Working Group 3

Electro-weak, Higgs & BSM

Conveners:

Simone Marzani, Peter Onyisi,

Seamus Riordan

EW Sessions Overview

Higgs+Joint QCD

4 experiment – ATLAS/CMS results, searches

4 theory

N^3LO, p_T corrections, off-shell production and width bounds, pseudo observables

3 BSM/Dark Matter/Exotics

11 experiment – SUSY,Z', dark matter, resonances, ν_R …

Contributions from ATLAS, CMS, JLab, BaBar, PHENIX

3 theory talks – WIMP annihilation rates, BSM phenomenology, W',Z' mass limits

Joint Future Expt.

LHeC Higgs

LHeC flavor violating signatures

ν,ν DIS, elastic LBNF

PVDIS SoLID, JLab

2 EW Bosons

5 experiment

W/Z properties/couplings at ATLAS, CMS, LHCb, ALICE

5 theory talks

EW corrections, Z' searches A_{fb} and finite widths, WW, WA fusion

2 Joint Heavy Flavors

8 experiment – ATLAS, CMS, D0, BaBar

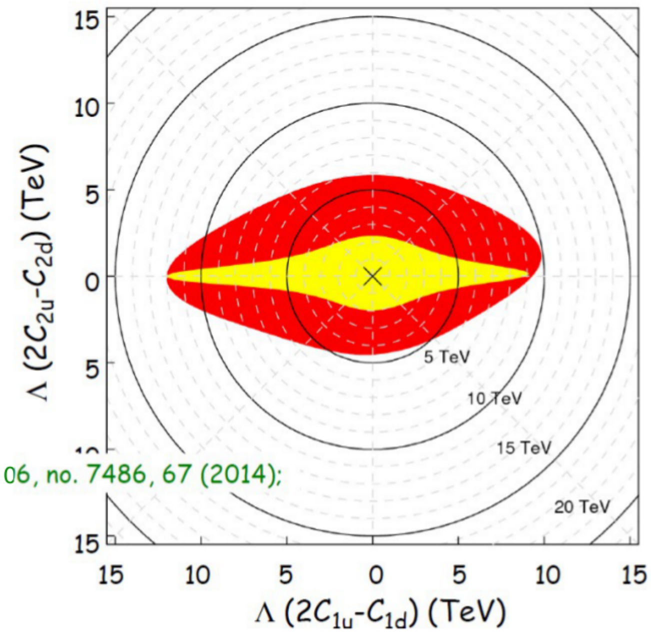
1 theory talk

Top production/properties and b CP

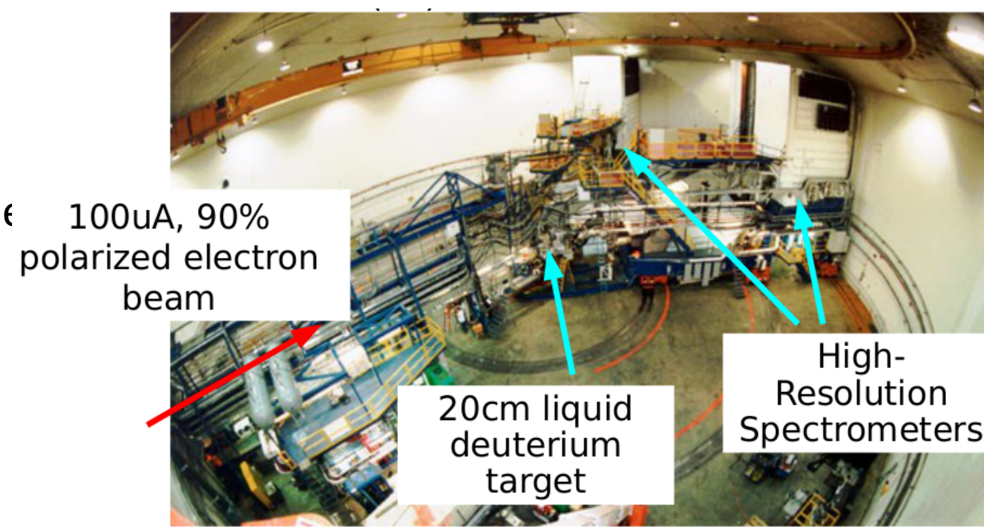
JLab 6 GeV PVDIS – V. Sulkosky

- Party-violating DIS at low Q^2 is sensitive to γ-Z interference
- Measurements on LD_2 constrain effective weak couplings $C_{12,du}$ and test for BSM, higher twist
- Hall A at Jefferson Lab:

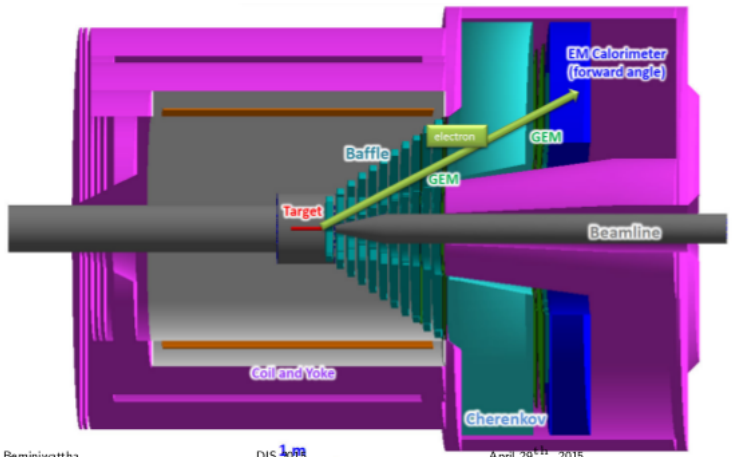
Wang et al., Nature 506, 7486, 67 (2014)
agreement with SM prediction of couplings and constraints to 5+ TeV

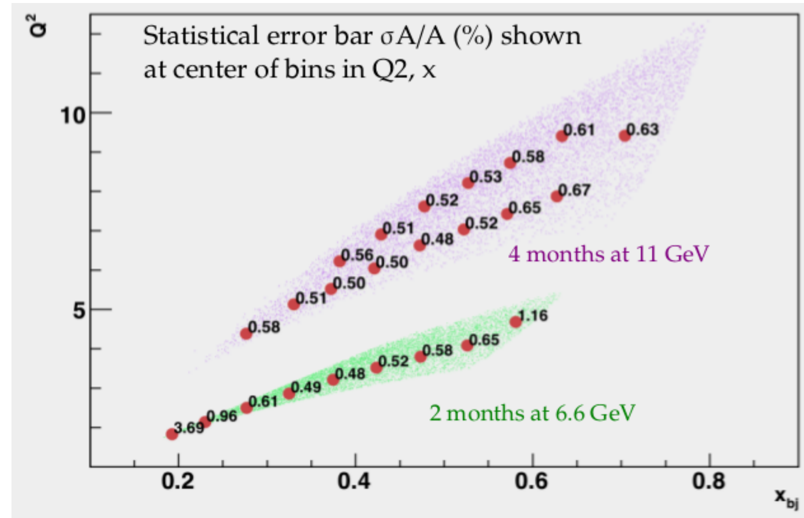


- Higher twist effects not observed at Q^2~1 GeV^2
- New PV Resonance data also now availabl



Future JLab 12 GeV PVDIS – SoLID
R. Beminiwattha



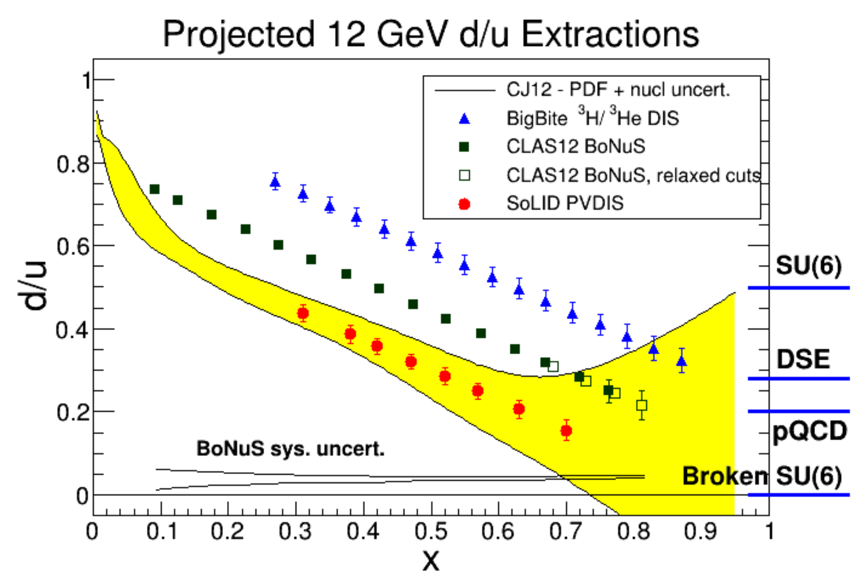


SoLID 12 GeV Program will extend
6 GeV results to broad kinematic coverage with multiple targets

LD_2 provides SM tests, quark-level CSV, Higher Twist

LH_2 tests high-x d/u predictions with free nucleons

Heavy targets could test flavor dependent nuclear modification



LBNF/DUNE - R. Petti

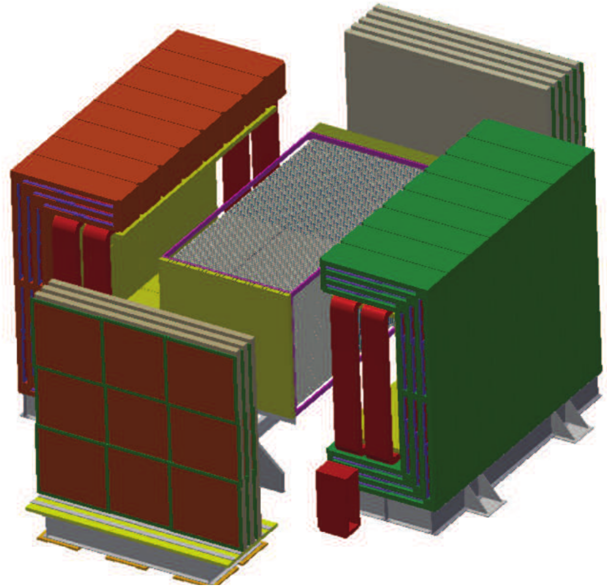
DUNE will provide high-statistics ν,ν measurements with nuclear targets with near detector at LBNF

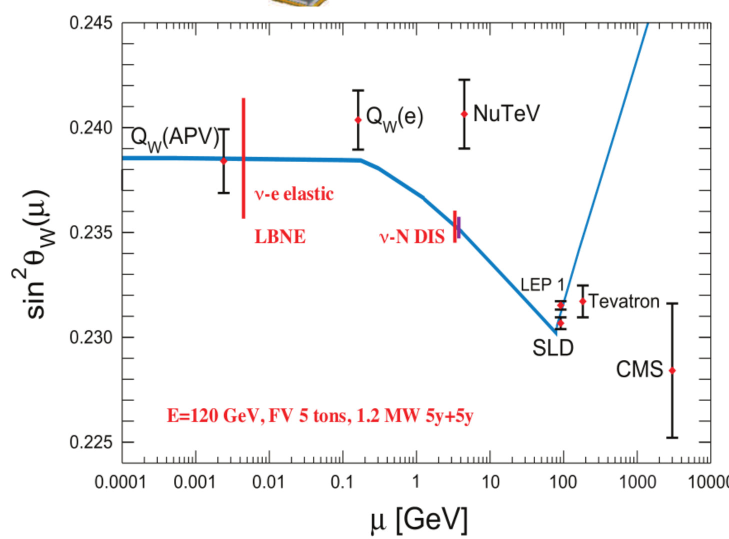
Nuclear elastic, quasielastic, and DIS with p, ^{12}C, Ca, Fe, Ar...

