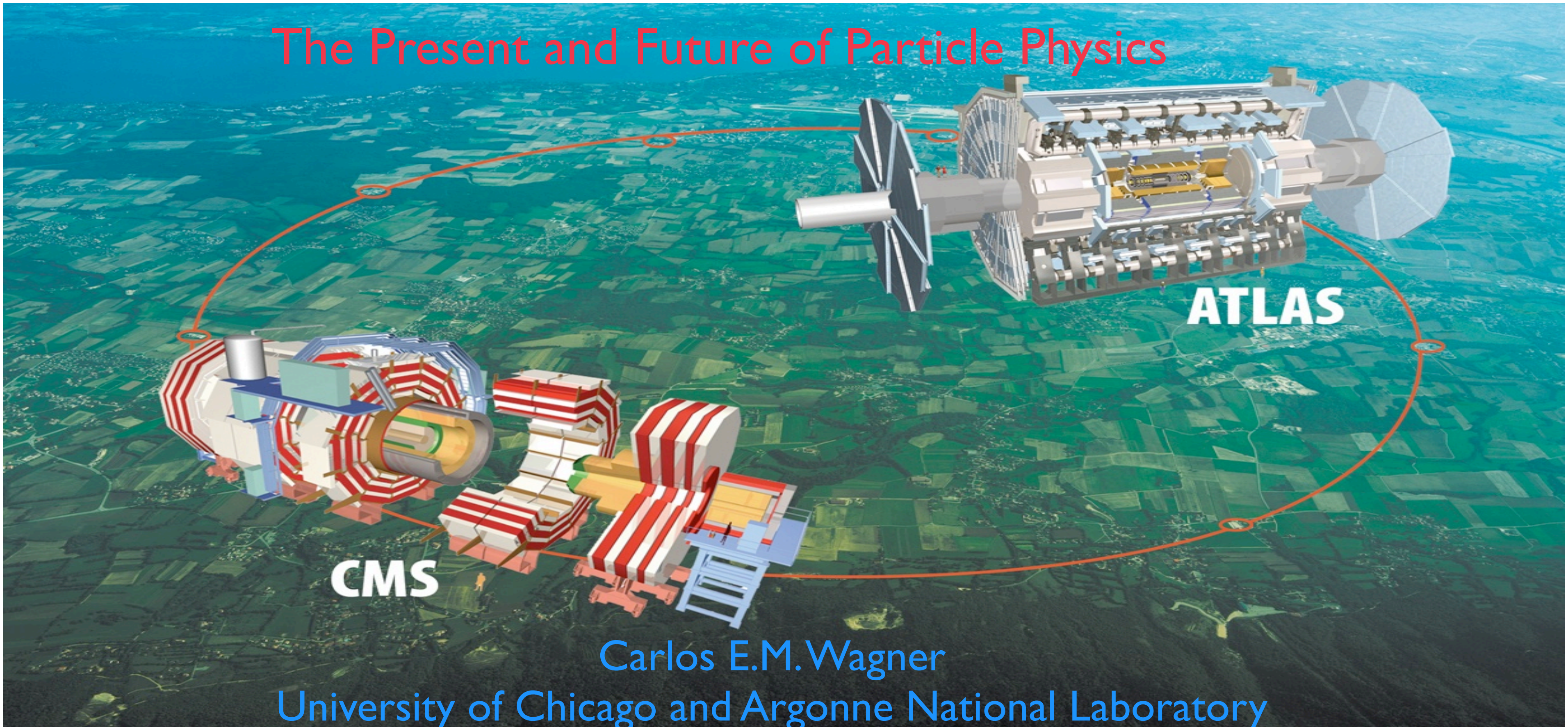
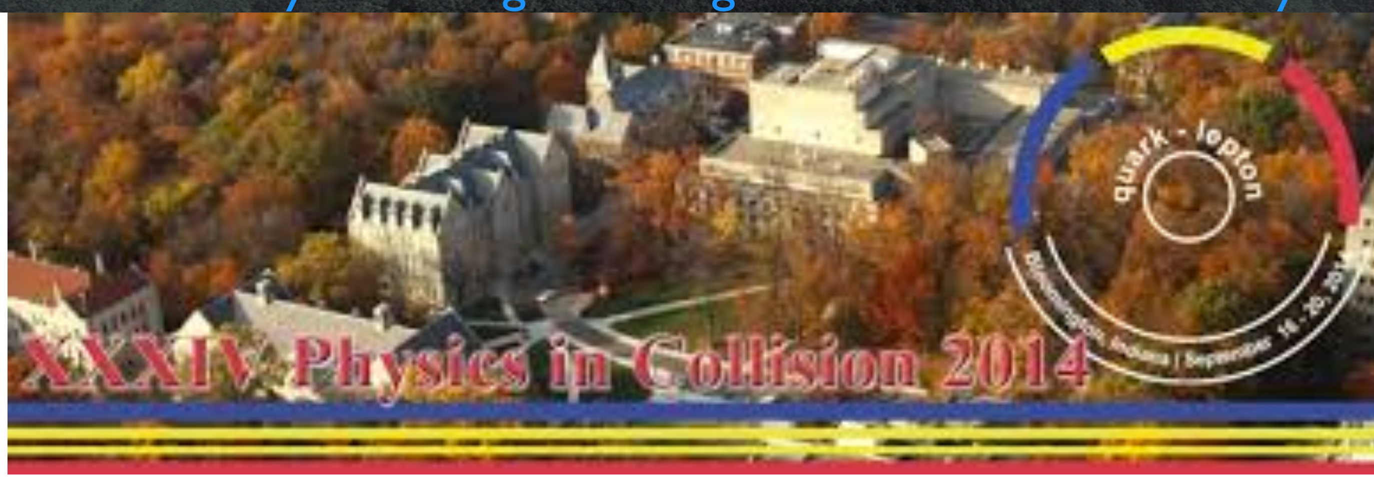
The Present and Future of Particle Physics



Carlos E.M. Wagner
University of Chicago and Argonne National Laboratory



University of Indiana, Bloomington, September 20, 2014

Particle Physics

- Goal : Study the fundamental particle properties and its interactions
- In the last century, a successful theory was developed, called the Standard Model
- It is based on the marriage of quantum mechanics and special relativity. It has some basic ingredients : Locality, Lorentz and Gauge Invariance and Renormalizability.
- These principles enable the existence of fundamental particles of spin zero, 1/2 (Dirac or Majorana), one (gauge bosons), 3/2 and two.
- A fundamental particle of spin two is associated with gravity (GR).
- We just got evidence of the possible existence of a particle of spino zero, which is required in this model.
- This is an incredible intellectual success, which has led to the understanding of all processes observed in nature.

Present of Particle Physics

- All Standard Model interactions may be written in a few basic lines.

$$\mathcal{L} = \bar{\psi}\gamma_\mu \mathcal{D}^\mu \psi - \frac{1}{2} Tr[F_{\mu\nu}F^{\mu\nu}]$$
$$-Y\bar{\psi}\Phi\psi + (\mathcal{D}^\mu \Phi)^\dagger \mathcal{D}^\mu \Phi - V(\Phi)$$

- No mass scale appears, apart from one in the scalar potential
- Renormalizability implies the absence of higher order interactions
- This is the starting point of our activities. We want to understand if this is correct.
- There are two aspects to this line of research. First understanding if with the particles we know this is the proper description. Are there deviations associated with a new physics scale ?
- Second, we want to see if there are new particles or new forces we don't know.
- After all, we want to investigate if the mass scale in the potential has a dynamical origin. If it does, it is natural that is associated with physics at the TeV scale.

Standard Model Particles

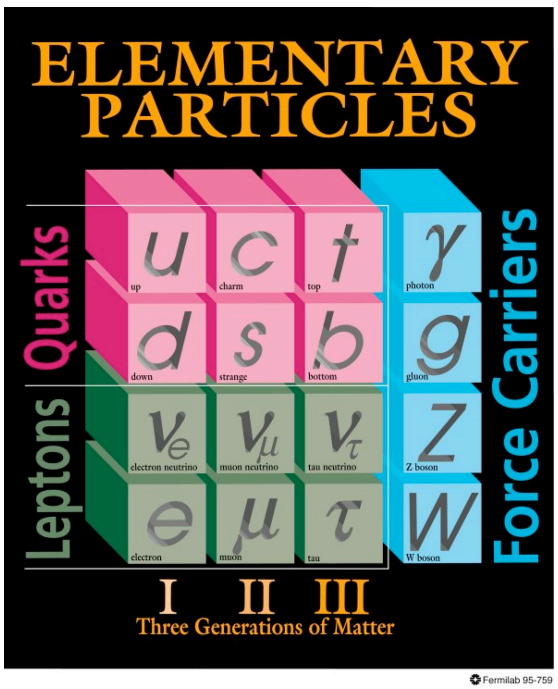
There are 12 fundamental gauge fields:

8 gluons, 3 W_μ's and B_μ

and 3 gauge couplings g_1, g_2, g_3

The matter fields:

3 families of quarks and leptons with same quantum numbers under gauge groups



But very different masses!

m_3/m_2 and $m_2/m_1 \simeq$ a few tens or hundreds

$m_e = 0.5\ 10^{-3}$ GeV, $\frac{m_\mu}{m_e} \simeq 200$, $\frac{m_\tau}{m_\mu} \simeq 20$

Largest hierarchies

$m_t \simeq 175$ GeV $\qquad m_t/m_e \propto 10^5$

neutrino masses smaller than as 10^{-9} GeV!

FERMIONS matter constituents spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2		
Flavor	Mass GeV/c^2	Electric charge
ν_e electron neutrino	<1×10^{-8}	0
e electron	0.000511	−1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	−1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	−1

Quarks spin = 1/2		
Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	−1/3
c charm	1.3	2/3
s strange	0.1	−1/3
t top	175	2/3
b bottom	4.3	−1/3

Only left handed fermions transform under the weak SM gauge group $SU(3) \times SU(2)_L \times U(1)_Y$

Fermion and gauge boson masses forbidden by symmetry

Historical Perspective

- Higgs Mechanism was proposed back in 1964 by several authors, including Higgs
- It was implmented by Weinberg in 1967
- A scalar boson, the Higgs particles, was predicted associated with this mechanism
- What were the prospects of its discovery in the late 60's ?

A Phenomenological Profile of the Higgs Boson

1976

Nuclear Physics B106 (1976) 292–340

A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

John ELLIS, Mary K. GAILLARD * and D.V. NANOPOULOS **
CERN, Geneva

Received 7 November 1975

The situation with regard to Higgs bosons is unsatisfactory. First it should be stressed that they may well not exist. Higgs bosons are introduced to give intermediate vector bosons masses through spontaneous symmetry breaking. However, this symmetry breaking could be achieved dynamically [10] without elementary Higgs bosons. Thus the confirmation or exclusion of their existence would be an important constraint on gauge theory model building. Unfortunately, no way is known to calculate the mass of a Higgs boson, at least in the context of the popular Weinberg-Salam [11]

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We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3,4] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.

But the Higgs is not weakly coupled to all fundamental particles !

- It is relatively strongly coupled to those particles which had not been discovered at that time
- Indeed, the W mass, the Z mass and the top quark masses are all of the order of 100 times the proton mass
- Some of the authors soon realized that these could be used to produce Higgs bosons
- It is in processes mediated by these particles that we have searched for, and eventually found the Higgs boson !

Tests of the Standard Model

Understanding the Properties of Fundamental Particles

Weak Gauge Bosons Properties at the LHC

Kuze

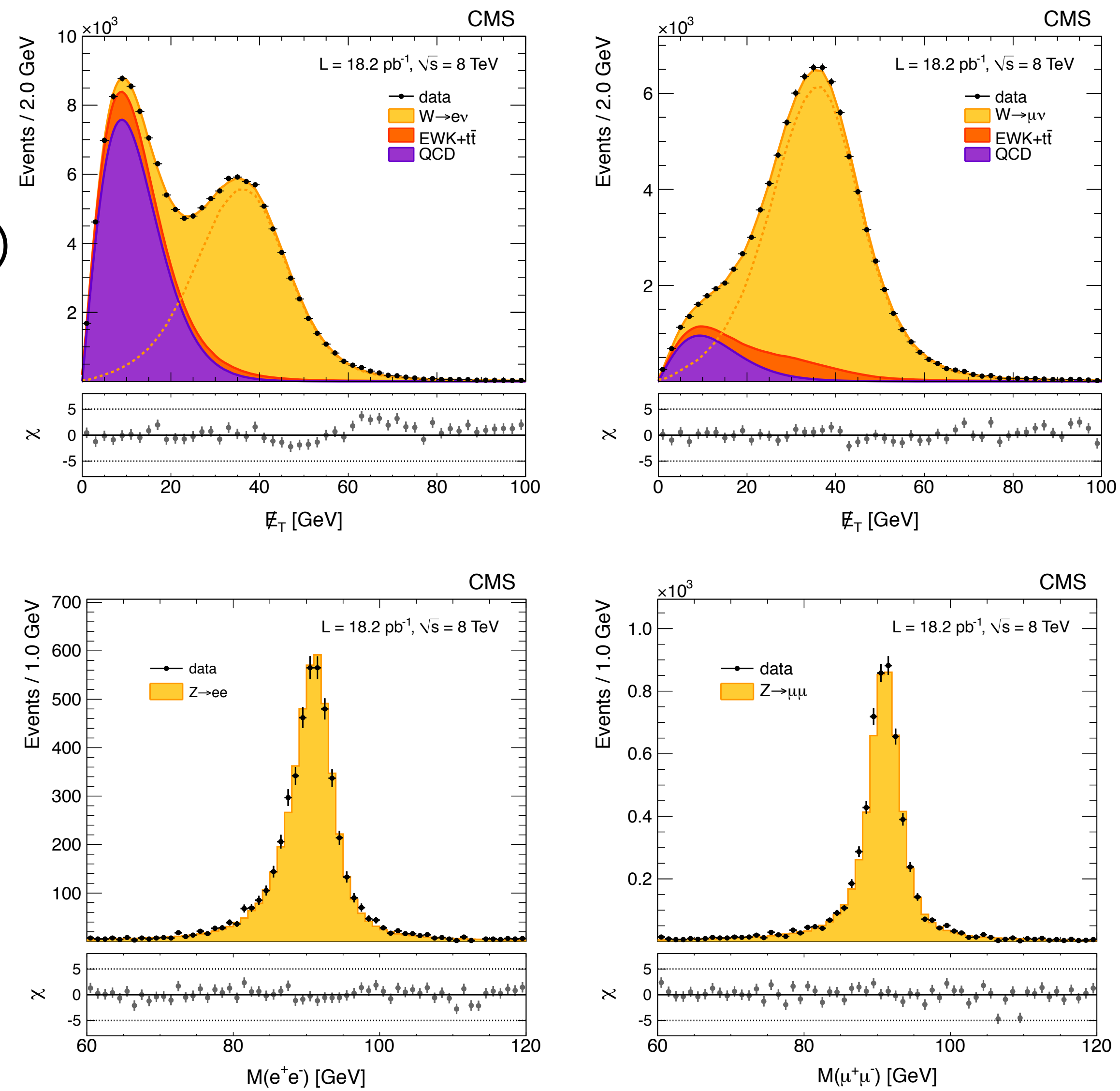
Inclusive W/Z at 8 TeV

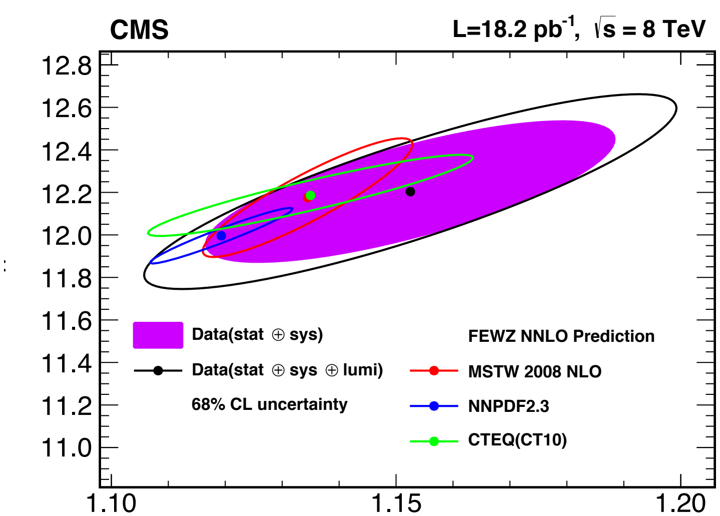
arXiv:1402.0923 PRL112 (2014) 191802

- Special data set with low pile-up

- $R_{W/Z}$ = 10.63±0.11(stat.)±0.25(syst.) (FEWZ NNLO: 10.74±0.04)

- R_{W^+/W^-} = 1.39±0.01(stat.)±0.02(syst.) (FEWZ NNLO: 1.41±0.01)



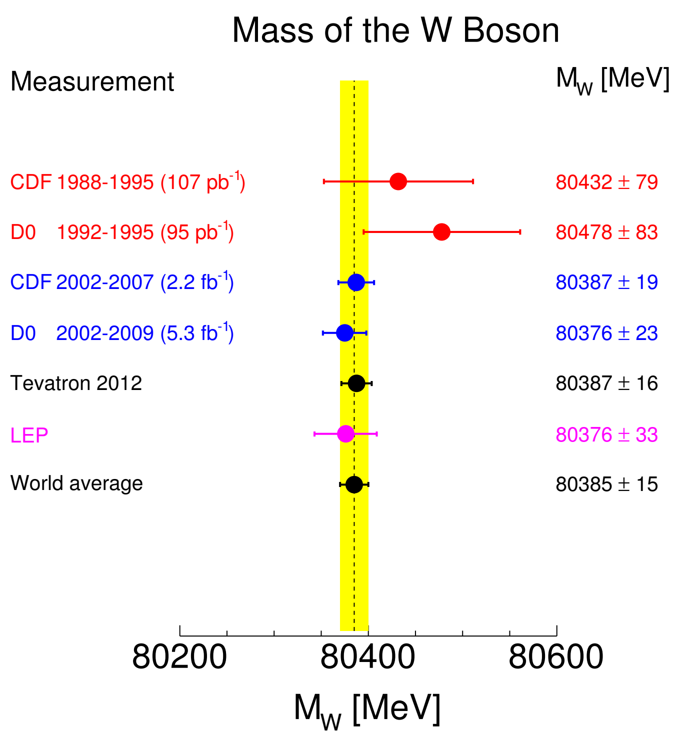


Lopes de Sa

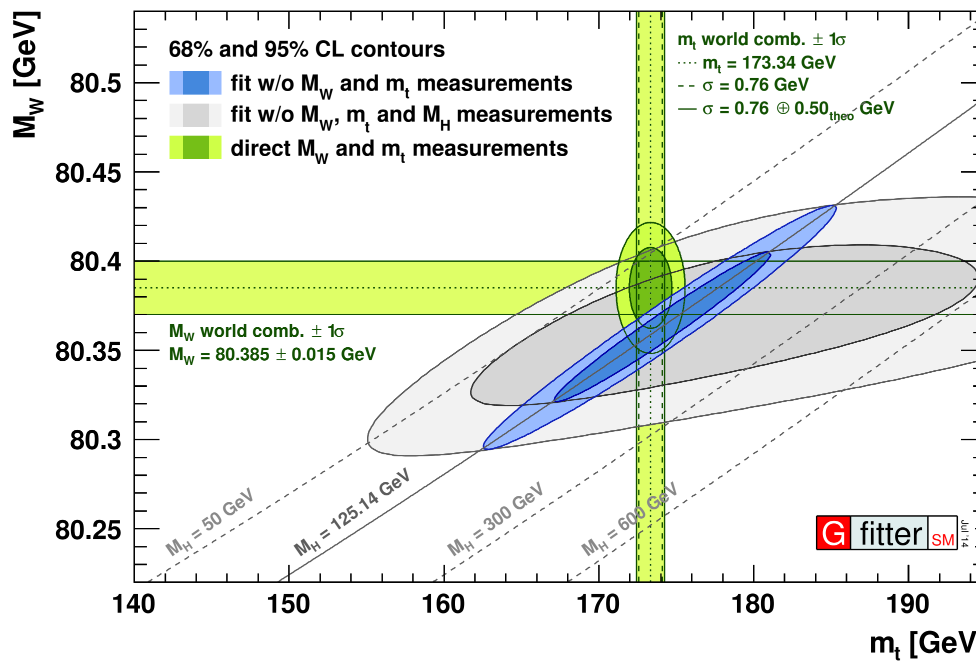
World average

W Mass Measurement

Tevatron + LEP combination: `arXiv:1307.7627`



From GFitter: `arXiv:1407.3792`



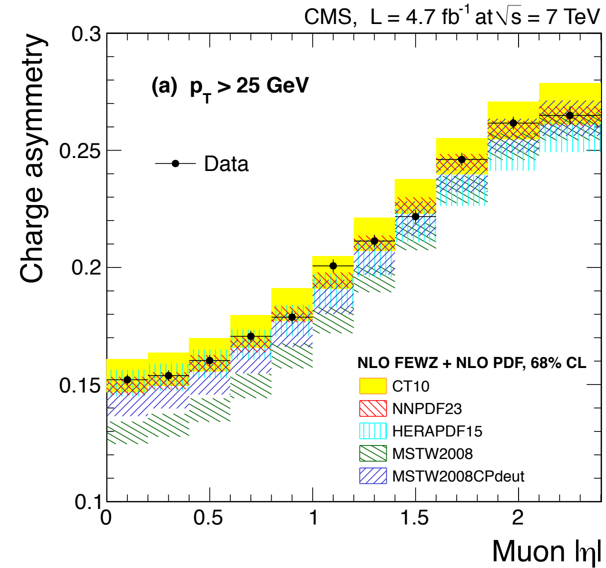
$M_W = (80.385 \pm 0.015)$ GeV. Relative precision of 2 parts in 10,000!

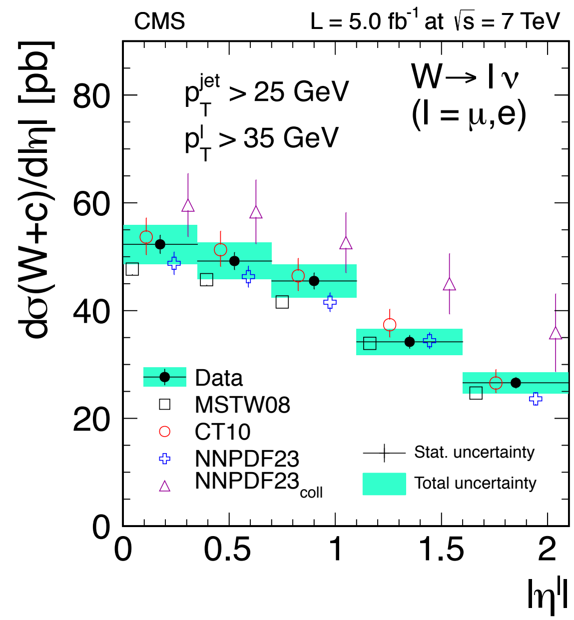
W boson mass measurement at the LHC - PDF (2/3)

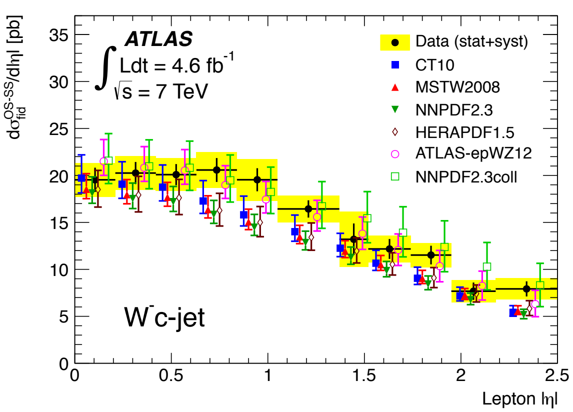
- The **u** and **d** PDFs can be constrained with W charge asymmetry measurements.
- The **s** PDF, that is relevant for W production at the LHC, can be constrained with $W + c$ measurements.

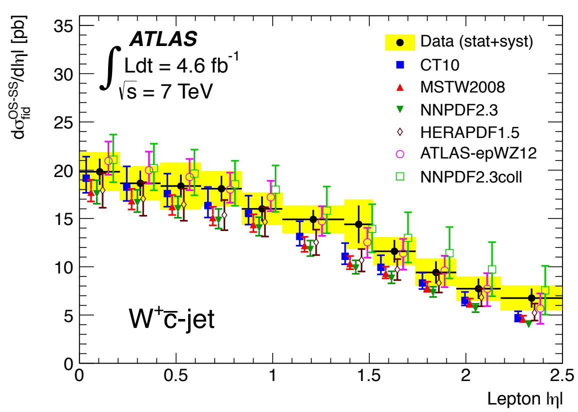
Plots here:

- CMS W charge asymmetry ($W \to \mu\nu$ channel, 7 TeV, 4.7 fb^{-1}, `arXiv:1312.6283`)
- CMS $W + c$(jet) (7 TeV, 5.0 fb^{-1}, `arXiv:1310.1138`)
- ATLAS $W + D/D^*$ and $W + c$(jet) (7 TeV, 4.6 fb^{-1}, `arXiv:1402.6263`)









Sood

Results

- **Observed EW Zjj production with significance > 5σ**

$$\sigma_{EW}^{m_{jj}>250\,GeV} = 54.7 \pm 4.6\,(stat)\,{}^{+9.8}_{-10.4}\,(syst) \pm 1.5\,(lumi)\;fb$$

$$\sigma_{EW}^{m_{jj}>1\,TeV} = 10.7 \pm 0.9\,(stat) \pm 1.9\,(syst) \pm 0.3\,(lumi)\;fb$$

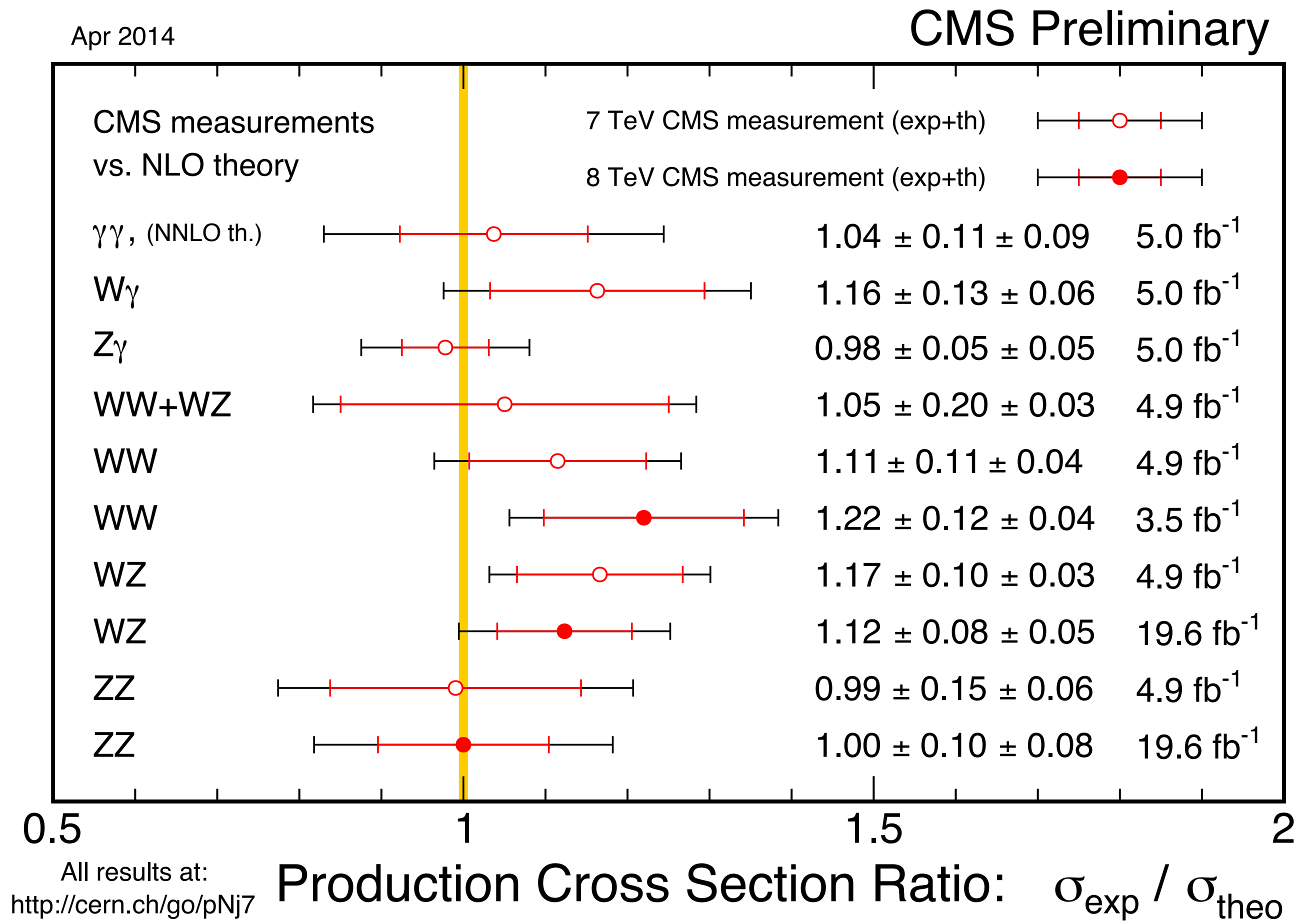
- **Measured fiducial cross sections agree with SM predictions of 46 fb ± 1 and 9.4 +0.3/-0.4 fb**
- Fitted number of EW events in m_{jj} > 1 TeV region used to set limits on aTGCs
  - aTGC parameters varied with and without form factor
  - Limits determined by profile likelihood test

aTGC	$\Lambda = 6$ TeV (obs)	$\Lambda = 6$ TeV (exp)	$\Lambda = \infty$ (obs)	$\Lambda = \infty$ (exp)
$\Delta g_{1,Z}$	[−0.65, 0.33]	[−0.58, 0.27]	[−0.50, 0.26]	[−0.45, 0.22]
λ_Z	[−0.22, 0.19]	[−0.19, 0.16]	[−0.15, 0.13]	[−0.14, 0.11]

