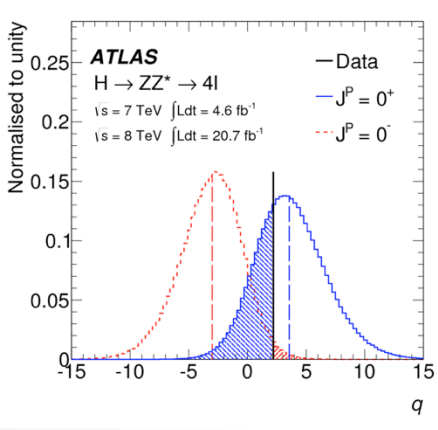
Higgs Boson *Measurements* (and searches)!

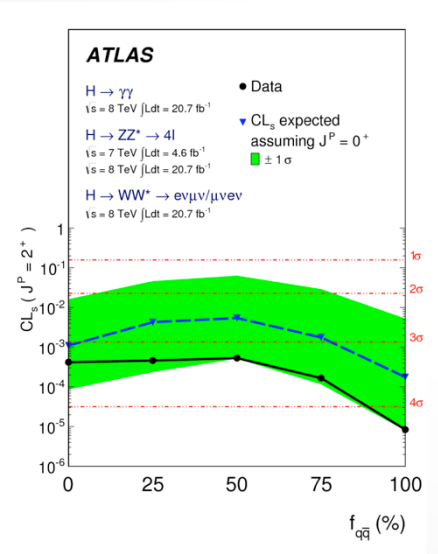
- Higgs Results at LLWI14:
  - Lidia Dell'Asta ***Search for the Higgs boson in fermionic channels using the ATLAS detector (including $\mu\,\mu$ decay)***
  - Fangzhou Zhang ***Combined Measurements of the Mass and Coupling Properties of the Higgs boson using the ATLAS Detector***
  - Haifeng Li ***Measurement of Properties of the Higgs boson in bosonic channels using the ATLAS detector (including Z γ decay)***
  - Nathan Readioff ***Search for Higgs boson decays to a photon and a Z boson in pp collisions at sqrt(s) = 7 and 8 TeV with the ATLAS detector – Poster***
- BSM Higgs Results at LLWI14:
  - Haleh Hadavand ***Beyond-the-Standard Model Higgs and invisible Higgs decays using the ATLAS Experiment***

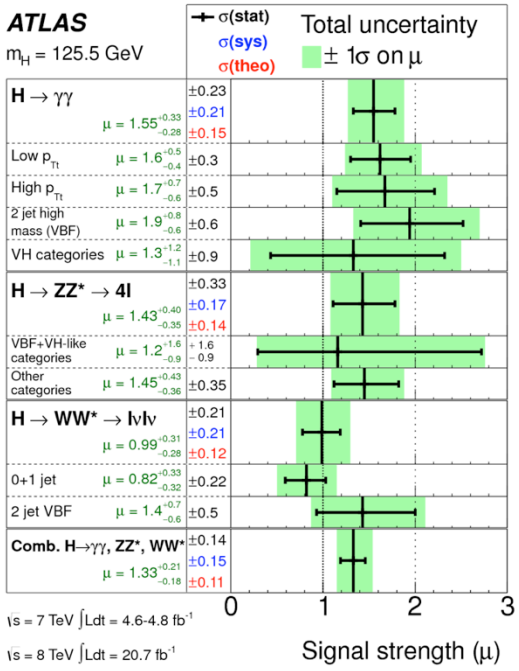


Higgs Couplings, Spin and Parity

- Enough $\gamma\gamma$, ZZ and WW Higgs candidates to measure properties!

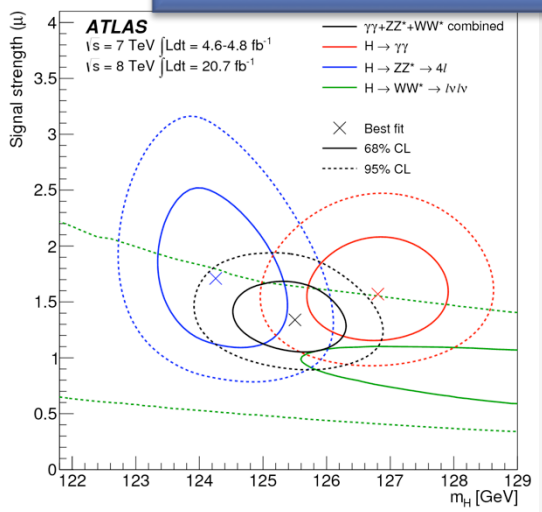


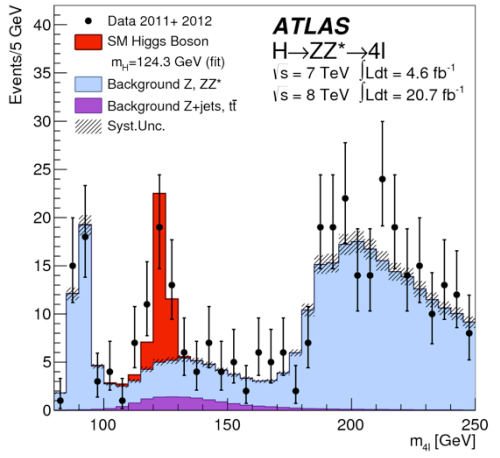




Phys. Lett. B 726 (2013), pp. 88-119, 120-144

ATLAS-CONF-2013-02



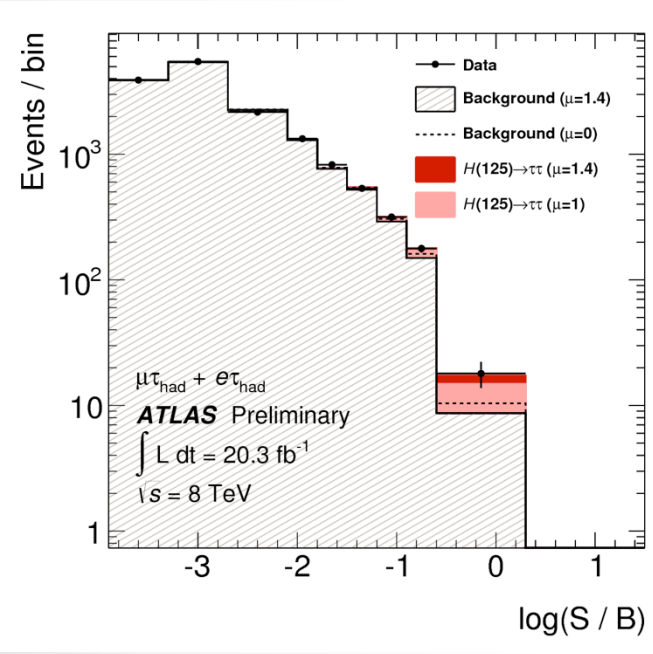


Much more detail in talks from F. Zhang, H. Li

Higgs decay to fermions

- Strong evidence for H to $\tau\ \tau$ (multi-channel, BDTs):
  - direct coupling to ("down-type") fermions, to leptons
- Limits on H to $\mu\ \mu$, bb (associated production)…

ATLAS-CONF-2013-108



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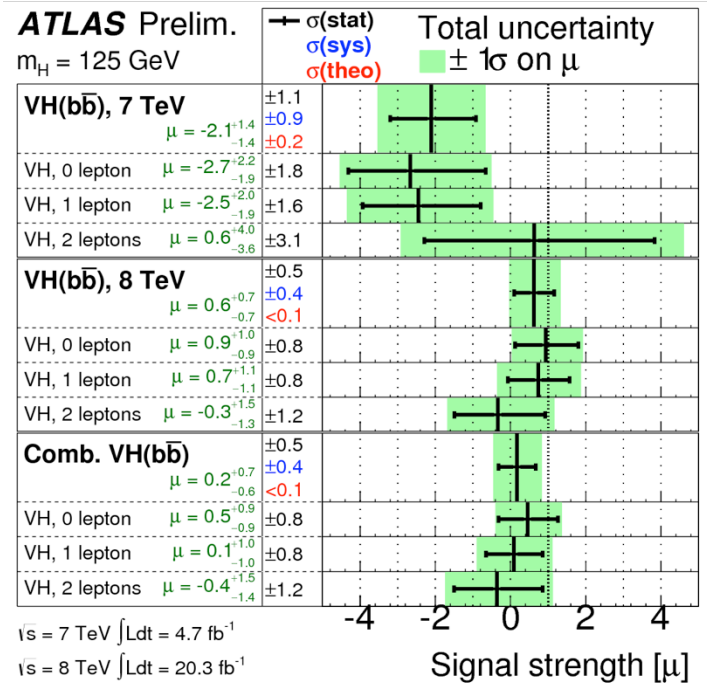

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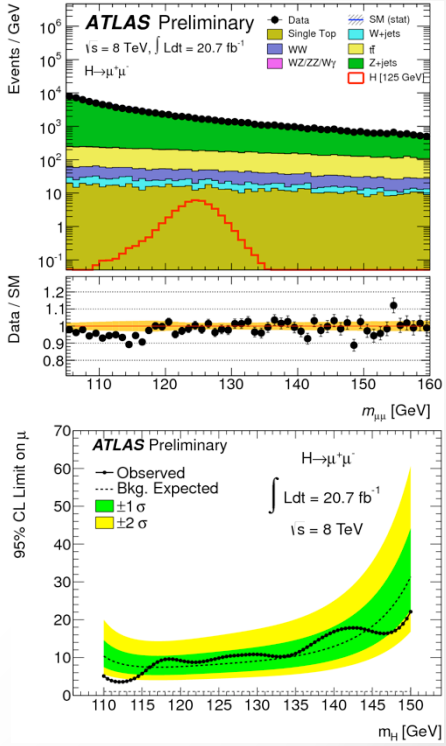


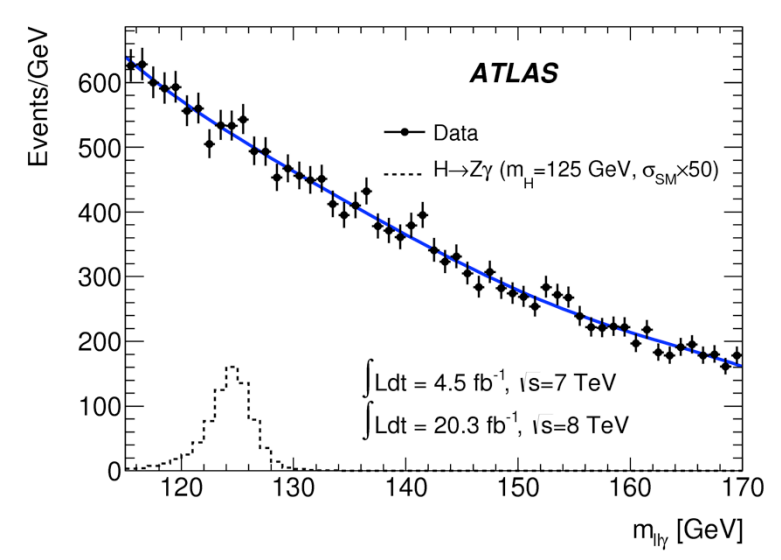
Details in talk from L. Dell'Asta

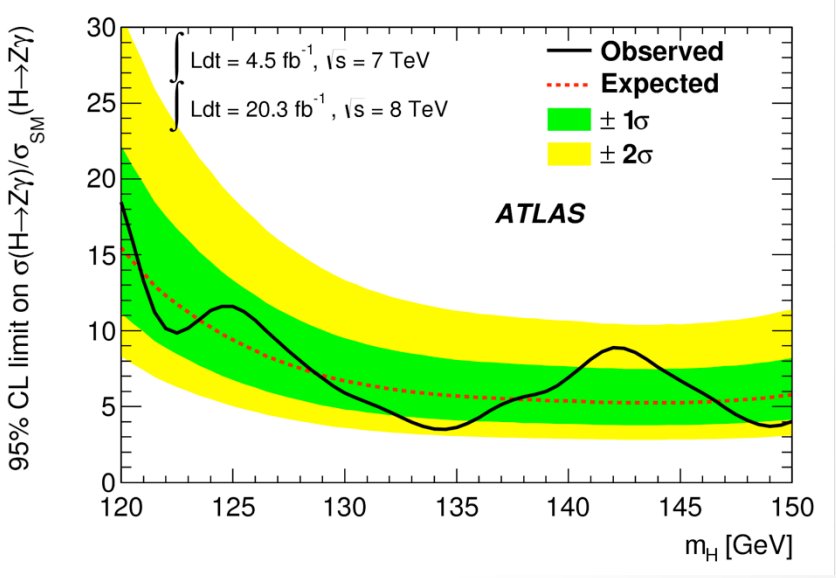
New!