Allows for measurements of $\sin^2\theta_W$ and check of NuTeV anomaly

Flavor dependent nuclear modification tests can be directly tested with fixed A varying N/Z

Constraints on strange sea with NC and CC weak couplings to quarks





Qweak – D. Gaskell

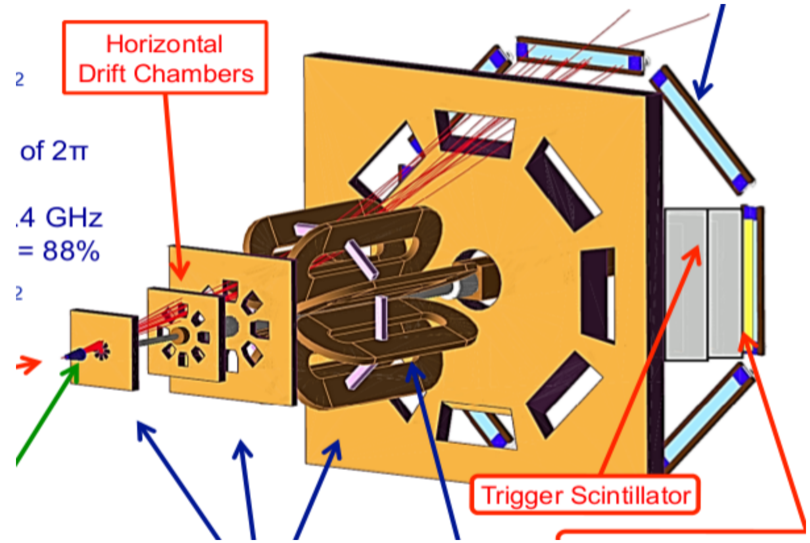
Qweak experiment at Hall C Jefferson lab measures proton weak charge

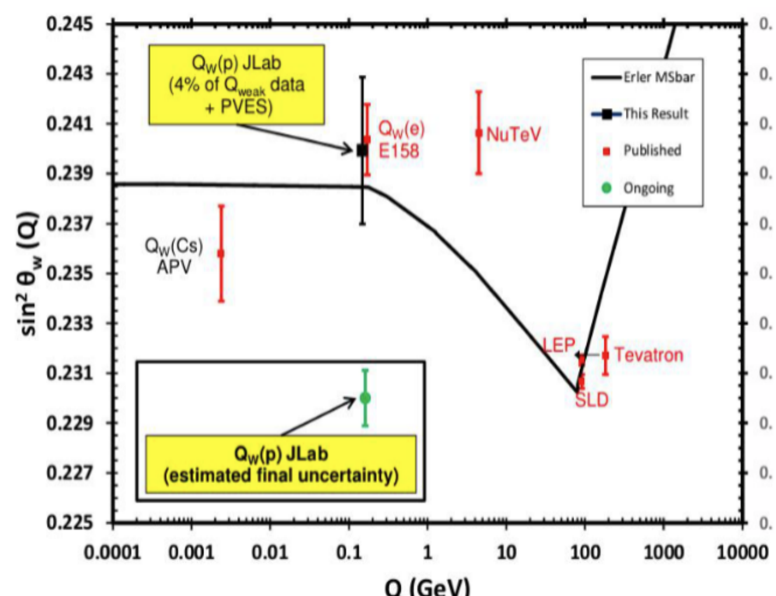
Parity-violating e⁻ sensitive to NC γZ interference and weak couplings

Low Q^2 elastic proton scattering tests standard model with $\sin^2\theta_W$ and access to BSM physics to few TeV

Commisioning run results consistent with SM

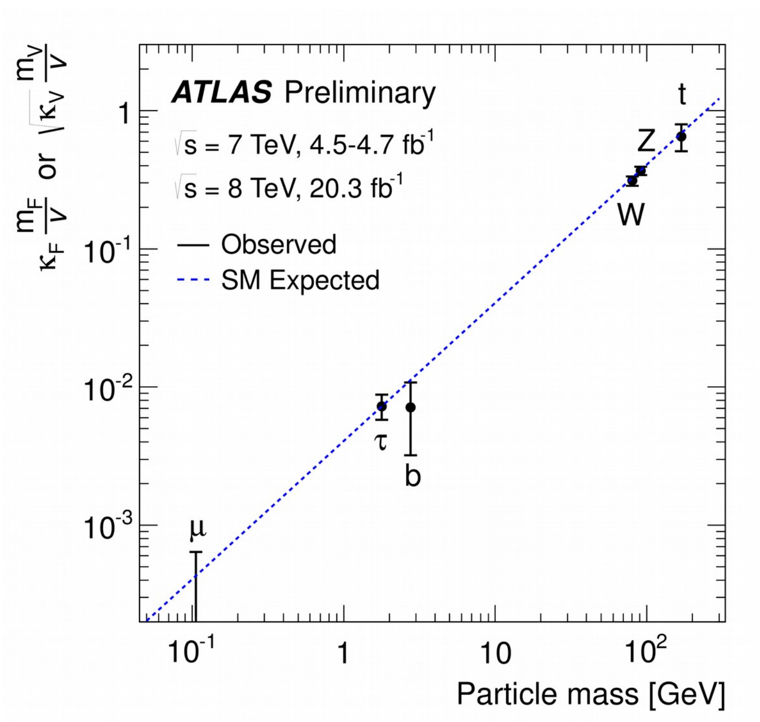
Full results with full data with improved systematics will be available “soon”





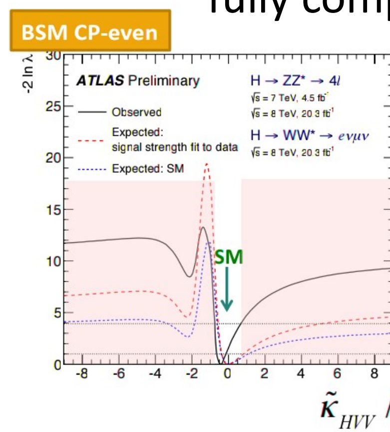
Higgs Boson Status

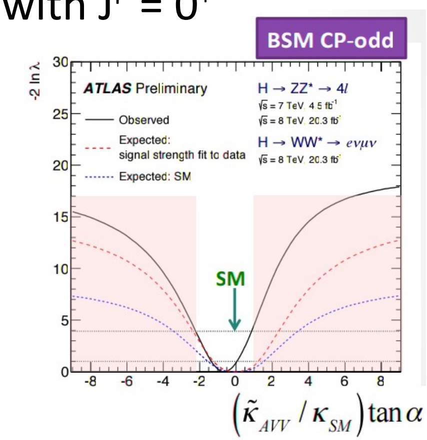
- 125 GeV object: Standard Model Higgs-like? *Yes*



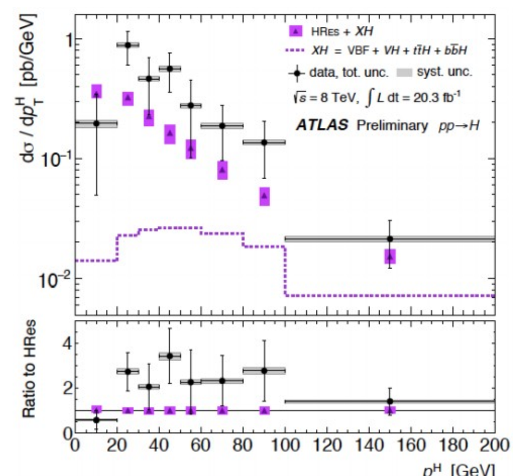
Coupling scales with mass

angular distributions:
fully compatible with $J^P = 0^+$





differential
measurements



Rossi

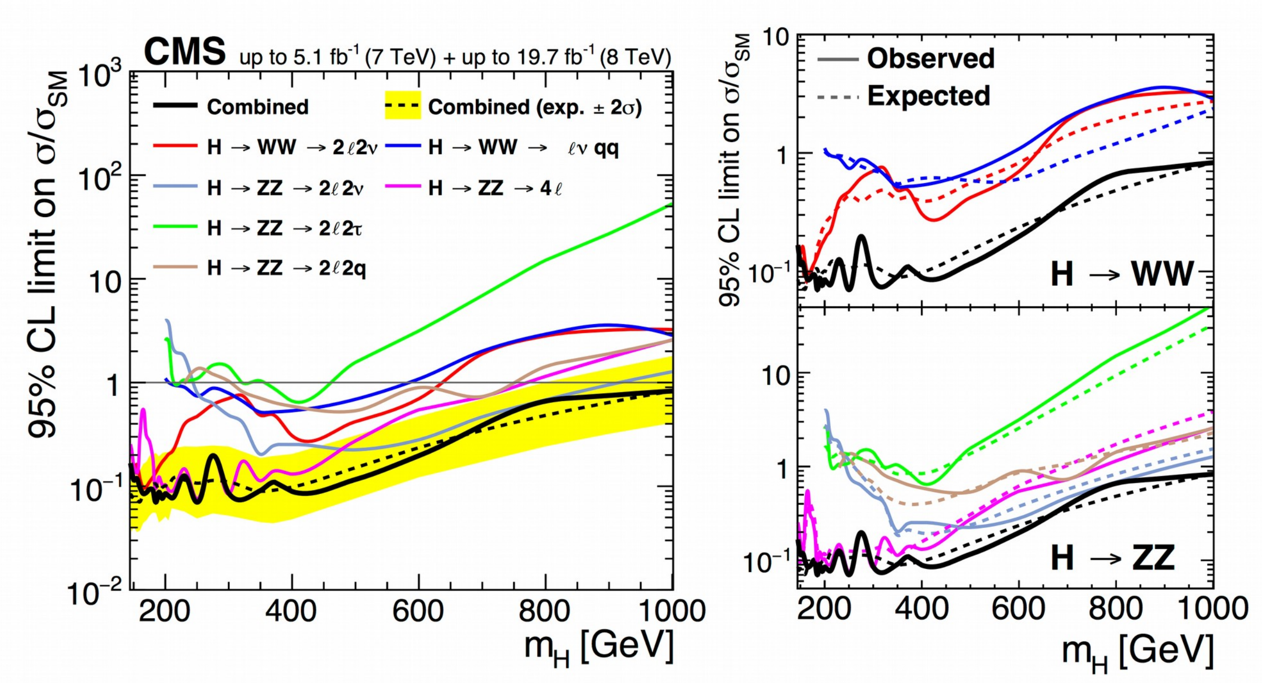
Searches for BSM Higgs Bosons

- Extensions of SM can add additional particles to the Higgs sector
  - e.g. supersymmetry gives at least four more
- Observation of any is evidence of new physics

Moran
Vanadia
Weinberg
Beaulieu

Heavy Higgs

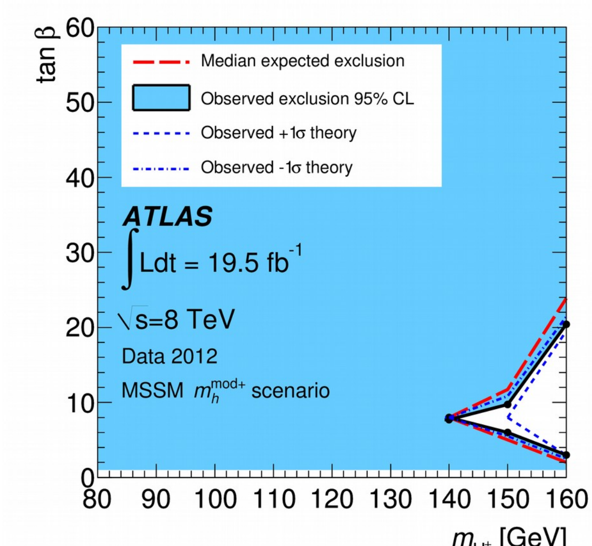
- High mass "Higgs-like" neutral boson search in several channels