Sood

Measured Cross Sections

Good overall agreement with SM

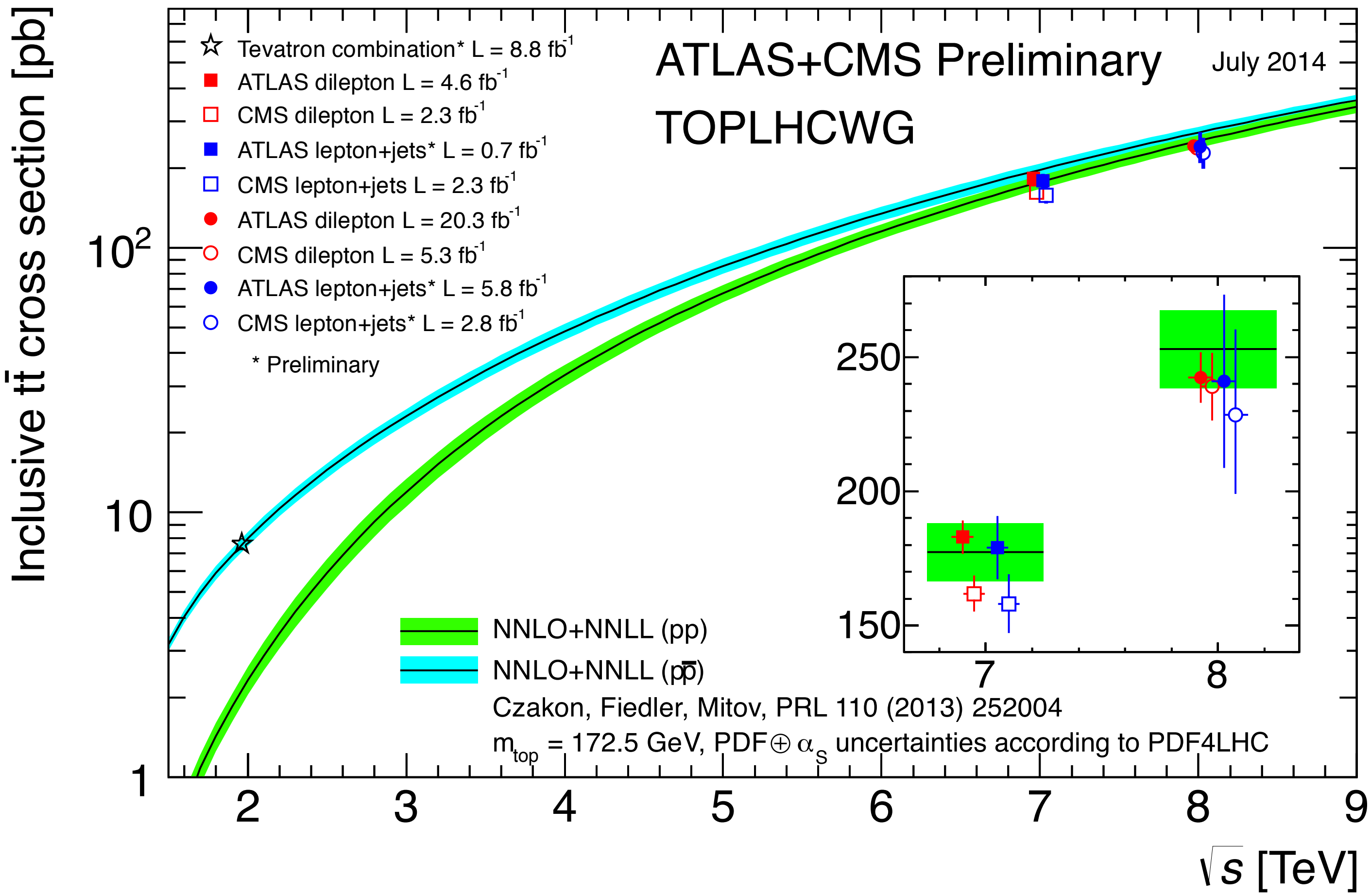


Similar results seen by ATLAS (summary plot in extra slides)

The Top Quark

Stupak

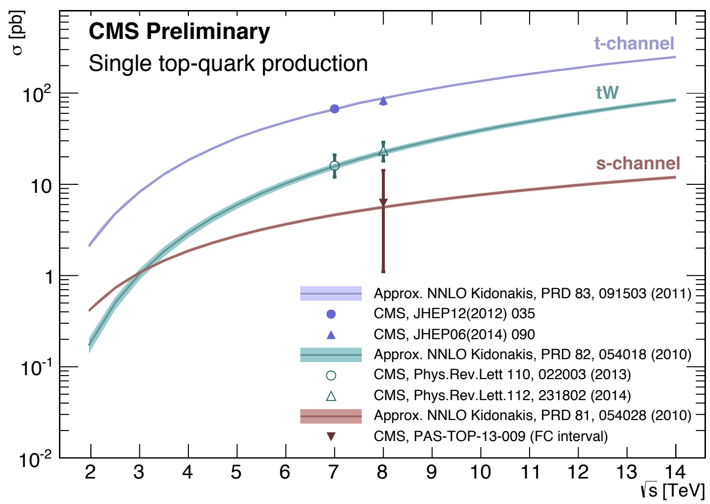
Inclusive $t\bar{t}$ cross section summary

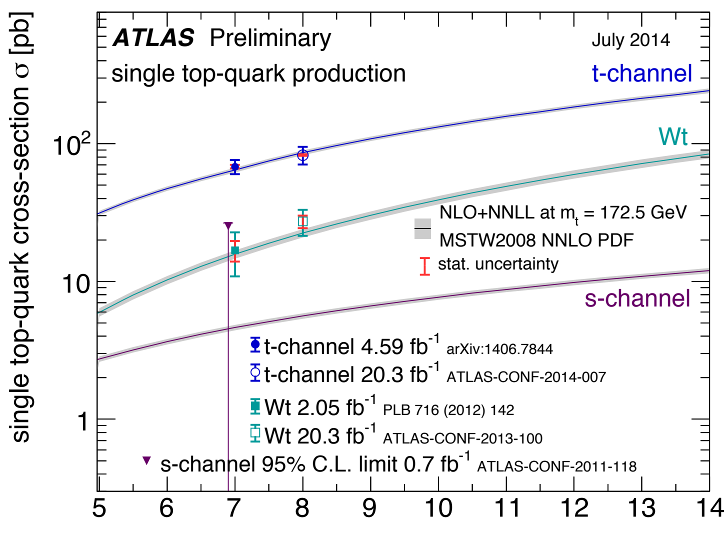


Consistency with the Standard Model from 2 to 8 TeV

Stupak

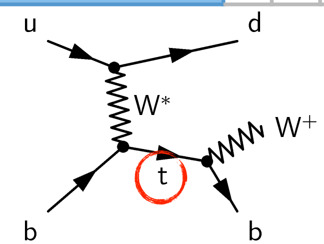
Single-top production: summary

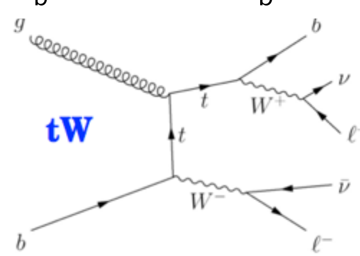


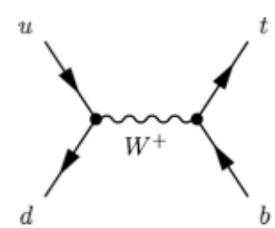


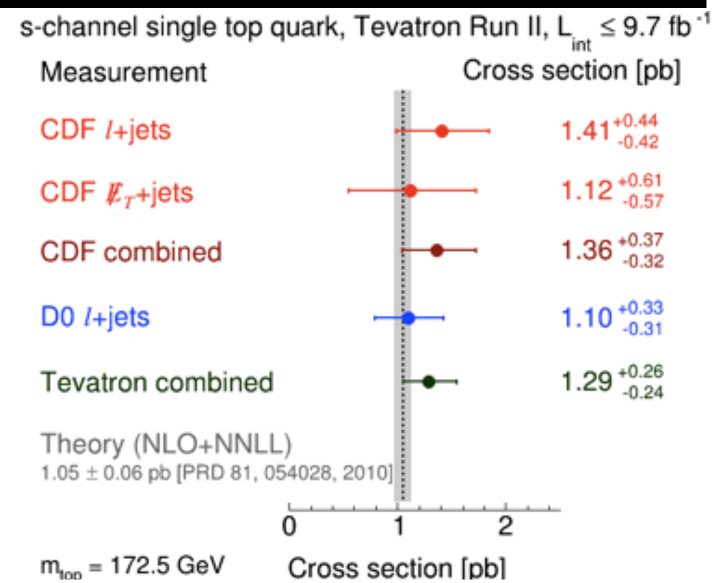
At least 3σ

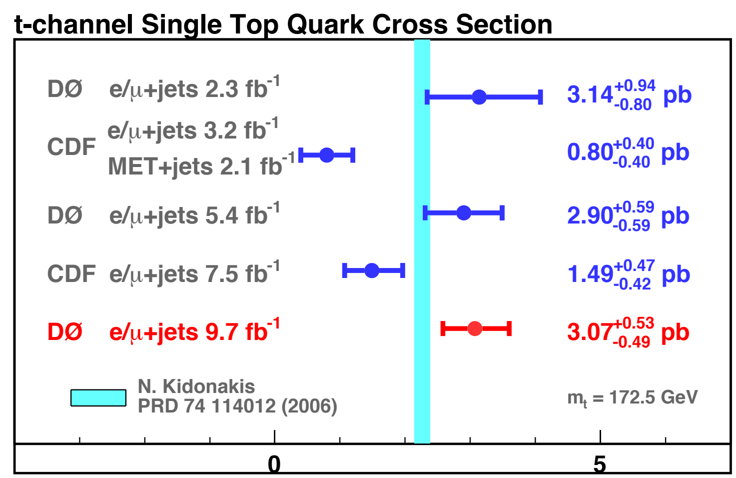
	2	7	8
t Channel	√	√	√
tW Channel		√	√
s Channel	√		





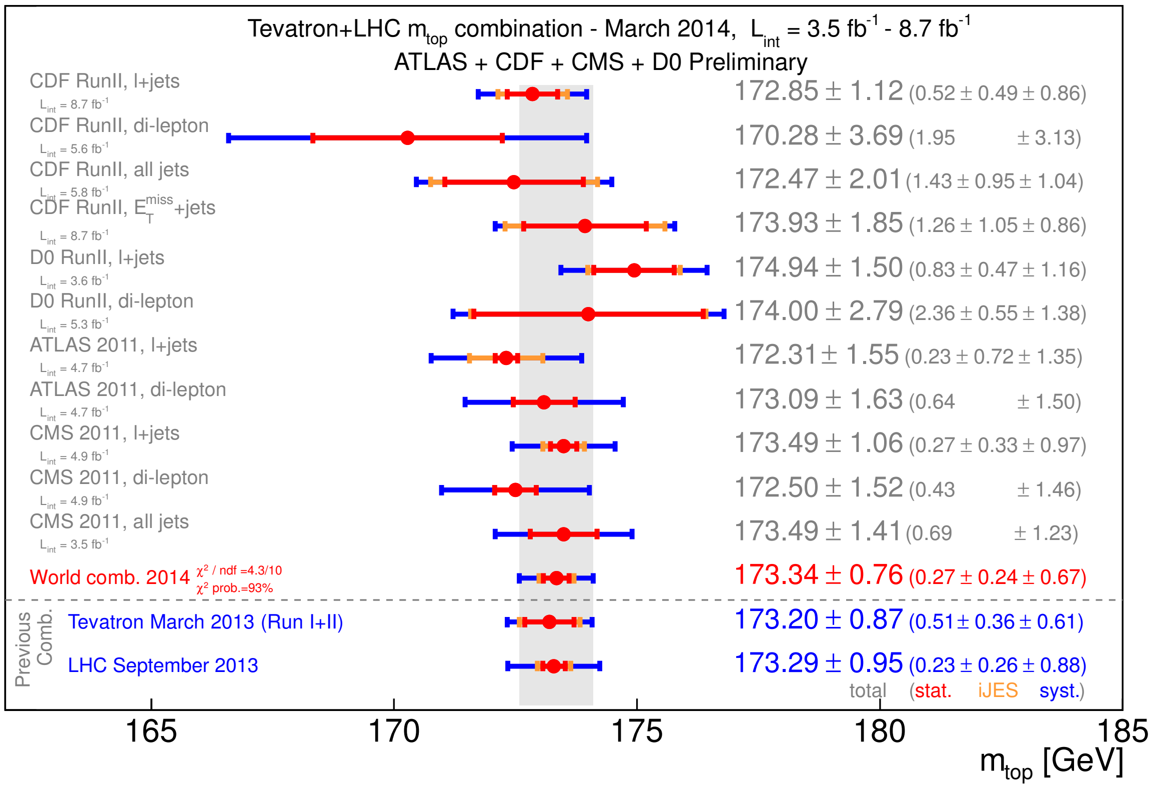






Hong

Top Mass World Combination



$$m_{top} = 173.34 \pm 0.76 \text{ GeV}$$

Relative uncertainty 0.44%

Hong

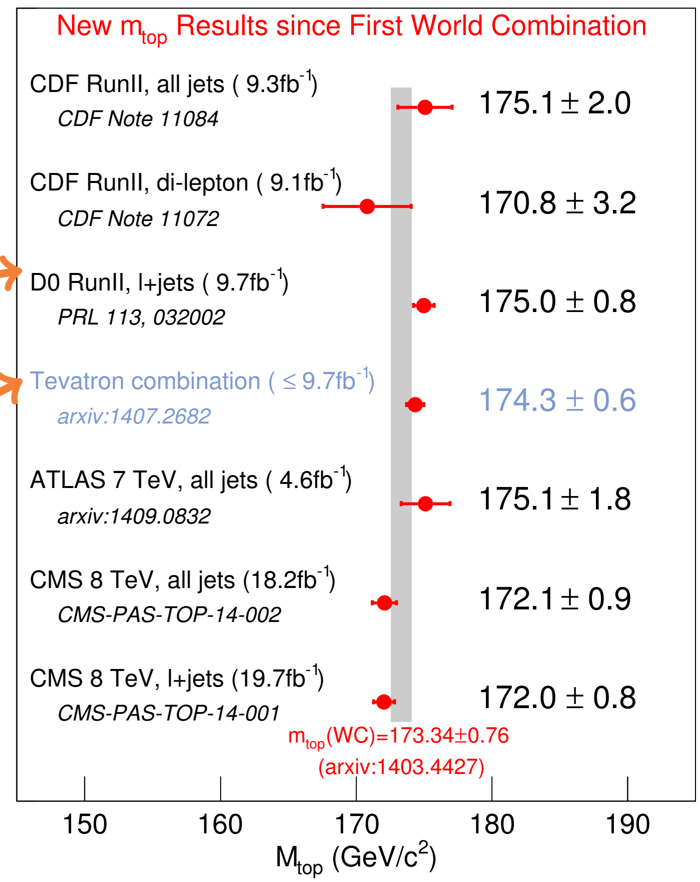
Updates since World Combination

- Updated measurements of m_{top} after first world combination
- D0 l+jets: most precise single measurement
- Tevatron combination gives smallest uncertainties:

$$m_{\text{top}} = 174.34 \pm 0.64$$

Relative uncertainty 0.37%

- Consistency between measurements is under study

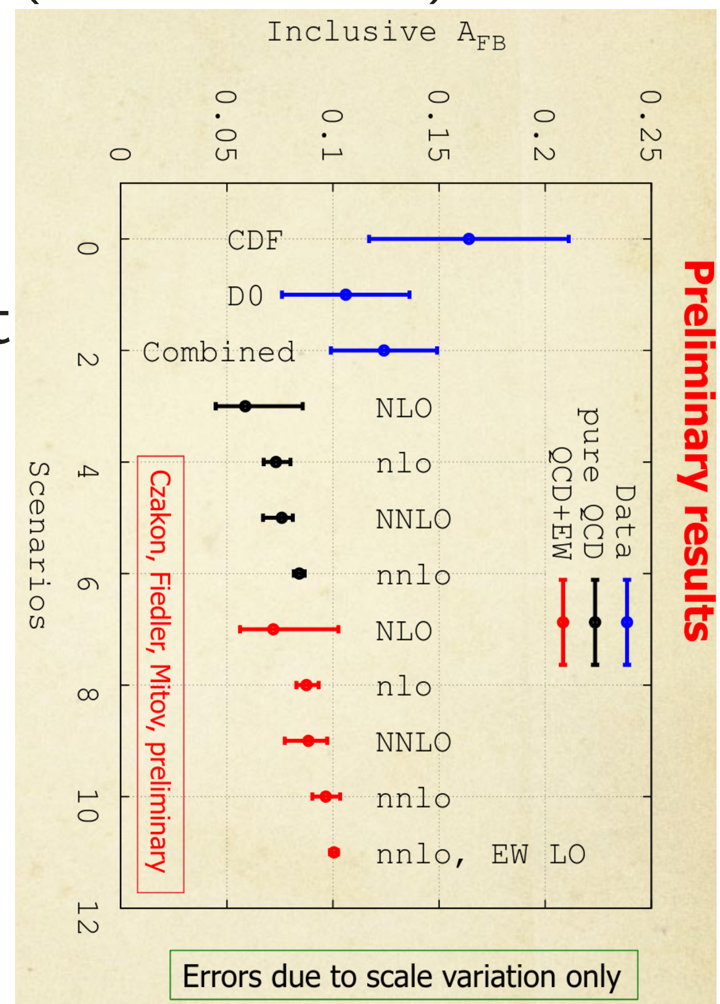


NNLO A_{FB} Prediction

A. Mitov, CKM 2014 (Sep. 9, 2014)

- Preliminary NNLO prediction suggests tension resolved
- NNLO QCD + LO EW $\rightarrow A_{FB}^{t\bar{t}} \sim 10\%$
- If this result holds up, it means that deviation between measurements and prediction no longer significant

NNLO QCD calculation needed for top kinematics!
Especially important for precision measurements happening at LHC

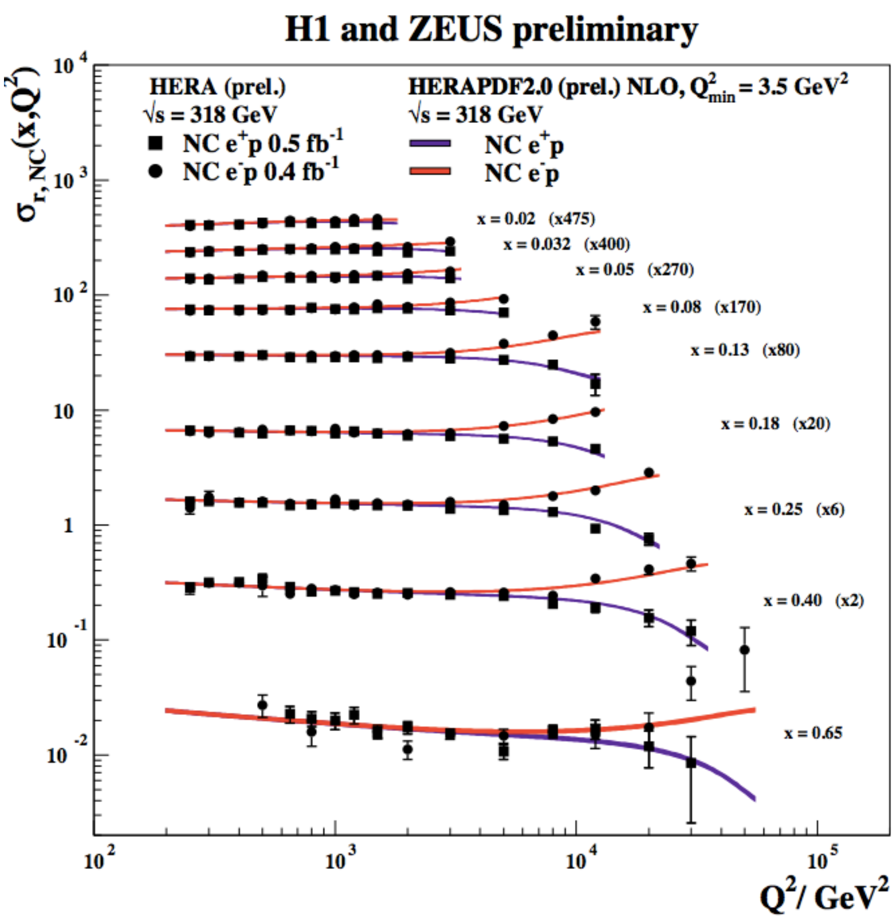


PDF’s and Hard Jets

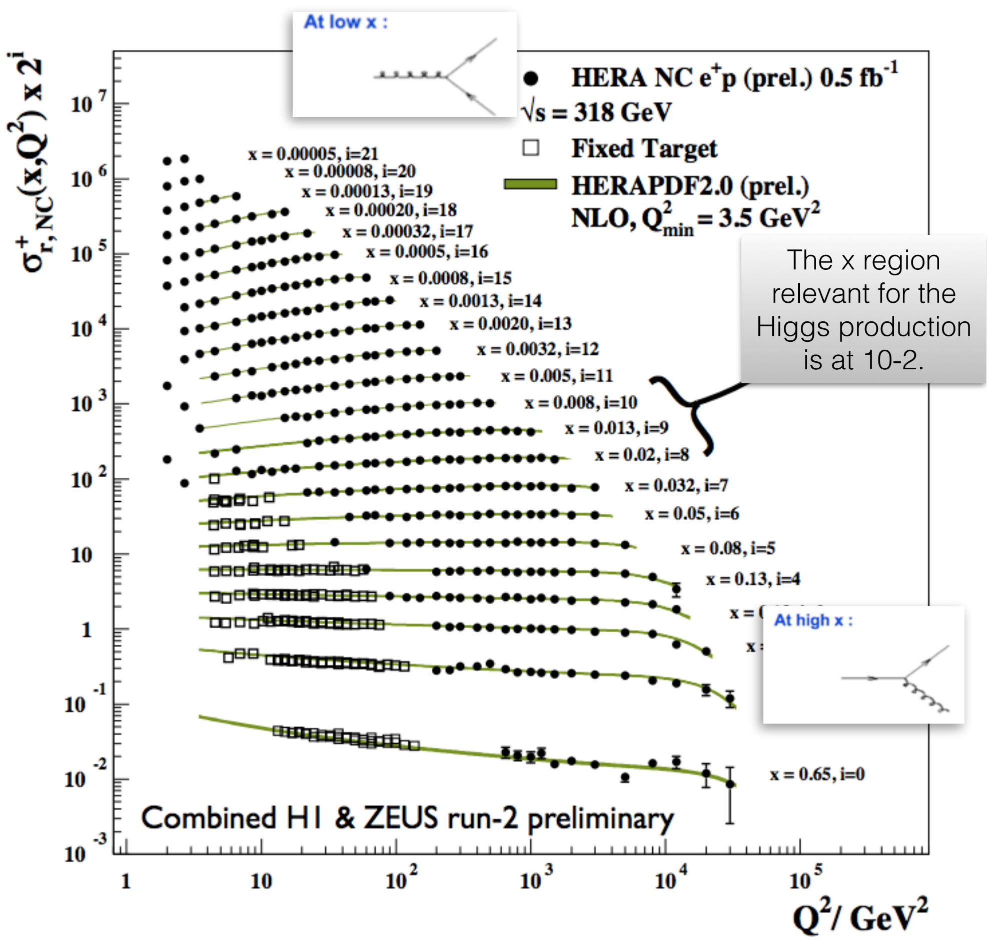
QCD scaling and EW effects

H1prelim-14-041 and ZEUS-prel-14-005

- EW effects clearly seen at high Q2:



QCD scaling violations nicely seen:



Impact of LHC data on PDFs

- Abundant LHC data with possible novel constraints on PDFs are investigated:

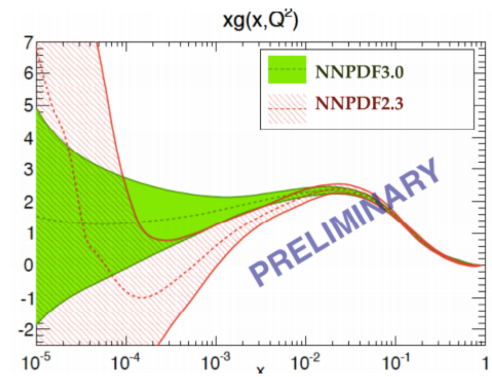
GLUON
- Inclusive jets and dijets **(medium/large x)**
- Isolated photon and γ+jets **(medium/large x)**
- Top pair production **(large x)**
- High p_T Z(+jets) distribution **(small/medium x)**

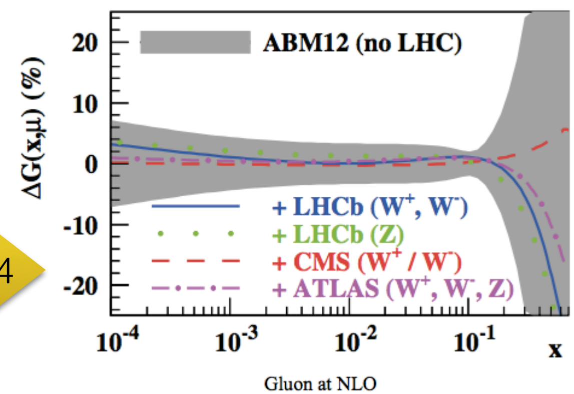
QUARKS
- High p_T W(+jets) ratios **(medium/large x)**
- W and Z rapidity distns **(medium x)**
- Low and high mass Drell-Yan **(small and large x)**
- Wc **(strangeness at medium x)**

PHOTON
- Low and high mass Drell-Yan
- WW production

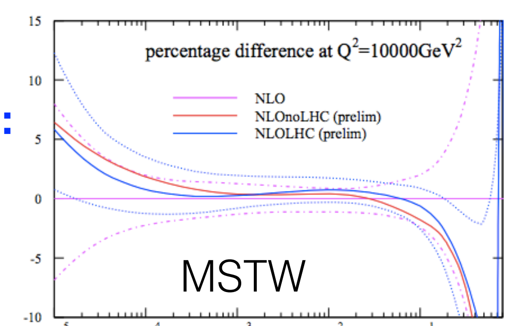
Intense activity of global PDF groups to include these measurements in the new PDF releases in time for Run2 data.