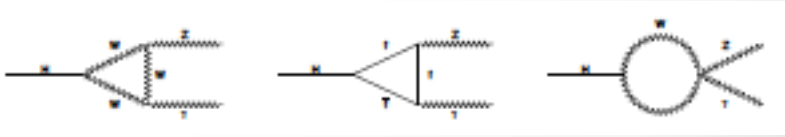
Search for Higgs decay to Zγ

arXiv:1402.3051

- Loop decay, similar to $\gamma\ \gamma$
  - But requiring ee or $\mu\ \mu$ final state, σ x BR only 5% of $\gamma\ \gamma$
  - No expectation of being able to see SM signal with this dataset
- Search done in broader mass range, look for anomalies







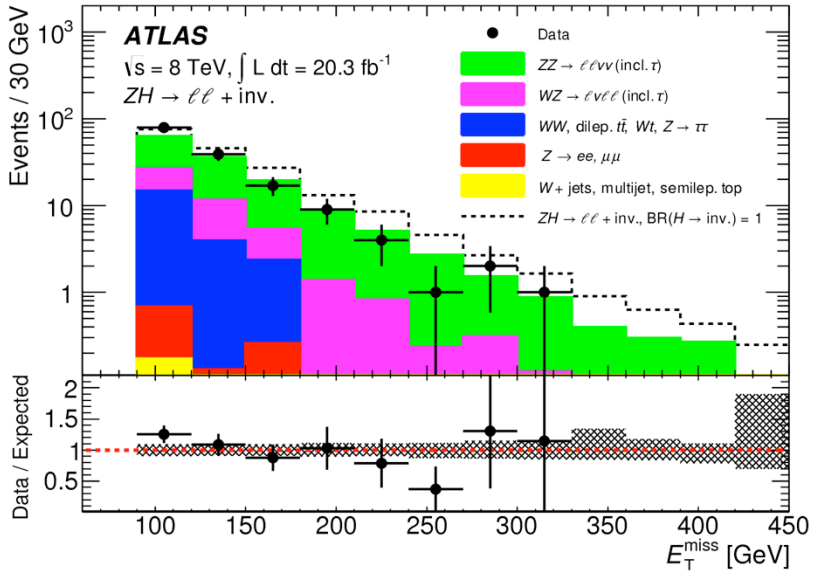
See talk from H. Li

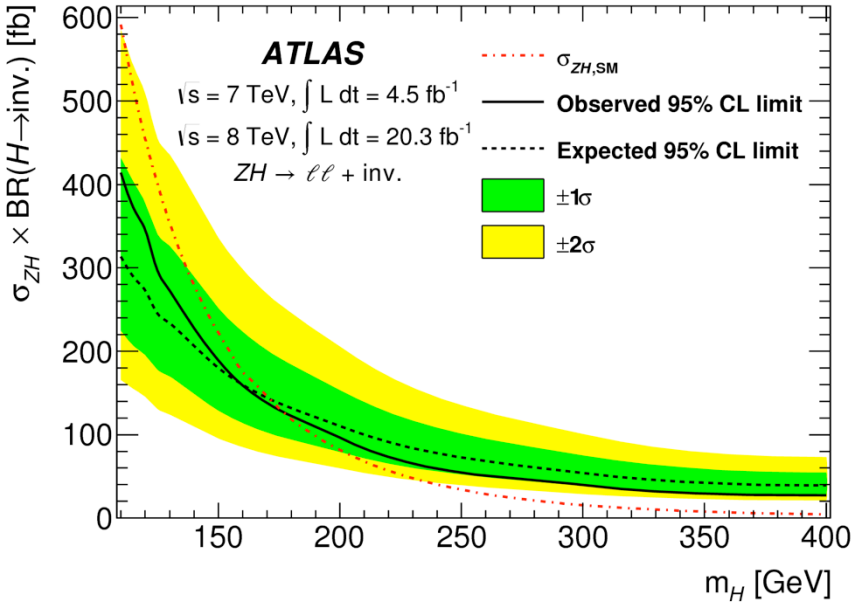
Search for Invisible Higgs Decays

New!

arXiv:1402.3244

- Look for ZH associated production
- In SM: ZH to Z(ZZ*) to Z+4 ν (too small to see)
- BSM models with WIMPs coupling to Higgs

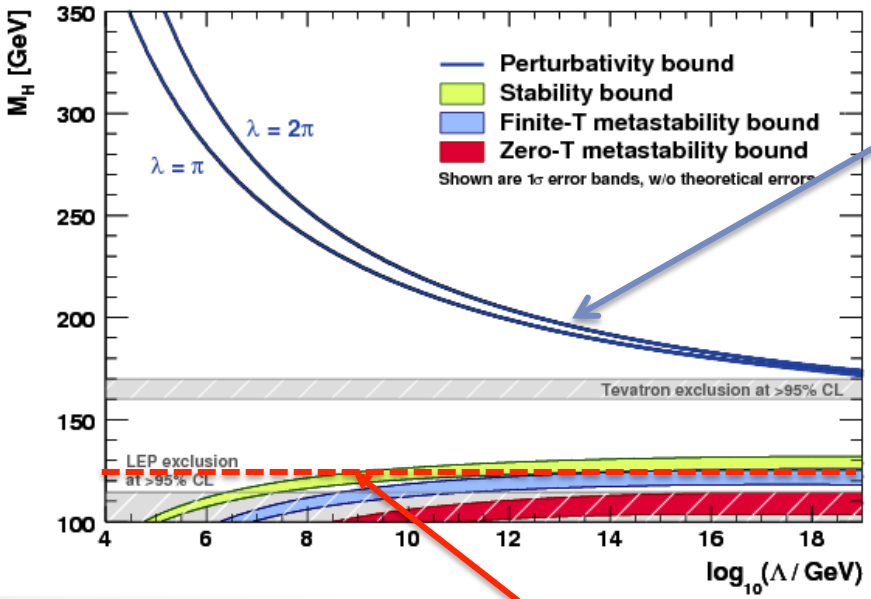




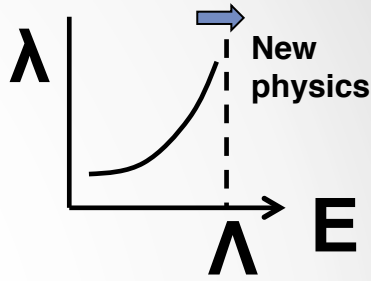
E_T^{miss} after full selection

See talk from H. Hadavand

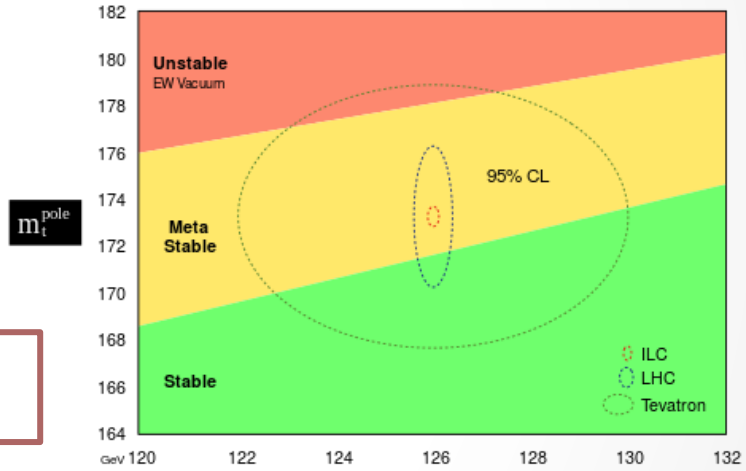
Implications of a 125-GeV Higgs Boson



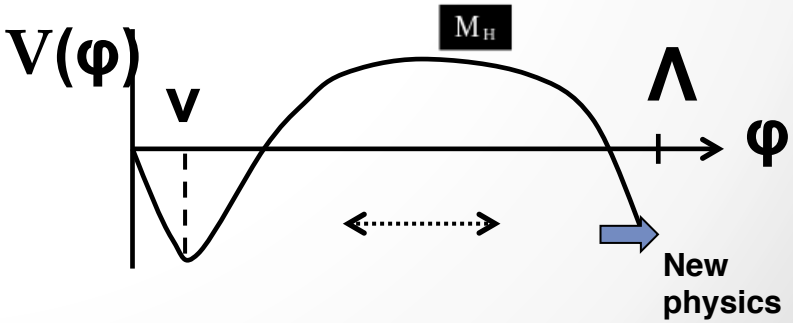
Perturbativity: M_H too big, Higgs self-coupling blows up at scale Λ (no longer a worry)



M_H~125 GeV: Requires new physics below M_{Planck}, but only at ~10^9 GeV; possible all BSM physics beyond LHC reach?



EW Vacuum Stability: M_H too small, Higgs potential develops 2nd (global!) minimum of order Λ



Expect "BSM" physics too

- Quantum theory of Gravity
- Quark/Lepton generations, masses
  - ⇒ Compositeness? Substructure? Strings?
  - ⇒ Common sub-elements quarks/leptons?
- Matter-Antimatter asymmetry
  - CPV in SM (K,B) + Big bang:
    - Not enough to explain observations
    - Neutrinos last "SM" hope (given ν mass$\neq$0)
- Cosmological constant (dark energy ...)
  - Higgs energy density $\approx 10^{50}$ GeV/cm^3 (could finesse)
  - Observationally: $< 10^{-4}$ GeV/cm^3
- Fine-Tuning of Higgs mass
  - Particle loop corrections to $M^2_H \sim \Lambda^2$
  - If theory cut-off $\Lambda \sim$ O(10^6 TeV) e.g. for m_H~125 GeV:
    - Fine tuning of m_t, $m_H \sim 1 : 10^6$ (or more) needed
- Dark Matter
  - Seems to be O(few 100 GeV)

Slide adapted from Rob McPherson
UVic/IPP LLWI 2011

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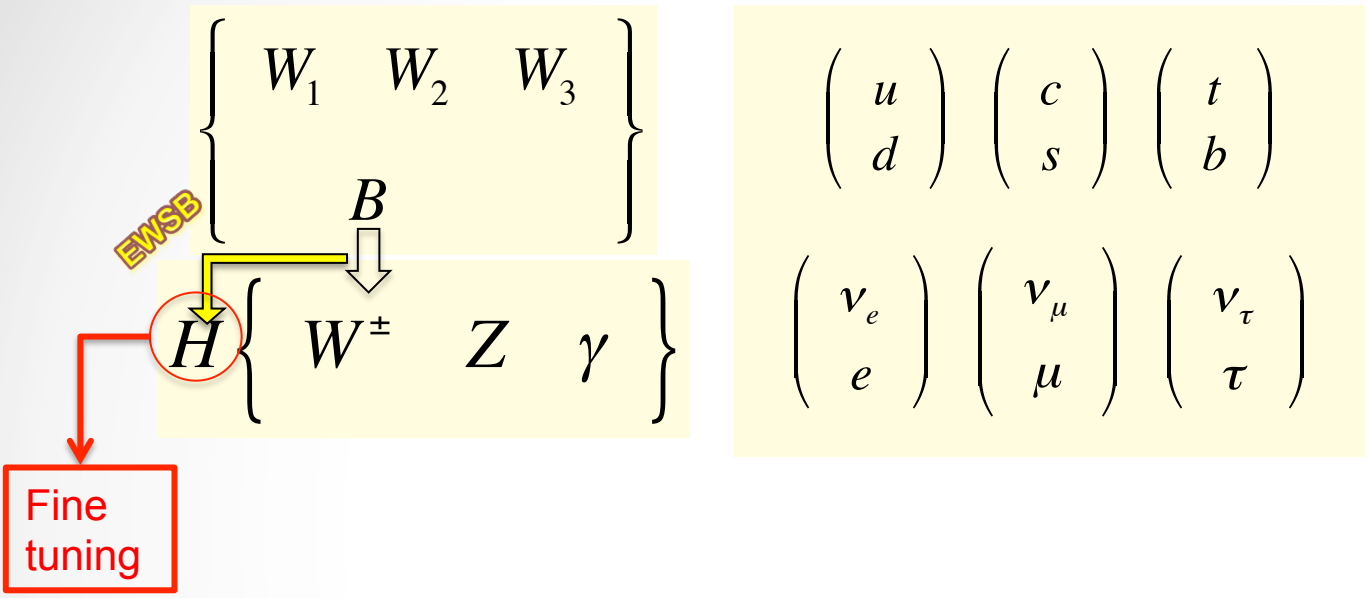
➢ **Case strong**

➢ **Scale?**

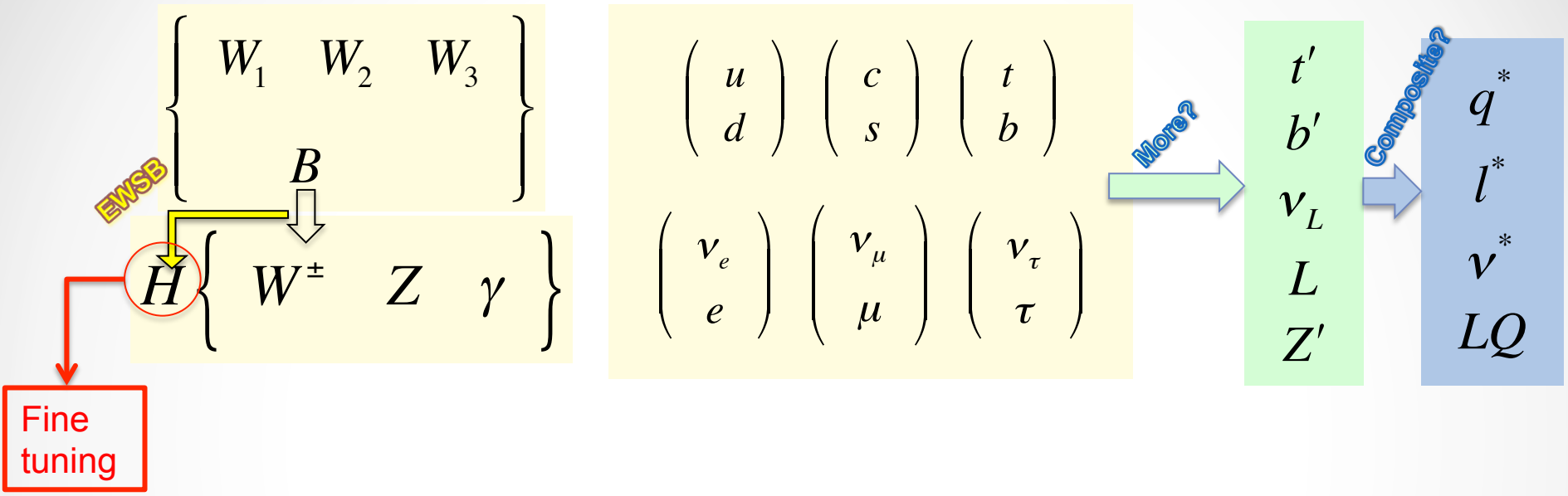
➢ **Here, case for EW scale new physics**