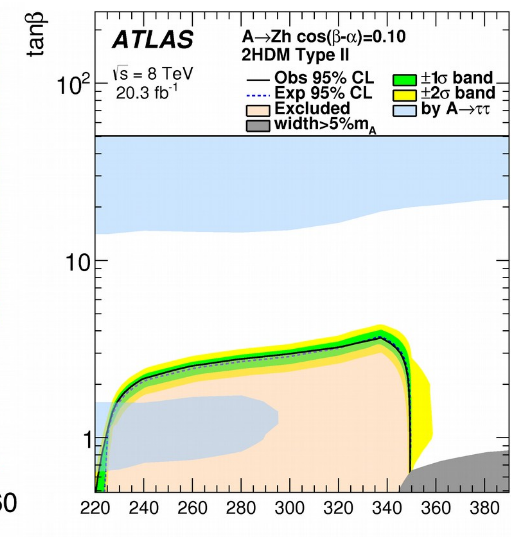
Moran

Other Higgs Bosons

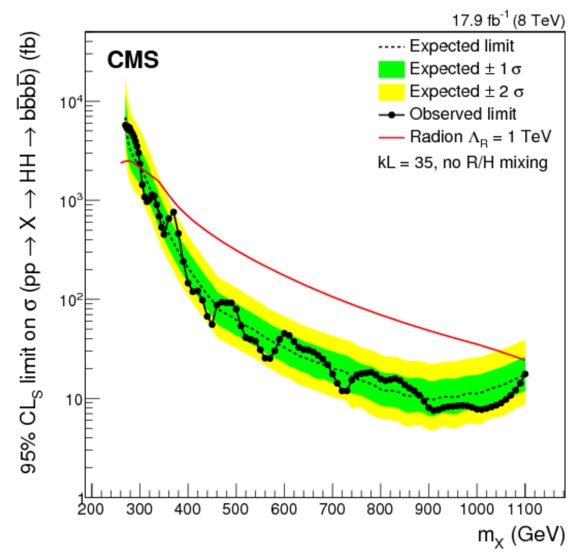
- Searches for other physical states of a two Higgs doublet model: $H^{\pm}$, H^0, A^0



$H^+ \rightarrow \tau\nu$



$A^0 \rightarrow Zh$



$X \rightarrow HH \rightarrow 4b$

Vanadia

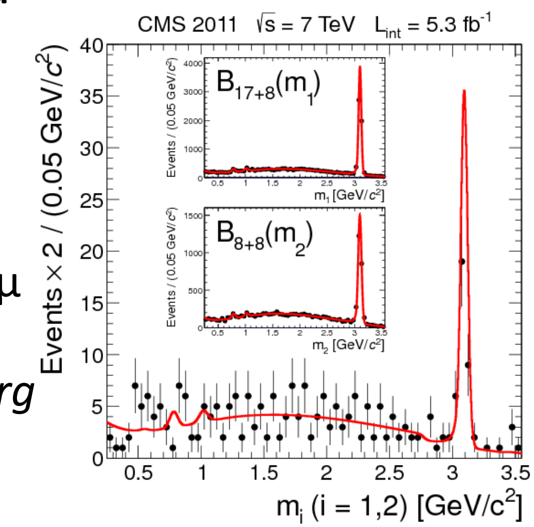
Weinberg

$a \to \ell\ell/qq$

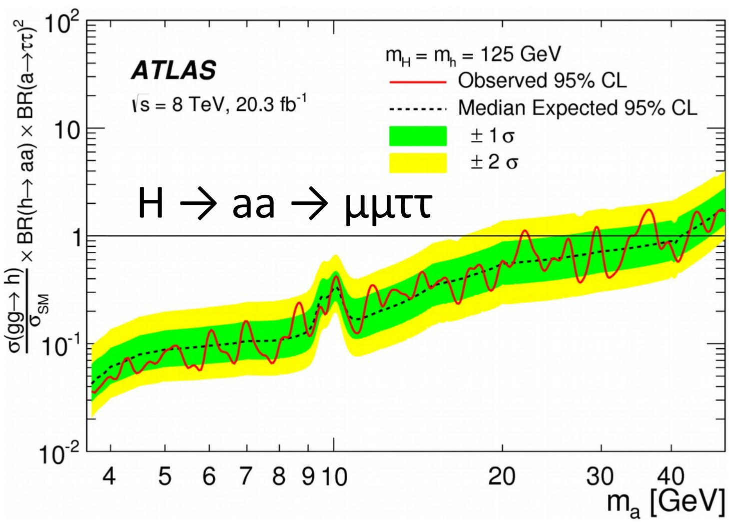
- NMSSM helps ease fine tuning problems in minimal SUSY, gives additional light pseudoscalar "a"
- Searches presented in $H \to aa$ and $\Upsilon \to \gamma a$

CMS

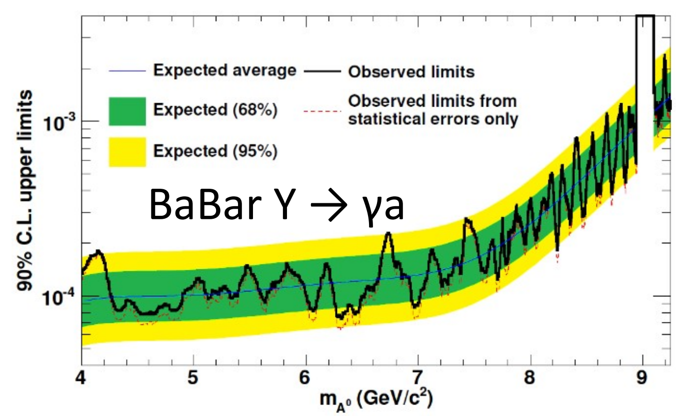
$H \to aa \to 4\mu$



Weinberg



Vanadia



Beaulieu

Electroweak Bosons at the LHC

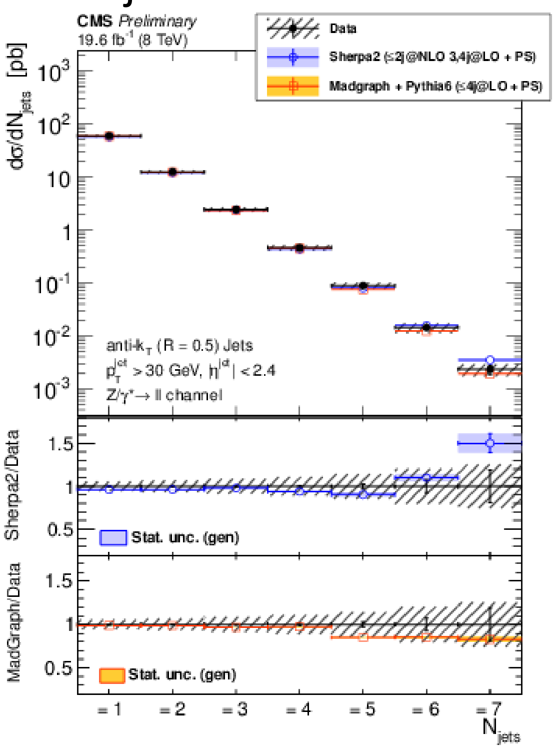
- W and Z production results from all major LHC experiments
- Cover large kinematic range (η, p_T) and environments (p-Pb collisions, additional jets, heavy flavor)
  - Test/confirmation of PDFs, high order/high multiplicity calculations
  - Extraction of EWK parameters, coupling structure

Buthelezi
Dragoiu
Brandt
Wallace
Perry

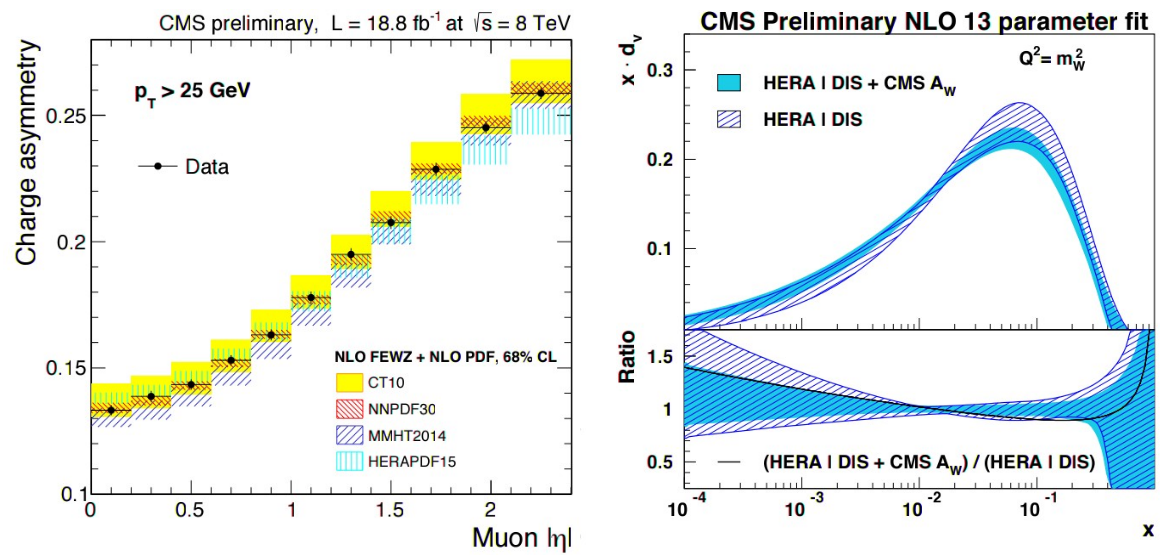
W/Z production

- Largely well described by simulation … pushing theoretical tools, PDFs to the limit

Z + n jets differential σ - *Perry*



pp → W^+ vs W^- asymmetry

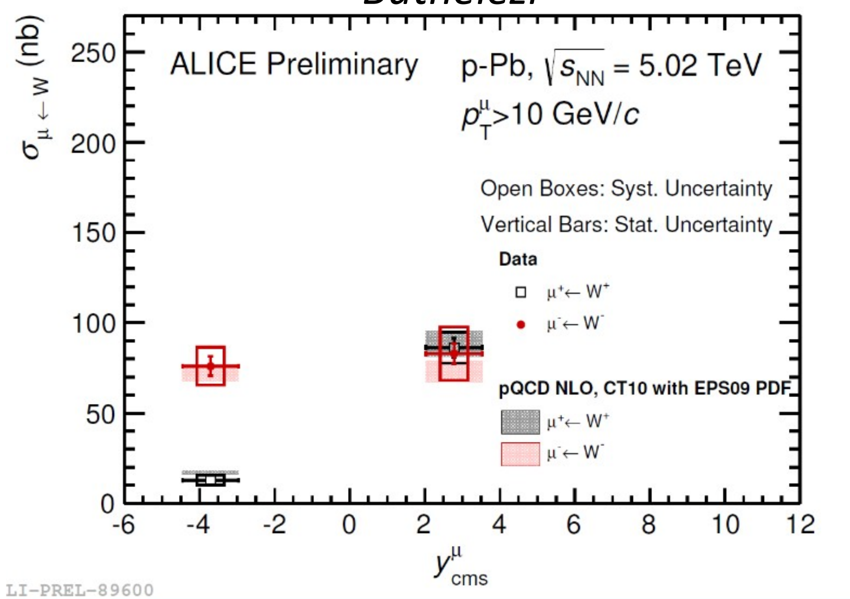


Dragoiu

Forward W/Z

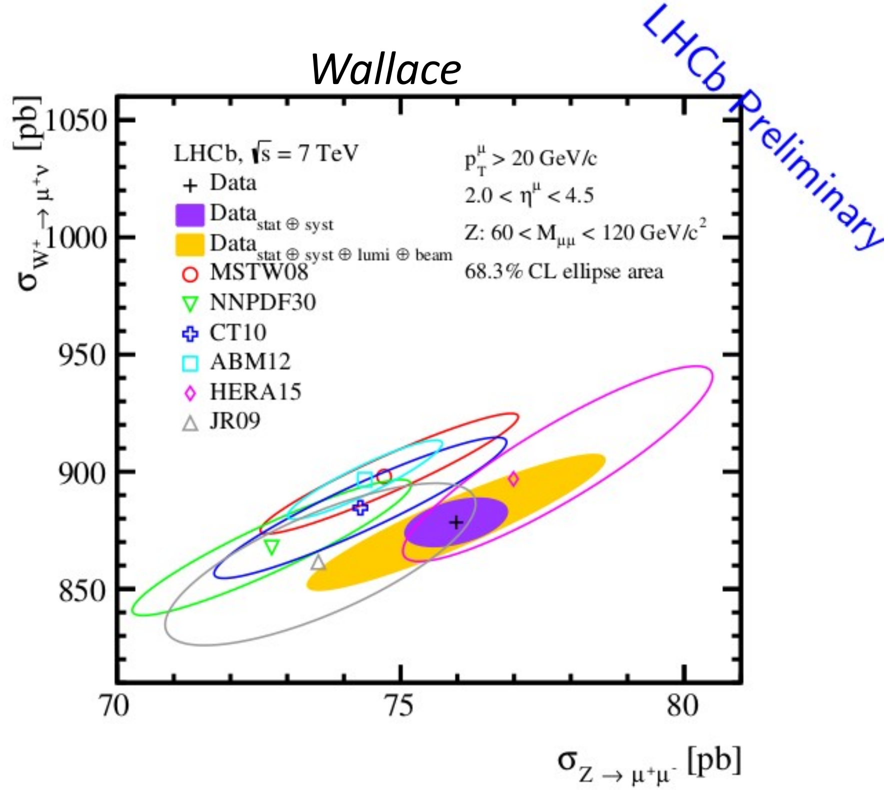
- Measured by LHCb (pp) and ALICE (pPb)
- Probe of PDF, nuclear effects