PDF4LHC, QCD@LHC, 2014





NNPDF3.0 is in LHAPDF, announced updates from: MSTW, HERA, CT, ABM



[see M. Kuze, S. Lee, J. Stupak]

Lee

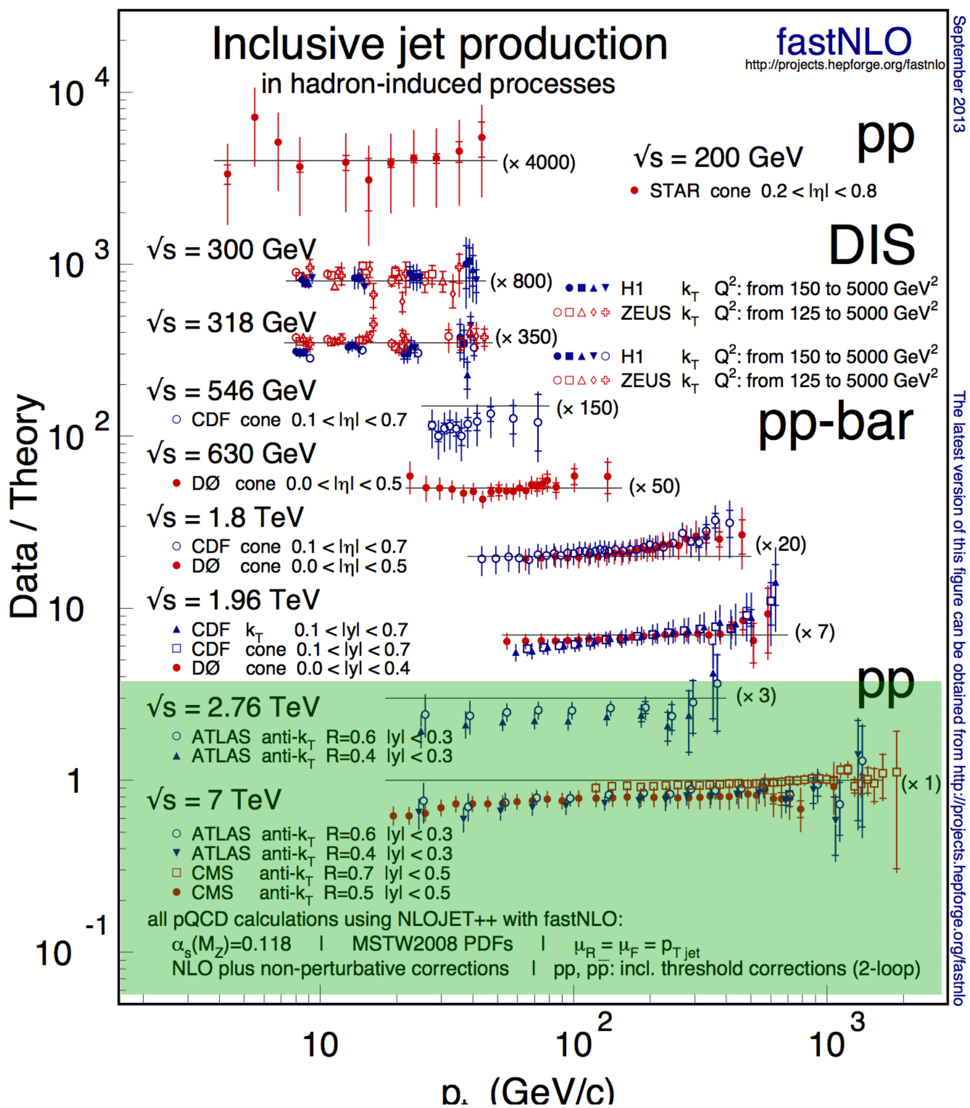
Inclusive Jet Cross Section Measurements

Global Jet Data Comparison

PDG 2014

- ✧ Ratios of data and theory for inclusive jet cross sections measured in various collisions at different center-of-mass energies.
- ✧ The ratios are shown as a function of jet p_T.
- ✧ In general, there is good agreement between theory and data.
- ✧ New LHC jet data have started to go beyond the p_T reach of the Tevatron experiments

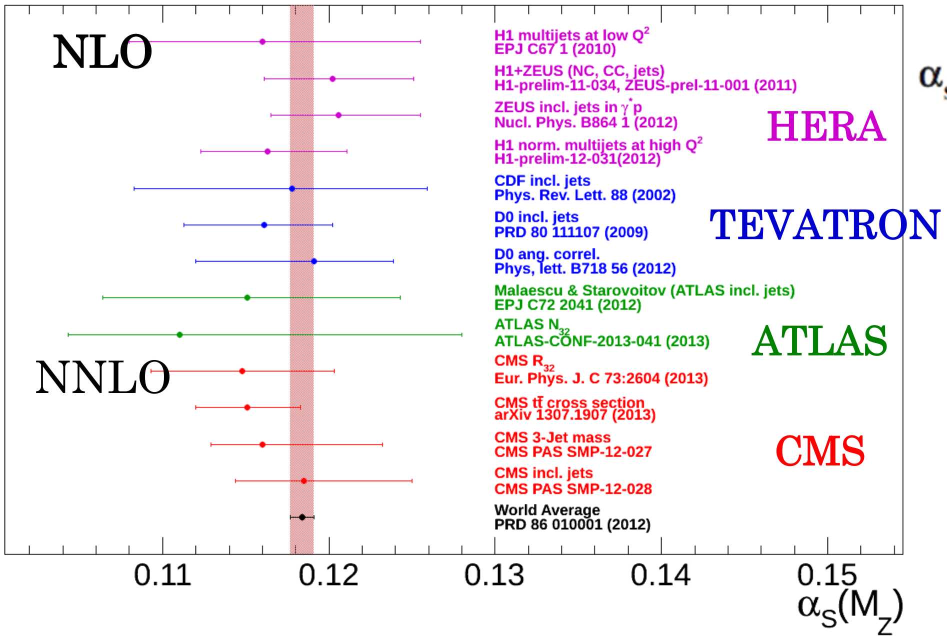
★ Beautiful jet results from ATLAS & CMS **start constraining PDFs**

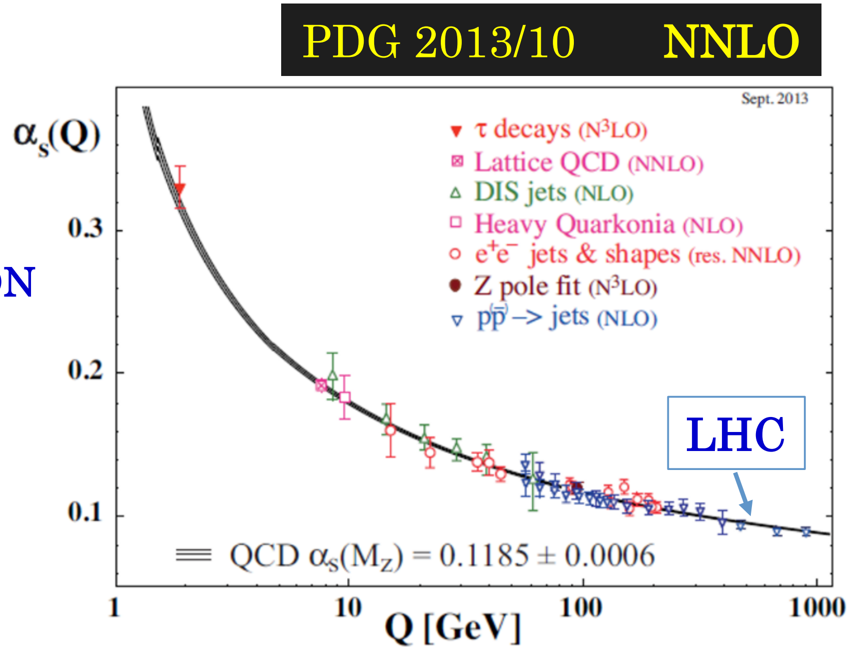


Lee

STRONG COUPLING CONSTANT

Overview of $\alpha_S(M_Z)$ measurements





- ✧ fantastic proof of α_s running up to the TeV region
- ✧ All results compatible with the world average
- ✧ precision limited by missing higher orders in QCD and PDF uncertainties
- ✧ Analysis with 2012 data at 8 TeV in progress.

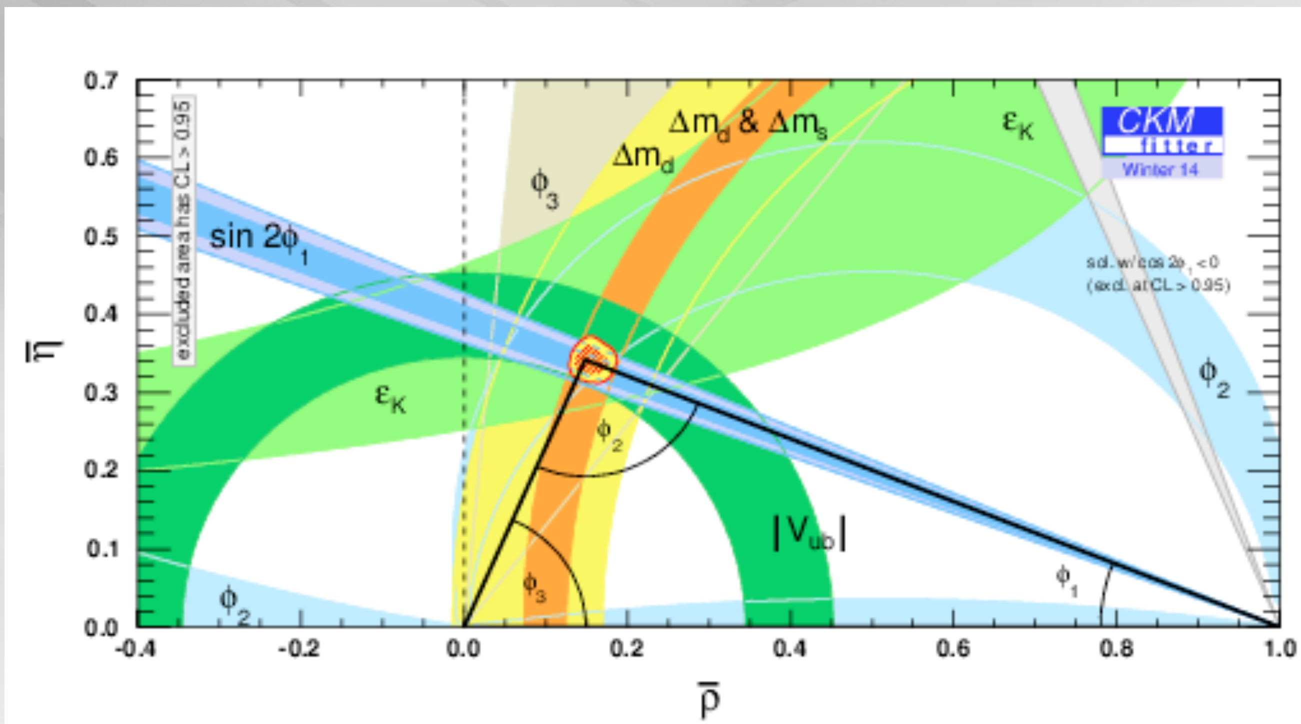
Flavor Physics

B-Physics, Charm and Kaon Physics

Result of 15 years of Belle, BaBar and LHC*b*

Pacific Northwest NATIONAL LABORATORY

Proudly Operated by **Battelle** *Since 1965*

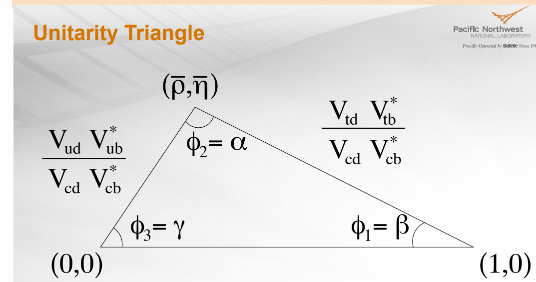


*CKM*fitter.in2p3.fr
global fit results

$$\phi_1(\beta) = (21.88 \pm^{0.81}_{0.71})^\circ$$

$$\phi_2(\alpha) = (91.7 \pm^{2.6}_{1.6})^\circ$$

$$\phi_3(\gamma) = (66.5 \pm^{1.3}_{2.5})^\circ$$



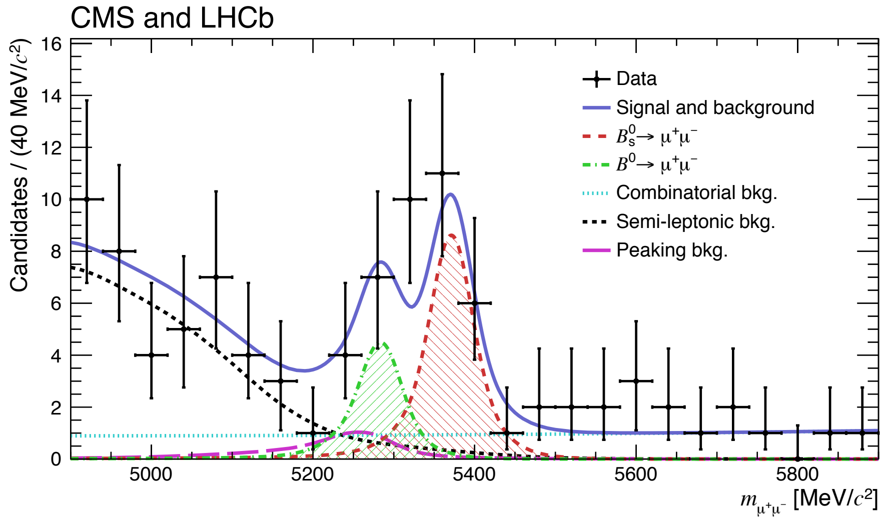
So far all triangle parameters are self-consistent

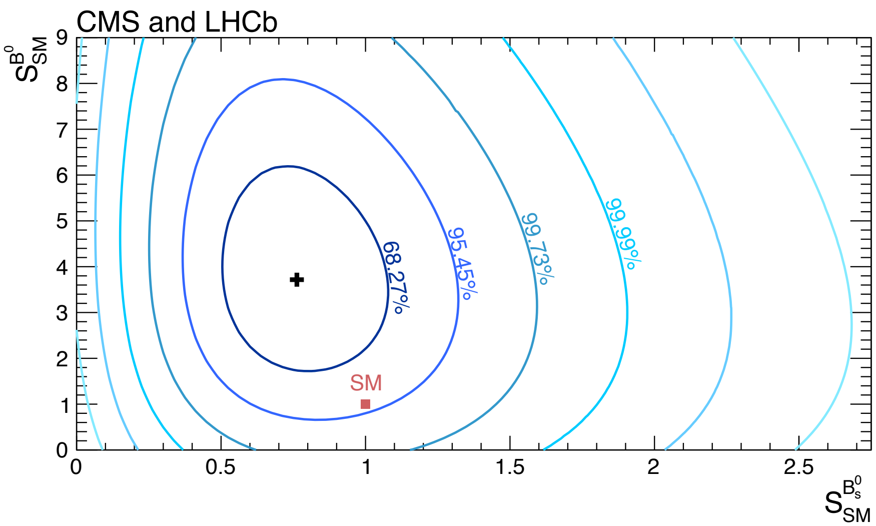
Don’t give up: we still have a chance to see New Physics in CKM with x50 more data from Belle II and upgraded LHCb

$\mathrm{B_s^0} \to \mu^+\mu^-$

- $B_s^0 \to \mu^+\mu^-$:
  $\mathcal{B} = 2.8^{+0.7}_{-0.6} \times 10^{-9}$
  6.2σ from Wilk's theorem
- $B^0 \to \mu^+\mu^-$:
  $\mathcal{B} = 3.9^{+1.6}_{-1.4} \times 10^{-10}$
  3.2σ from Wilk's theorem
  3.0σ from Feldman-Cousins
- $B_s^0 \to \mu^+\mu^- / B^0 \to \mu^+\mu^-$
  $\mathcal{R} = 0.14^{+0.08}_{-0.06}$
- Compatible with SM at 2.3σ
- SM prediction
  $\mathcal{B}(B_s^0) = 3.66 \pm 0.23 \times 10^{-9}$
  $\mathcal{B}(B^0) = 1.06 \pm 0.09 \times 10^{-10}$

$$S_{SM} = \frac{\text{Experiment}}{\text{Theory}}$$

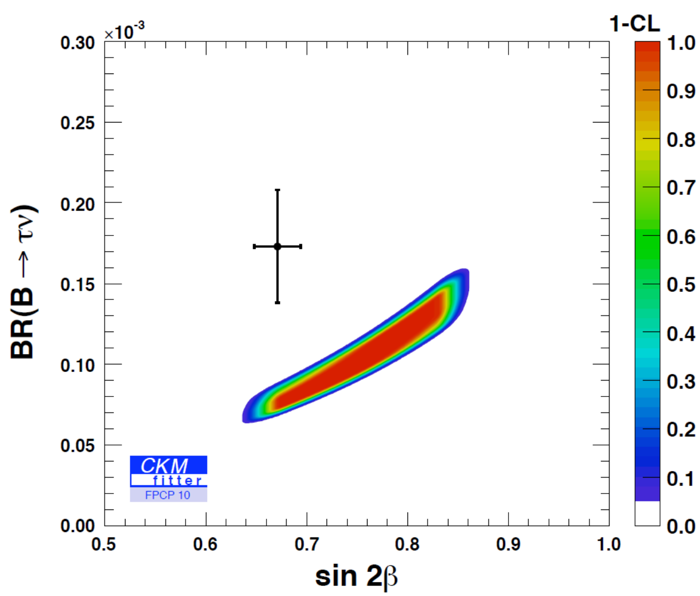


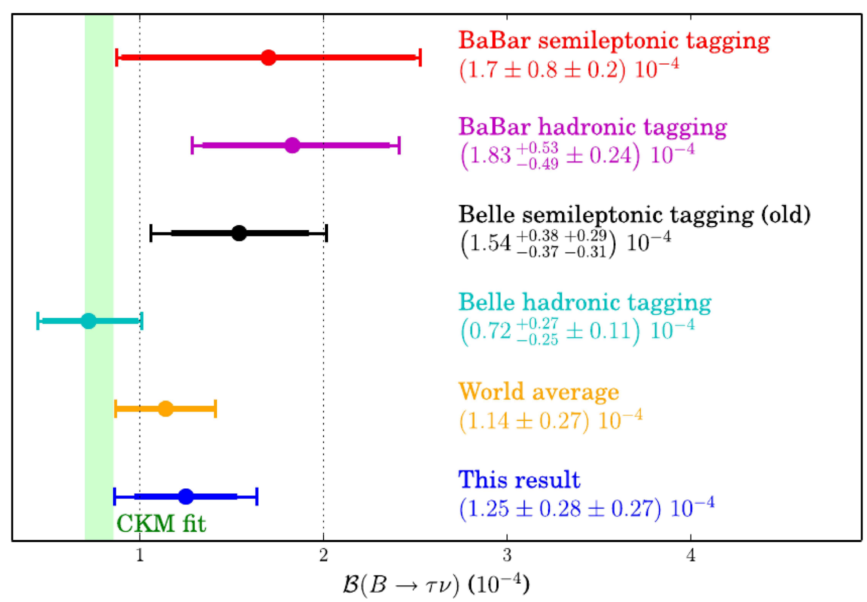


Fast, Kreps

$\mathrm{B}^+ \to \tau^+\nu_\tau$

- For long time, tension between V_{ub}, $\sin 2\beta$ and $B^+ \to \tau^+\nu_\tau$ BF
- Tension decreased after Belle updated analysis with fully reconstructed tag
- Now update with semileptonic tag (with lot of improvements to analysis)
- $\mathcal{B}(B^+ \to \tau^+\nu_\tau) = 1.25 \pm 0.28 \pm 0.27 \times 10^{-4}$

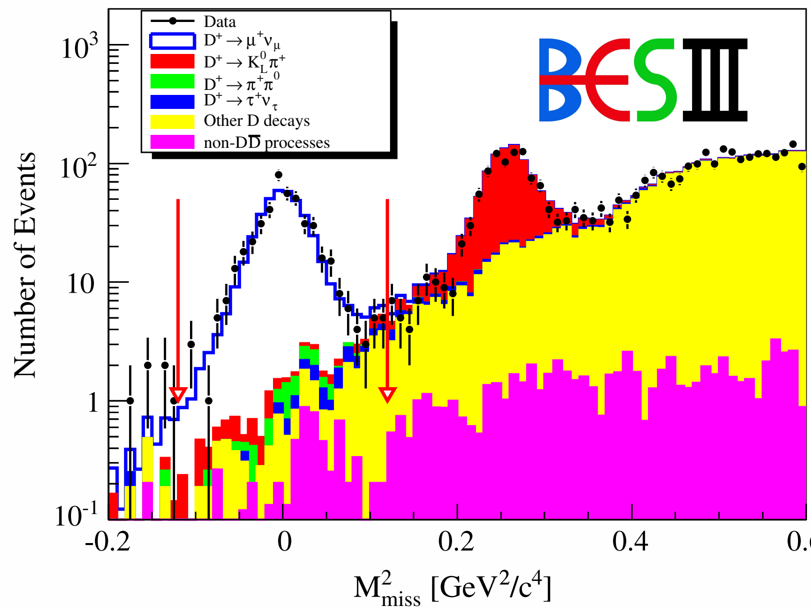




Muramatsu

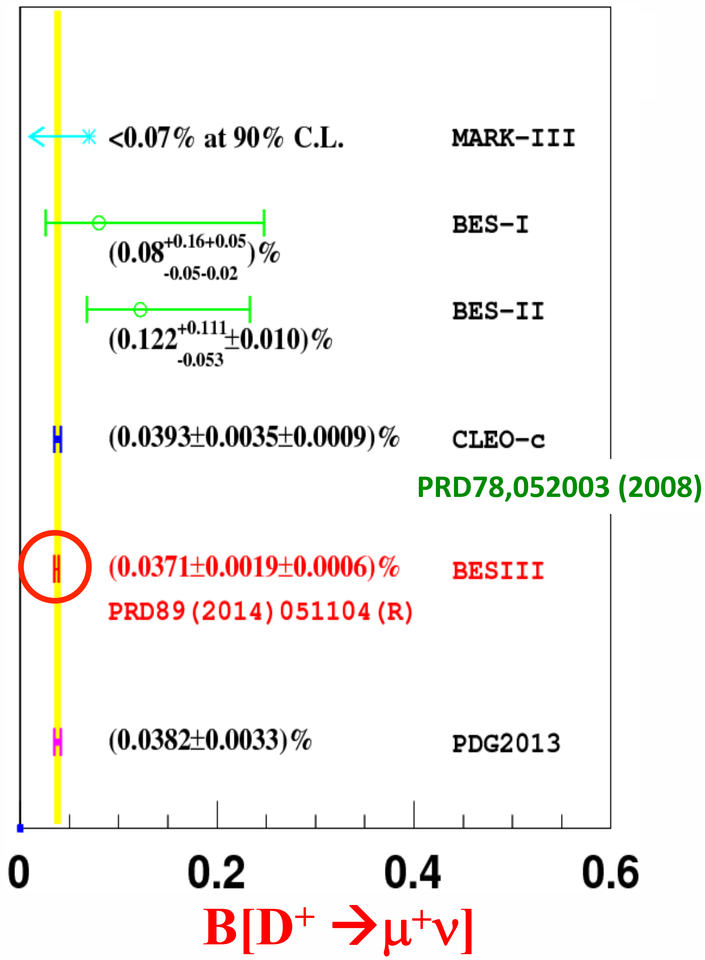
$D^+ \to \mu^+ \nu_\mu$

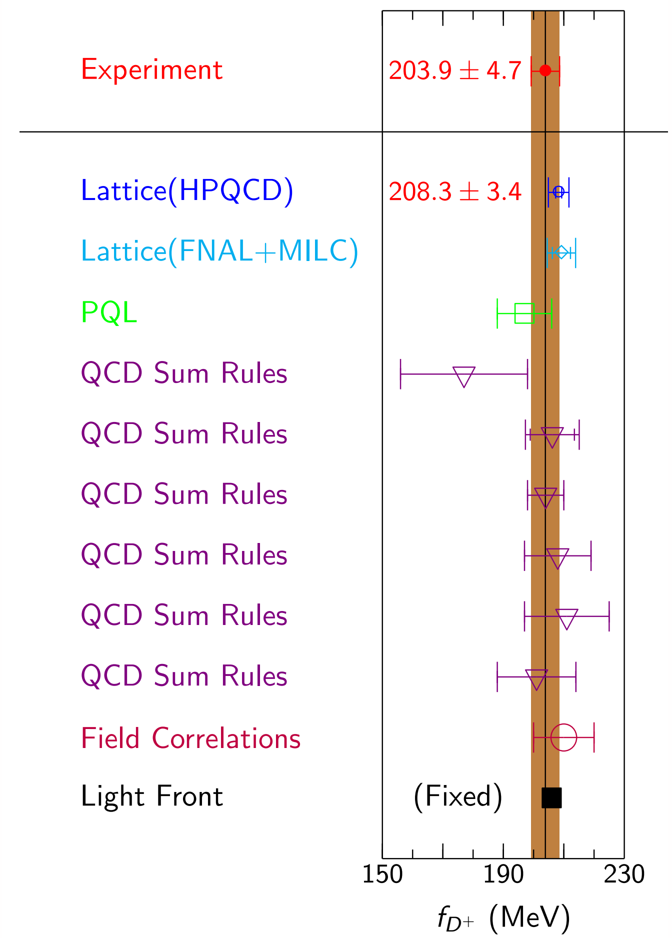
- BESIII (PRD89, 051104(R) (2014)) : 2.9 fb^{-1} at E_{cm} = 3.773 GeV.
- Measured $B(D^+ \to \mu^+ \nu_\mu) = (3.71 \pm 0.19 \pm 0.06) \times 10^{-4}$
  The most precise measurement to date.
  - With $|V_{cd}|$ of CKM-fitter input, $f_{D+} = (203.2 \pm 5.3 \pm 1.8)$ MeV
  - With f_{D+} of LQCD input (PRL100, 062002 (2008))
    $|V_{cd}| = 0.2210 \pm 0.0058 \pm 0.0047$.
- Statistically limited.
  More data would be welcome.
- BESIII plans to take
  ~10 fb^{-1} in the future!



Muramatsu

Comparison of $B(D^+ \to \mu^+ \nu_\mu)$ and f_{D+}



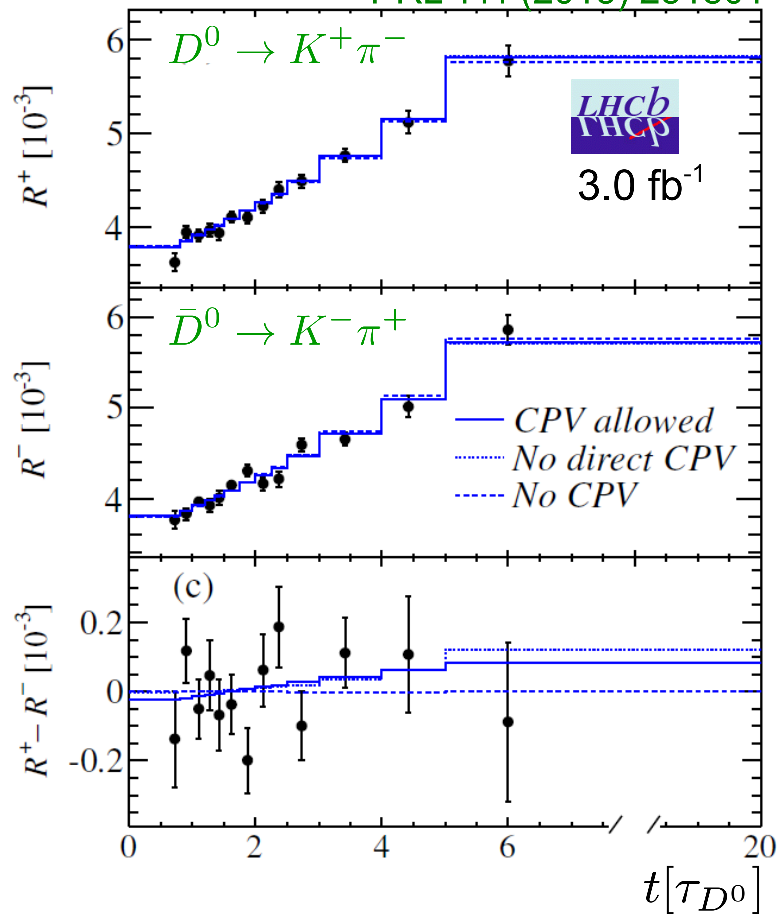


Good consistencies are seen among the previous experimental results.