Slide adapted from Rob McPherson
UVic/IPP LLWI 2011

Roadmap: Beyond the SM



Roadmap: Beyond the SM



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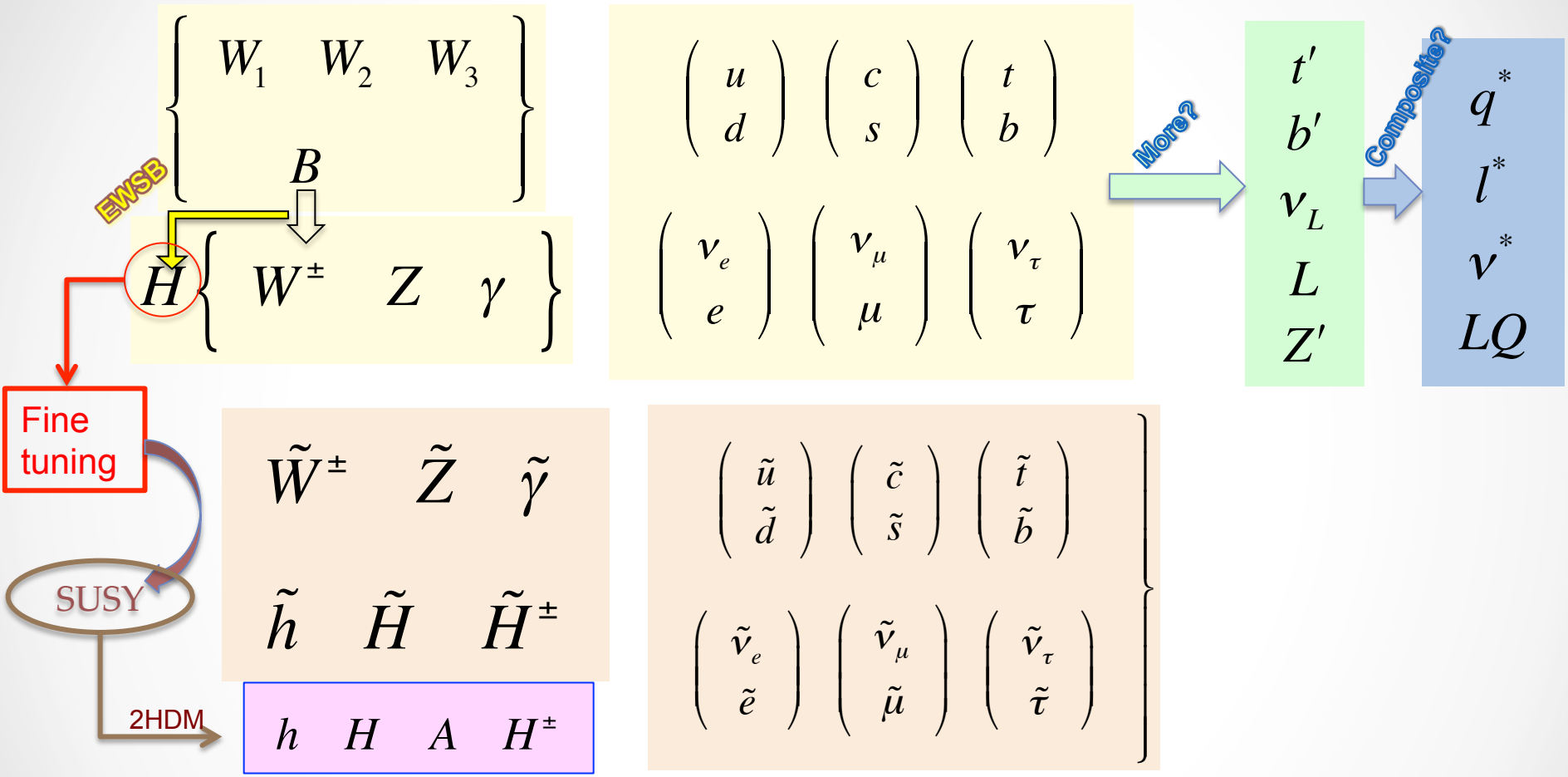

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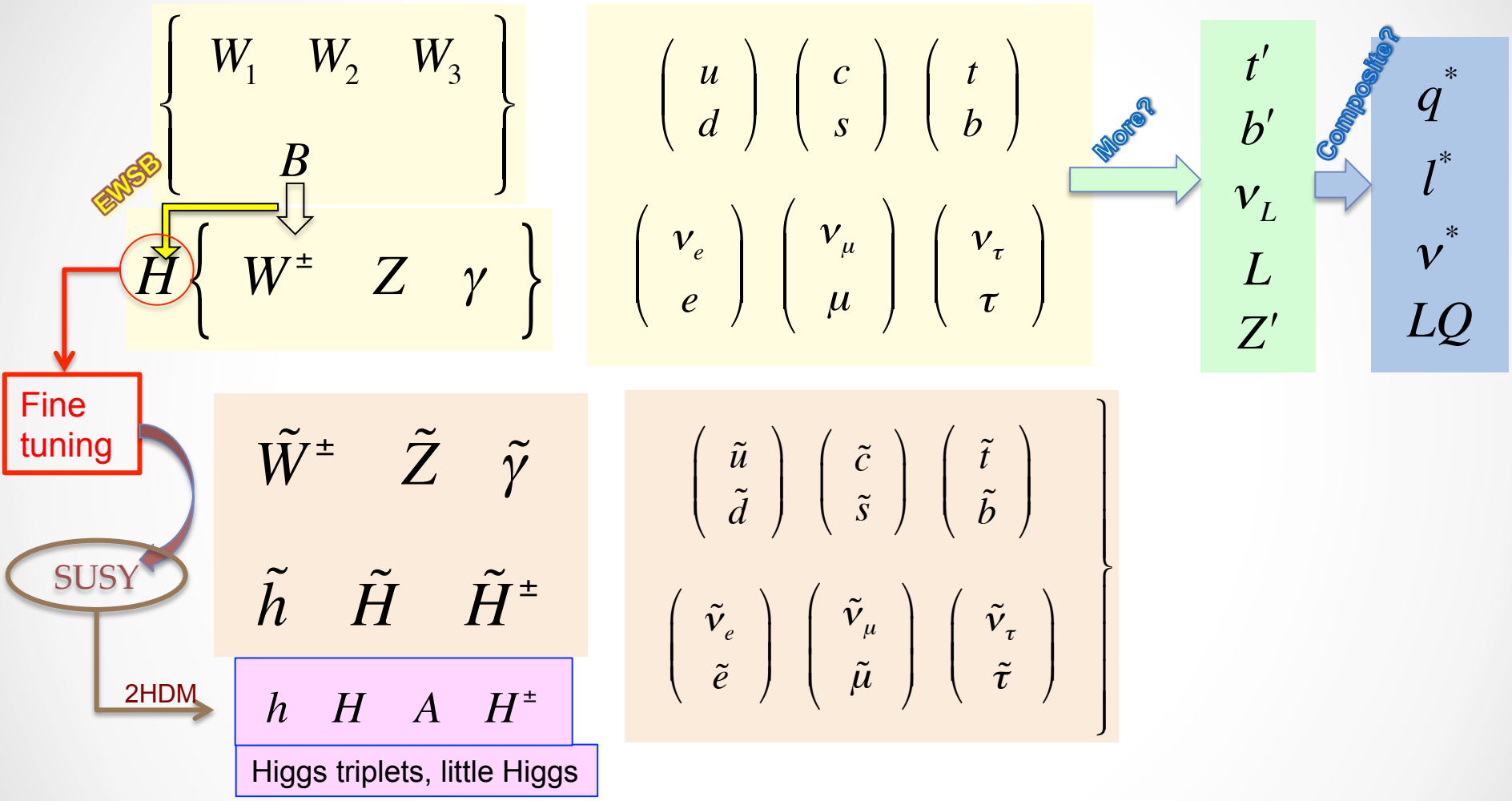
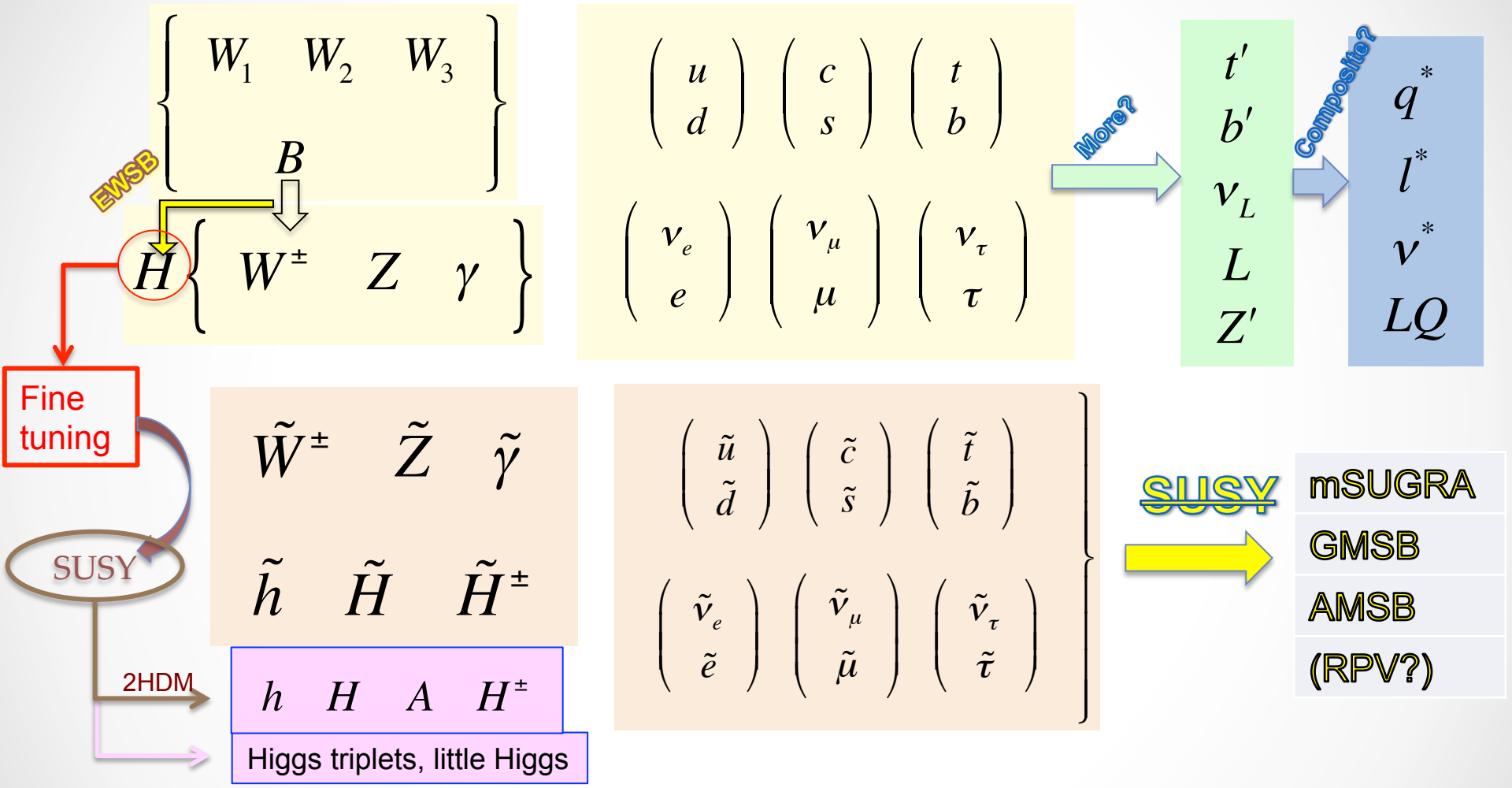