Buthelezi



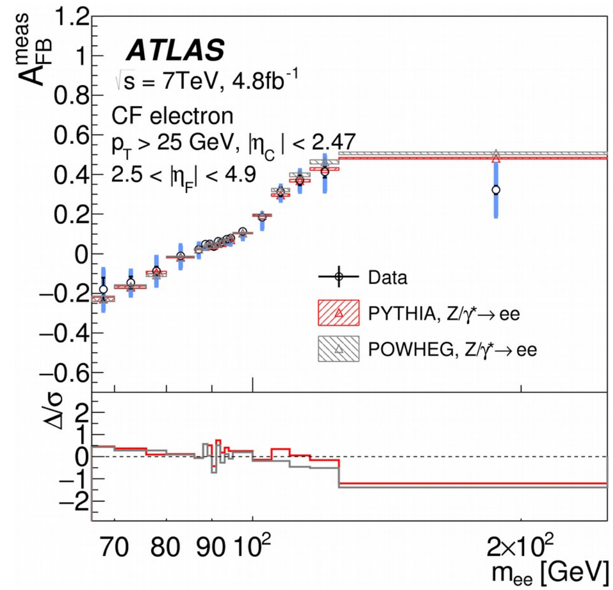
Better agreement with nuclear PDFs

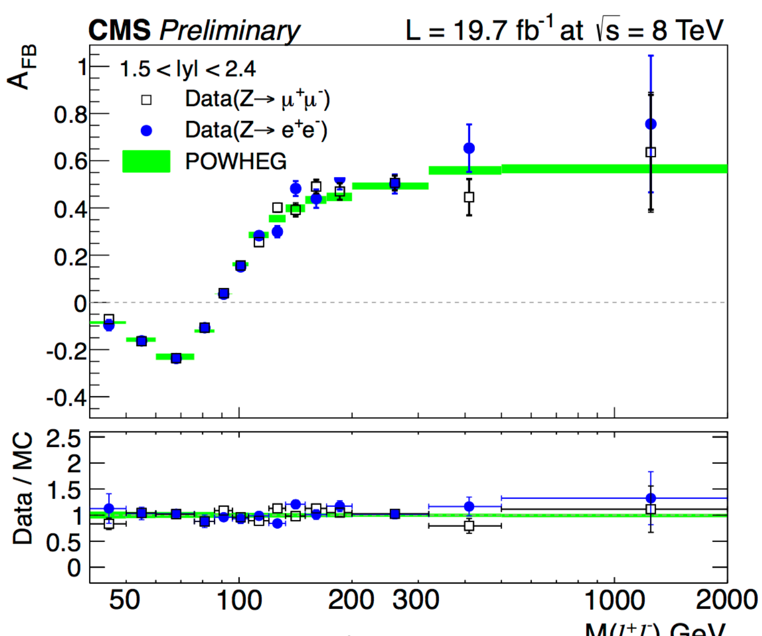
Wallace



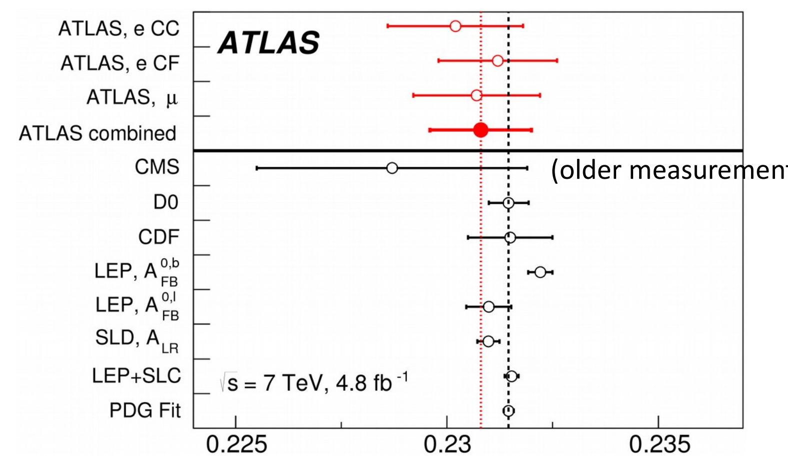
Z Forward-Backward Asymmetry

- Sensitive to new particles coupling to fermions
- Measures effective weak mixing angle





Dragoiu

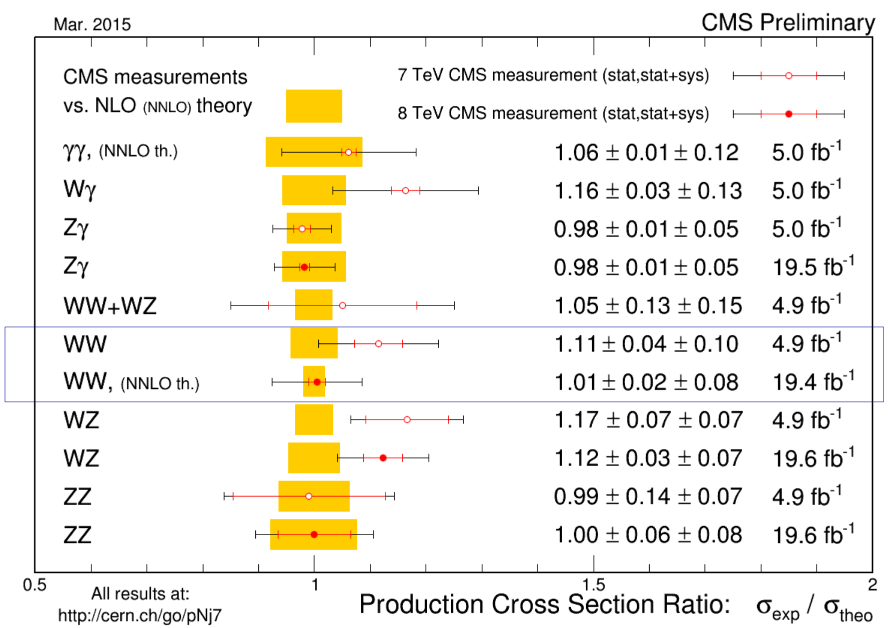


Brandt

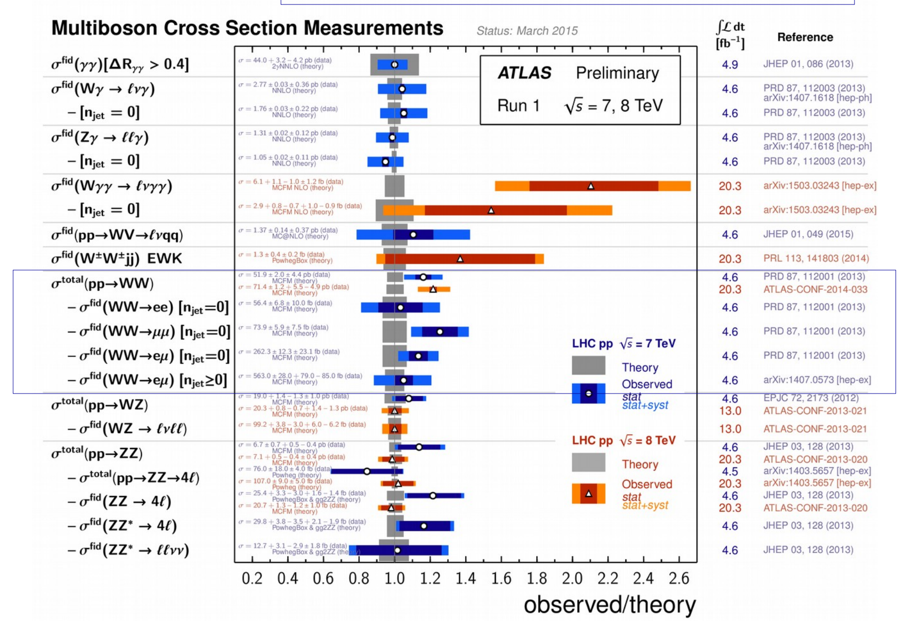
Multiple EW Boson Production

- Constraints on anomalous gauge boson couplings from diboson/triboson production
- Hot topic: discrepancy between experiment and theory for WW cross section: resolved?

$\sigma_{NNLO}/\sigma_{NLO}$ = 1.09 (PRL 113, 212001)
Jet vetoes sensitive to higher order terms, resummation



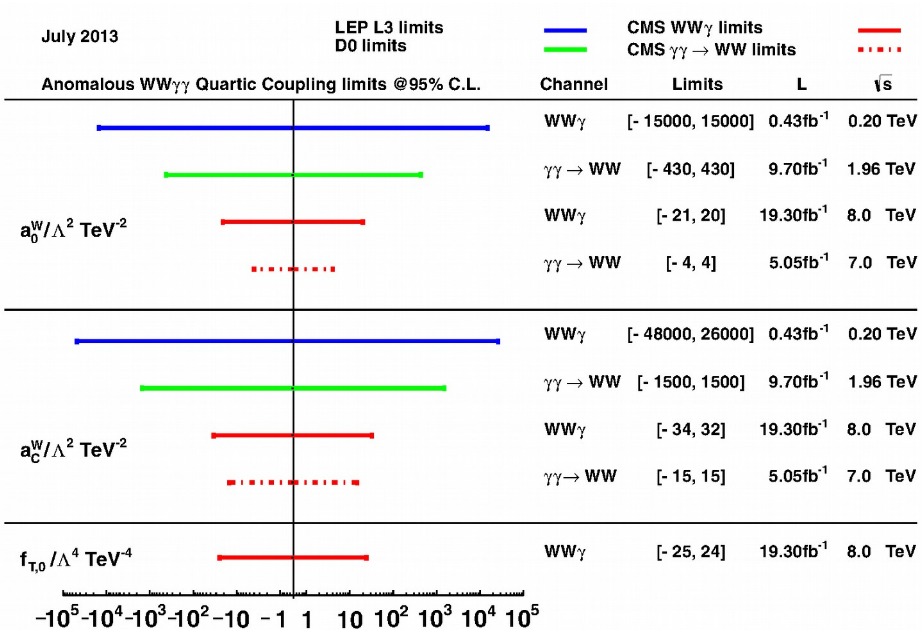
Damgov



Chen

Anomalous Gauge Couplings

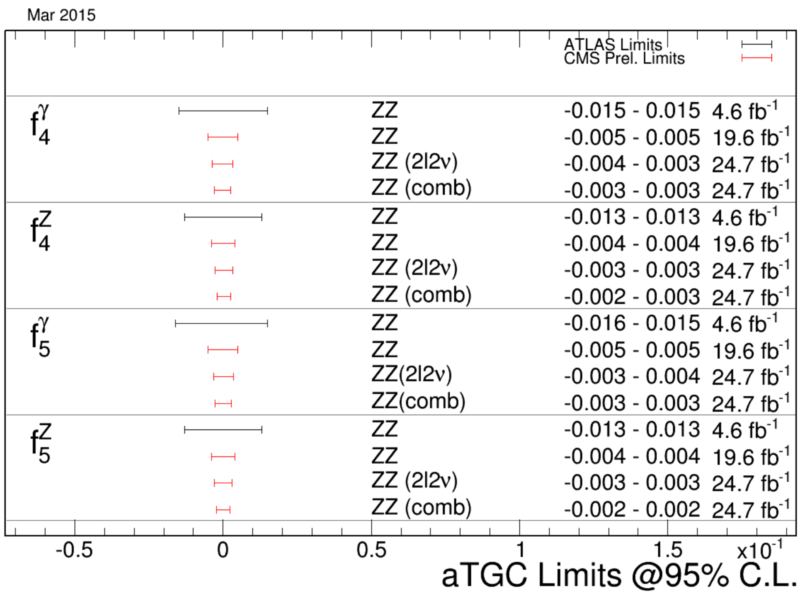
WWγγ coupling



Note log scale

Damgov

ZZZ, ZZγ (0 in SM)