LHCb - CPV in WS $D^0 \to K\pi$

A determination of mixing parameters for D^0 and $\bar{D}^0$ gives access to CPV

PRL 111 (2013) 251801



➢ Fit parameter

Direct and indirect CP violation		
R_D^+	$[10^{-3}]$	$3.545 \pm 0.082 \pm 0.048$
y'^+	$[10^{-3}]$	$5.1 \pm 1.2 \pm 0.7$
x'^{2+}	$[10^{-5}]$	$4.9 \pm 6.0 \pm 3.6$
R_D^-	$[10^{-3}]$	$3.591 \pm 0.081 \pm 0.048$
y'^-	$[10^{-3}]$	$4.5 \pm 1.2 \pm 0.7$
x'^{2-}	$[10^{-5}]$	$6.0 \pm 5.8 \pm 3.6$
χ^2/ndf		$85.9/98$

➢ CP violation parameters

- CPV in mixing

$$0.75 < |q/p| < 1.24 \quad @\, 68.3\,\%\, CL$$

- direct CPV of DCS component

$$A_D = \frac{R^+ - R^-}{R^+ + R^-} = (-0.7 \pm 1.9)\%$$

No indication for direct or indirect CPV

Kaon Golden Modes and NP

Branching ratios theoretical prediction are good to 2-4% (excluding parametric uncertainty)

$BR(K^{+} \to \pi^{+} \nu\bar{\nu}) = (7.81 \pm 0.75 \pm 0.29) \times 10^{-11}$

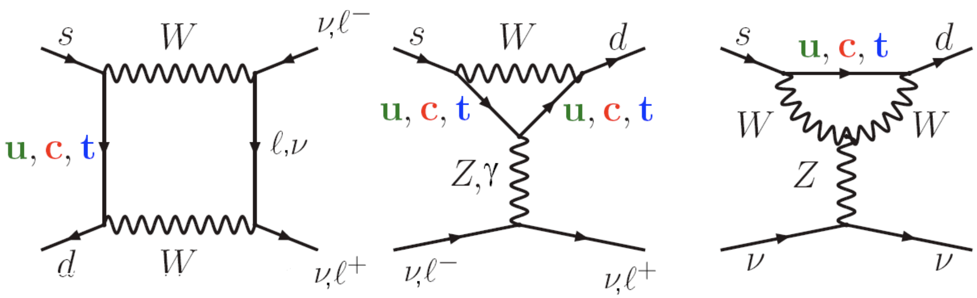
$BR(K_{L} \to \pi^{0} \nu\bar{\nu}) = (2.43 \pm 039 \pm 0.06) \times 10^{-11}$

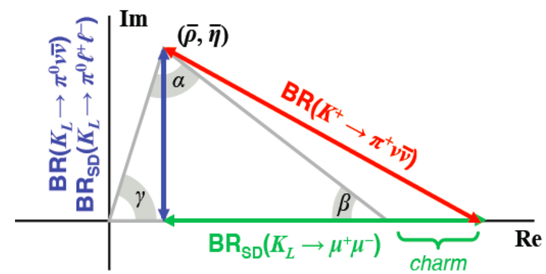
(Brod, Gorbhan, Stamou, PRD 83,0340030 (2011)

Direct measurements:

$BR(K^{+} \to \pi^{+} \nu\bar{\nu}) = (1.73{+}1.15{-}1.05) \times 10^{-10}$ (BNL E787/E949: PRL 101 (2008) 191802)

$BR(K_{L} \to \pi^{0} \nu\bar{\nu}) < 2.6 \times 10^{-8}$ (KEK E391a: PRD 81 (2010) 072004)





- KOTO achieved similar sensitivity as E391a in only 100 hours of data taking!

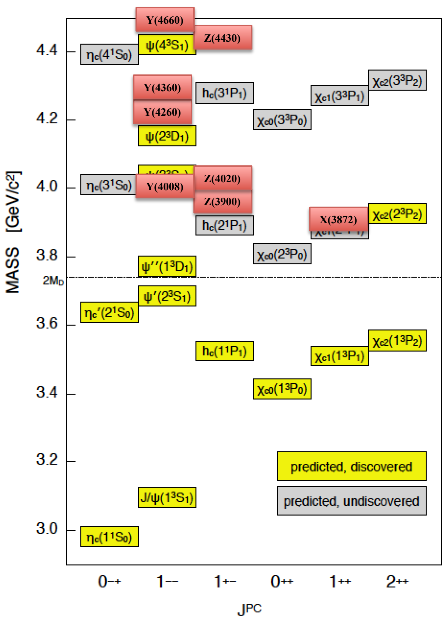
NA62

- Upcoming run (October-December 2014): commission detector with lower intensity beam. Likely reach SM sensitivity!

Bian

Exotic Heavy States

There are lots of XYZ states



A number of new states above open-charm threshold.

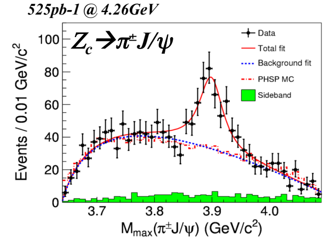
Charmonium in the final state, but not an obvious charmonium state (charmoniumlike or *XYZ*)

What are they?

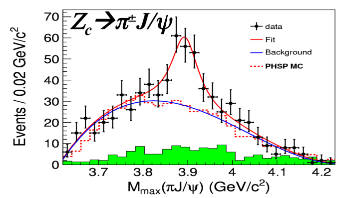
- Charmonium?
- Tetraquark?
- Molecule?
- Hybrid?
- Hadrocharmonium?
- …

Observation of $Z_c(3900)^{\pm}$ in $e^+e^- \rightarrow \pi^+\pi^- J/\psi$

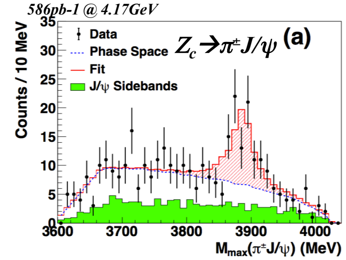
BESIII[PRL 110 252001 (2013)]
525pb-1 @ 4.26GeV



Belle PRL 110 252002 (2013)
967fb-1, in e+e-→γ_ISR π+π-J/ψ



CLEO-c data [PLB 727 366-370 (2013)]
586pb-1 @ 4.17GeV



- **$Z_c(3900)^{\pm}$: first confirmed charged charmonium-like states observed in $\pi^+\pi J/\psi$ by BESIII, Belle and confirmed in CLEO-c data (NWU group).**

BESIII
M = 3899.0±3.6±4.9 MeV
Γ= 46±10±20 MeV 307±4
events, >8σ

Belle
M = 3894.5±6.6±4.5 MeV
Γ=63±24±26 MeV
159 ± 49 events, >5.2σ

CLEO-c data
M = 3886±4±2 MeV
Γ= 37±4±8 MeV
81±16 events, >5σ

- **Couple to ccbar.**
- **Has electric charge.**
- **At least 4 quarks.**
- **Mass close to DD* threshold.**
- **Molecular state? Tetraquark? Hadrocharmonium? Threshold effect? …**

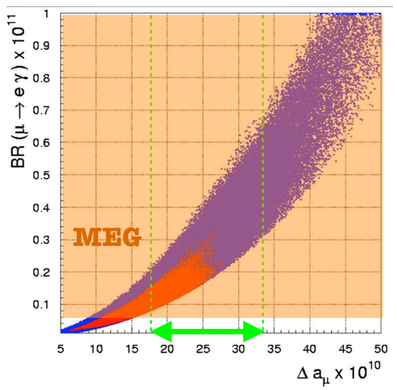
Lepton Flavor Violation in Charged Lepton and Neutrinos

MEG Result and MEG-II

Tecchio

- Using data up to 2011:
  $BR(\mu^+ \rightarrow e^+\gamma) < 5.7\times10^{-13}$ @90% C.L.
  J.Adam et al., PRL 110 (20), 201801

- Set constraints on NP models accommodating anomalous muon magnetic moment (G.Isidori, PRD 75, 115019 (2007))



- In 2012-2013 already collected more than twice the statistics (analysis in progress) but reaching MEG final sensitivity of 5×10^{-13}

- MEG-II upgrade with larger acceptance and better resolution for higher beam intensity promises to reach 5×10^{-14} in sensitivity.

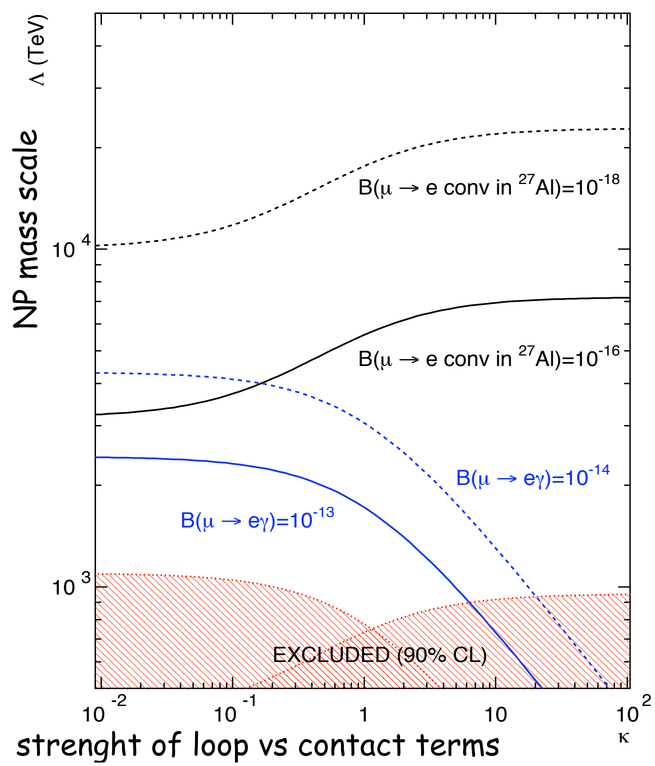
R.H. Bernstein, P.S. Cooper / Physics Reports 532 (2013) 27–64

$\mu^- + N \rightarrow e^- + N$

- Two experiments, Mu2e @ FNAL and COMET @ J-PARC, have been proposed for searching $\mu \rightarrow e$ conversion in presence of a nucleus (Al)

- Present limit from SINDRUM-II @ PSI: $BR(\mu^+ \rightarrow e^+\gamma) < 5.7\times10^{-13}$ @90% C.L.

Govea and Vogel, arXiv:1303.4097v2 [hep-ph], 2013

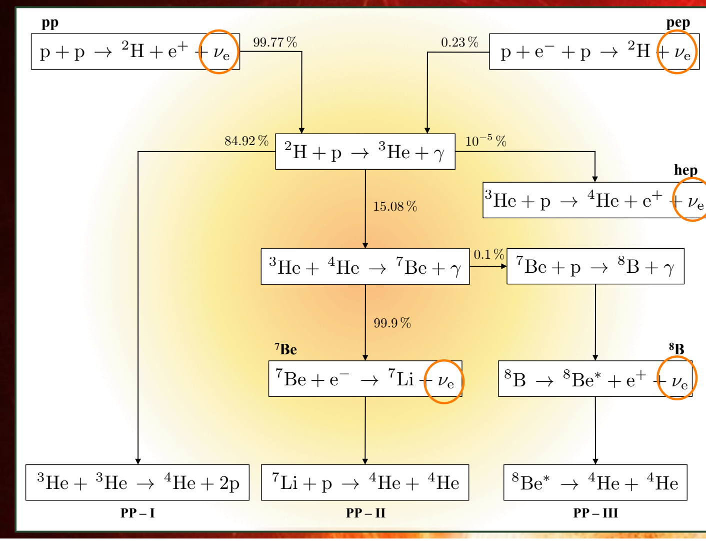


Re

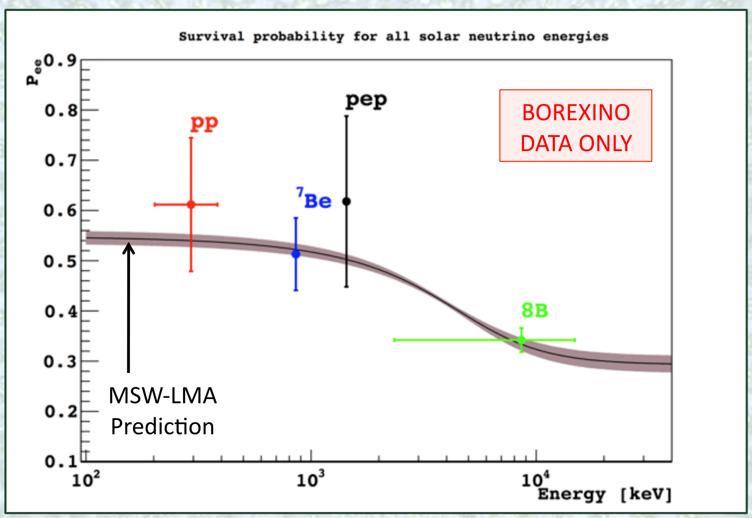
SOLAR NEUTRINOS: SUMMARY
SOLAR PHYSICS

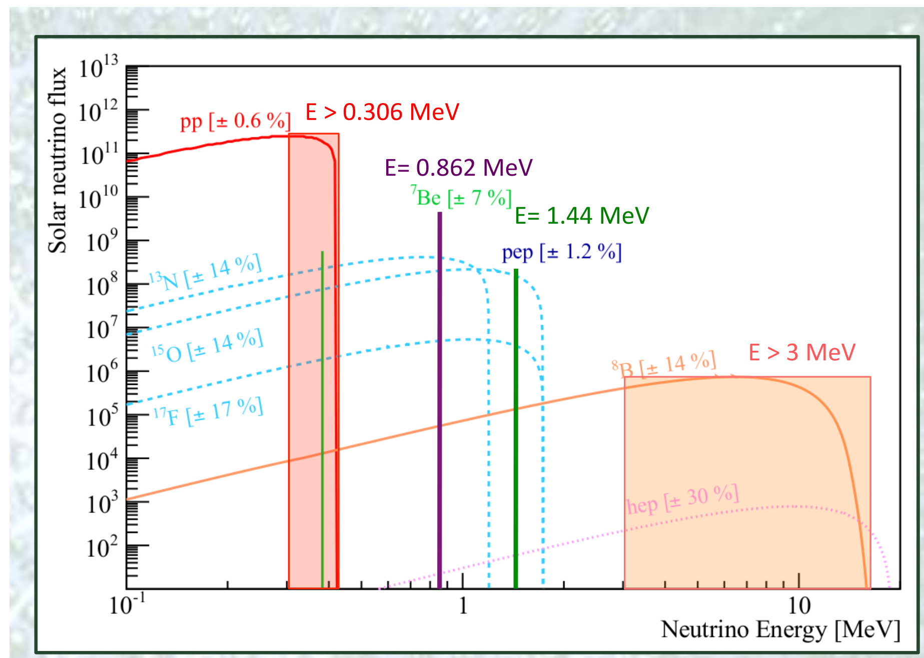
	pp	^{7}Be	pep	CNO	^{8}B
SuperK					± 1.4%, $E_\nu \geq 3.5$ MeV Ref. 1
SNO					± 3.8%, $E_\nu \geq 3.5$ MeV Ref. 2
Kamland		± 15% Ref. 8			± 15%, $E_\nu \geq 5.5$ MeV Ref. 3
Borexino	± 10.6% Ref. 7	± 5% Ref. 6	± 19% Ref. 5	UpperLim. Ref. 5	± 17%, $E_\nu \geq 3$ MeV Ref. 4

THE STANDARD SOLAR MODEL: THE PP CHAIN



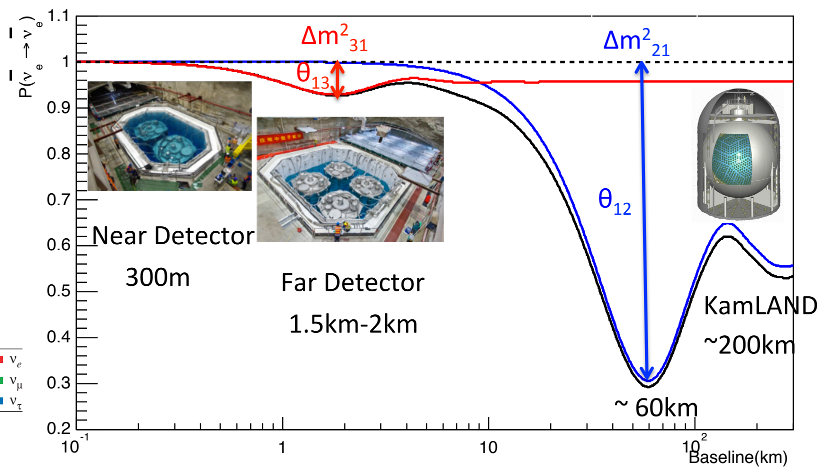
SOLAR NEUTRINOS: SUMMARY
OSCILLATIONS(2)

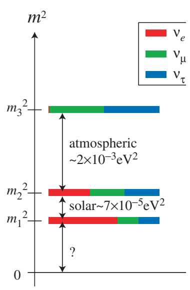




Ling

Reactor Neutrino Oscillation





$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \sin^2 \Delta_{31} + \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \Delta_{21}$$

Two different oscillation length scale:

- $\Delta m^2_{31} \approx 2.4 \times 10^{-3}$ eV²
- $\Delta m^2_{21} \approx 7.6 \times 10^{-5}$ eV²

$$\Delta_{ij} = \Delta m^2_{ij} \frac{L}{4E}$$

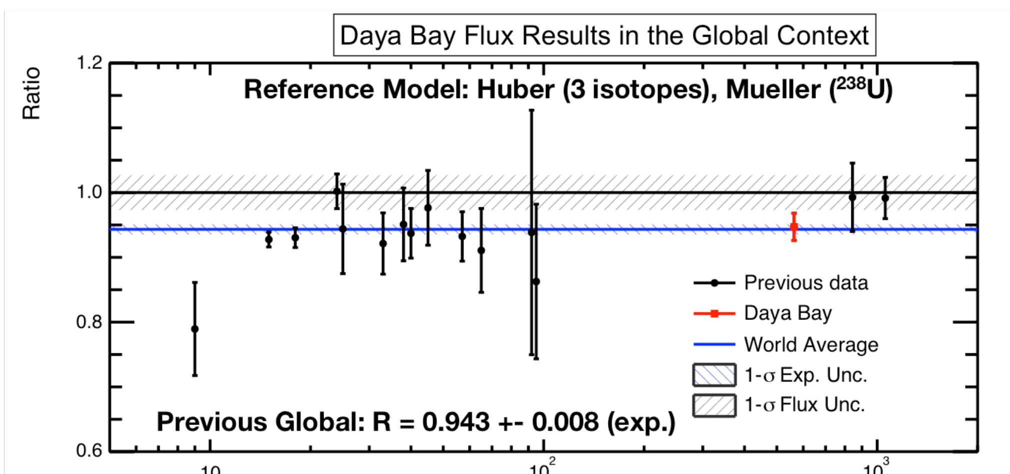
Largely Independent θ_{13} measurement

- Capture time: 30µs (nGd) -> 200µs(nH)
- Delayed E: 8MeV (nGd) -> 2.2 MeV (nH)
- More Energy leakage at boundary

Double Chooz (Rate+Spectra):
$\sin^2 2\theta_{13} = 0.097 \pm 0.034(\text{stat}) \pm 0.034\ (\text{syst})$
Phys. Lett. B723 (2013) 66-70

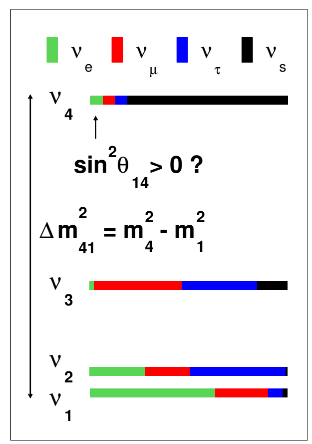
Daya Bay (Rate Only) :
$\sin^2 2\theta_{13} = 0.083 \pm 0.018$
arXiv: 1406.6468

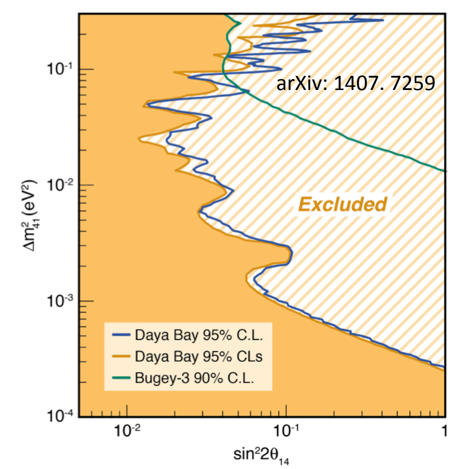
RENO (Rate Only) :
$\sin^2 2\theta_{13} = 0.095 \pm 0.015(\text{stat}) \pm 0.025\ (\text{syst})$
Neutrino 2014



Flux uncertainties

Light Sterile Neutrino Search





Long Base-line Neutrino Experiments

Marino

$$P(\nu_\mu \to \nu_\mu) \simeq 1 - \sin^2 2\theta_{23} \cdot \sin^2 (\Delta m^2_{32} L/4E)$$

$$P(\nu_\mu \to \nu_e) \simeq \sin^2 2\theta_{13} \cdot \frac{\sin^2 \theta_{23}}{(A-1)^2} \cdot \sin^2 ((A-1)\Delta m^2_{31} L/4E)$$

$$-\frac{|\Delta m^2_{21}|}{|\Delta m^2_{31}|} \frac{\sin\delta \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \cos\theta_{13}}{A(1-A)} \sin\Delta \sin(A\Delta) \sin((1-A)\Delta)$$

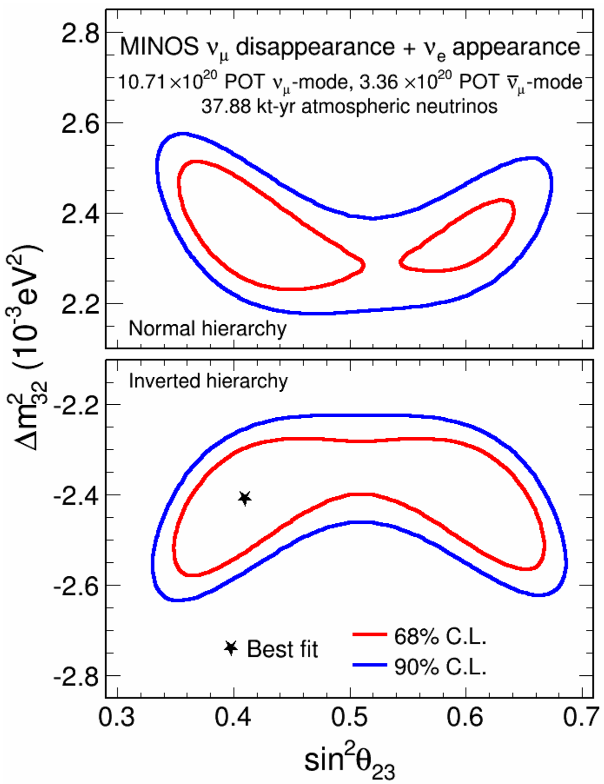
$$A = \sqrt{2} G_F N_e \frac{2E}{\Delta m^2_{31}}$$

hierarchy

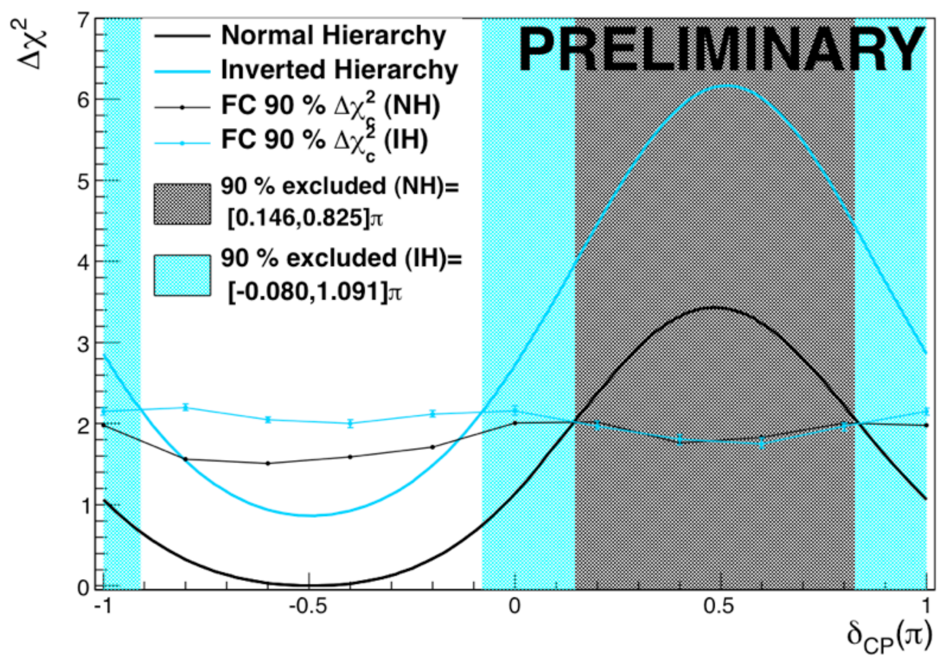
where $\Delta = \Delta m^2_{31} L/4E$

- Changes sign for anti-ν. So positive δ will decrease $P(\nu_\mu \to \nu_e)$ and increase $P(\bar\nu_\mu \to \bar\nu_e)$.