Roadmap: Beyond the SM



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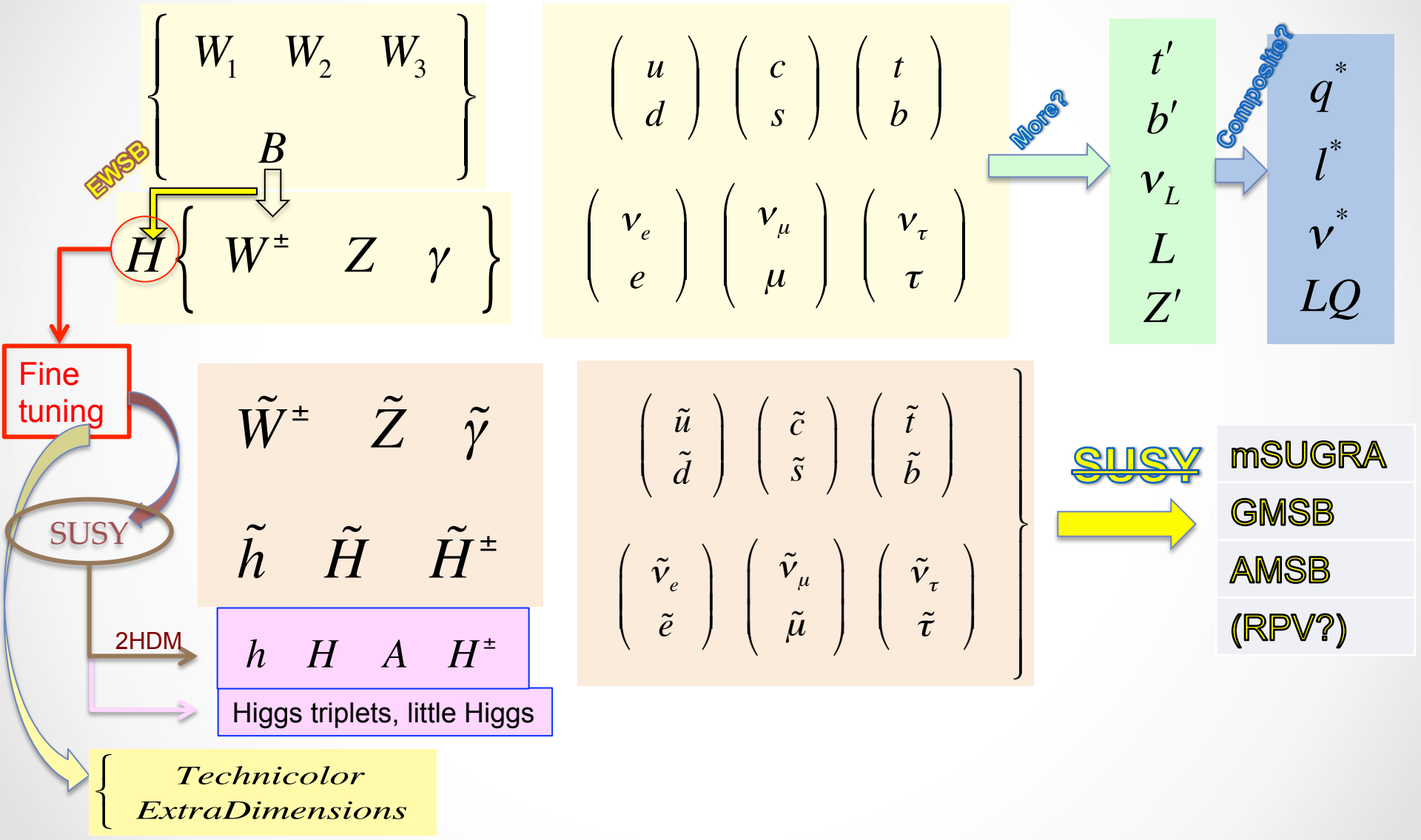
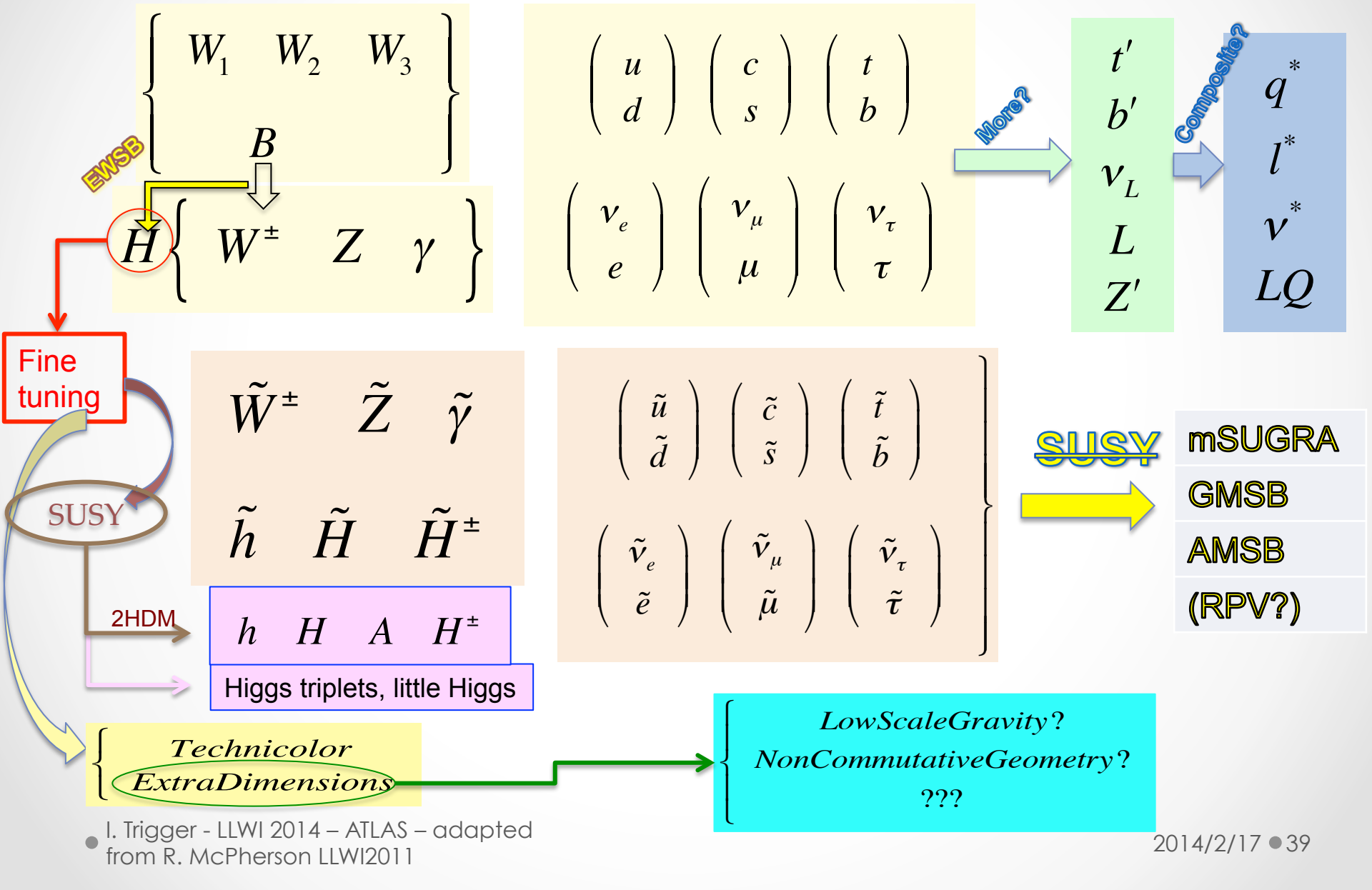
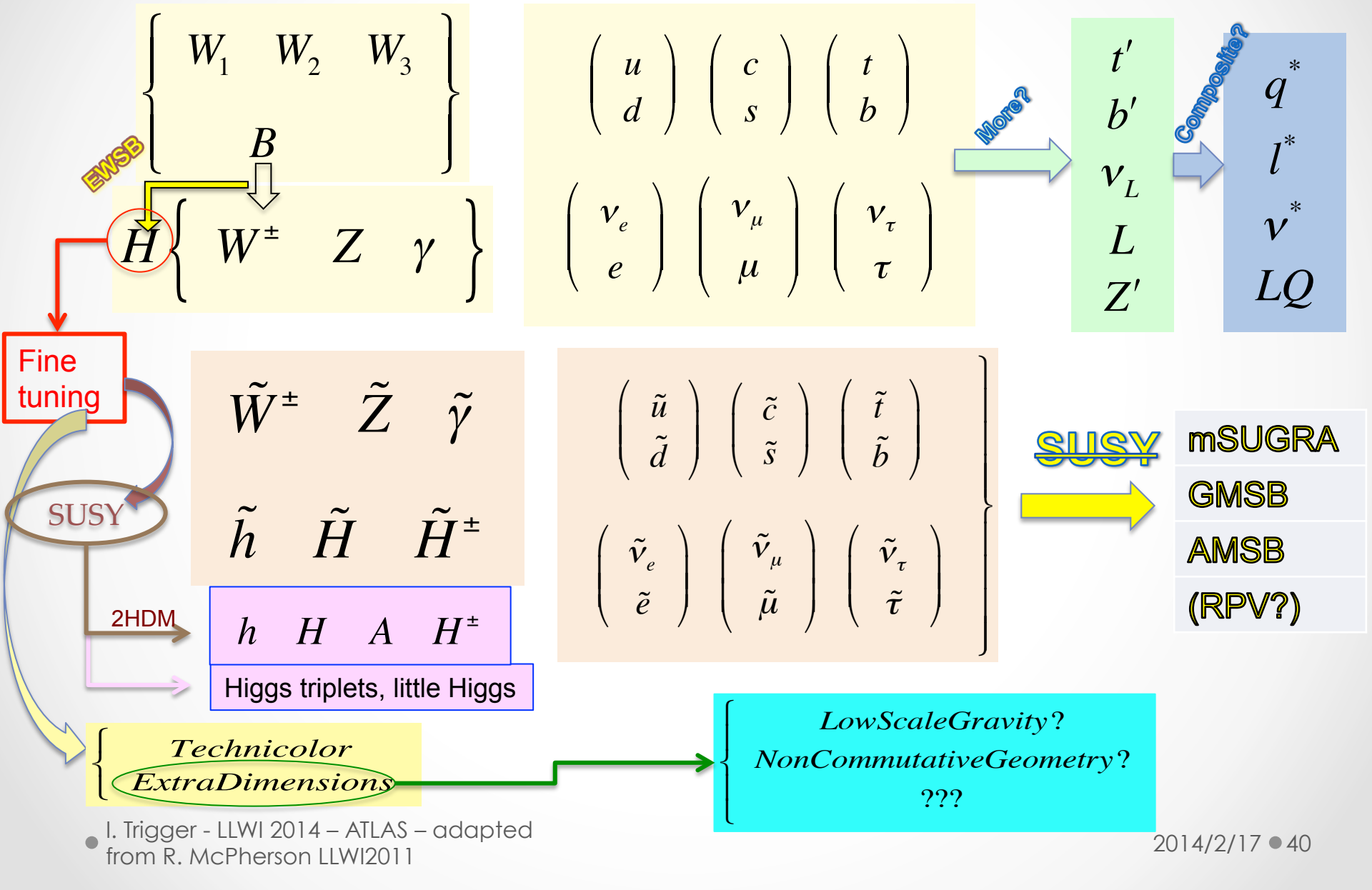


Roadmap: Beyond the SM

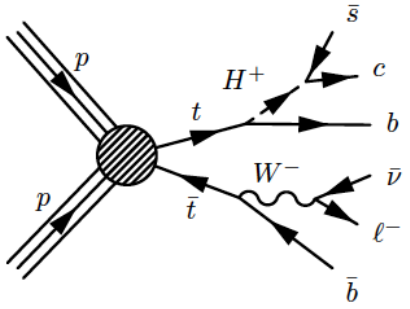


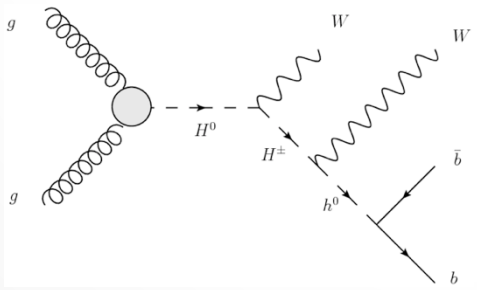
Roadmap: Beyond the SM

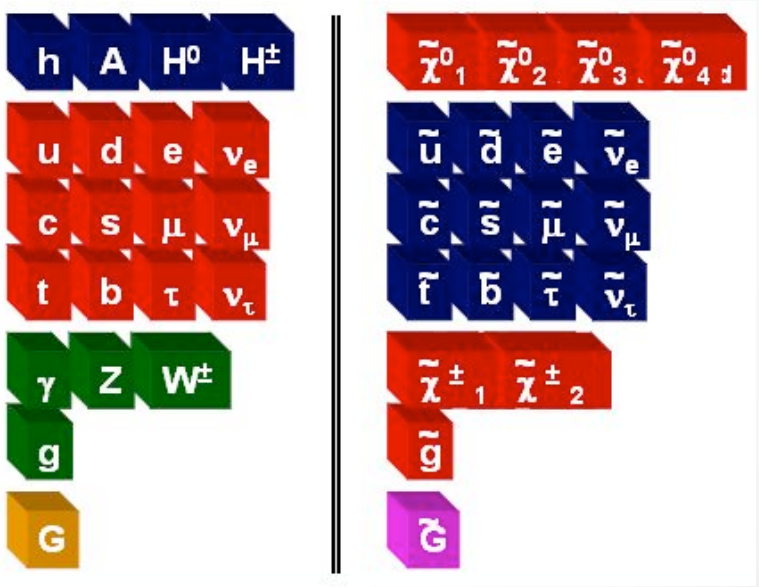


Extended Higgs Sector Searches

- Invisible Higgs & Higgs to Z γ , μ μ
  - SM too small; if we actually saw a signal, BSM
- $H^{\pm}$➔cs (in top pairs)
- WW cascades (2HDM+)