Chen

LHC sets strong constraints on electroweak boson couplings

The Dark Sector

- Searches for places the dark sector touches ours

  Yamaguchi, Beaulieu

  - "dark photons": vectors that mix with our photon
  - "Higgs portal": Higgs boson coupling to dark matter

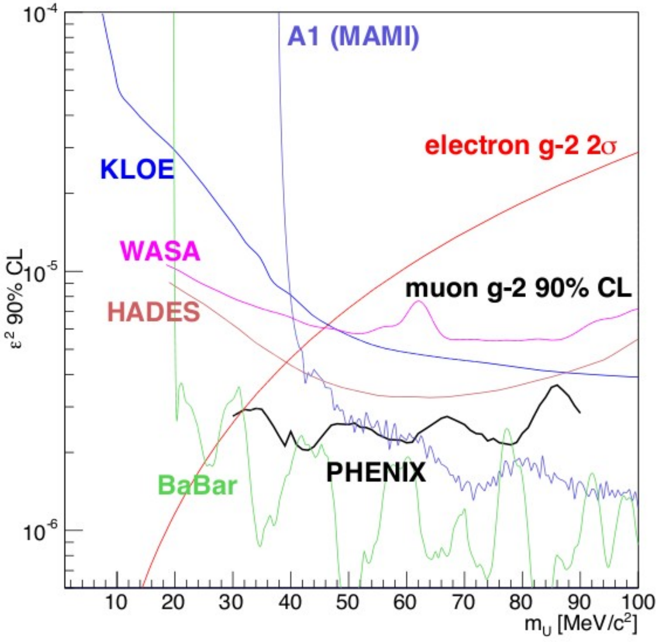
    Weinberg

  - "Mono-X": Direct production of dark matter

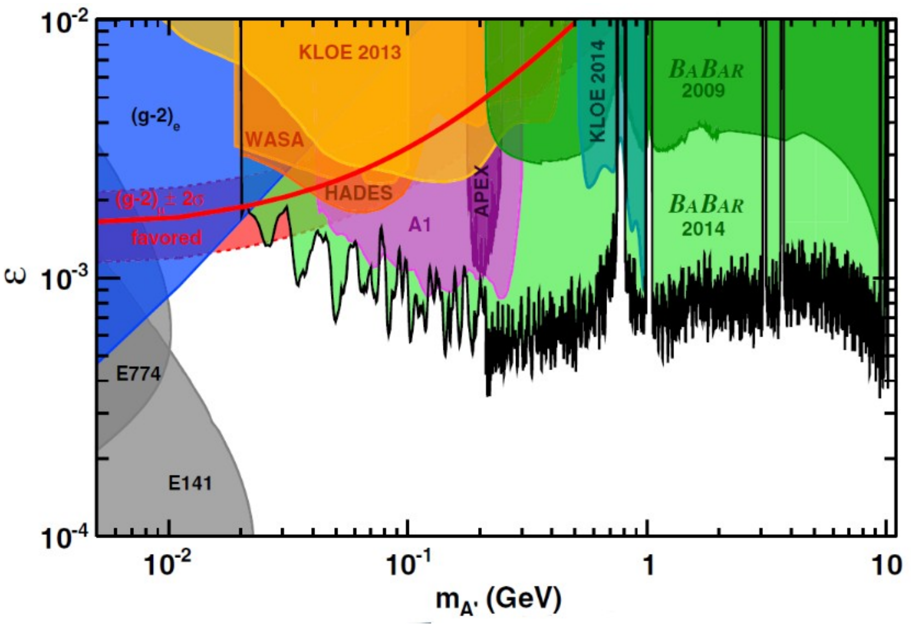
    Lei, Turner

Dark Photons

- Results presented from PHENIX ($\pi^0/\eta \rightarrow \gamma A$) , BaBar ($e^+e^- \rightarrow \gamma A$)
  - muon g-2 favored region excluded



Yamaguchi

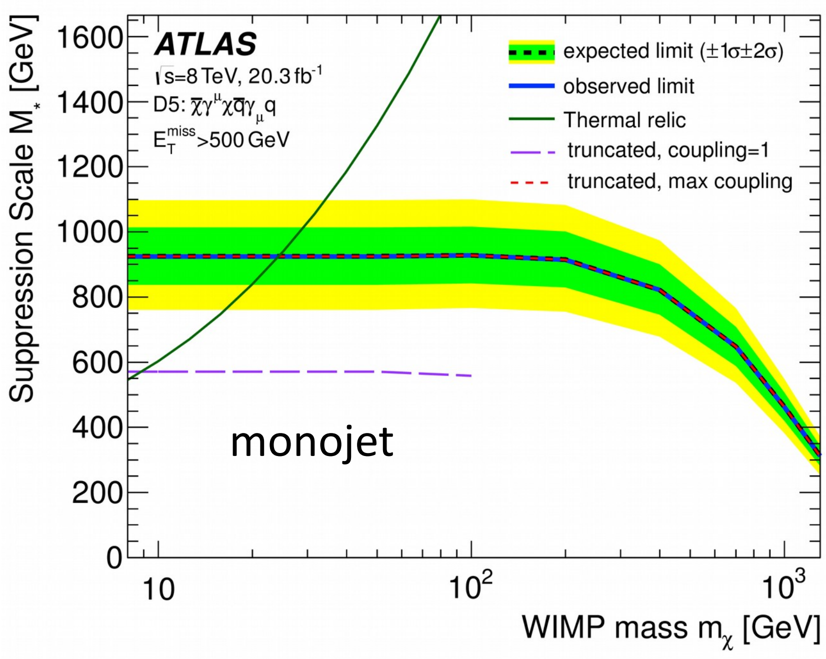


Beaulieu

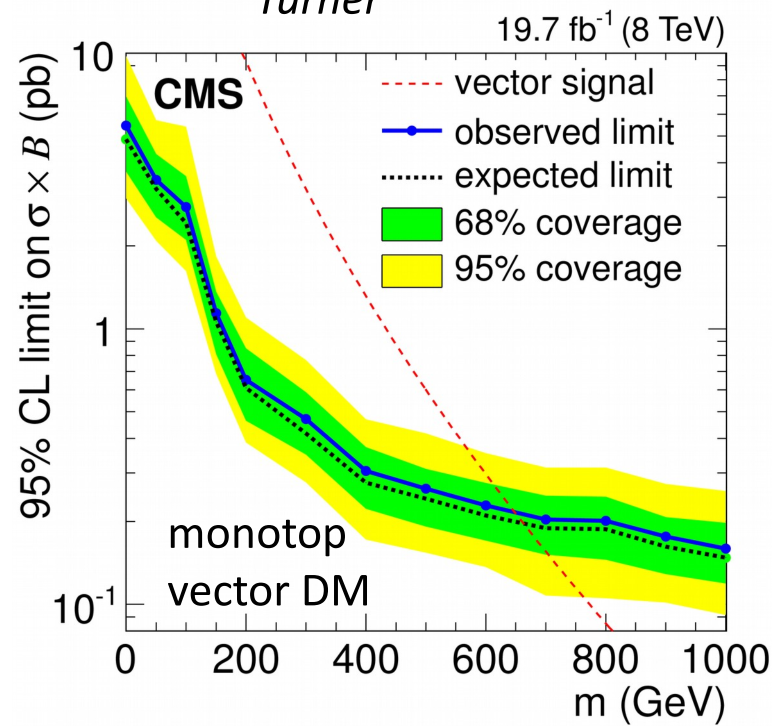
Mono-X

- Search for visible particles recoiling against invisible dark matter (X = jet, photon, Z, Higgs, top, $t\bar{t}$ …)

Lei



Turner

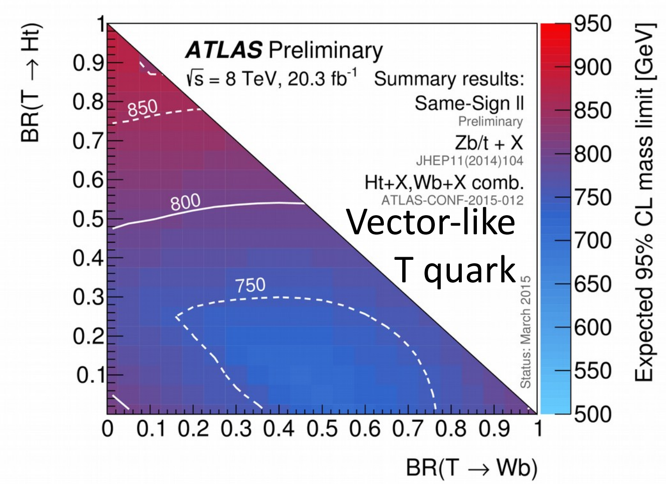


New Heavy Particles

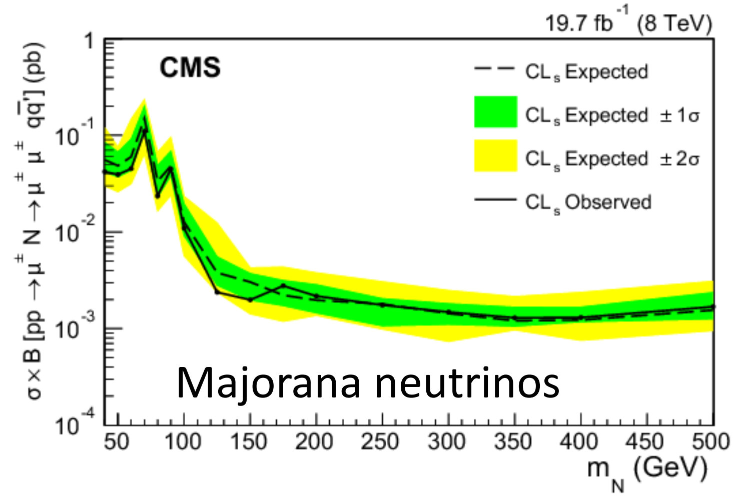
- Smoking gun sign of new forces or types of matter
- Z', W', Majorana neutrinos, vector-like quarks, excited quarks, technicolor, Kaluza-Klein gravitons & resonances in large extra dimensions...