Phys Rev Lett **112** 191801 (2014)



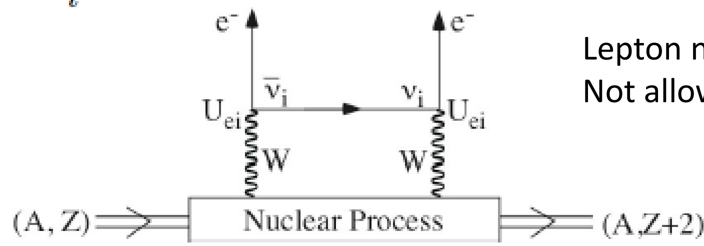
T2K Preliminary



Tornow

Neutrinoless (0νββ) Double-Beta Decay

Hypothetical ββ decay mode allowed if neutrinos are Majorana particles, i.e $\bar{\nu}_i \equiv \nu_i$



Lepton number violation
Not allowed in SM

Phase space factor

Nuclear matrix element

$$\frac{1}{T_{1/2}^{0\nu}} = G^{0\nu}|M^{0\nu}|^2|\langle m_{\beta\beta}\rangle|^2$$

Decay half-life

Effective Majorana neutrino mass: $m_{\beta\beta} \equiv \left|\sum_{i=1}^{3} U_{ei}^2 m_i\right|$

$M^{0\nu}$ is not known; estimates vary by factor of ~2 depending on method

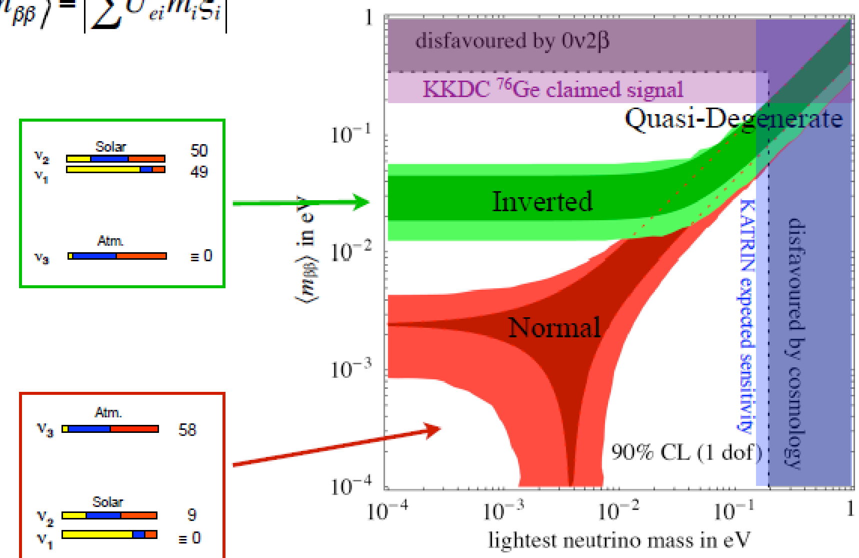
For $m_{\beta\beta}$ = 50 meV estimated half lives 10^{25} - 10^{27} years ! depending on the nuclear system

T.O'Donnell

$0\nu\beta\beta$ Decay Sensitivity to $\langle m_{\beta\beta} \rangle$

$$\langle m_{\beta\beta} \rangle = \left| \sum U_{ei}^2 m_i \xi_i \right|$$

$0\nu\beta\beta$ limits for: ^{48}Ca, ^{76}Ge, ^{82}Se, ^{100}Mo, ^{116}Cd, ^{128}Te, ^{130}Te, ^{136}Xe, ^{150}Nd



F. Feruglio *et al.*, hep-ph/020191 (2002). J.F. Wilkerson

Half-Life Limits

EXO: $T_{1/2} > 1.1 \times 10^{25}$ yr (90% CL) ^{136}Xe WIPP
Nature, **510**, 229 (2014)

KamLAND-Zen: $T_{1/2} > 3.1 \times 10^{25}$ yr (90%CL) ^{136}Xe Kamioka
very preliminary

GERDA: $T_{1/2} > 2.1 \times 10^{25}$yr (90% CL) ^{76}Ge LNGS
PRL, **111**, 122 (2013)

GERDA combined with HDM and IGEX: $T_{1/2} > 3.0 \times 10^{25}$ yr

H.V. Klapdor-Kleingrothaus *et al.*, Eur. Phys. J. A **12**, 147 (2001)

C.E. Aalseth *et al.*, Phys. Rev. D **65**, 092007 (2002)

H.V. Klapdor-Kleinkrothaus *et al*. $T_{1/2} = 1.19 \times 10^{25}$ yr Phys. Lett. B **586**, 198 (2004)

Look into the Future

KamLAND-Zen

CUORE

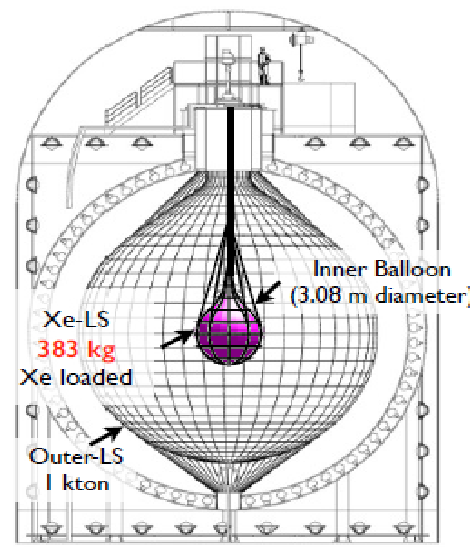
SuperNEMO

NEXT

SNO+

1-tonne ^{76}Ge Experiment

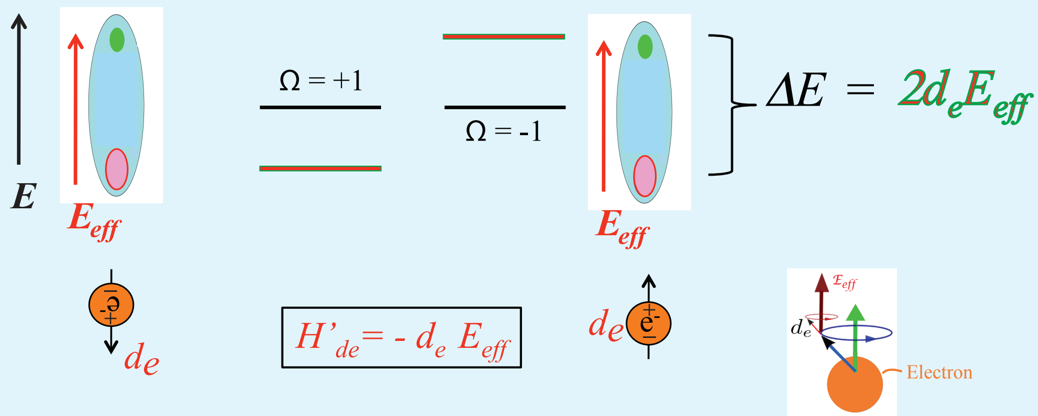
KamLAND-Zen Phase 2

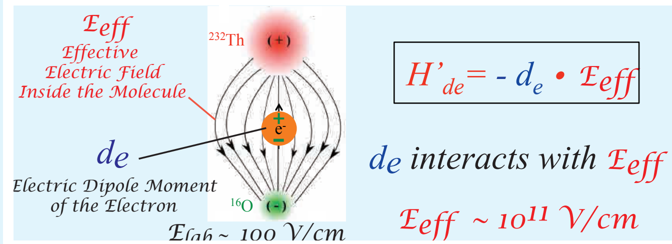


Doyle

Electron Electric Dipole Moment

Add the eEDM - Levels Shift, Electron Spin Precesses





$$P_- \equiv \phi_{E,B} = (2g\mu_b B + 2d_e E_{eff} + \ldots)\tau/\hbar \;-\; \phi_{-E,B} = (2g\mu_b B - 2d_e E_{eff} + \ldots)\tau/\hbar = (4d_e E_{eff} + \ldots)\tau/\hbar$$

ACME — Advanced Cold Molecule Electron EDM — Harvard University — Yale University

$$d_e = (-2.1 \pm 3.7_{\text{stat}} \pm 2.5_{\text{syst}}) \times 10^{-29}\, e{\cdot}\text{cm}$$

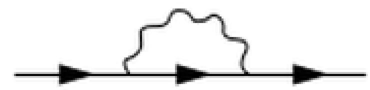
using Eeff = 84 GV/cm, calculated by Skripnikov, Petrov and Titov JCP (2013) and Meyer and Bohn PRA (2008)

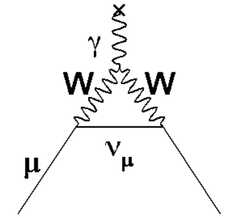
Tensions in the SM Description ?

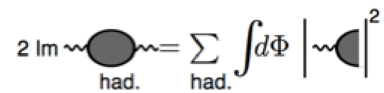
Casey

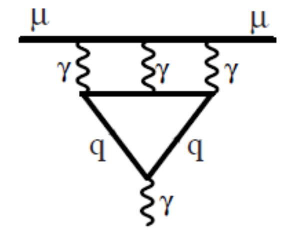
Muon Anomalous magnetic Moment

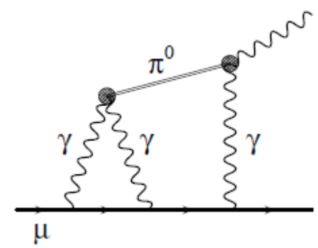
$$i\hbar\frac{\partial\psi}{\partial t} = [\frac{p^2}{2m} - \frac{e}{2m}(\vec{L}+2\vec{S})\cdot\vec{B}]\psi$$



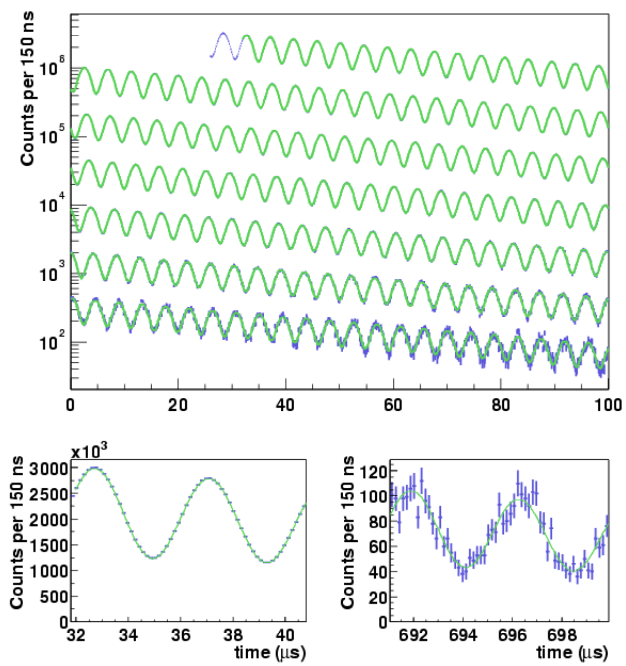








Brookhaven result



$$\frac{(g-2)}{2}(BNL) = 0.00116592089(63)$$

0.54 ppm uncertainty

$$\frac{(g-2)}{2}(SM) = 0.00116591802(49)$$

0.42 ppm uncertainty

$$diff = (287 \pm 80)\quad 10^{-11}$$

2.5 ppm difference

Big effect, needs confirmation

New Experiments at FNAL and JPARC

Proton Radius

The cross section:

$$\frac{\left(\frac{d\sigma}{d\Omega}\right)}{\left(\frac{d\sigma}{d\Omega}\right)_{Mott}} = \frac{1}{\varepsilon\,(1+\tau)}\left[\varepsilon G_E^2\left(Q^2\right) + \tau G_M^2\left(Q^2\right)\right]$$

with:

$$\tau = \frac{Q^2}{4m_p^2}, \quad \varepsilon = \left(1 + 2\,(1+\tau)\tan^2\frac{\theta_e}{2}\right)^{-1}$$

Fourier-transform of $G_E,\ G_M \longrightarrow$ spatial distribution (Breit frame)

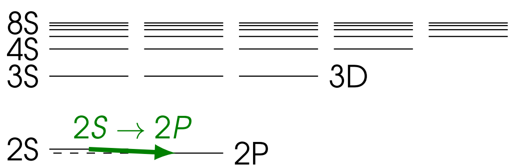
$$\left\langle r_E^2 \right\rangle = -6\hbar^2 \left.\frac{\mathrm{d}G_E}{\mathrm{d}Q^2}\right|_{Q^2=0} \qquad \left\langle r_M^2 \right\rangle = -6\hbar^2 \left.\frac{\mathrm{d}\left(G_M/\mu_p\right)}{\mathrm{d}Q^2}\right|_{Q^2=0}$$

Final result from flexible models

$$\left\langle r_E^2 \right\rangle^{\frac{1}{2}} = 0.879 \pm 0.005_{\mathrm{stat.}} \pm 0.004_{\mathrm{syst.}} \pm 0.002_{\mathrm{model}} \pm 0.004_{\mathrm{group}}\ \mathrm{fm},$$

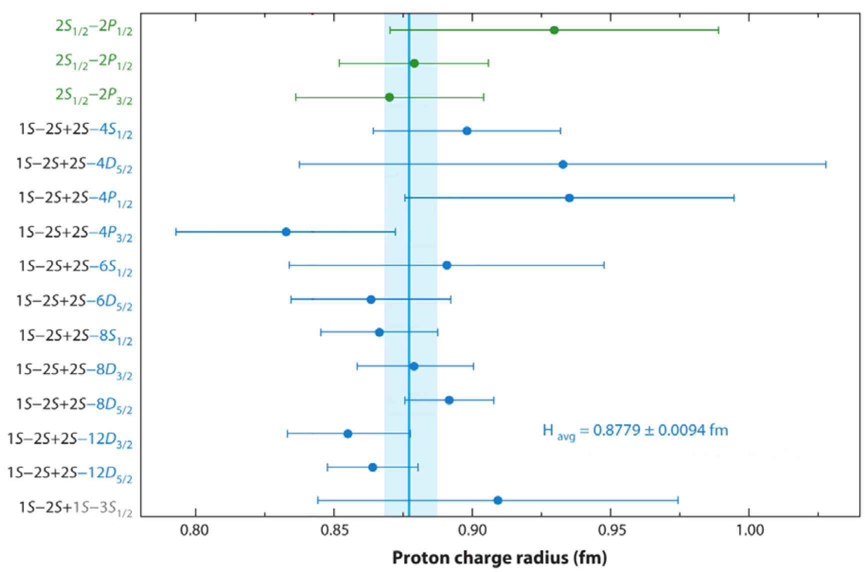
$$\left\langle r_M^2 \right\rangle^{\frac{1}{2}} = 0.777 \pm 0.013_{\mathrm{stat.}} \pm 0.009_{\mathrm{syst.}} \pm 0.005_{\mathrm{model}} \pm 0.002_{\mathrm{group}}\ \mathrm{fm}.$$

"Normal" Hydrogen Spectroscopy

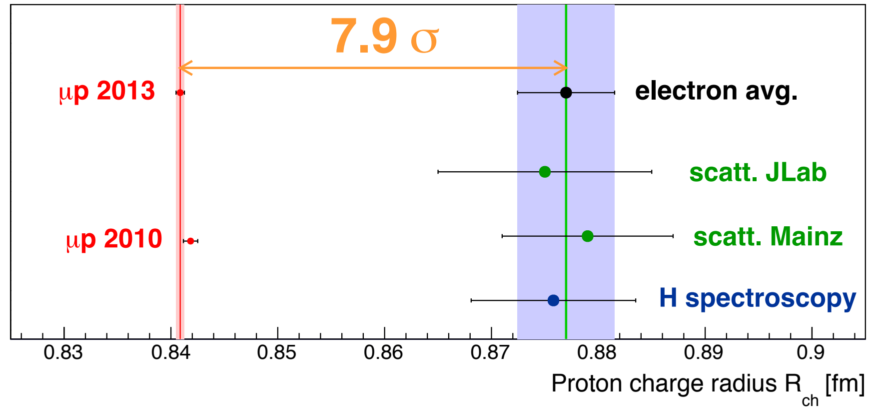


- $E_{nS} \approx -\frac{R_\infty}{n^2} + \frac{L_{1S}}{n^3}$
- Two transitions for two unknowns:
  - Rydberg constant R_∞
  - 1S Lamb shift $\Longrightarrow$ radius
- Direct Lamb shift $2S \to 2P$

1S $L_{1S} = 8171.626(4) + 1.5645 \langle r_p^2 \rangle$ MHz



Muonic Hydrogen Spectroscopy Results



- μp experiment wrong?
  - internal consistency
  - 4 linewidths!
- ep experiments wrong
  - Scattering AND H-spectroscopy wrong
  - Scattering: Many extractions agree, some don't.
  - H-spectroscopy: most measurements from one group.
- Theory wrong?
  - Checked throughly.
  - But maybe framework is wrong?
- Everybody is right?
  - New physics!

Test of Fundamental Properties

Lorentz Symmetry Violation   Altschul

$$\mathcal{L} = \bar{\psi}\left(i\Gamma^{\mu}\partial_{\mu} - M\right)\psi$$

$$M = m + \not{a} - \not{b}\gamma_5 + \frac{1}{2}H^{\mu\nu}\sigma_{\mu\nu}$$

$$\Gamma^{\mu} = \gamma^{\mu} + c^{\nu\mu}\gamma_{\nu} - d^{\nu\mu}\gamma_{\nu}\gamma_5 + e^{\mu} + if^{\mu}\gamma_5 + \frac{1}{2}g^{\lambda\nu\mu}\sigma_{\lambda\nu}$$

Measurement Type	System	Coefficients	*log* Sensitivity	Source
oscillations	K (averaged)	*a* (d, s)	—20	E773 Kostelecký
	K (sidereal)	*a* (d, s)	—21	KTeV
	D (averaged)	*a* (u, c)	—16	FOCUS
	D (sidereal)	*a* (u, c)	—16	FOCUS
	B (averaged)	*a* (d, b)	—16	BaBar, BELLE, DELPHI, OPAL
	neutrinos	*a*, *b*, *c*, *d*	—19 to —26	SuperK Kostelecký, Mewes
birefringence	photon	k_{AF} (CPT odd)	—43	Carroll, Field, Jackiw
		k_F (CPT even)	—32 to —37	Kostelecký, Mewes
resonant cavity	photon	k_F (CPT even)	—17	Muller et al.
anomaly frequency	e-/e+	*b* (e)	—23	Dehmelt et al.
	e- (sidereal)	*b*, *c*, d (e)	—23	Mittleman et al.
	mu/anti-mu	*b* (mu)	—22	Bluhm, Kostelecký, Lane
cyclotron frequency	H-/anti-p	*c* (e, p)	—26	Gabrielse et al.
hyperfine structure	H (sidereal)	*b*, *d* (e, p)	—27	Walsworth et al.
	muonium (sid.)	*b*, *d* (mu)	—23	Hughes et al.
clock comparison	various	*b*, *c*, *d* (e, p, n)	—22 to —30	Kostelecký, Lane
	He-Xe	*b*, *d* (n)	—32	Bear et al. Cane et al.
torsion pend.	spin-polarized solid	*b*, *d* (e)	—29	Heckel et al. Hou et al.
gamma-ray astronomy	e- /photons	*c*, *d* (e)	—15 to —20	Altschul

Mass Diff. $K^0 - \bar{K}^0$

$$\delta_K \propto \gamma \frac{v_{\mu}\left(a_q^{\mu} - a_{q'}^{\mu}\right)}{m_{K_L} - m_{K_S}}$$

[Kostelecký, PRL **80**, 1818 (1998)]

Synchrotron Emission Bounds

Neglecting higher order corrections, the maximum electron velocity in a direction $\hat{e}$ is:

$$v < 1 - c_{jk}\hat{e}_j\hat{e}_k - c_{0j}\hat{e}_j$$

New States of Matter

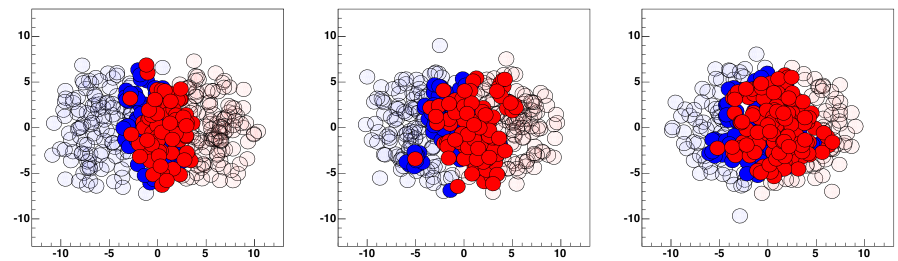
Heavy Ion Collisions

Sickles

Heavy Ion Collisions

each event is unique

nucleon distributions for 3 single collisions (xy-plane)

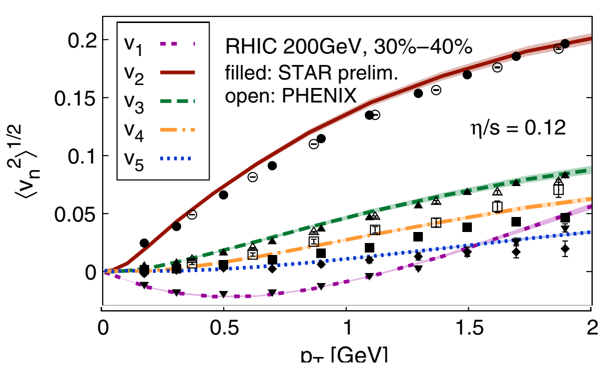


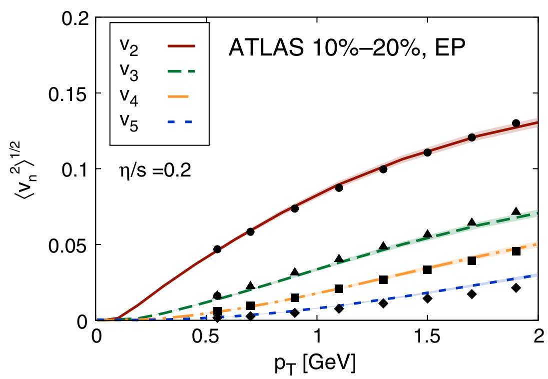
not just v_2 describing cos2Φ, but v_n:

$$\frac{dN}{d\phi} \propto 1 + \sum^{n} 2v_n \cos n\,(\phi - \Psi_n)$$

state of the art hydrodynamic calculations

- large v_2 → viscosity is small





RHIC: η/s = 1.5 / 4π   LHC: η/s = 2.5 / 4π

II.2 – pp, pA, AA : defining some notions…

1. - p_T spectra : $\frac{1}{N_{evt}} \frac{d^2N}{dp_T\, dy} = f(p_T)$

2. - Yields : $1/N_{evt}\ dN/dy$

} To be measured in pp, pA, AA

3. - $R_{AA}(p_T) = \frac{(1/N_{evt}^{AA})\ d^2N^{AA}/dp_T\,dy}{\langle N_{coll}\rangle\ (1/N_{evt}^{pp})\ d^2N^{pp}/dp_T\,dy}$

} "1 x (Pb–Pb) ≠ n x (pp) ?" …

Notes :

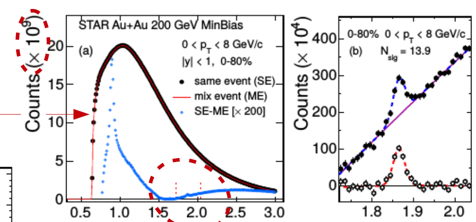
→ $R_{AA} = 1$, nothing special in AA ..
e.g. direct photons, $W^{\pm}$, Z^0

→ $R_{AA} > 1$, enhancement in the AA system
e.g. strange baryons Λ, Ξ, Ω at low momenta (p_T < 3 GeV/*c*)

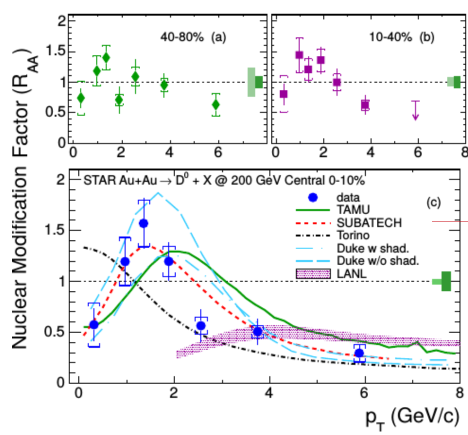
→ $R_{AA} < 1$, suppression in the AA system
e.g. $h^{\pm}$, π, K, p, Λ, D, J/ψ at mid/high p_T (p_T > 3-5 GeV/*c*)

III.A.1 – Open charm : incl. $D^0+\overline{D}^0$, from 0 p_T, by STAR

D^0(1.865 GeV/c²) → $K^- \pi^+$
|y| < 1
0 < p_T < 6 GeV/c
2010, 2011 pp, Au-Au $\sqrt{s_{NN}}$ = 200 GeV
no Silicon tracker, just TPC and TOF…



STAR, http://arxiv.org/abs/1404.6185

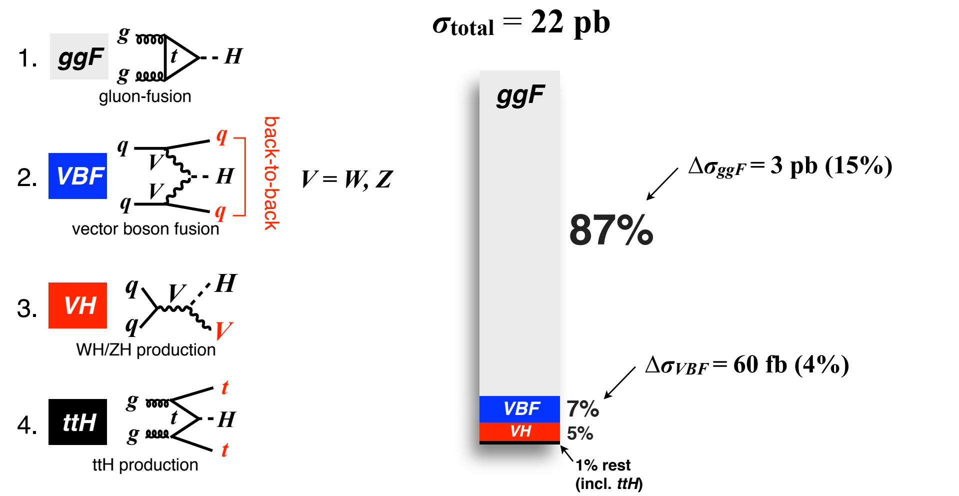


- Suppression for $p_T(D^0)$ > 2.5 GeV/c
- R_{AA} ≥ 1 for $p_T(D^0)$ ~ 1.5 GeV/c

Higgs Physics

Chang Higgs Boson

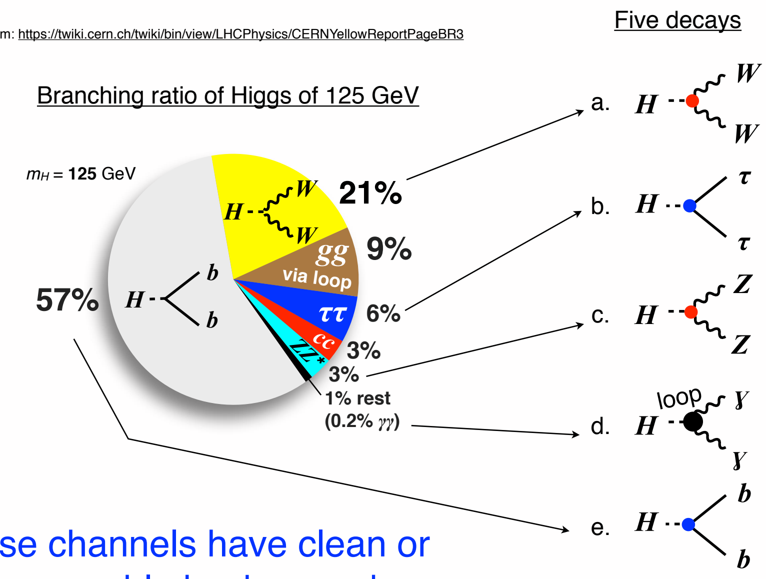
xsec values from: https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CERNYellowReportPageAt8TeV



These are extra handles for Higgs

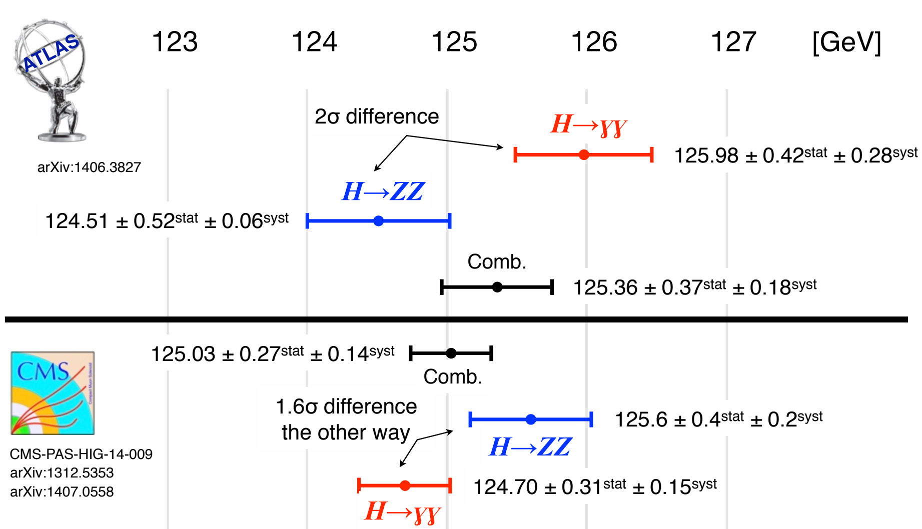
Relative production cross-section of 125 GeV Higgs at 8 TeV

BR values from: https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CERNYellowReportPageBR3