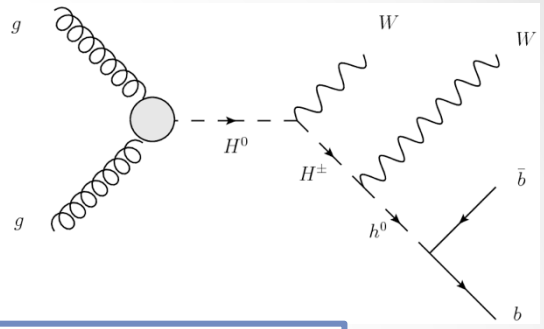




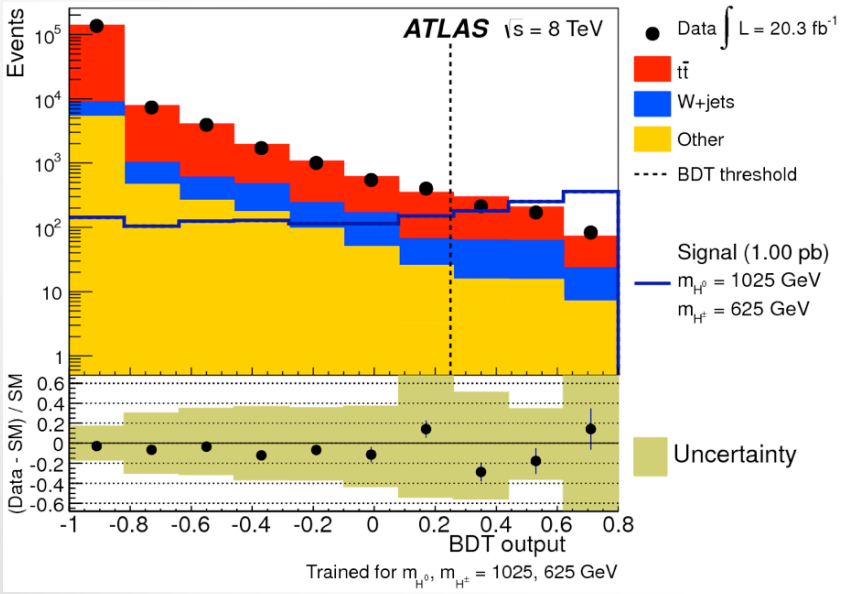
Multi-Higgs Cascades with WWbb

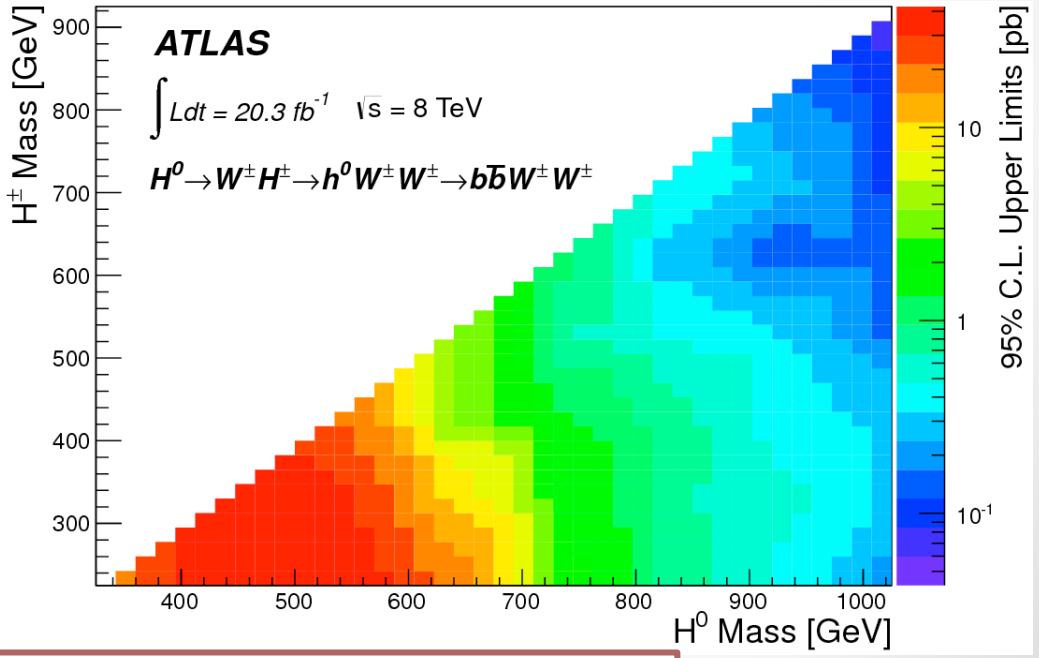
arXiv:1312.1956

- Non-minimal Higgs sectors
  - e.g. Supersymmetry
  - Assuming several light Higgs bosons…
- BDT analysis



Observed limit:



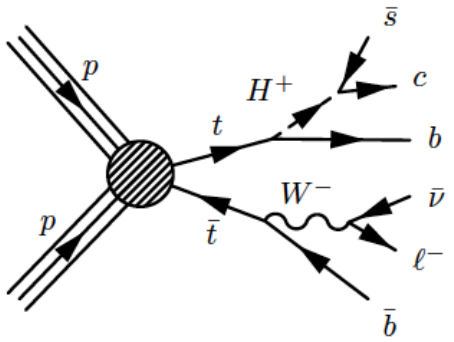


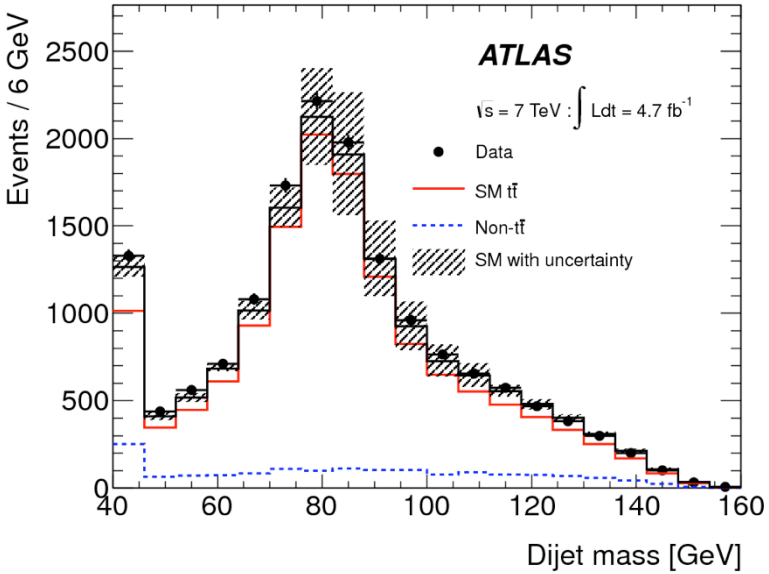
Details in talk from H.Hadavand

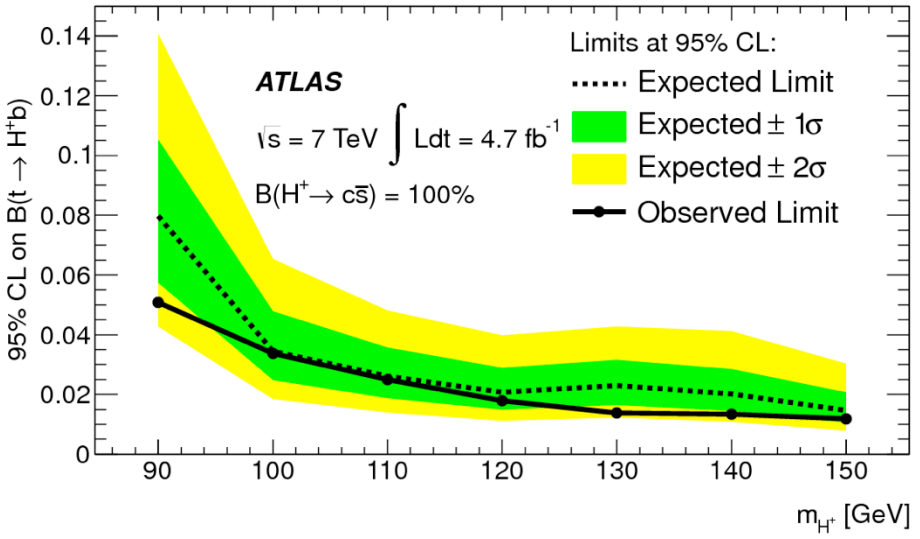
Search for light charged Higgs decaying to cs in top-pair decays

Eur. Phys. J. C, 73 6 (2013) 2465

- "Light": $m_{H+}<m_t$
- Assume all-hadronic decays of H^+
  - BR depends on tan β and m_{H+}
  - Plugs small tan β hole
- LEP limits: >75-91 GeV in all Type-II 2HDM (depends on BR assumption)





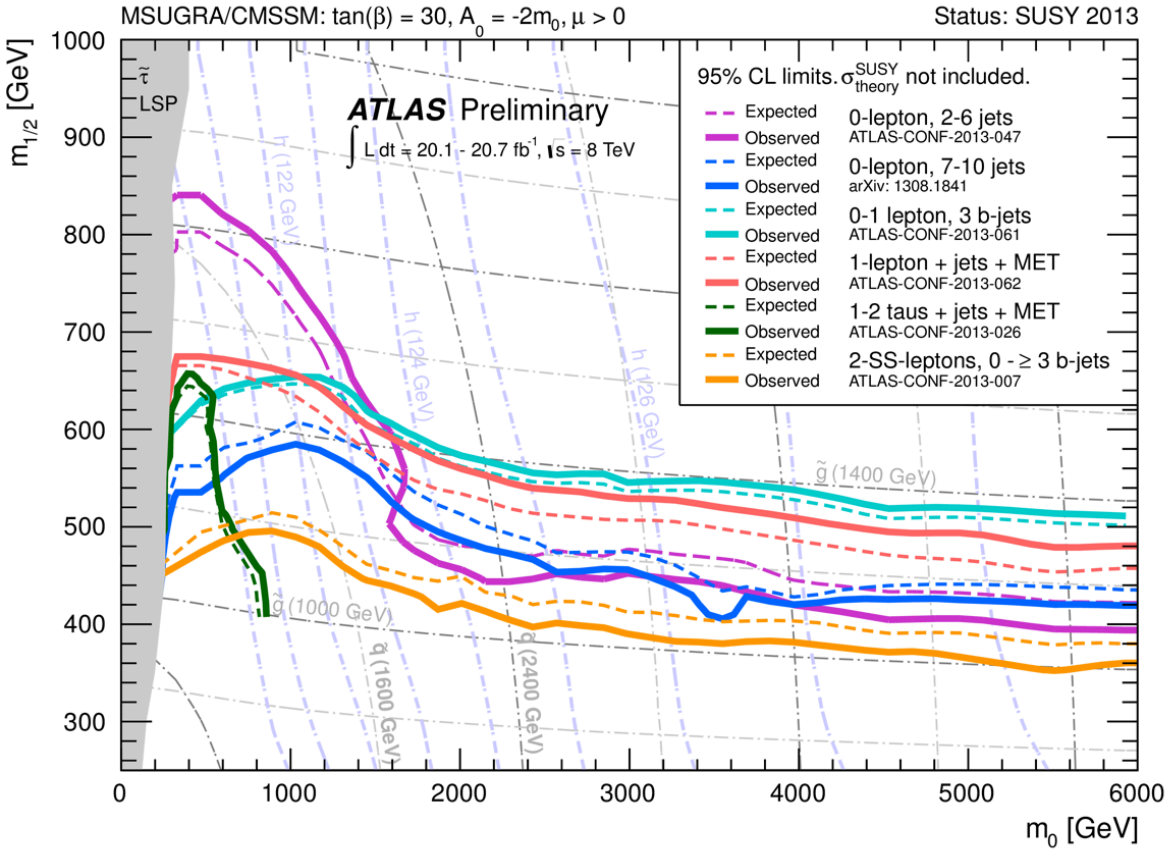


$H^+ \rightarrow \tau\nu$ in talk from H.Hadavand

Supersymmetry Searches

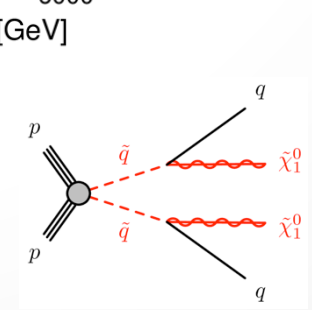
- LHC Dream – new partner for every known one
- Squarks & Gluinos strongly produced, huge cross-section if light enough
- LSP as Dark Matter Candidate (if R-parity conserved)
- Rich Higgs sector (2HDM or more)
- *BUT* … 125.5 GeV Higgs discovery and non-discovery of squarks / gluinos so far strongly constrains, suggesting:
  - "Natural" Supersymmetry (only light stop, $\chi^{\pm}$, χ^{0}, gluino)
  - … "Higgs-aware" benchmarks of old favourites (e.g. mSUGRA)
  - Or sneaky scenarios (split SUSY, RPV, long-lived (N)LSP,…)
- Supersymmetry talks at LLWI14:
  - Pawel Klimek ***Recent results on searches for R-parity conserving supersymmetry at the ATLAS experiment***
  - Adrian Chitan ***Searches for R-parity violating supersymmetry and long-lived particles at the ATLAS experiment***

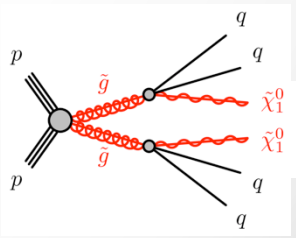
Strong-production Supersymmetry Searches



- LHC was *really* hoping for:
  - Light squarks / gluinos, copiously produced
- Searches for jets + E_T^{miss} (possibly with leptons and b-jets) set powerful constraints