Pastika
Lei
Romeo
Hayden
Turner

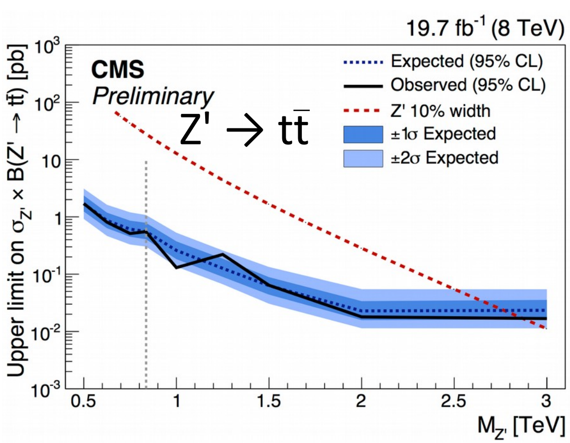
New Heavy Particle Searches



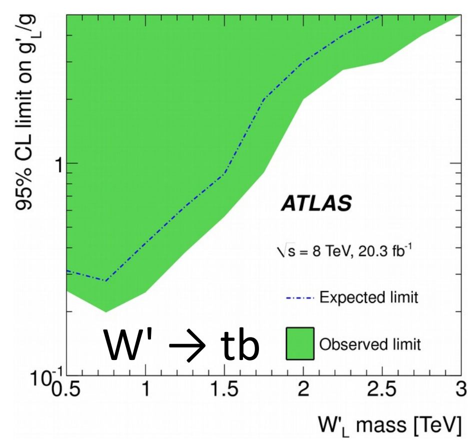
Lei



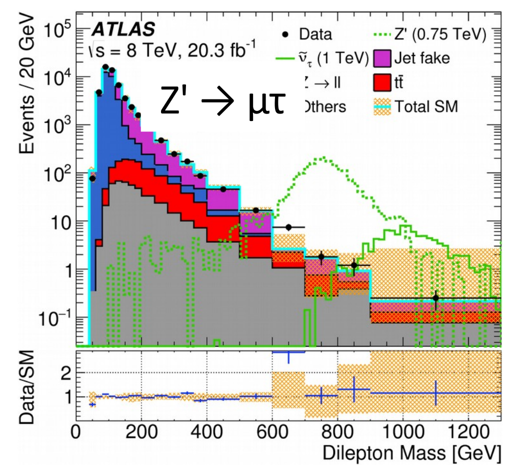
Pastika



Turner



Hayden

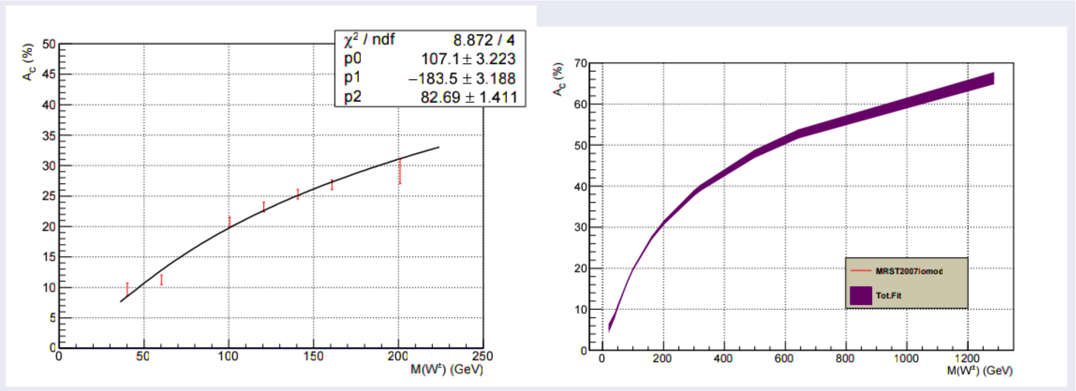


Hayden

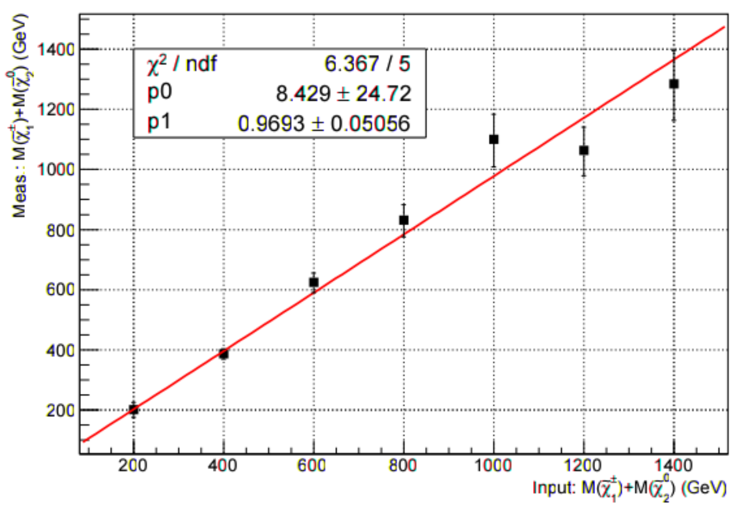
New Heavy Particles

- Method for determining mass of particles produced by charged current at LHC, exploiting charge asymmetry & proton PDF

Muanza

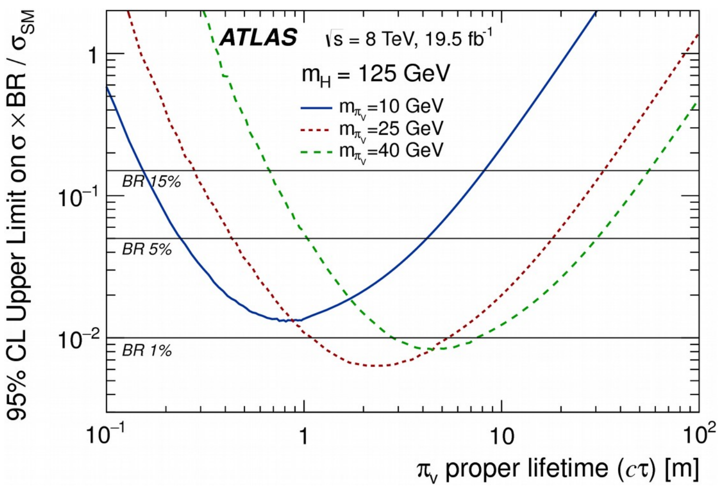


$$A_C^{Meas}(W^{\pm} \rightarrow e^{\pm} + \nu_e) = -107.1 - 183.5 \times Log(Log(M_{W^{\pm}})) + 82.69 \times Log(Log(M_{W^{\pm}}))^2$$



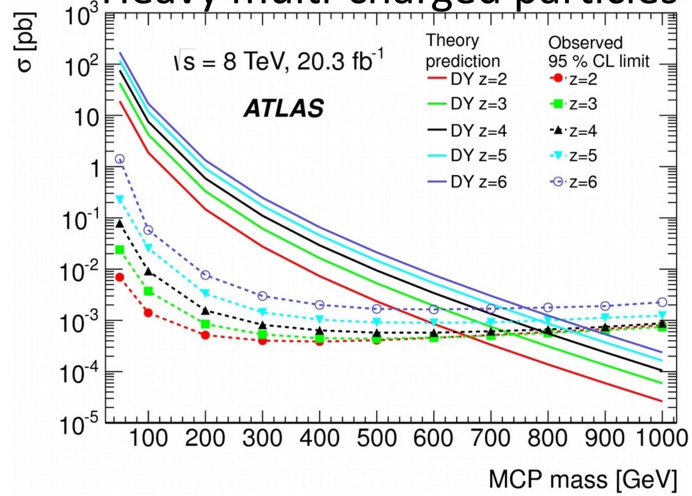
More Exotic ...

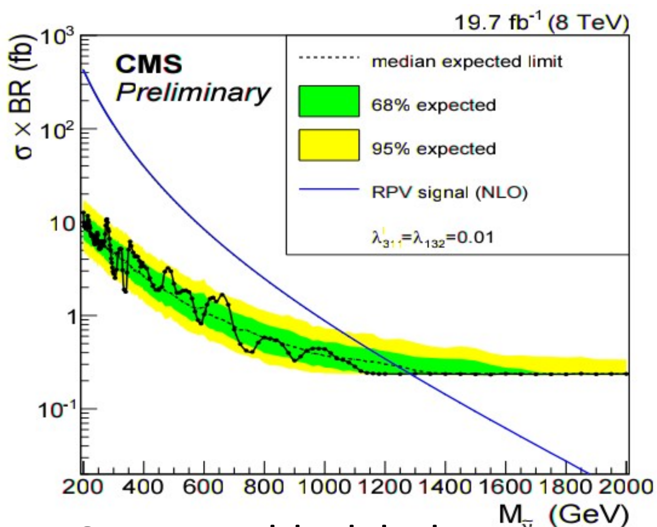
Long-lived neutrals



Lei

Heavy multi-charged particles





Romeo

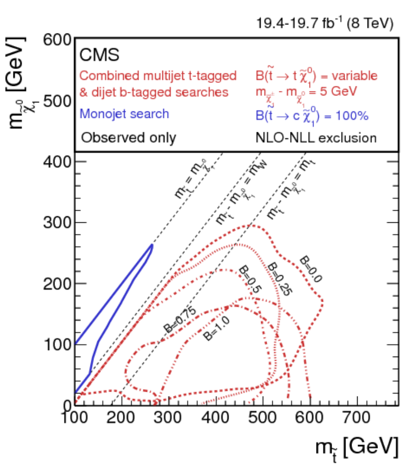
Quantum black holes

Supersymmetry

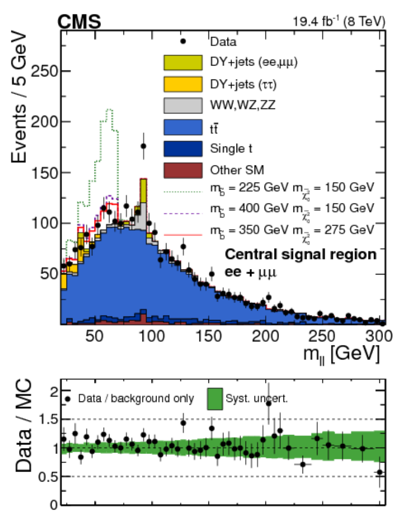
Rathjens
Meloni

- Extensive searches at CMS & ATLAS
  - “classic” jets + MET signatures; also targeting third-generation squarks, electroweak/VBF production, R-parity violating scenarios
  - Addressing hard regions of parameter space!

Rathjens

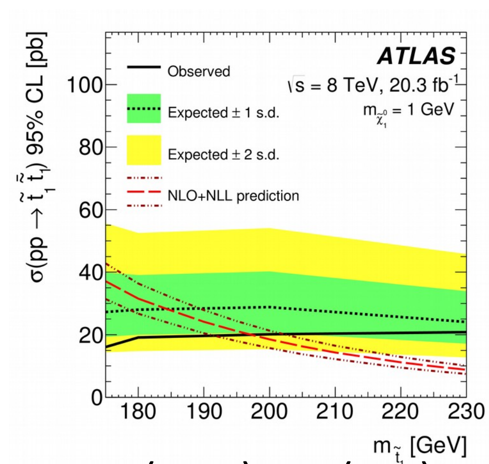


stop tagging

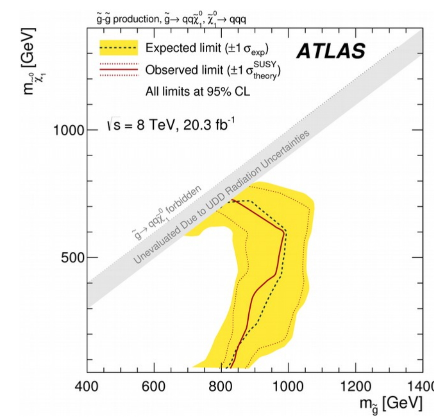


dilepton edge search

Meloni



m(stop) ~ m(top)



RPV multijet

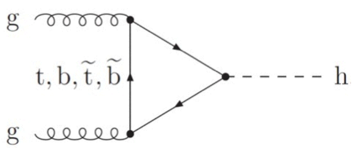
THEORY CONTRIBUTIONS

…sharpening
our tools…

www.ancientcraft.co.uk

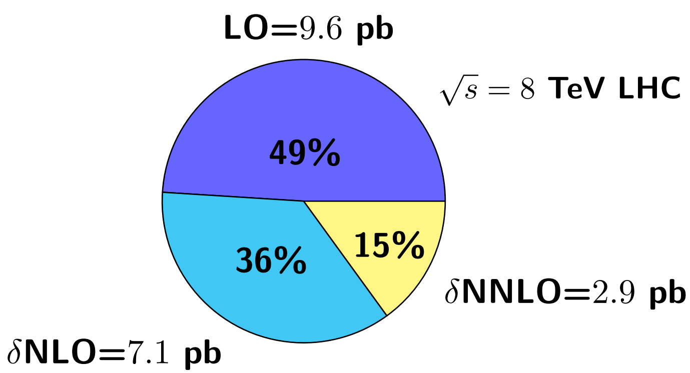
Higgs production in ggF

Ye Li



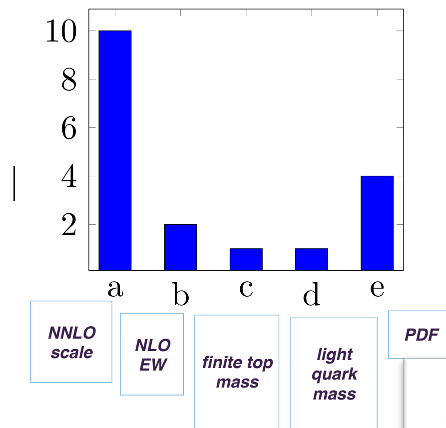
Why do we care about N^{3}LO ?