These channels have clean or manageable backgrounds

Mass measurement



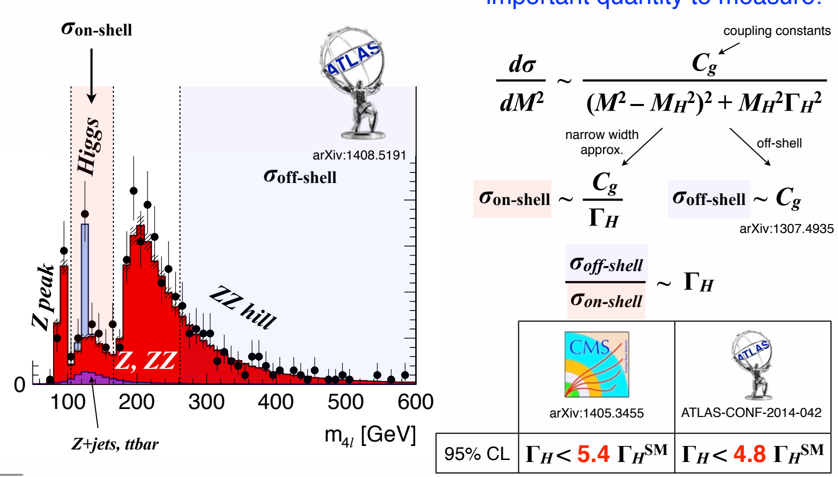
Some tension between measurements but overall in agreement around ~125 GeV

Disclaimer: data points generated by spreadsheet software for visualization purpose

Indirect Higgs width measurement

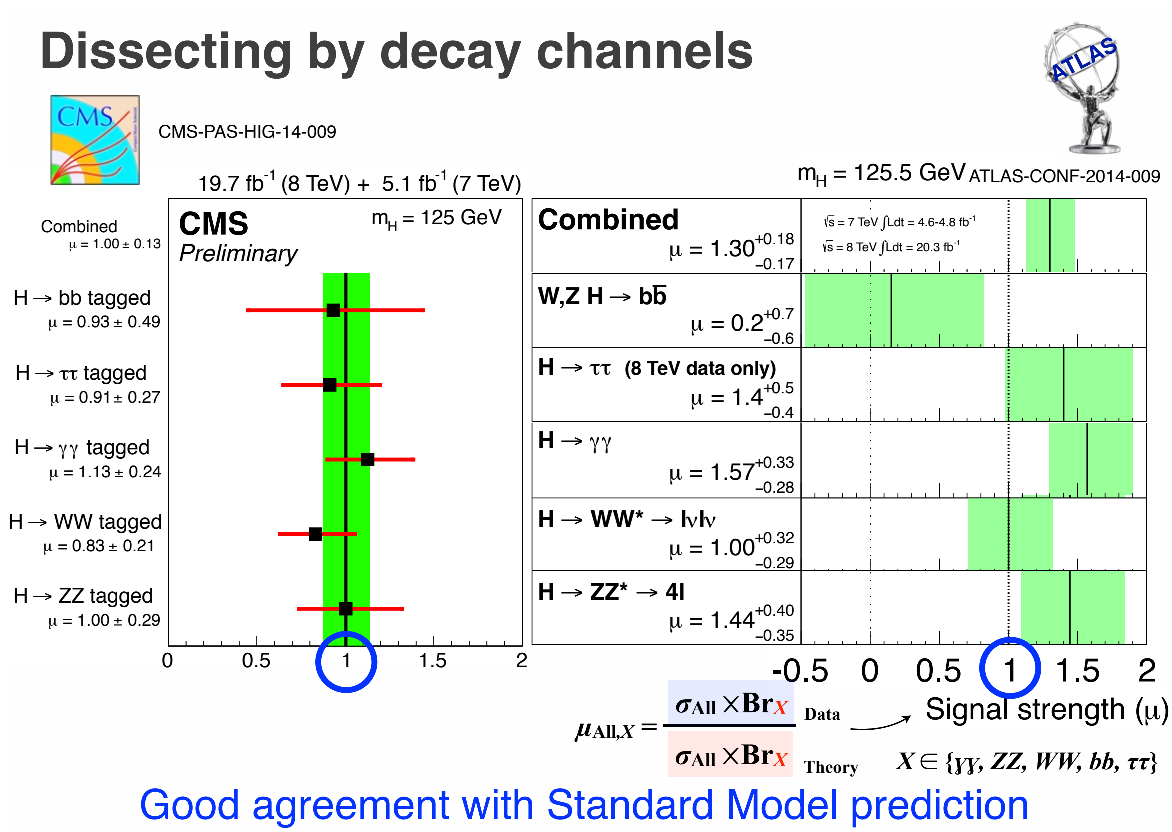
SM prediction: $\Gamma_H = 4.1$ MeV at $M_H = 125.5$ GeV

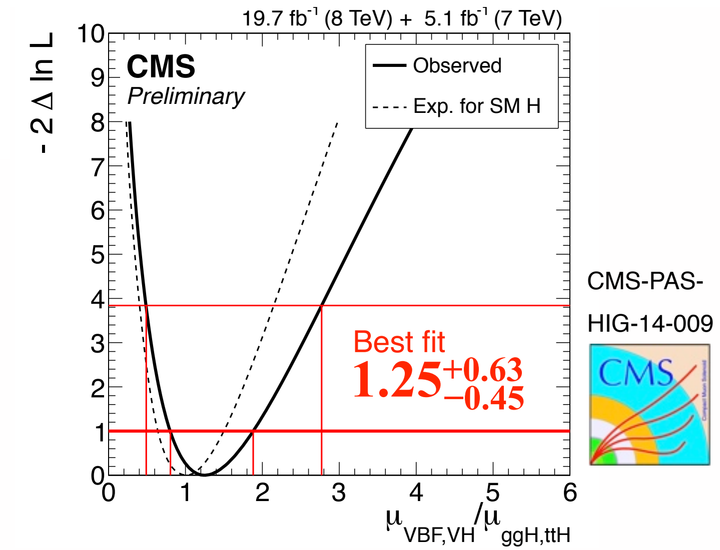
New physics can alter Γ_H hence important quantity to measure!

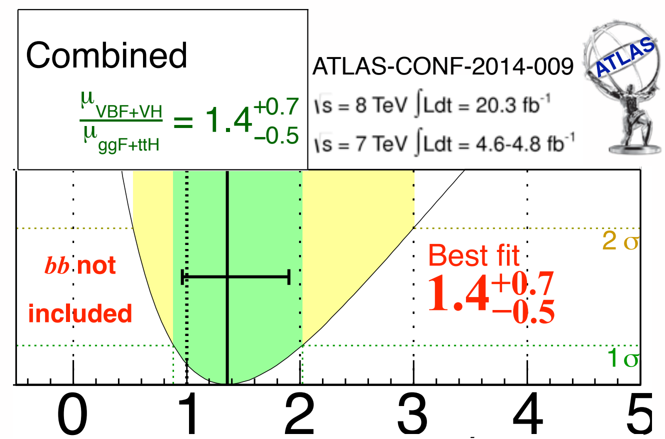


Chang

Production and Decay Channels





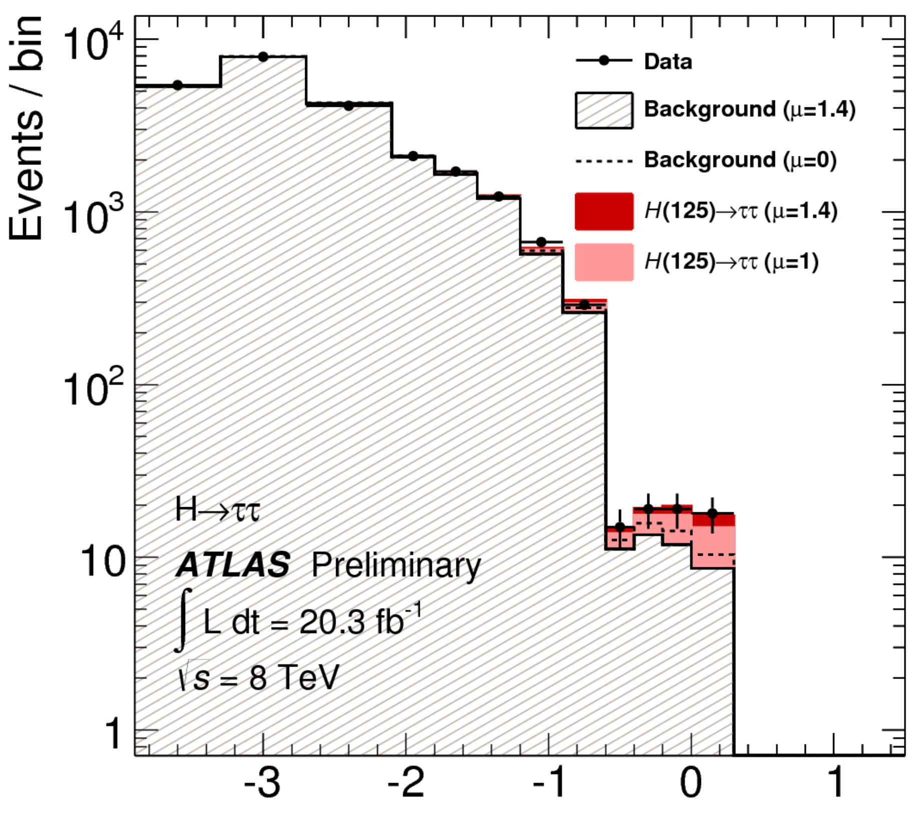


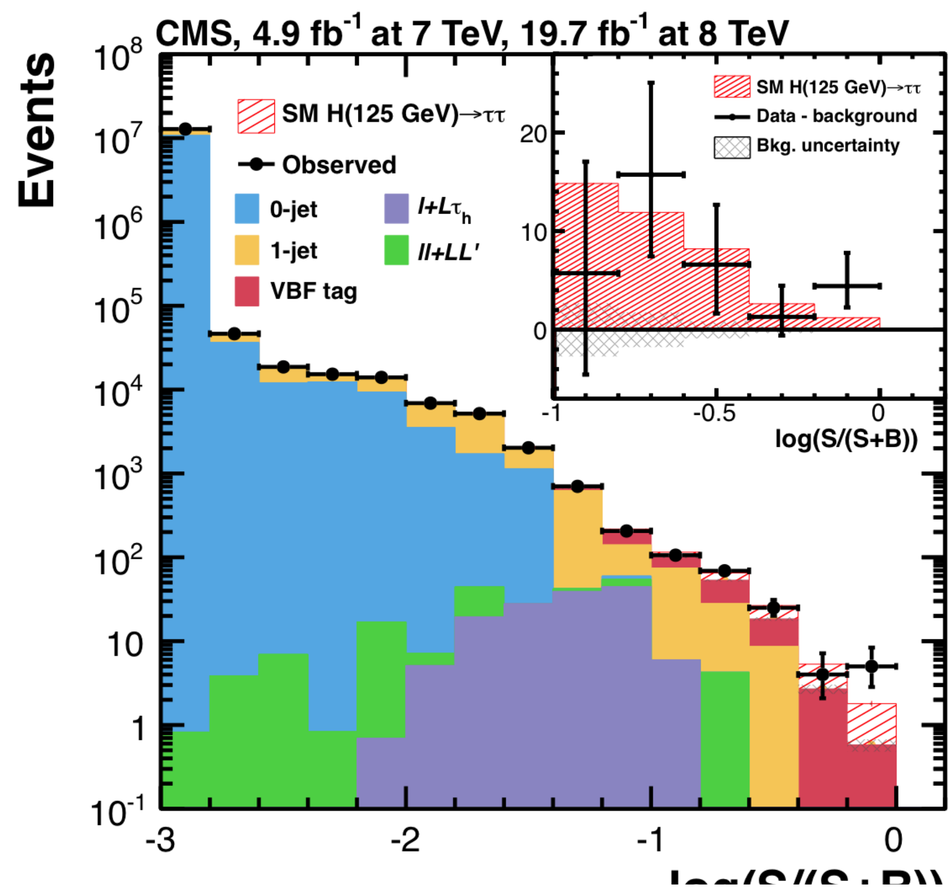
Fermionic Decay Channels

Pozdnyakov

H → ττ, S/B plots

- Event distributions in bins of signal to background ratio are shown





Are there New Particle/Forces at the Weak Scale ?

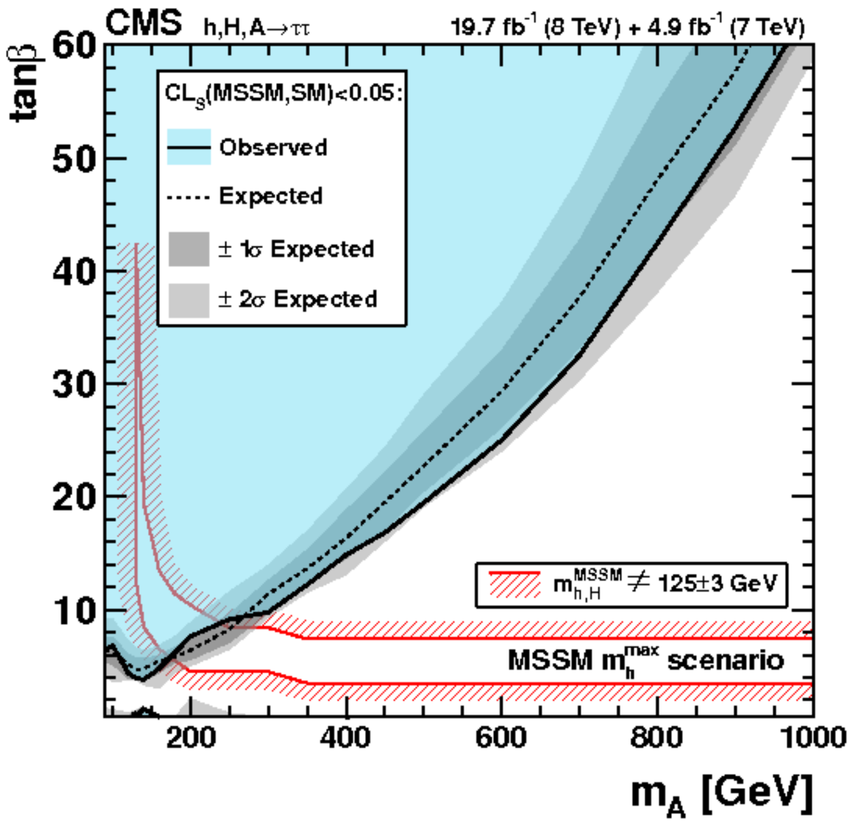
New Physics Searches

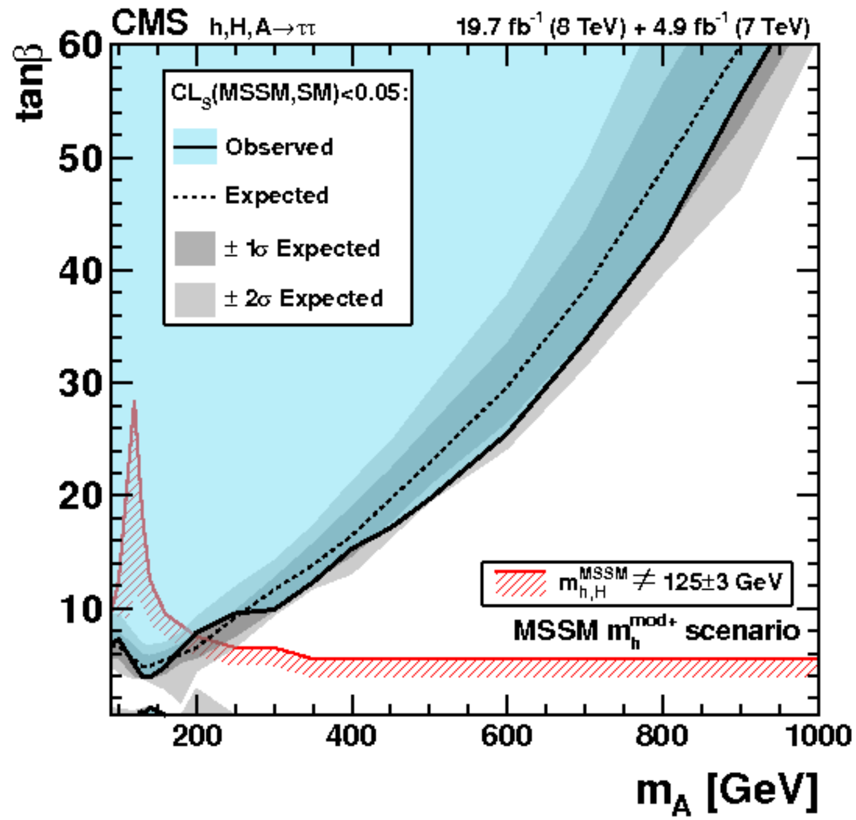
Lange

University of Zurich[UZH]
Physik-Institut

heavy neutral Higgs: $\phi \rightarrow \tau\tau$

Submitted to JHEP (arXiv:1408.3316)
ATLAS-CONF-2014-049





- interpretation in several scenarios taking Higgs @ 125 GeV into account

Lange

University of Zurich[UZH]

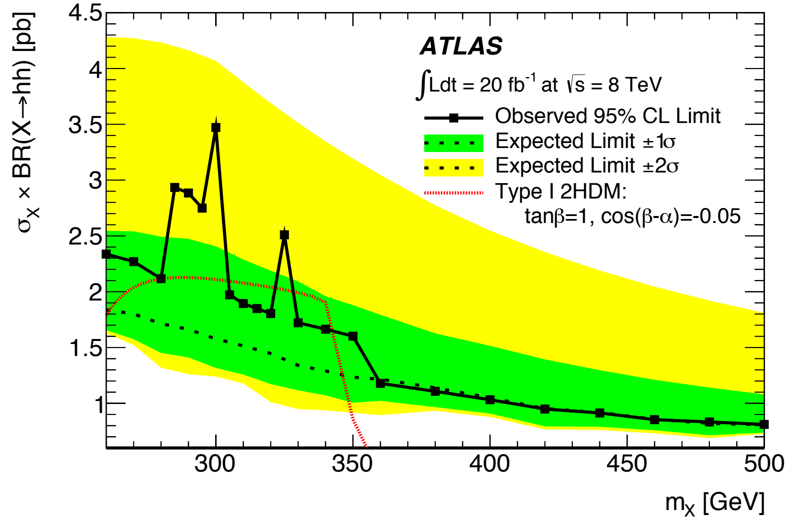
Physik-Institut

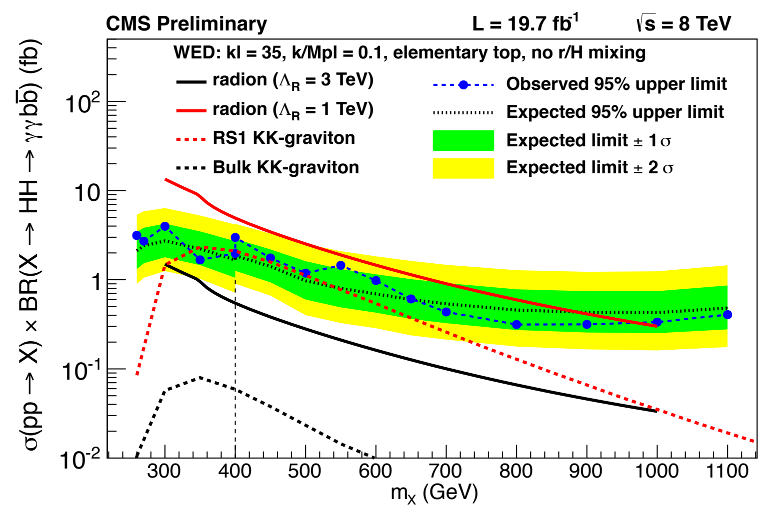
heavy H → hh → bbγγ

CMS-PAS-HIG-13-032

arXiv:1406.5053 (submitted to PRL)

- hh → bbγγ: selection similar to SM Higgs analyses
- mass constraint (CMS)/mass window (ATLAS) on bb candidate using known H(125) mass
  - suppress SM continuum
- ATLAS: search also for non-resonant hh production
  - observe 2.4σ excess compatible e.g. with a type I 2HDM
- resonant searches do not show deviation from SM expectations
  - ATLAS range up to 500 GeV
  - CMS 260-400 and 400-1100 GeV
  - exclude radions with m < 970 GeV
  - exclude RS1 KK-graviton from 340-400 GeV



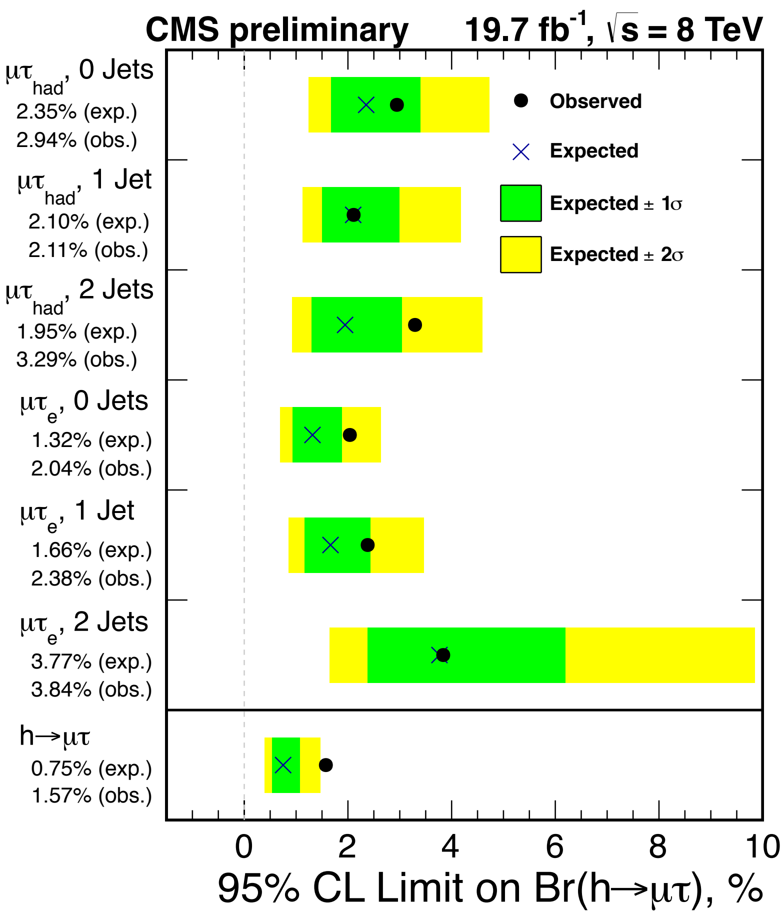


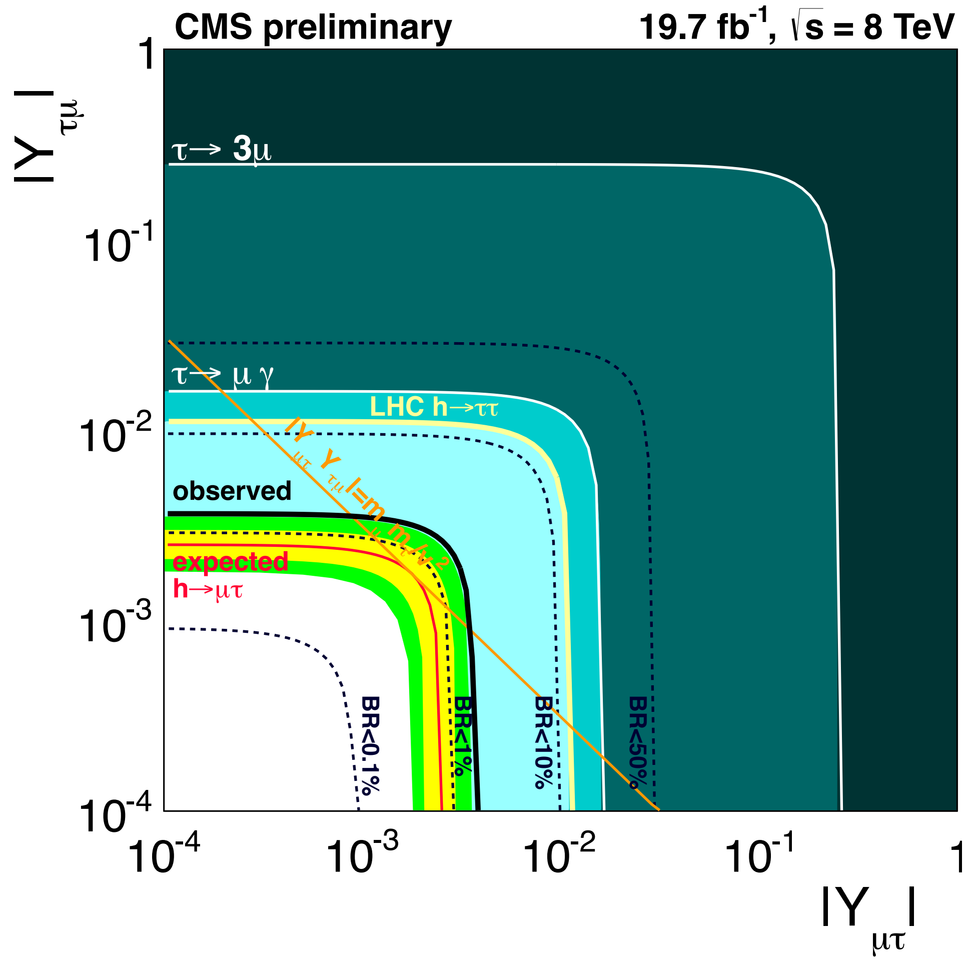
University of Zurich[UZH]

Physik-Institut

lepton flavour violating Higgs

CMS-PAS-H

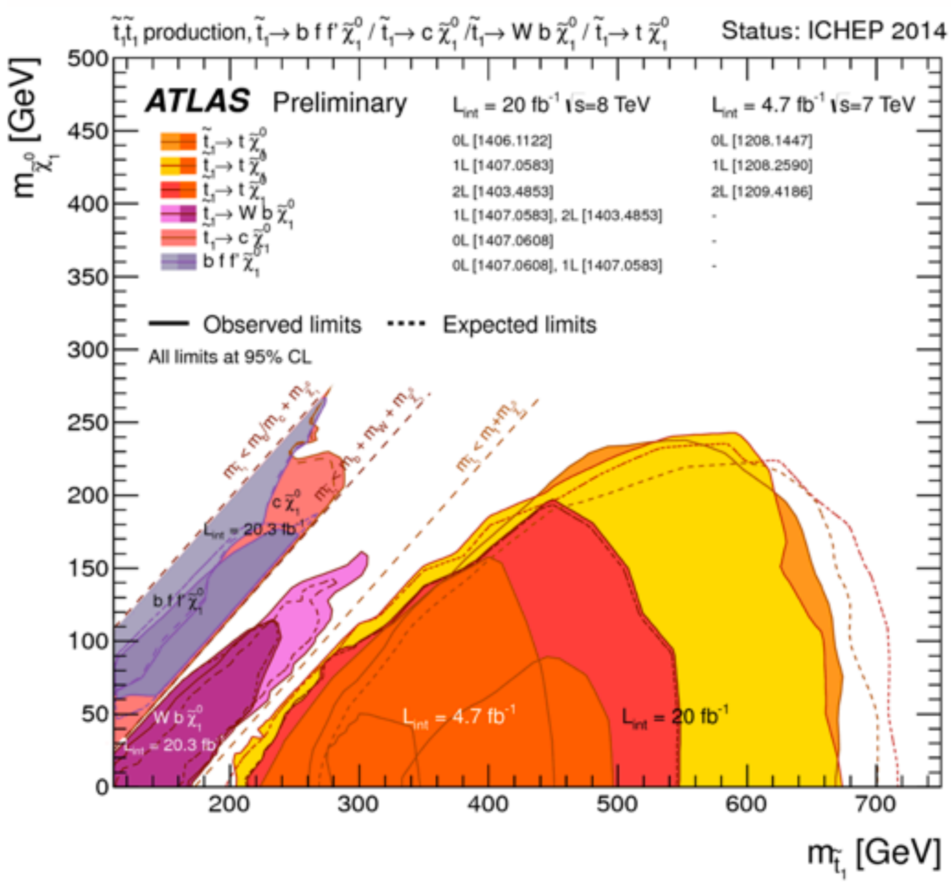


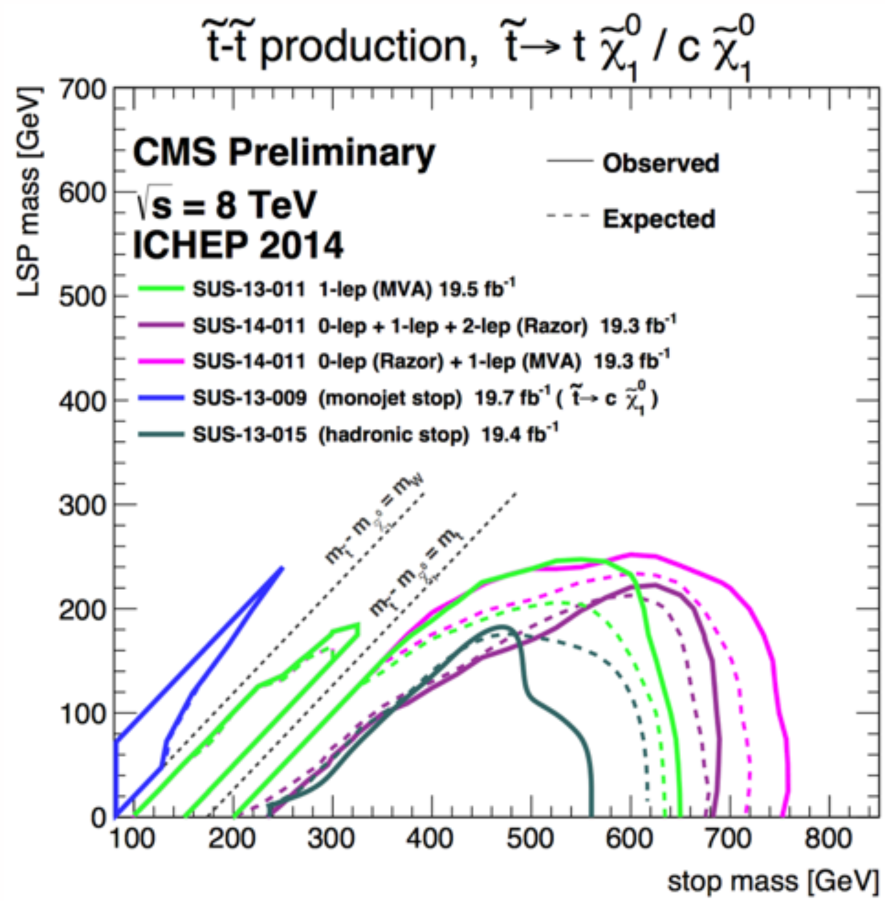


Gecse

Supersymmetry Searches

Summary of Stop (No Chargino in Decays)