Benchmark for "conventional" SUSY

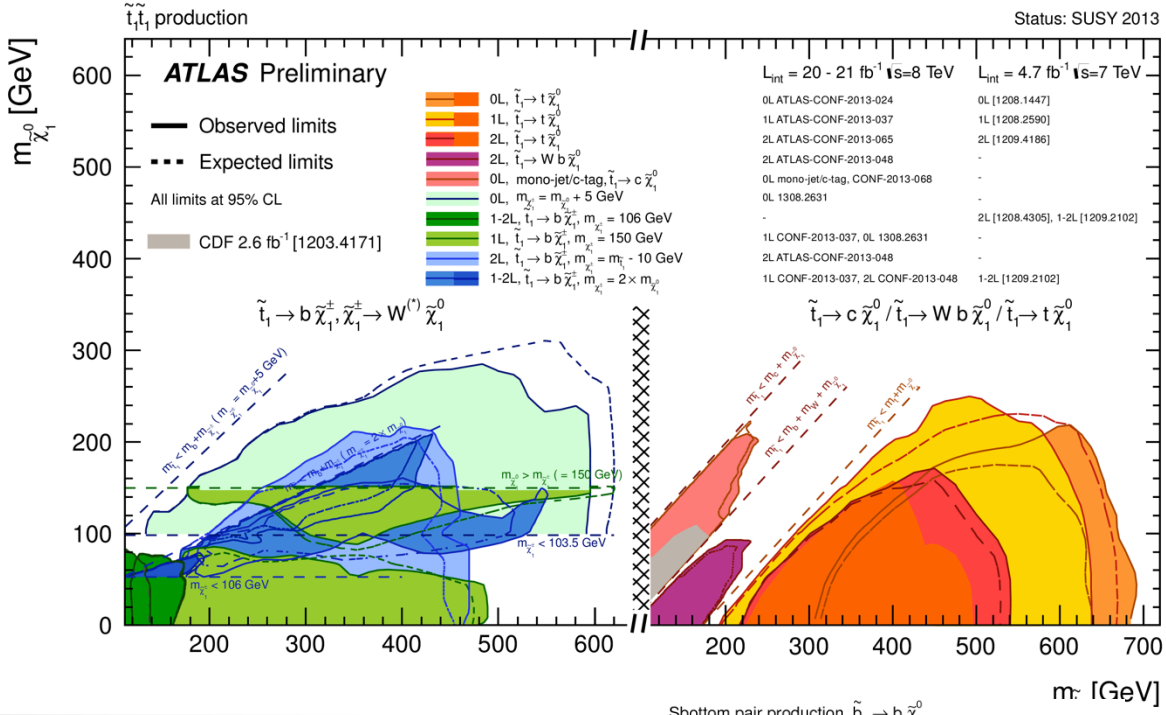


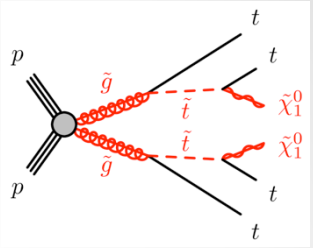


etc.

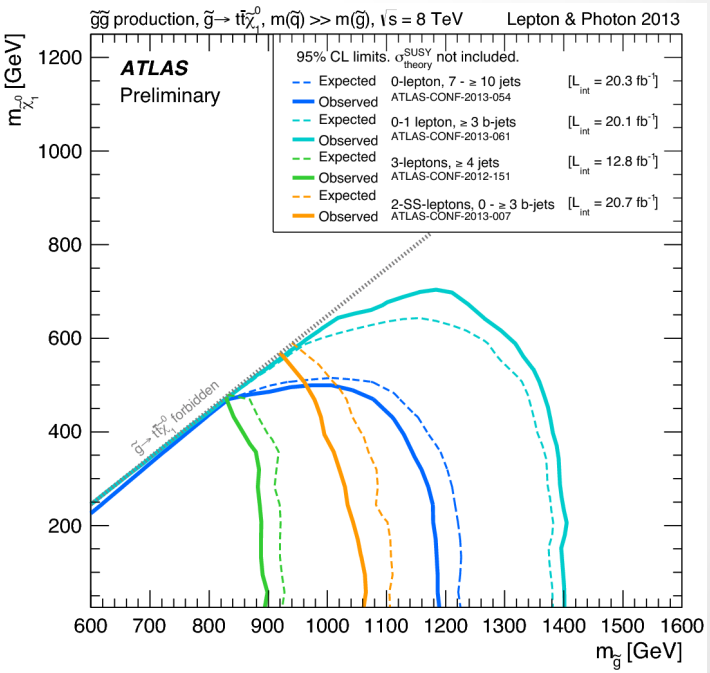
"Natural" SUSY: 3rd generation focus

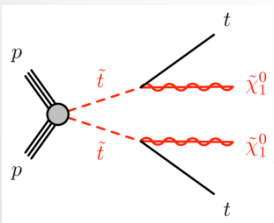
Summary of stop exclusion from various scenarios

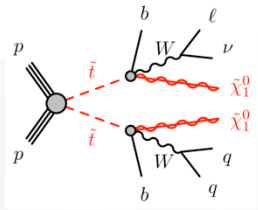


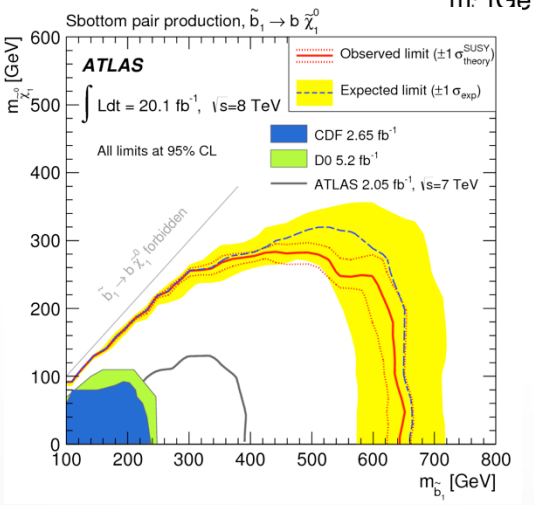


Light gluino->stop->tt+E_T^{miss}







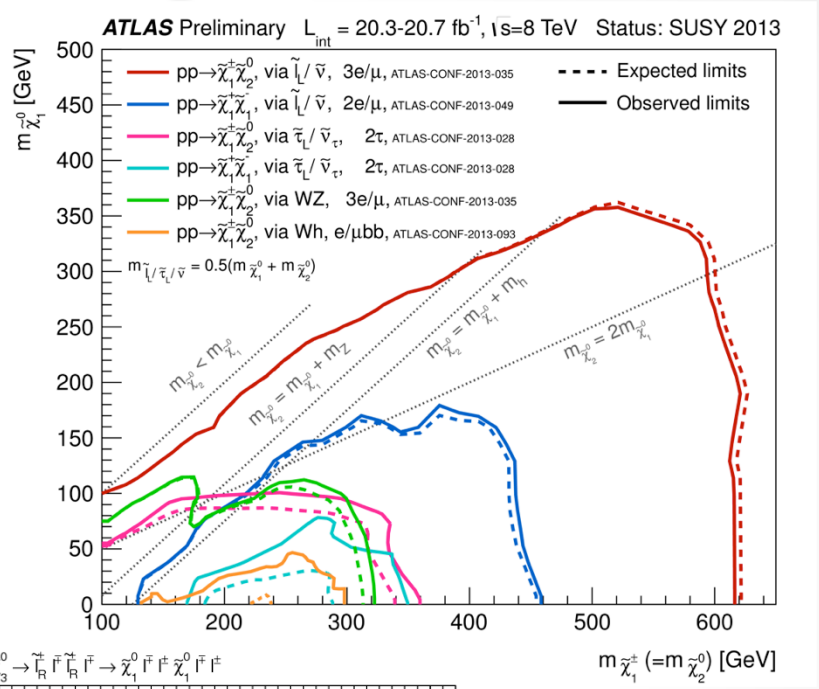


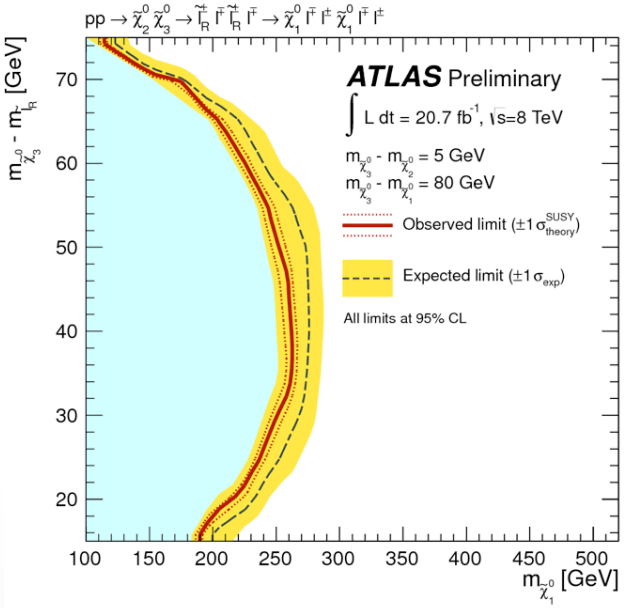
Sbottom limits

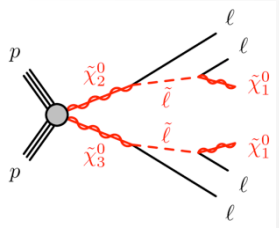
JHEP10(2013)189

Electroweak SUSY production

- Difficult situation where only EW partners are light…
  - LHC σ_{EW} generally small
- Search for 2,3,4 leptons + E_T^{miss} (or lepton + h^0➔bb + E_T^{miss})
- Exclusions for specific (simplified) models







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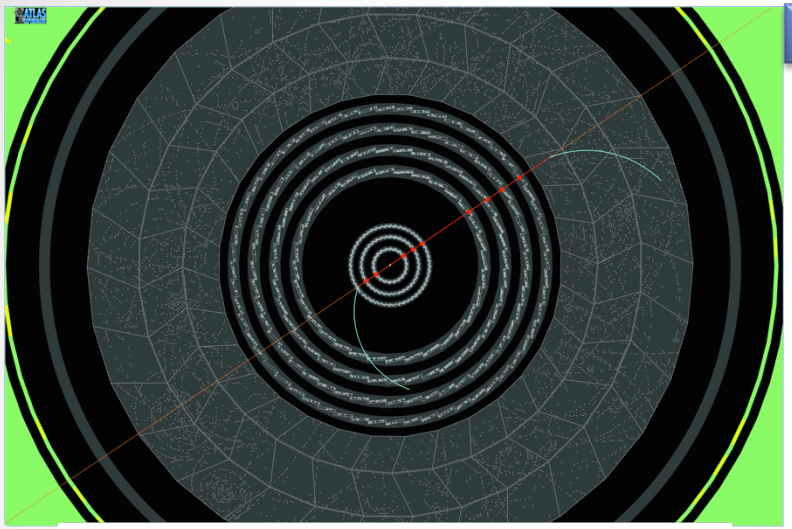
Much more in talk from P.Klimek

Long-lived LSP and R-Parity Violation



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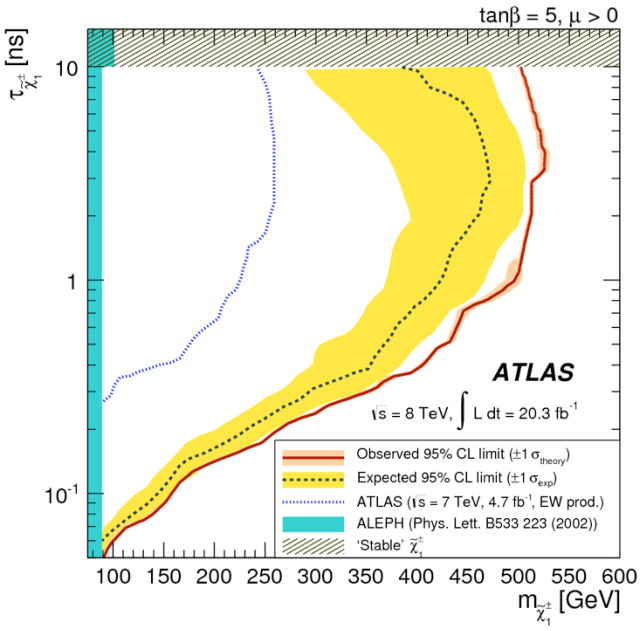
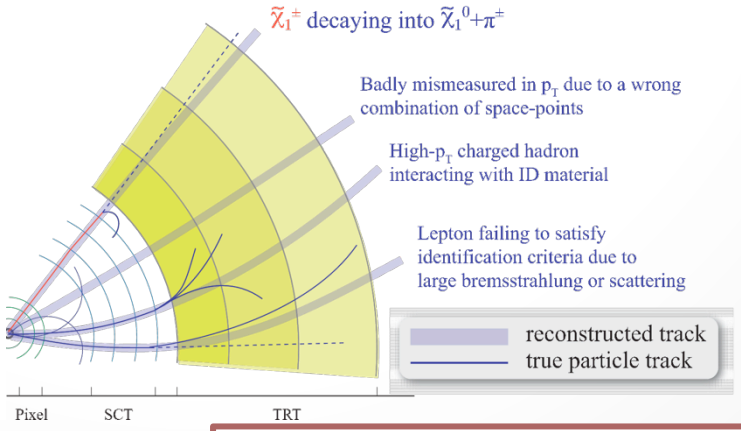
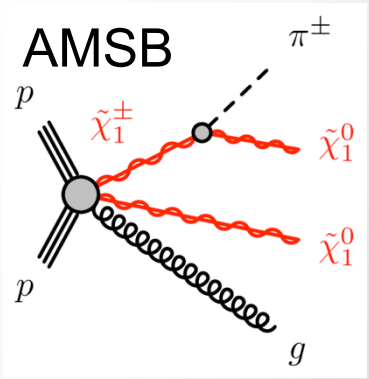
- Contemplating possibility SUSY exists but does *not* solve all our problems: RPV (weak couplings not yet constrained by FCNC), split-SUSY, compressed scenarios
- Or does, but is well hidden: AMSB (near-degeneracy), GMSB (with long-lived NLSP)…