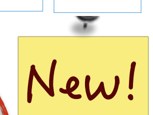
1) Large perturbative corrections



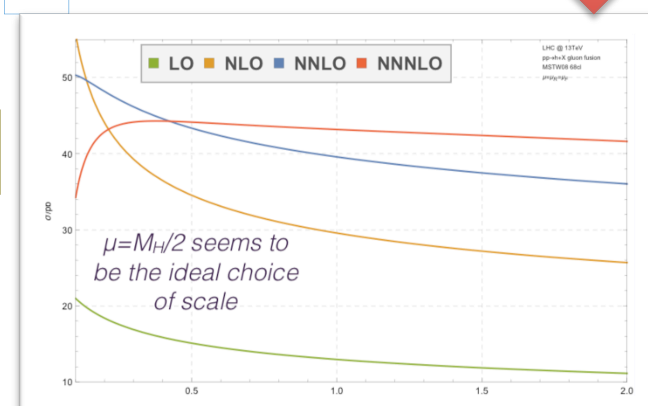
2) Sizeable NNLO scale variation

Higgs working group report





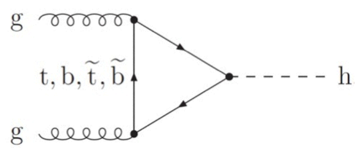
N^{3}LO:
Small correction
Flat scale dependence



Shifman, Vainshtein, Voloshin, Zakharov	*Dawson; Djouadi, Spira, Zerwas*	*Harlander, Kilgore; Anastasiou, Melnikov; Ravindran, Smith, van Neerven*	*Anastasiou, Duhr, Dulat, Herzog, Mistlberger*
HEFT 1979	NLO 1991	NNLO 2002	NNNLO 2015

Soft-virtual contributions confirmed by Li, Manteuffel, Schabinger, Zhu

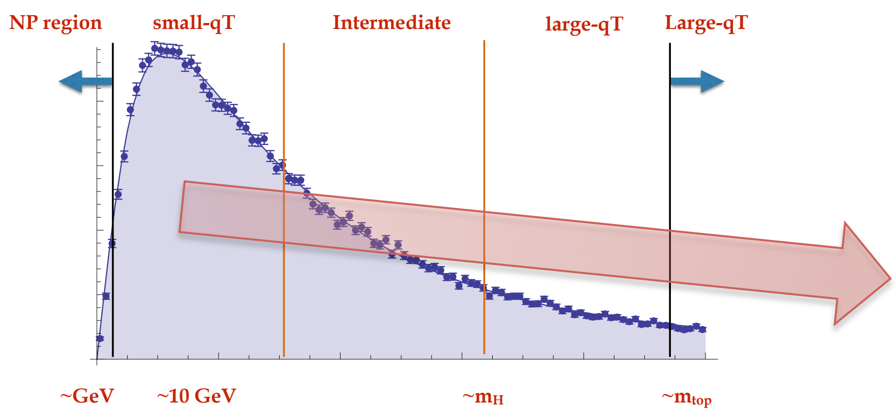
Higgs production in ggF



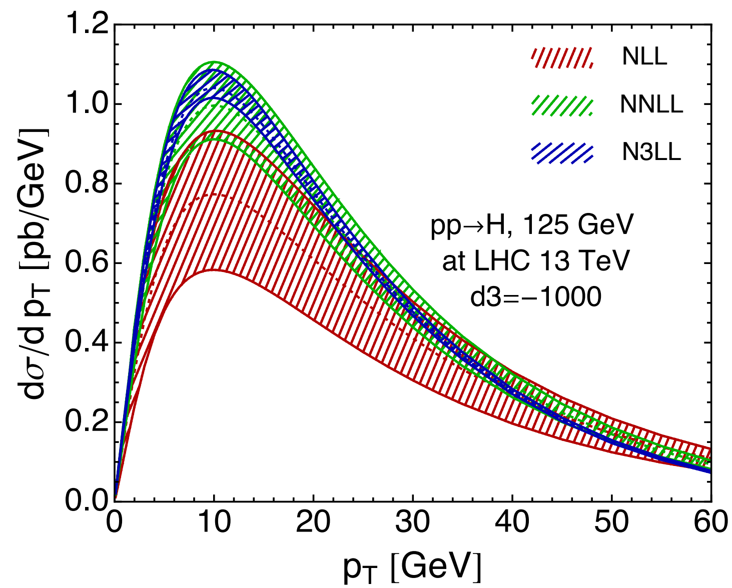
Jun Gao

Why do we care about Higgs Q_T?

1) Probe of EW dynamics



2) Clean test of QCD factorization



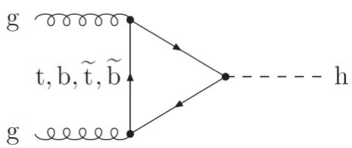
Two unknowns prevent full N^3LL accuracy

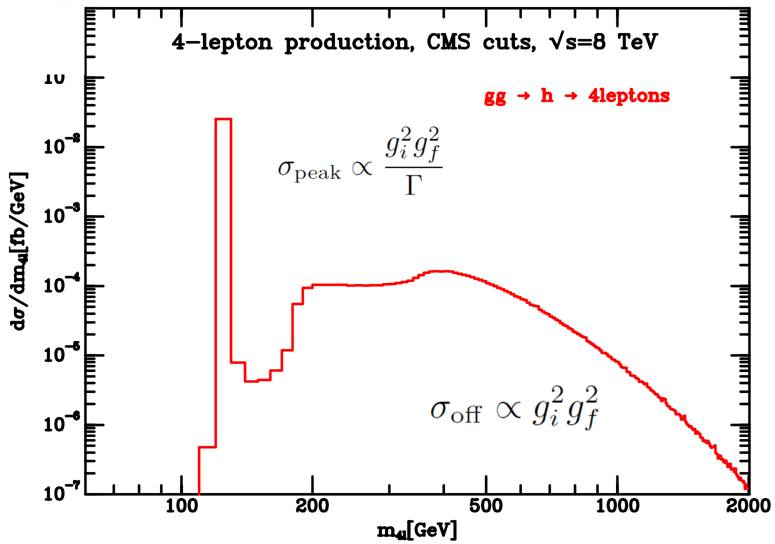
Nevertheless, scale dependence reduced (10%)

Matching to recent H+jet at NNLO (ie N^3LO matching)

Higgs properties: width

Keith Ellis



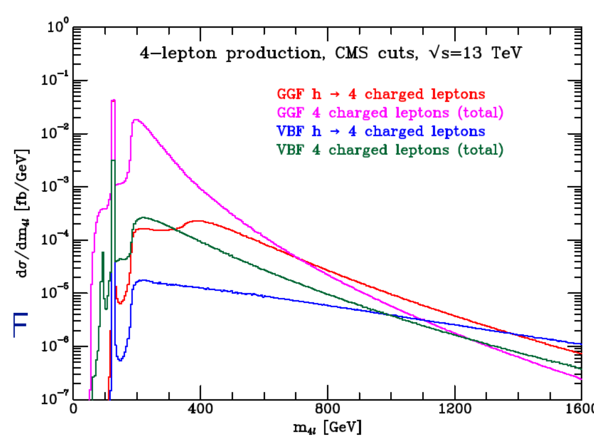


Caola Melnikov method

$$\frac{\left(\frac{\sigma_{\rm off}}{\sigma_{\rm peak}}\right)_{\rm experimental\ gg}}{\left(\frac{\sigma_{\rm off}}{\sigma_{\rm peak}}\right)_{\rm theoretical\ SM}} = \frac{\Gamma}{\Gamma^{\rm SM}}$$

Used by ATLAS and CMS: 5-6 x SM:
2 orders of magnitude improvement
Caveat: true if couplings are the same
(Englert and Spannowsky)

Idea: look at VBF which is tree-level, not loop-induced in the SM



- Possible width bounds with (100, 300fb^{-1}) are similar to those currently obtained from gg fusion (20fb^{-1}).

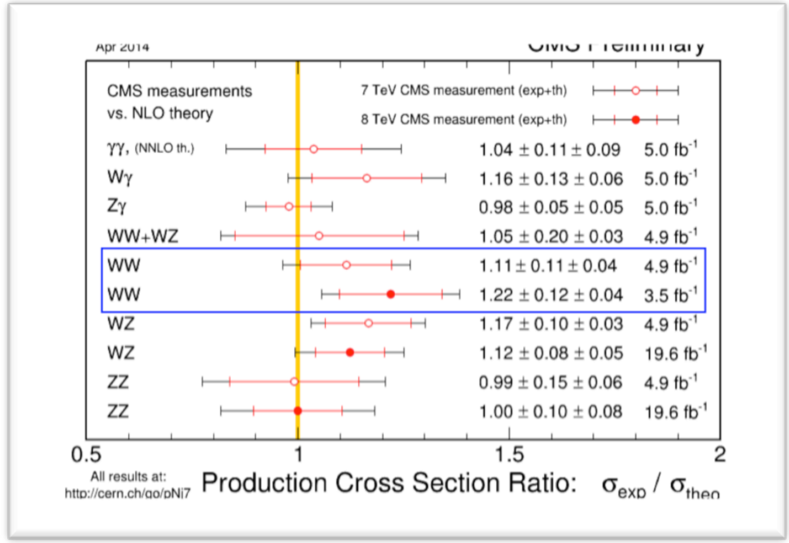
The WW story

Hari Ramani

Importance of WW

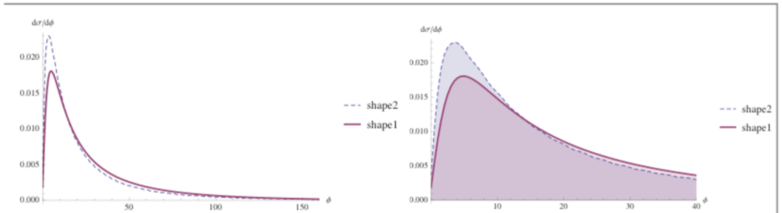
- LHC Era of Electroweak precision measurements
- WW is large background to H->WW. Higgs Precision Analysis
- WW huge background to many BSM searches

~~Inclusive~~ fiducial cross-section: Jet veto is applied, which results into a distorsion of p_{TWW} spectrum



Excess reported by both ATLAS and CMS

Can shape affect reported cross section?



Full Phase-space.
Both curves Normalized to unity.