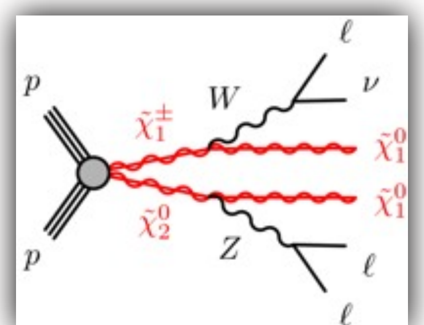


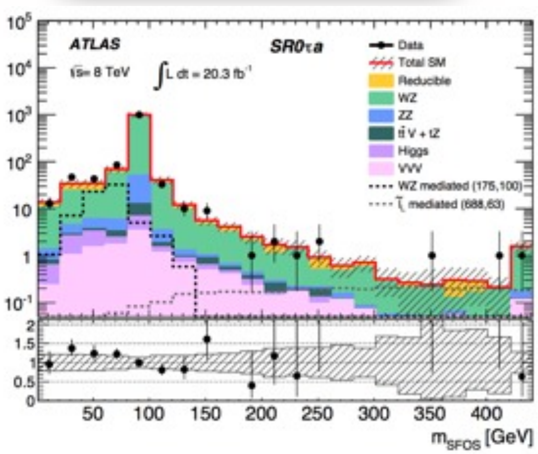


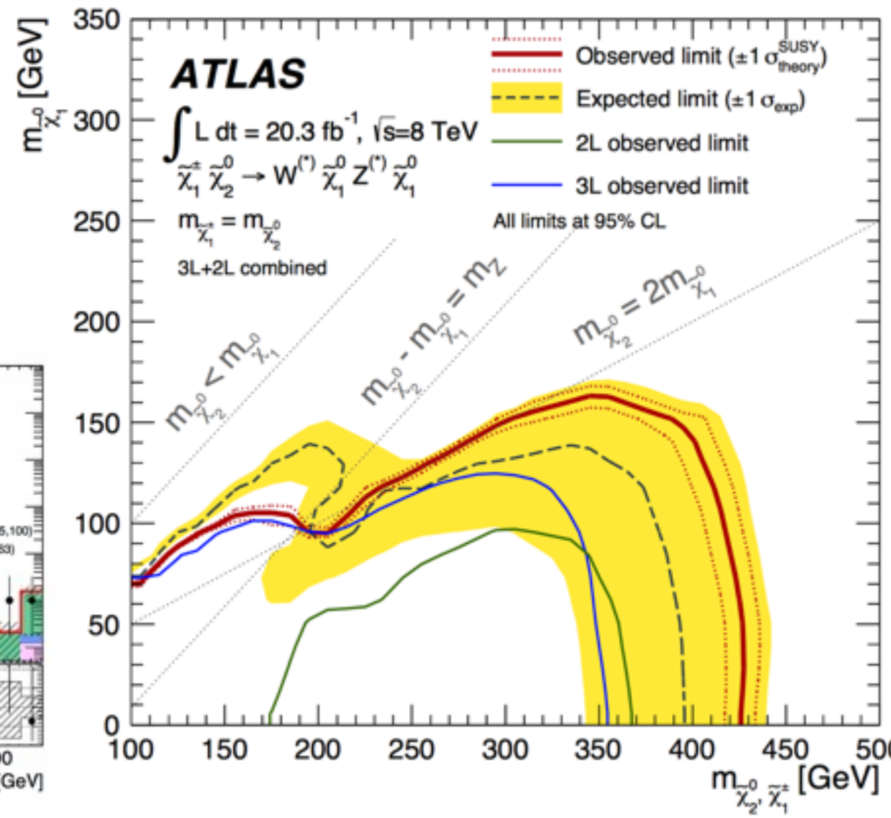
Gecse

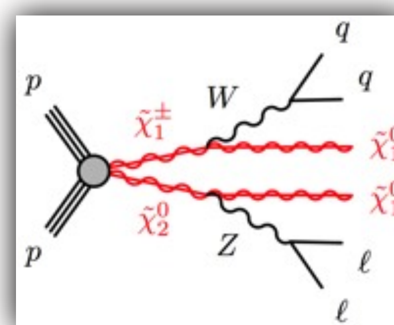
Scenarios with Decoupled Sleptons

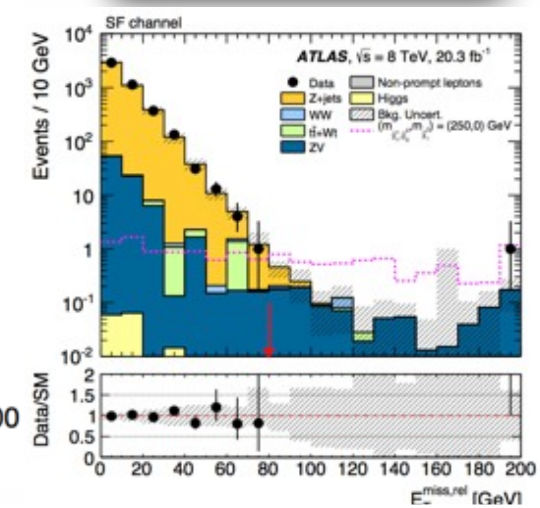
- **Natural scenarios**
- **Sensitivity up to ~400 GeV charginos and heavy neutralinos**
  - 2L+2j covers scenarios with large mass gap, while 3L has sensitivity for most of the parameter space
  - best sensitivity from statistical combination of results from various searches





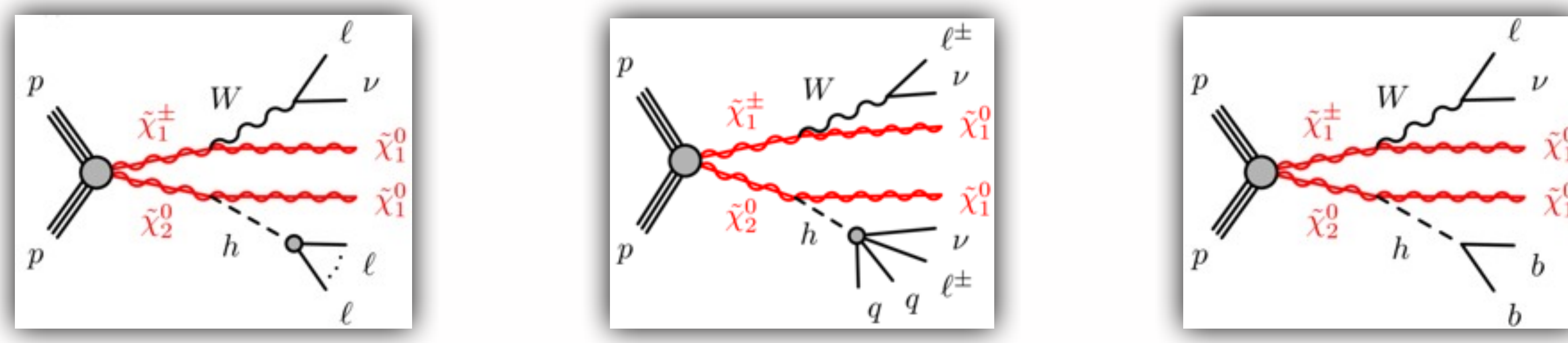




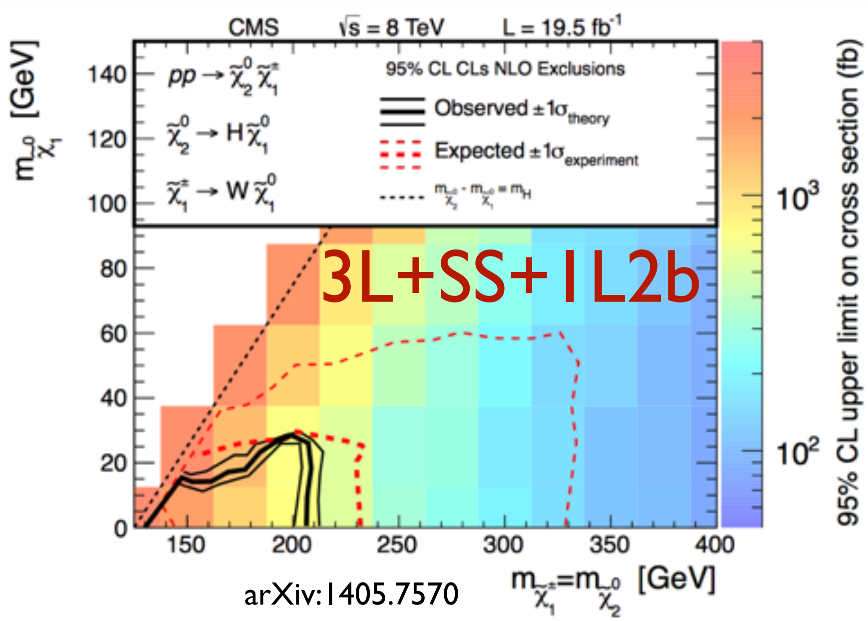


arXiv:1402.7029

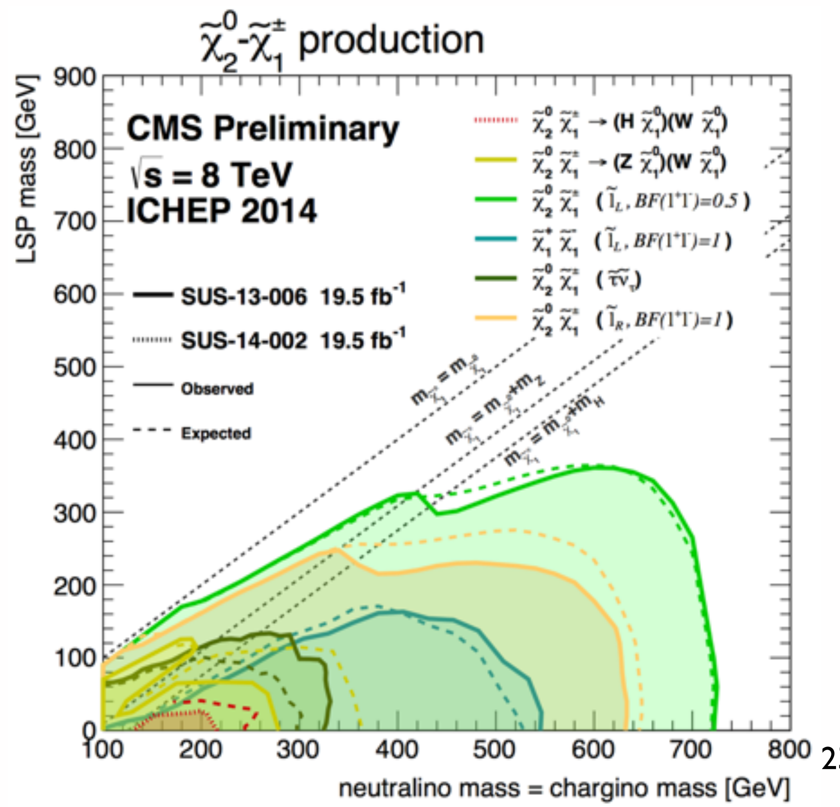
Higgs Boson as Probe for EWK SUSY



- Very challenging due to low BR of the Higgs into lepton final states, and high background when Higgs decays into b-quarks



arXiv:1405.7570

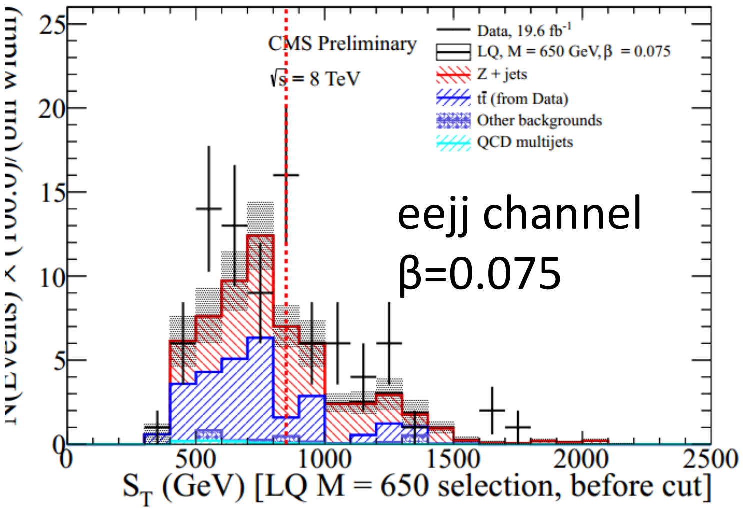


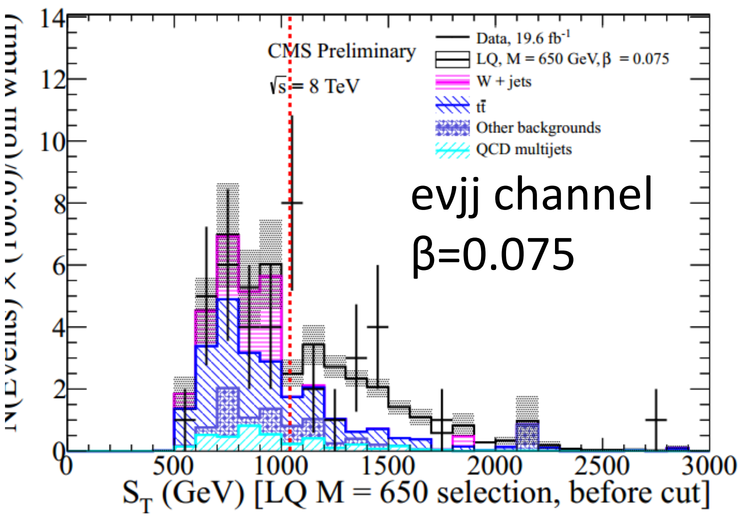
Maruyama

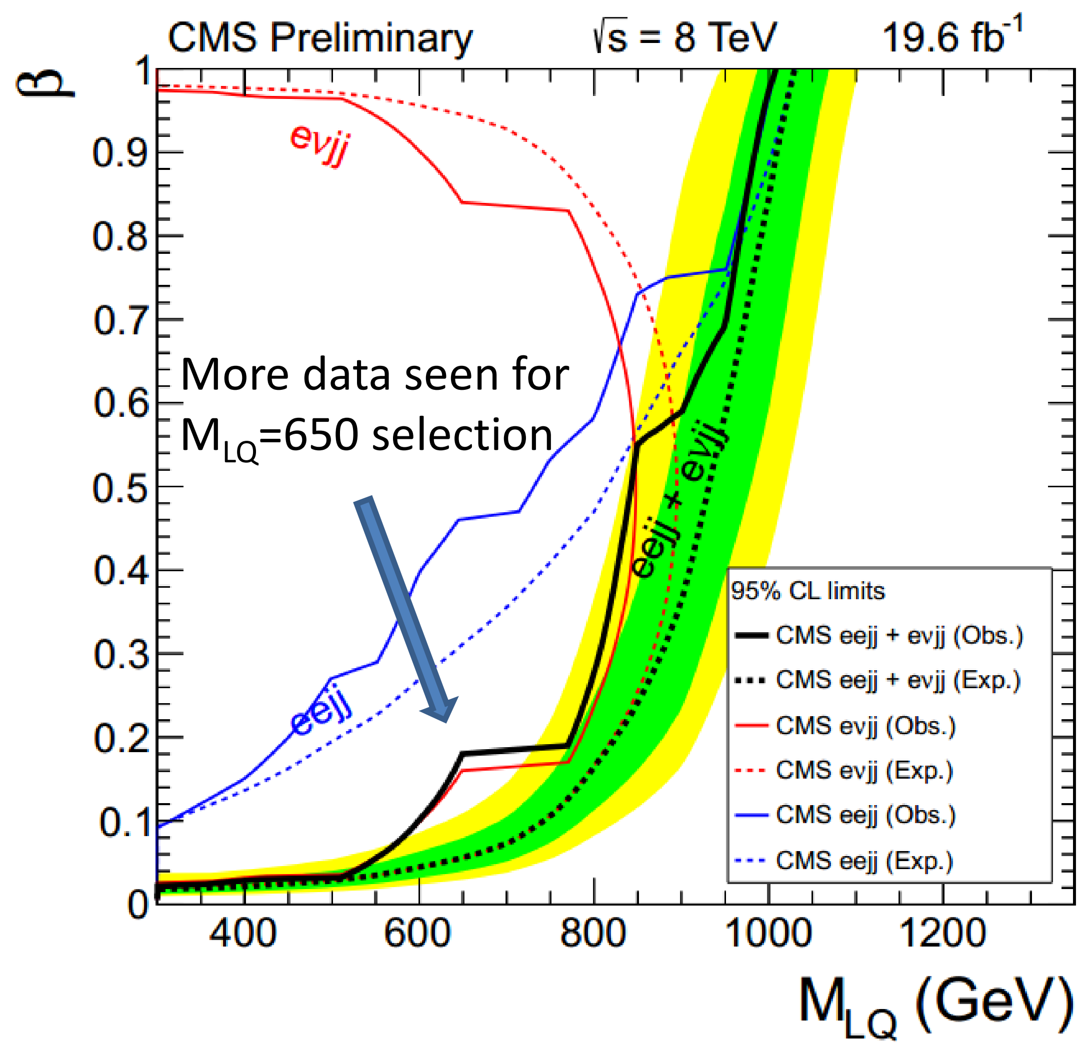
Scalar Leptoquarks (1/2)

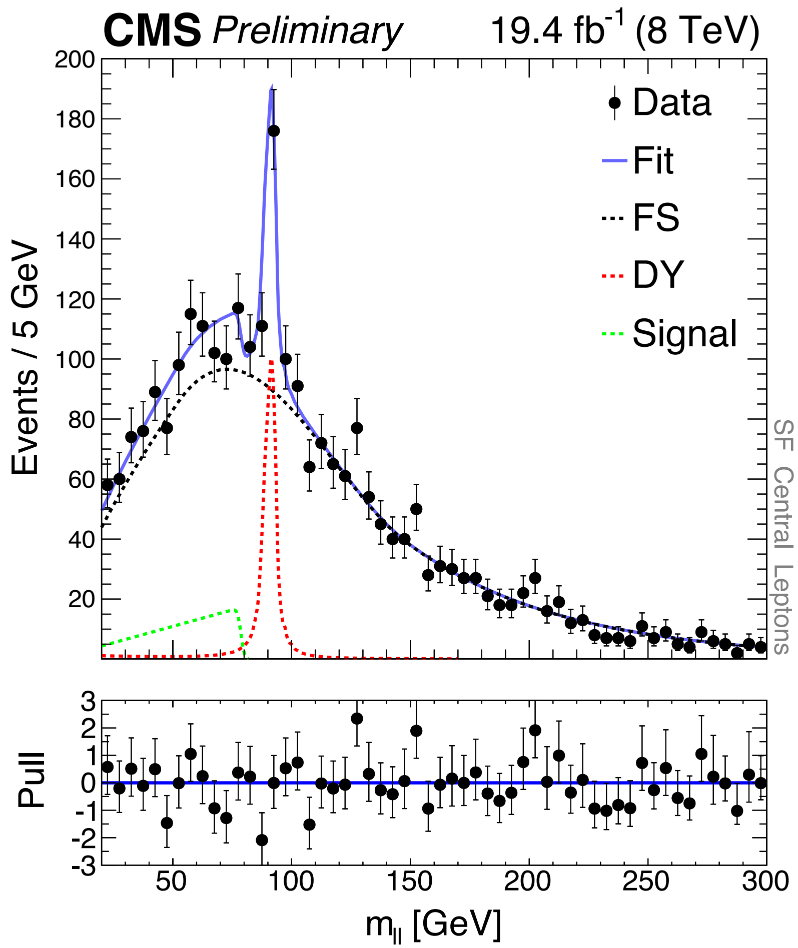
1^{st} gen LQ → evqq or eeqq

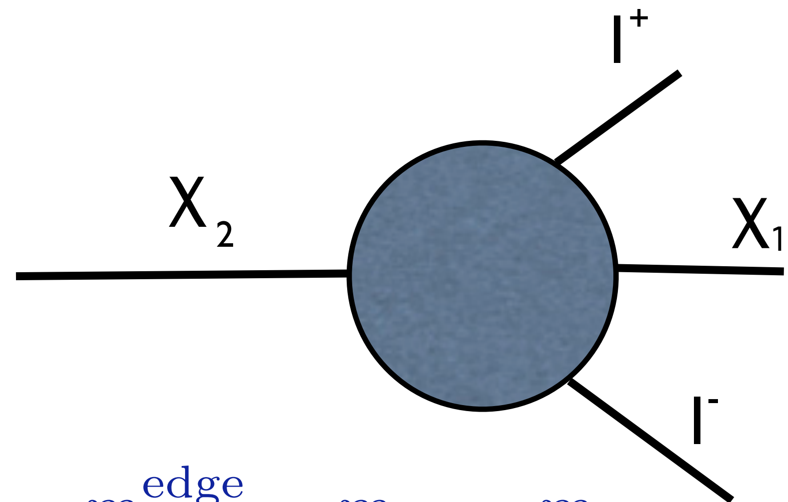
BR(LQ → charged lepton plus quark) = β











$$m_{ll}^{\text{edge}} = m_{\chi_2} - m_{\chi_1}$$

	Central	Forward
Drell–Yan	158 ± 23	71 ± 15
Flav. Sym. [OF]	2270 ± 44	745 ± 25
$R_{\text{SF/OF}}$	1.03	1.02
Signal events	126 ± 41	22 ± 20
$m_{\ell\ell}^{\text{edge}}$ [GeV]	78.7 ± 1.4	
Local Significance [σ]	2.4	

Behr

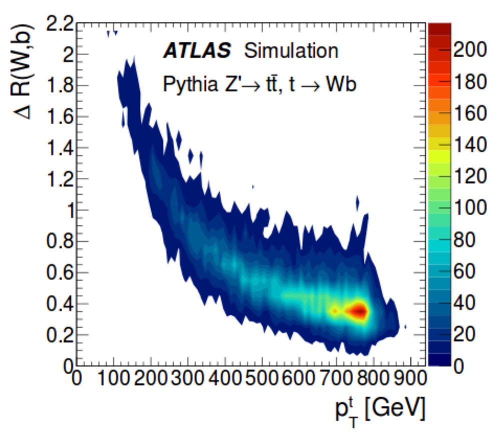
Boosted Signatures (1)

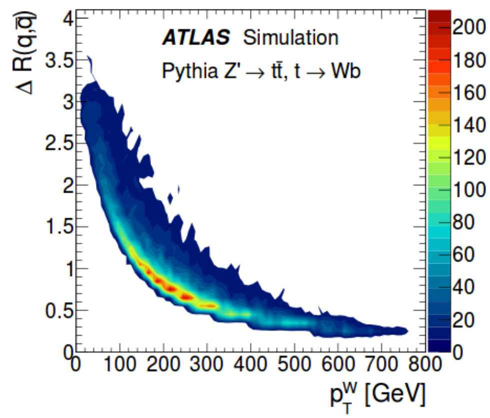
- **Boosted** means transverse momentum $\gtrsim 2$ times mass
- Decay products collimated in direction of mother particle
- Angular separation $\Delta R(a, b)$* for products of boosted decay X $\rightarrow$ a b

Rule of thumb

$$\Delta R(a, b) \approx 2m^X / p_T^X$$

ATLAS-CONF-2012-065



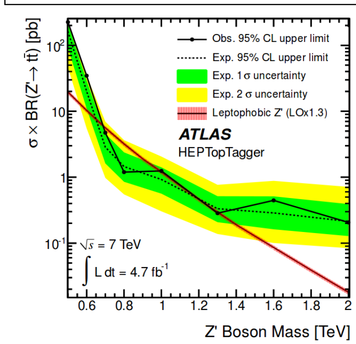


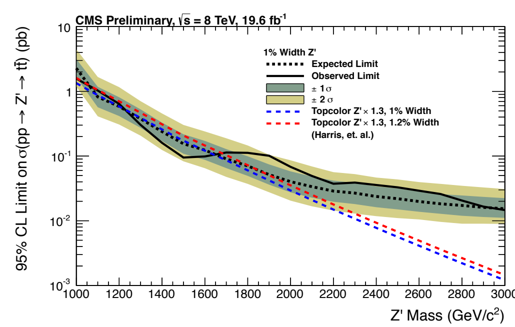
ATLAS

- HEPTopTagger (moderate p_T)
- Top Template Tagger (high p_T)

CMS

- CMS Top Tagger
- Combination with 1ℓ+jets channel in [CMS-B2G-13-001]

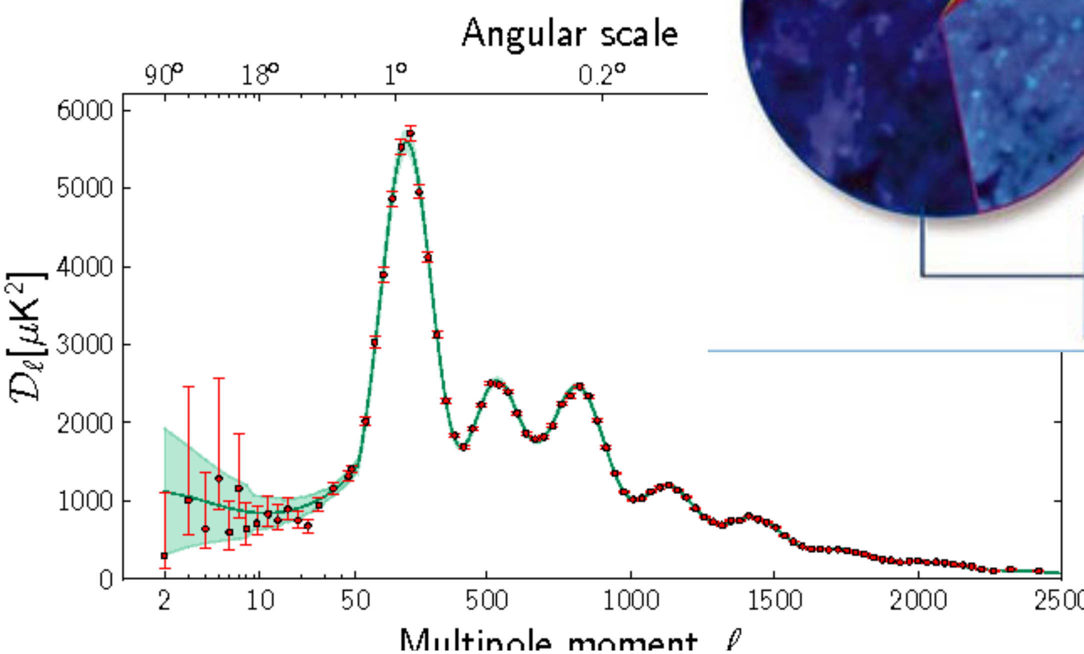




Dark Matter

Ogburn

All the data agree to amazing precision with the concordance cosmological model known as "ΛCDM". Just six parameters needed to fit the CMB data.