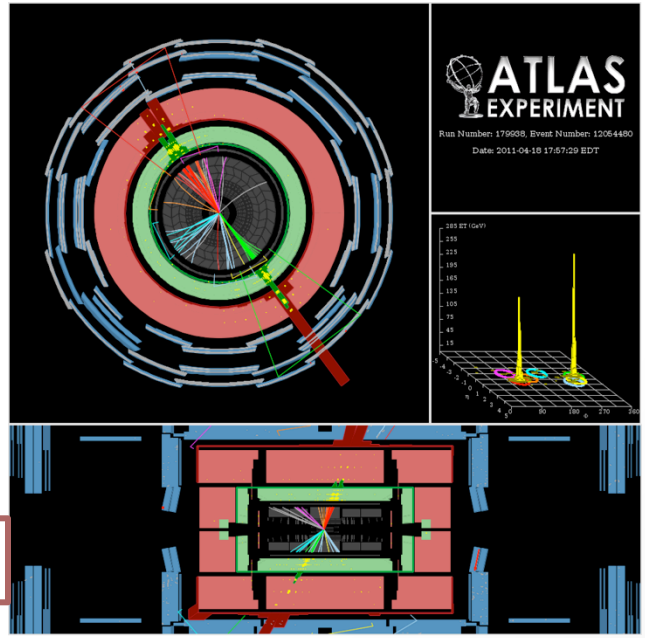




More in talk from A.Chitan

"Exotic" Beyond-Standard-Model Searches

- Consider non-SUSY-specific extensions to SM
  - e.g. extra dimensions, compositeness
  - Generic signatures
- Exotics talks at LLWI14:
  - Wendy Taylor ***Searches for new phenomena with the ATLAS detector***
  - Camille Bélanger- Champagne ***Search for new phenomena in photon+jet events collected in proton-proton collisions at sqrt(s) = 8 TeV with the ATLAS detector – Poster***



dijet event with m_{jj}=4040 GeV

Dilepton resonance search

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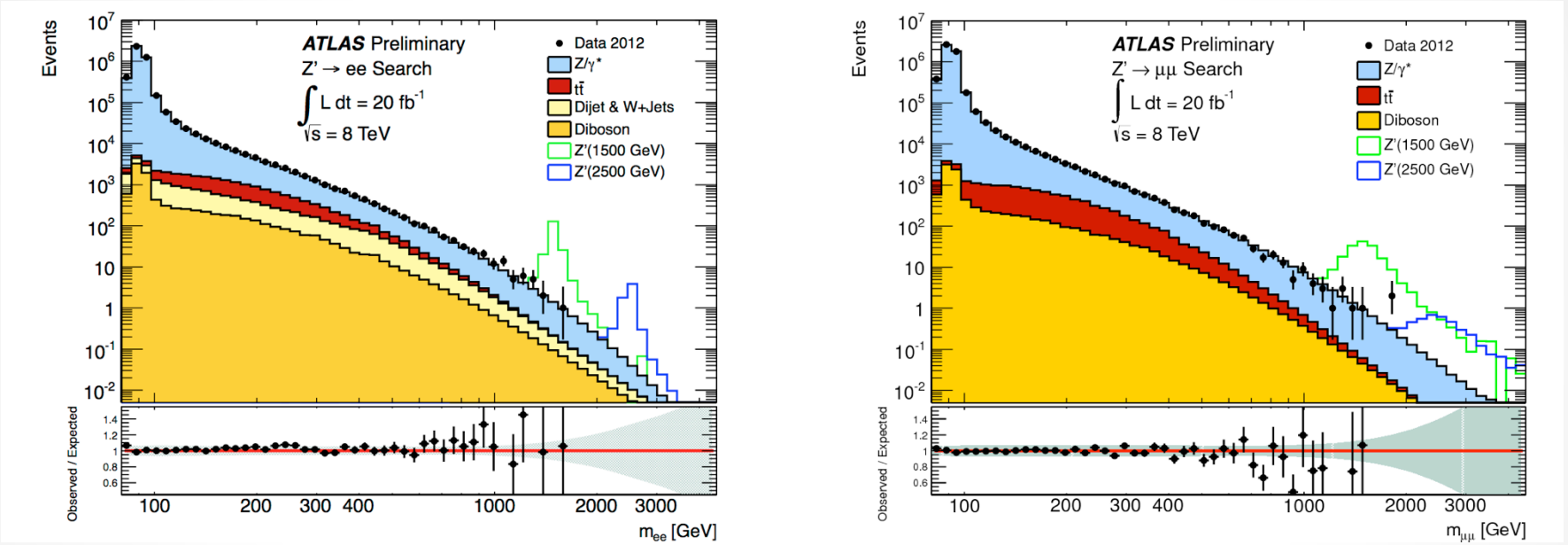
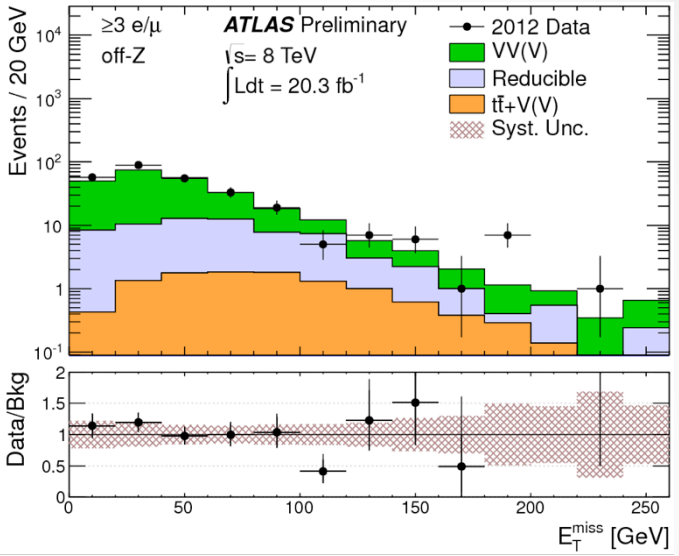


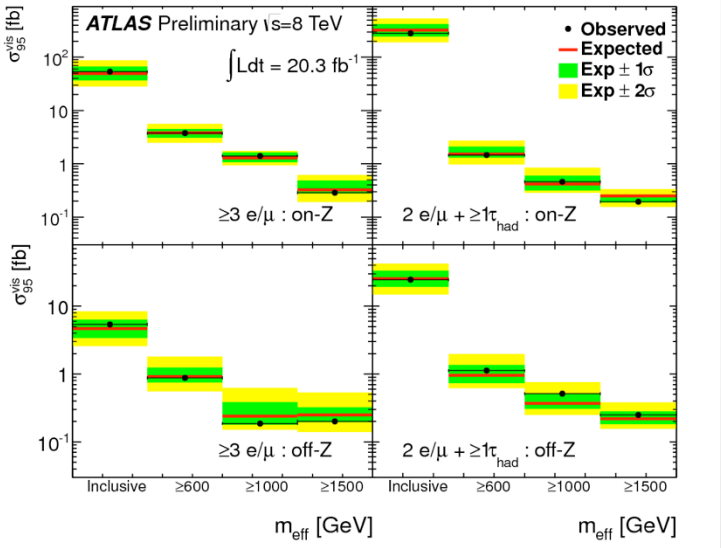
- Simple search, many interpretations
- Sequential SM Z', E6 Z'
- Kaluza-Klein Graviton

See talk from W. Taylor for limits in several models

Inclusive multilepton search

- Look for events with more than 2 energetic, isolated leptons
- Classify:
  - Consistent with Z?
  - Presence of τ_{had}?
- Compare to SM background, measured from control regions
- Set 95% CL limits on visible cross-section and on specific models





$$\sigma_{95}^{\text{fid}} = \frac{N_{95}}{\epsilon_{fid} \int Ldt} = \frac{\sigma_{95}^{\text{vis}}}{\epsilon_{fid}}.$$

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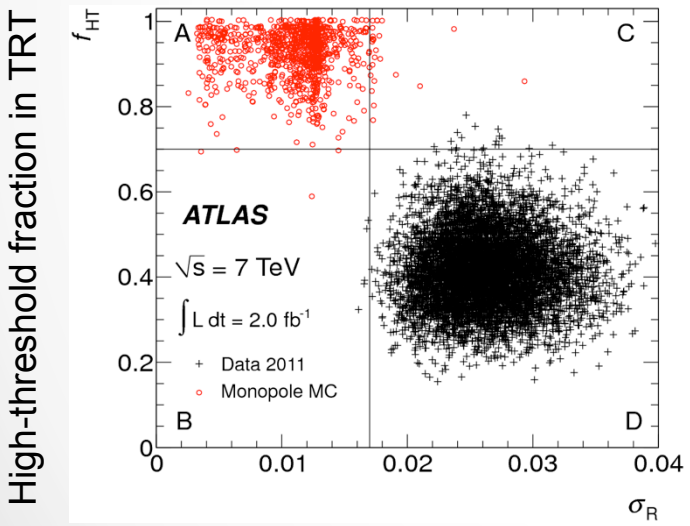
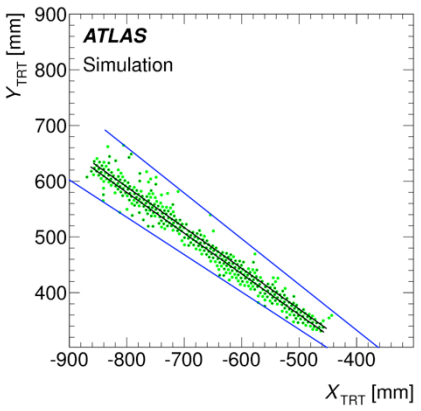
Search for Magnetic Monopoles

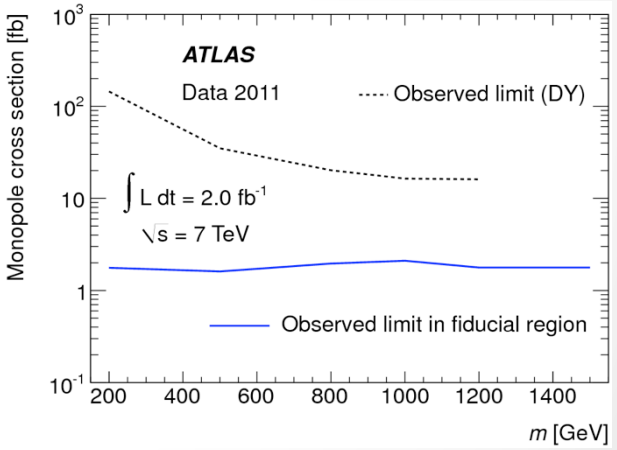
- Electrically neutral, magnetically charged!
  - Bend in r-z (not r-Φ) in the Inner Detector
  - Highly ionizing
  - Drell-Yan-style production, e➔g β , assume no Z-coupling
  - Look like electrons (stop in LAr calorimeter)



Cluster dispersion in ECal



Simulated TRT track in R-Φ plane
Green=low threshold
Black=high threshold



Fiducial: $|\eta|<1.37$, $(E_T^{kin})_{min}<E^{kin}\sin\theta<1400$ GeV
Where $(E_T^{kin})_{min}$=600 GeV for monopoles of mass 500-1500 GeV

Searches for vector-like quarks

- Vector-like quarks decaying to
  - Z+b/t, H+t,W+b, same-sign dileptons+b+E_T^{miss}