Shape effect translates to different Fiducial cross-section

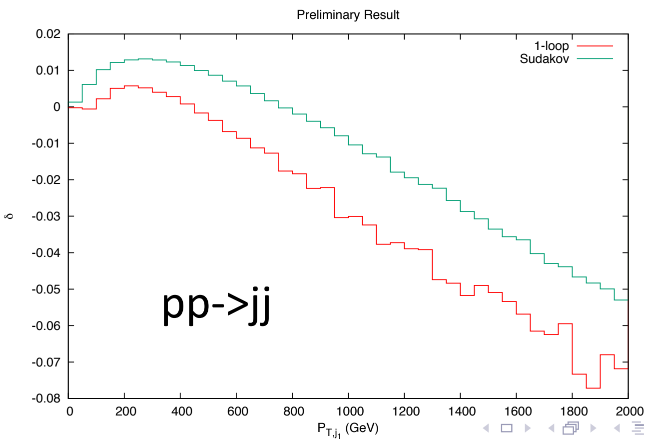
Two theoretical improvements:

1) Resummation (pT or jet veto) (Ramani *et al.*, Jaiswal & Okui 2014)
2) NNLO corrections (Gehrmann *et al.* 2014)

- CMS(old) :69.9 ±7.0 pb
- CMS(new) :60.1 ± 4.8 pb
- NNLO theory:59.8 ±1.3 pb
- Old theory :57.3 ±1.0 pb

Comparison between pT and jet veto resummation is on-going

EW physics at high-energy



Implementation in MCFM: comparison Sudakov approx vs 1-loop

Main source of discrepancy: angular dependence which is absent in Sudakov approx

Electro-weak corrections

Jia Zhou

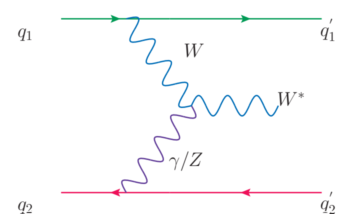
$W\gamma$ fusion and photon PDF

Richard Ruiz

Perturbative photon PDF matched to resolved calculation

VBF: Great for Probing High-Mass Scales

In weak boson scattering, t-channel propagators give rise to logarithms that scale with the hard scattering process



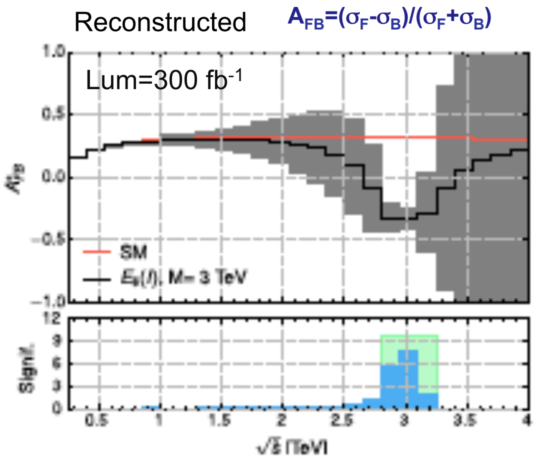
$$\int_0^{E^2} \frac{dQ_V^2}{Q_V^2 - M_V^2} \to \log \frac{E_V^2}{M_V^2} \sim \log \frac{\hat{s}}{M_V^2}$$

Logs are regulated by weak boson **masses**.

In principle (and in nature), logs for t-channel **photons** are regulated by fermion masses. In practice:

1. Introduce a cutoff, e.g., η, p_T cuts on associated jet
2. Collinearly factorize to obtain a γ PDF

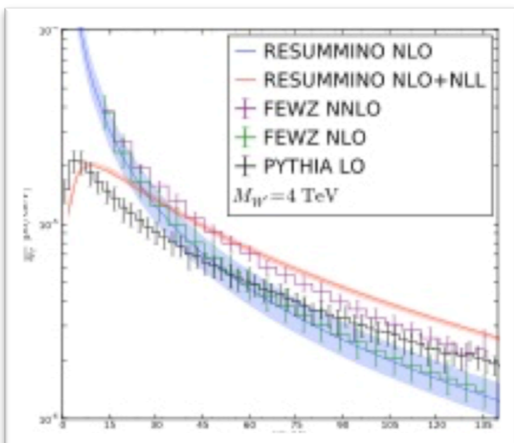
Studies of Z' resonances



F/B asymmetry as a discovery tool

Elena Accomando, Juri Fiaschi

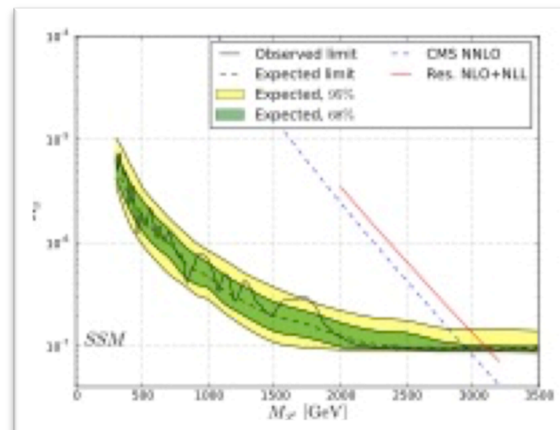
- **The A_{FB} can in fact give rise to a significance comparable to or even bigger than that one expected from the default bump search.**
- **The A_{FB} is moreover much more robust against PDF's uncertainties.**



NLL resummation

Florian Lyonnet

- Sizeable resummation effects
- Interferences with W/Z large!
- Public code Resummino



Clear message for the DIS crowd:

Improving large-x PDF's uncertainties is mandatory for high energy DY.

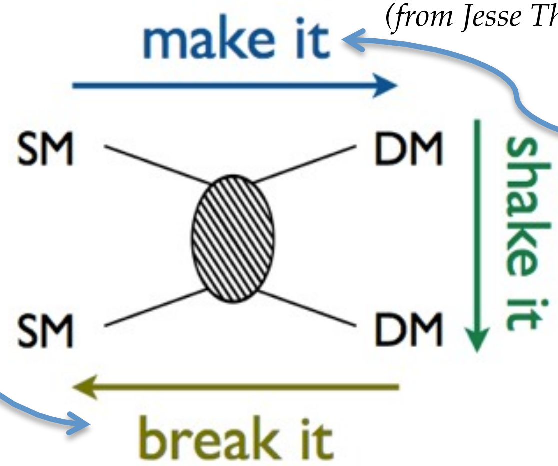
Dark matter

WIMP cross-section annhilation

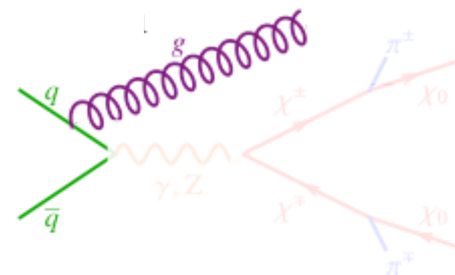
Calculation includes:

- Sommerfeld enhancement
- Resummation of EW logarithms

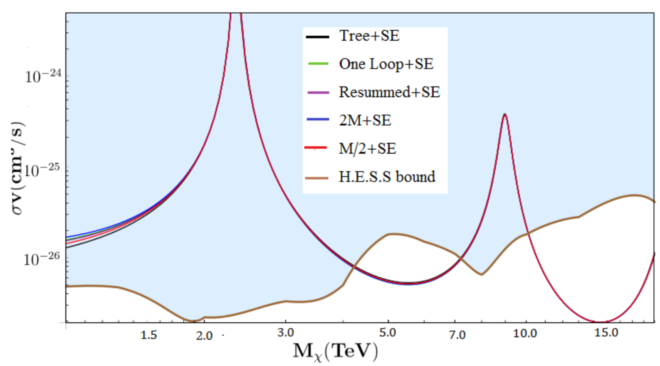
(from Jesse Thaler)

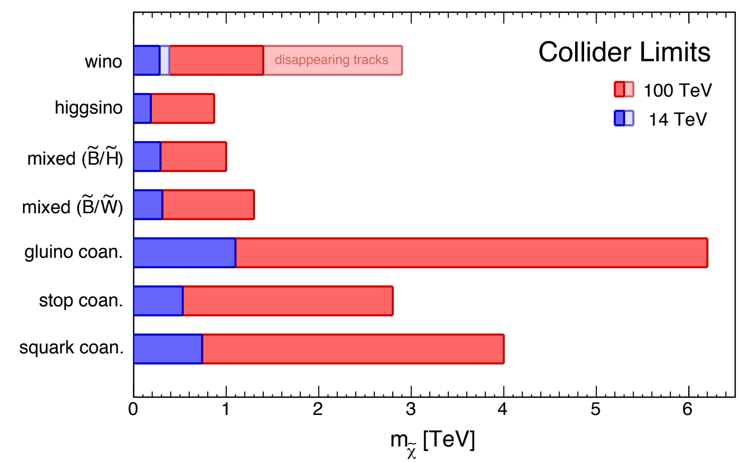


Mono-something



$$M_{\rm DM} \lesssim 1.8\ {\rm TeV}\left(\frac{g_{\rm eff}^2}{0.3}\right)$$





Varun Vaidya

Matthew Low

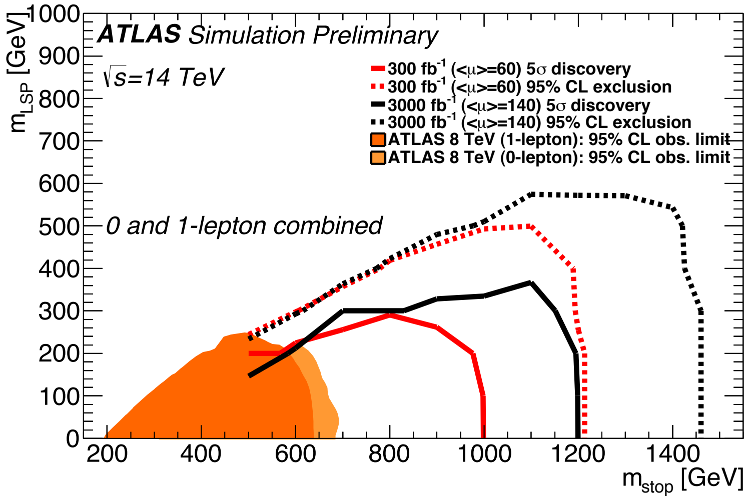
The naturalness strategy

This is a *strategy* for new physics near m_h, not a *no-lose theorem*, because the theory does not break down if it is unnatural.

Nathan Craig

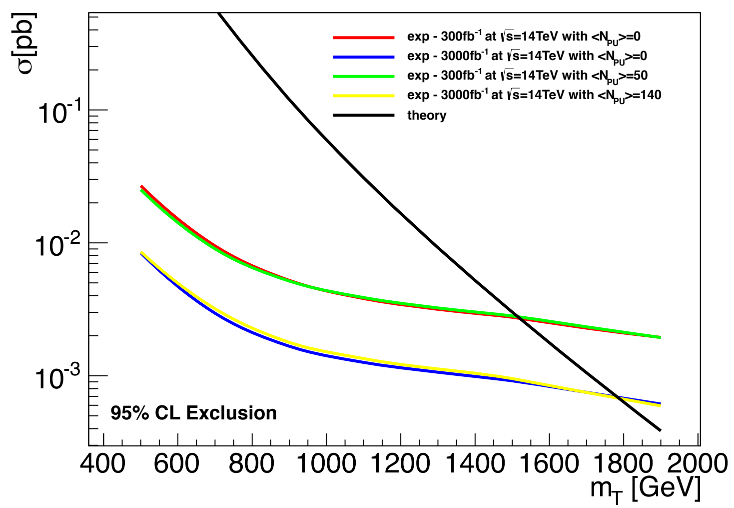
But naturalness has often been a very *successful* strategy.

Local symmetry



Global symmetry

[Snowmass EF WG Report]



Where we'll be @ end of LHC: "generically" **~1% level (global) ~2% level (SUSY)**

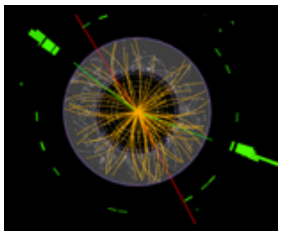
where 100% is totally natural

Where we'll be @ 100 TeV: "generically" **~.05% level**

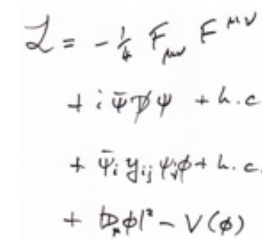
Or maybe we've been looking in the wrong place, e.g. Twin Higgs (no new particle accessible, need for precision studies in Higgs couplings)

Pseudo Observables

David Marzocca



$$\mathcal{A}(Z(\varepsilon) \to f\bar{f}) = i \sum_{f=f_L,f_R} g_Z^f \, \varepsilon_\mu \, \bar{f}\gamma^\mu f$$



Realistic Observables

Raw data,
Fiducial cross sections,
etc…

Pseudo Observables

Pole masses, decay widths,
kappas, distributions, etc..

Lagrangian parameters

Couplings,
running masses,
Wilson coefficients
etc …

PO encode experimental information in idealized observables, of easy theoretical interpretation. This approach is old: developed at LEP to describe the Z properties.

PO can then be matched, by theorists, to any explicit scenario — SM EFT, SUSY, Composite Higgs, etc.. — at the desired order in perturbation theory.

Thank you to all the speakers for the exciting talks and the many interesting discussions