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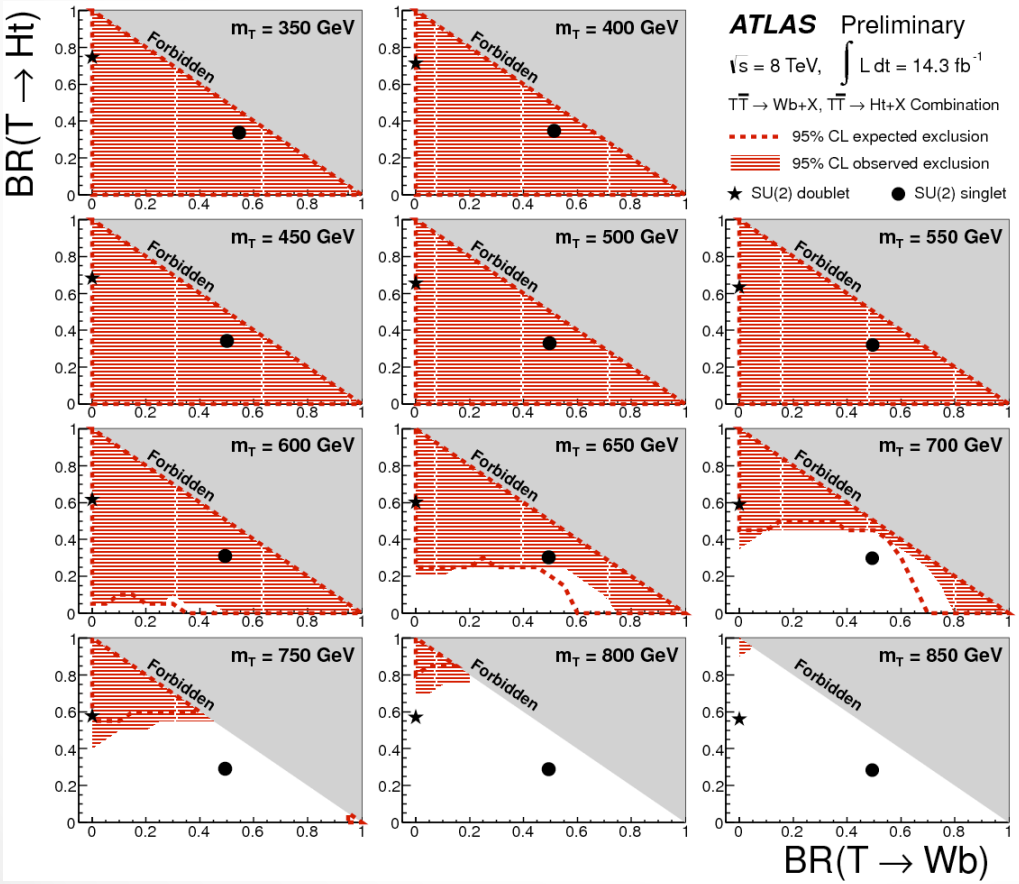
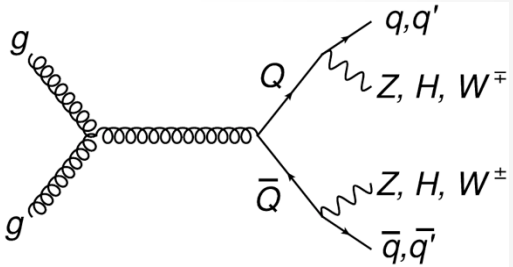
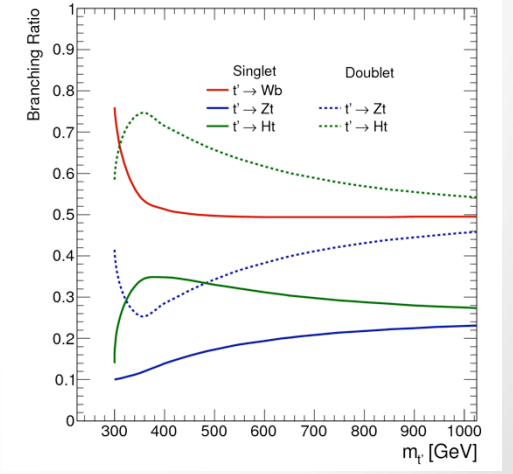
ATLAS-CONF-2013-056

ATLAS-CONF-2013-051

ATLAS-CONF-2013-018



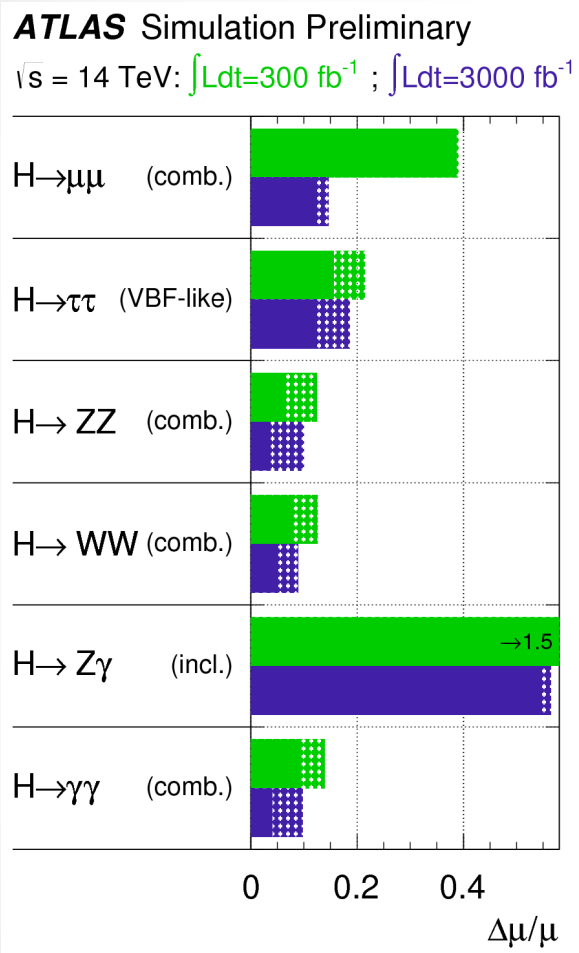




Long-term Timeline for LHC

- Run 1: 25 fb^{-1} at 7-8 TeV, up to $7x10^{33}$ /cm^2/s
- Run 2: 2015-17 – 75-100 fb^{-1} at 13 TeV, 10^{34} /cm^2/s
- Run 3: 2020-2022 – ~300 fb^{-1} at 13-14 TeV, $2x10^{34}$ /cm^2/s
- HL-LHC - ~3000 fb^{-1} at 13-14 TeV, $5x10^{34}$ /cm^2/s… 3-year runs with ~1-yr stops

What the future may bring…



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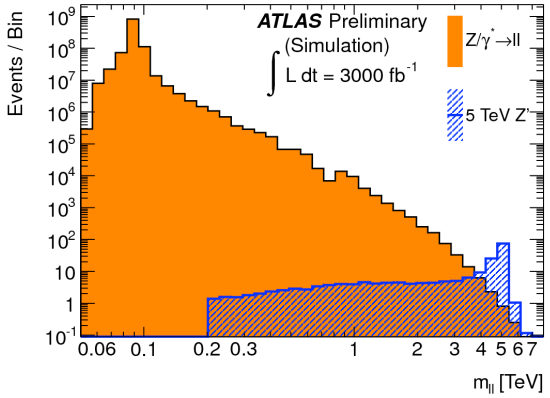

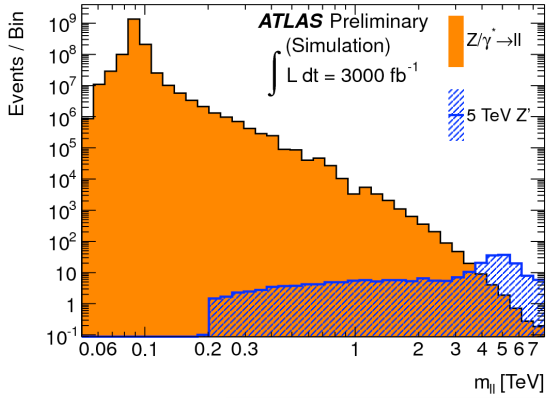

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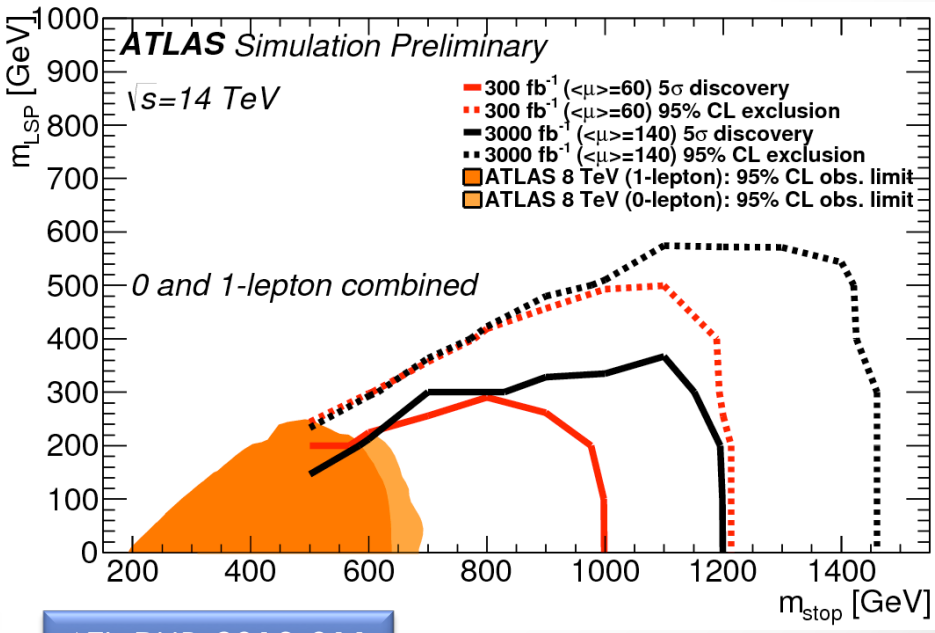


ATL-PUB-2013-011

Summary and Conclusions

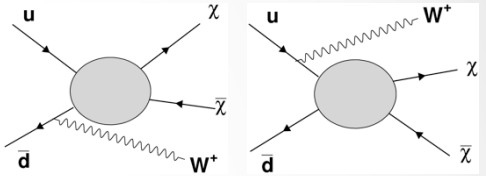
- LHC Run 1 resoundingly accomplished primary mission:
  - Higgs boson found!
- Detector and accelerator performance excellent!
- LHC also provided unprecedented wealth of data:
  - electroweak interaction at EWSB scale, perturbative QCD, top & heavy flavour physics
- Unfortunately, *so far*, no real smoking guns…
- Still much to learn from this run, but great motivation to look forward to ~13 TeV in 2015!

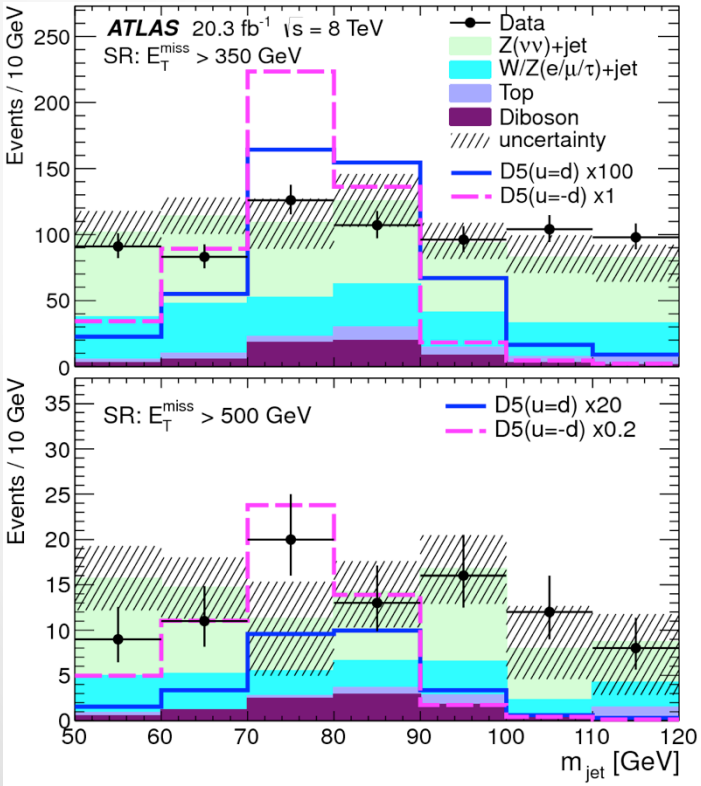
Backups

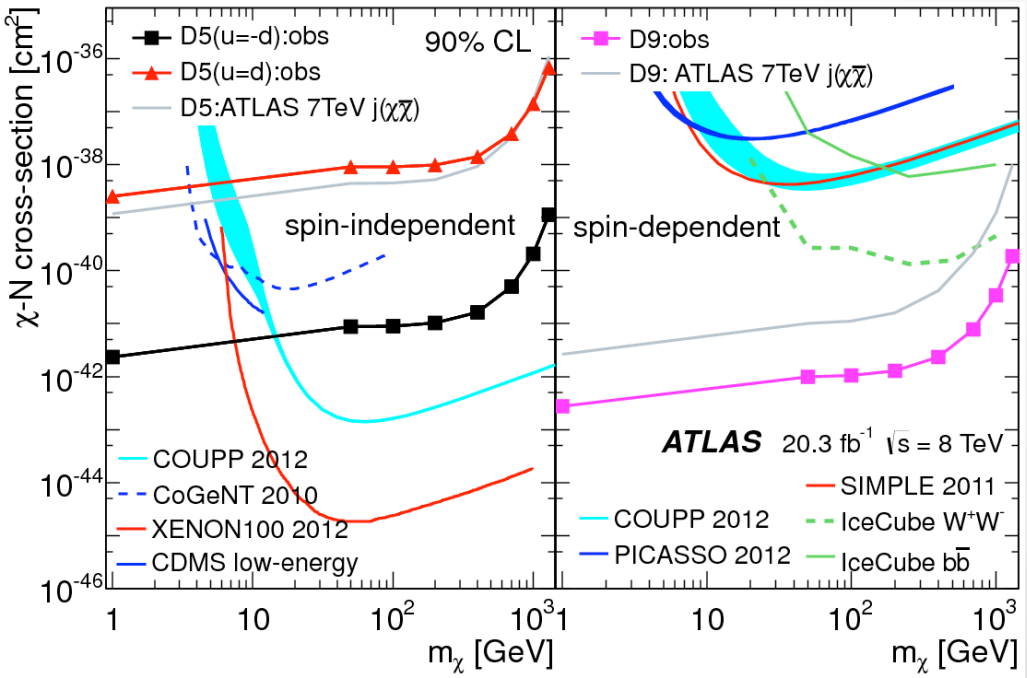
Dark matter search in mono-W/Z

- Tag "invisible" particles by producing them with something else
- Complementary to underground and astronomical DM searches

arXiv:1309.4017







Top mass stability tests