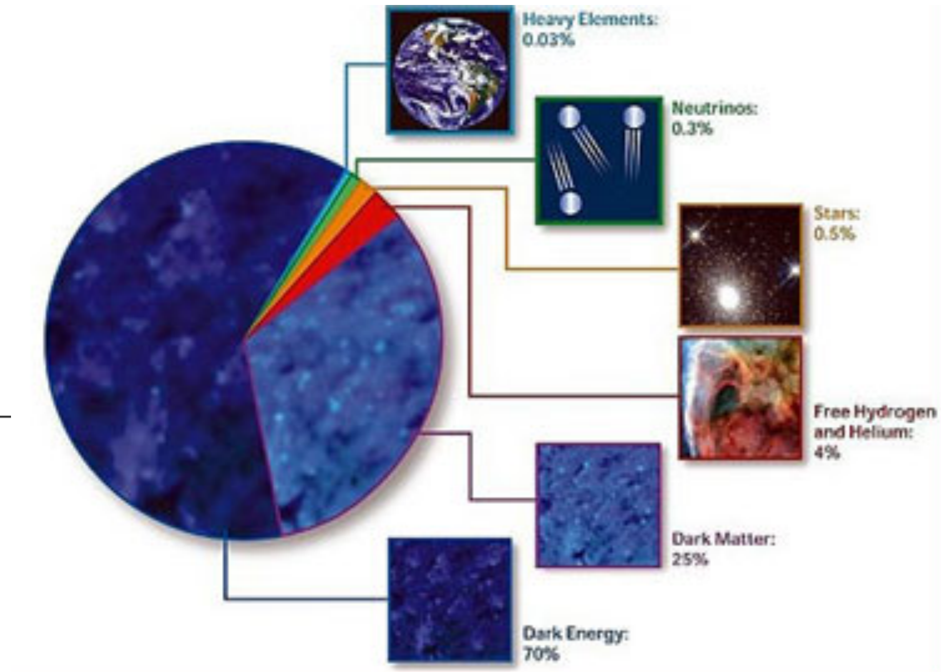
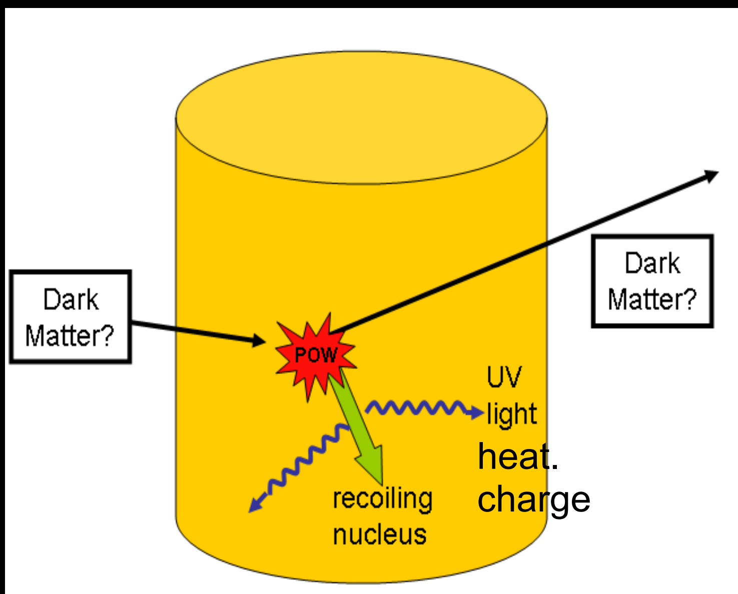


Figure: NASA

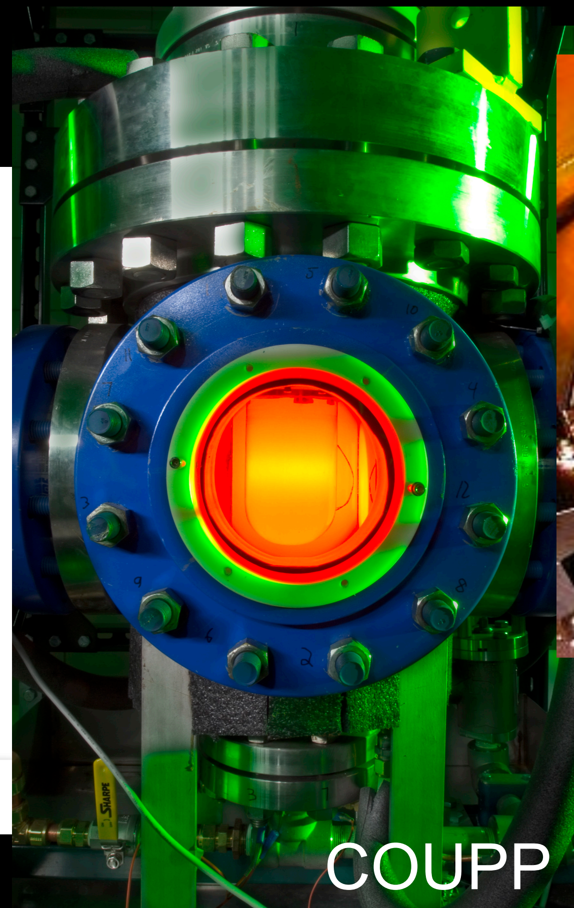
Dark Matter Search in Direct Detection Experiments

It can *collide with a single nucleus in your detector*



Underground detector

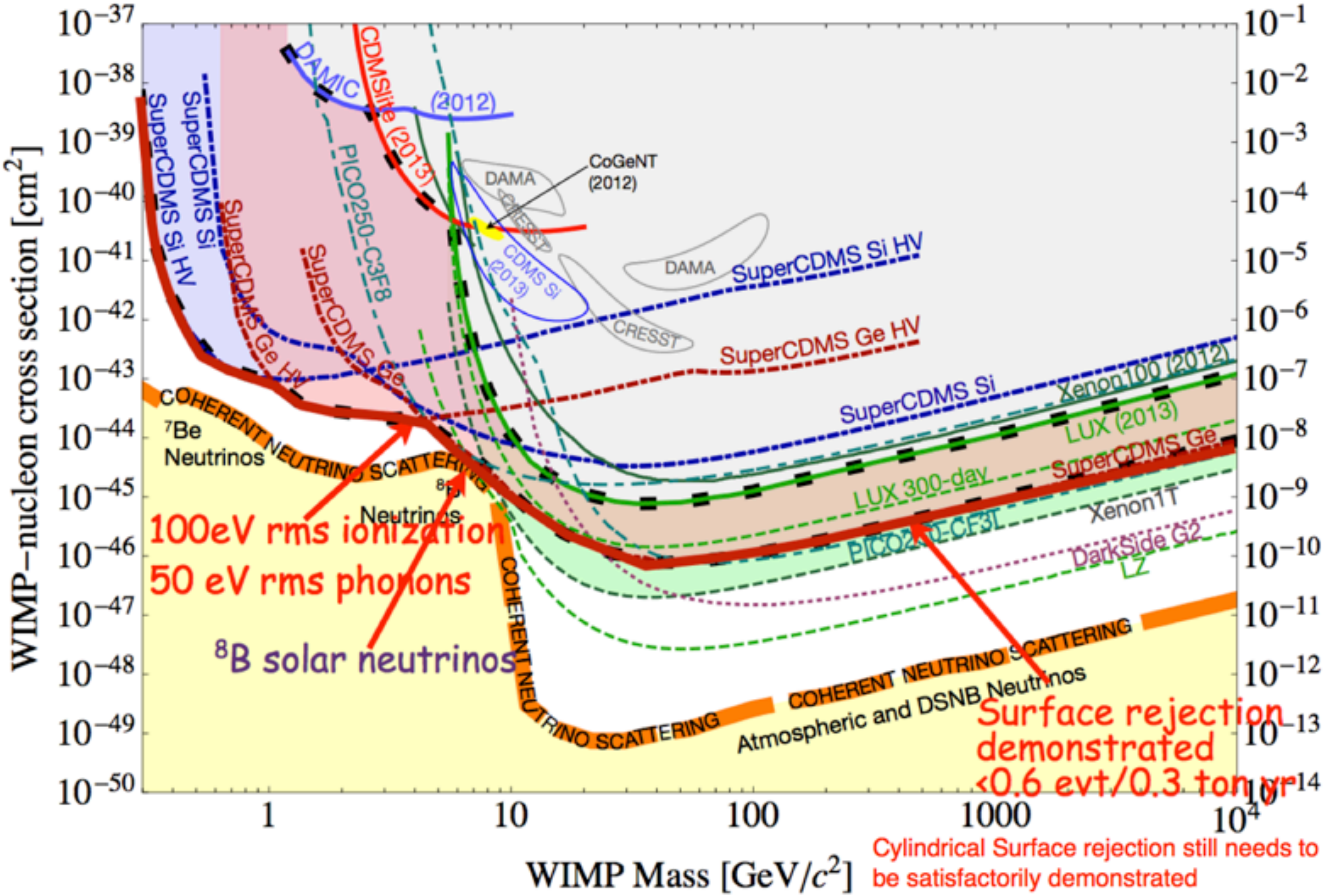
XENON, LUX



also GoGeNT
DAMIC
DarkSide

McKinsey

Direct Dark Matter Detection

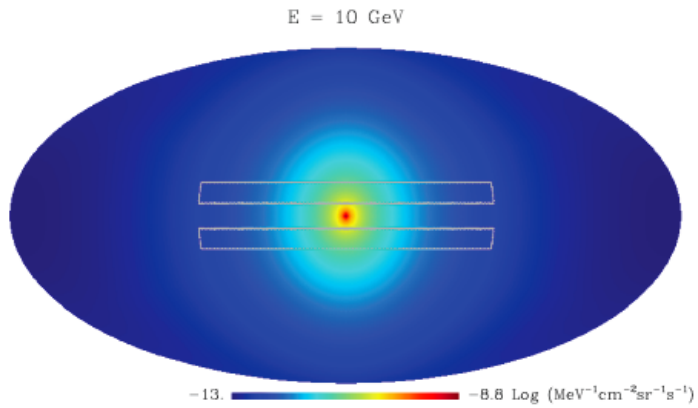


Cylindrical Surface rejection still needs to be satisfactorily demonstrated

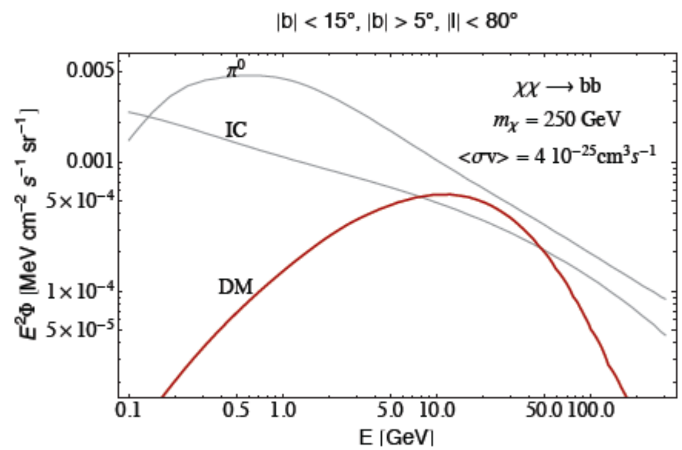
Lees-Rosier

Galactic Halo   Fermi LAT Interpretation

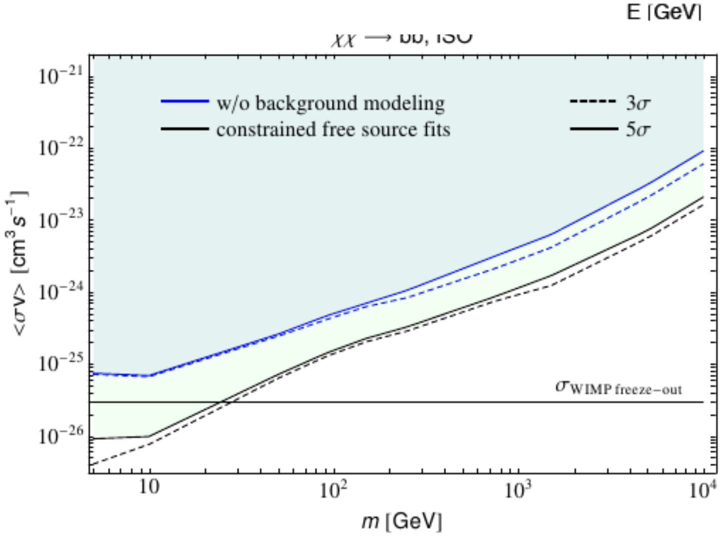
Dark Matter density distribution (NFW profile)



Gamma spectrum – M_{wimp}=250 GeV



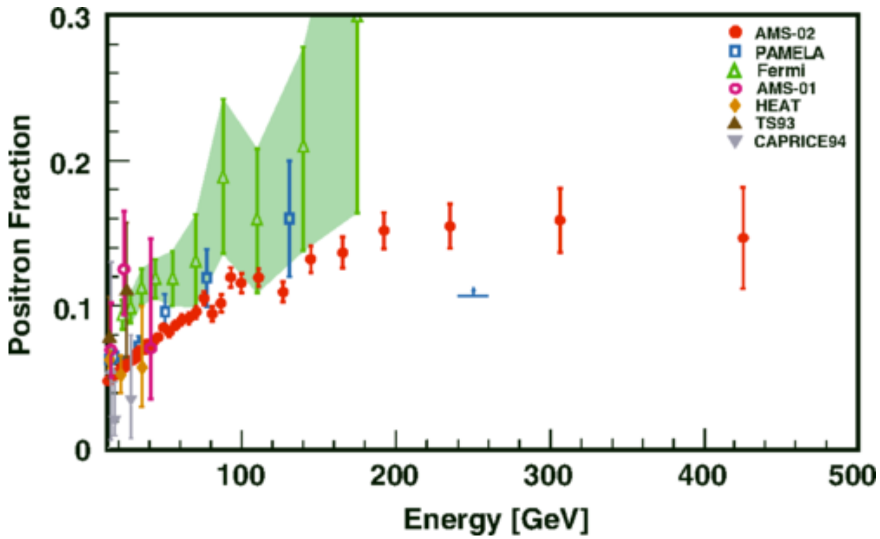
-> Upper limits on <σv> with or without background subtraction

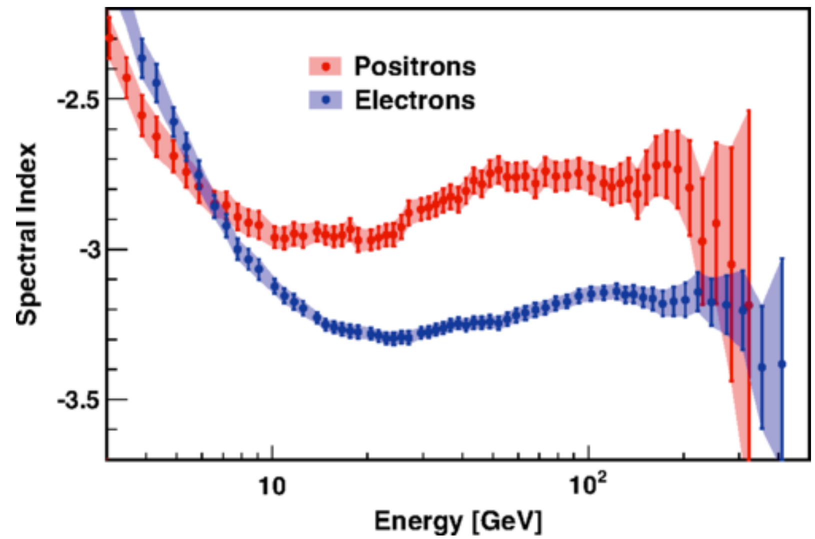


Fermi Coll., 2012, ApJ, 761, 91

Lees-Rosier/ D'Urso

Dark Matter and Cosmic Rays





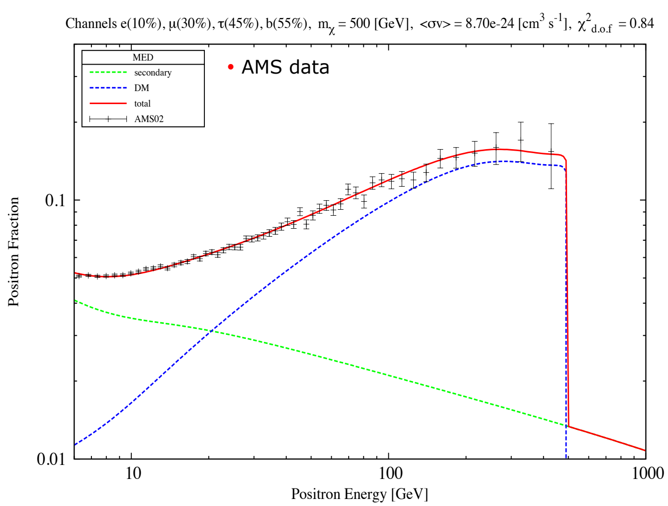
Dark Matter origin of positron fraction rise

If 100% WIMP DM origin: different masses are tested

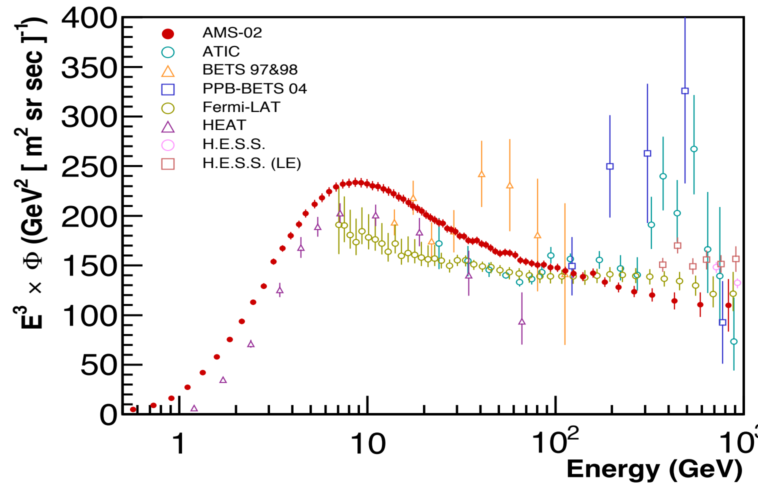
Mathieu BOUDAUD et al, LAPTh and LAPP

MicrOmegas

- Low masses are disfavored (Energy cut off)
- Large masses are disfavored (very high boost factor)



Positron plus Electron flux (1) : AMS02 1 TeV



D'Urso

The "GZK Cutoff"

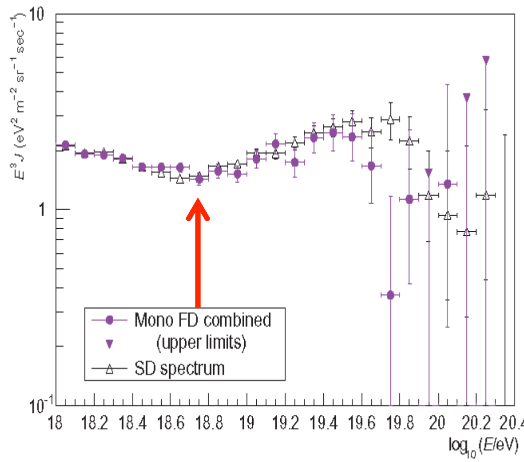
The proton energy threshold for pion photoproduction on the CMB is a **few x 10^{19} eV**. E.g.,

$p + \gamma\ (2.7^oK) \rightarrow \Delta^+ \rightarrow p + \pi^o\ ,\ n + \pi^+\ , ...$

1. Any observed CR proton **above this energy** must have originated "nearby" (within ~ 100 Mpc)

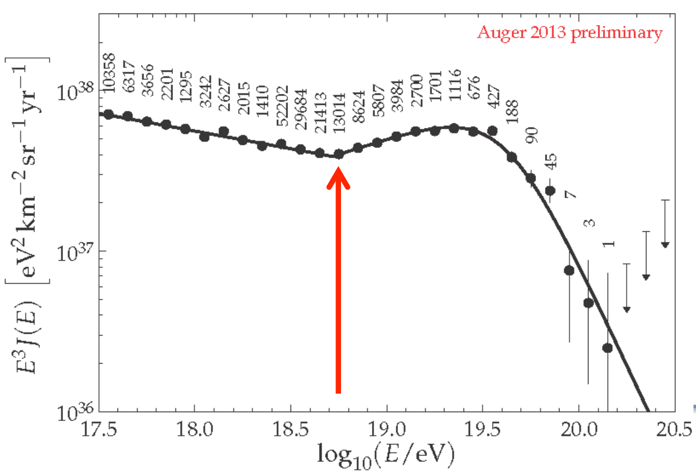
2. Similar thresholds, distances for nuclear photodisintegration.

3. Spectrum **suppressed** if non-local sources



TA

Astropart. Phys. ***48*** *(2013) 16*



Both experiments see spectral structure:

Flux **suppression** (GZK?)
Interaction or source scenario?

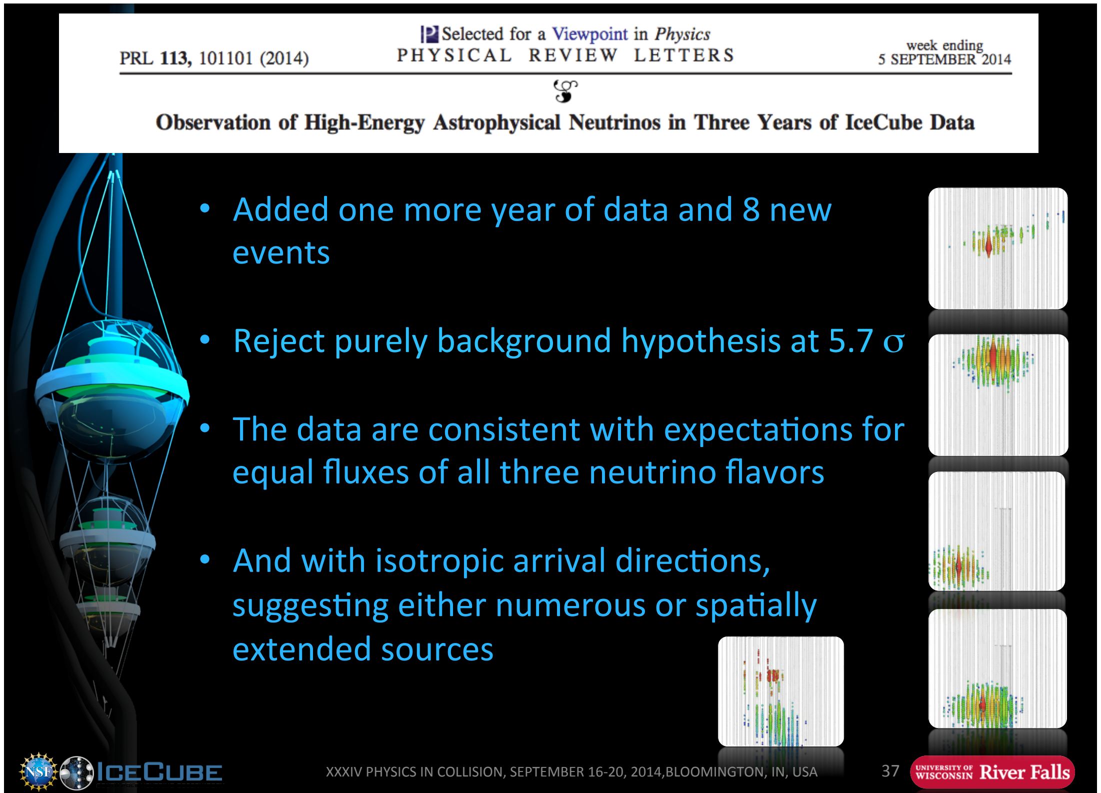
The **"ankle"**

(structures in the same place)

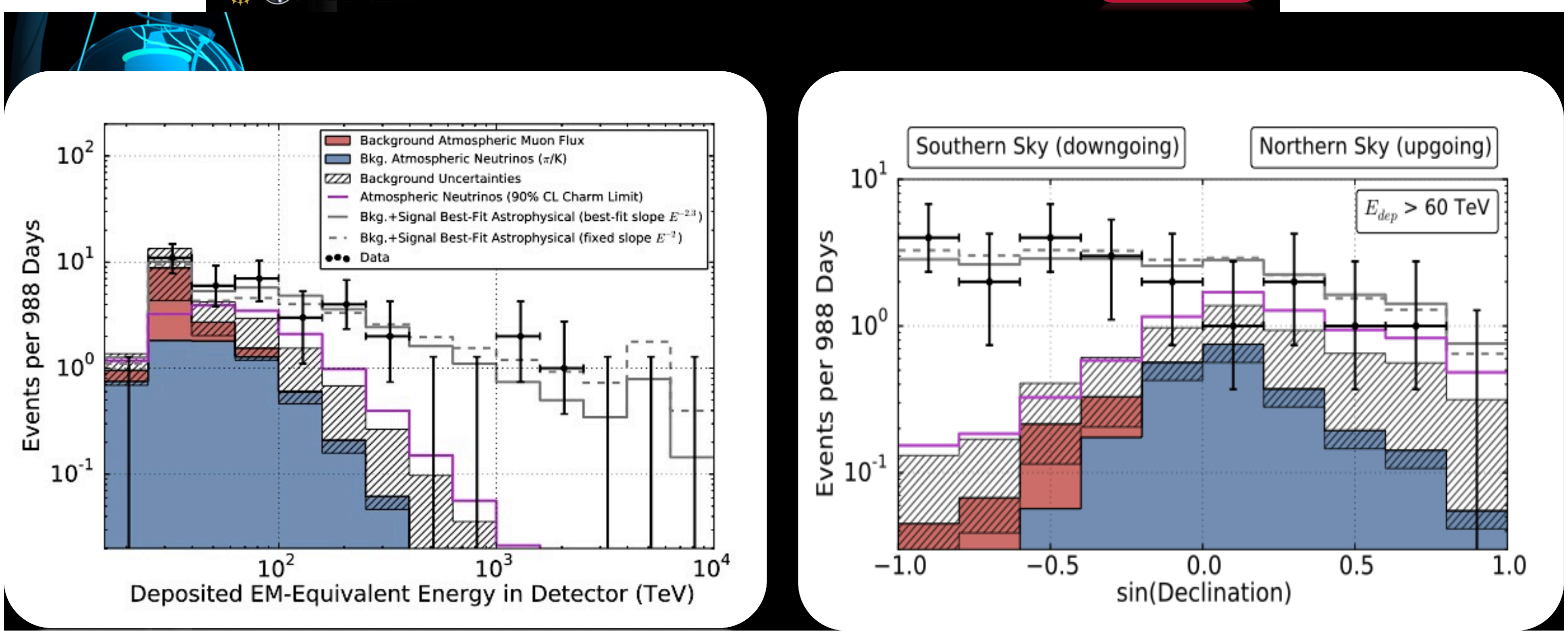
Auger

ICRC 2013

Seunarine



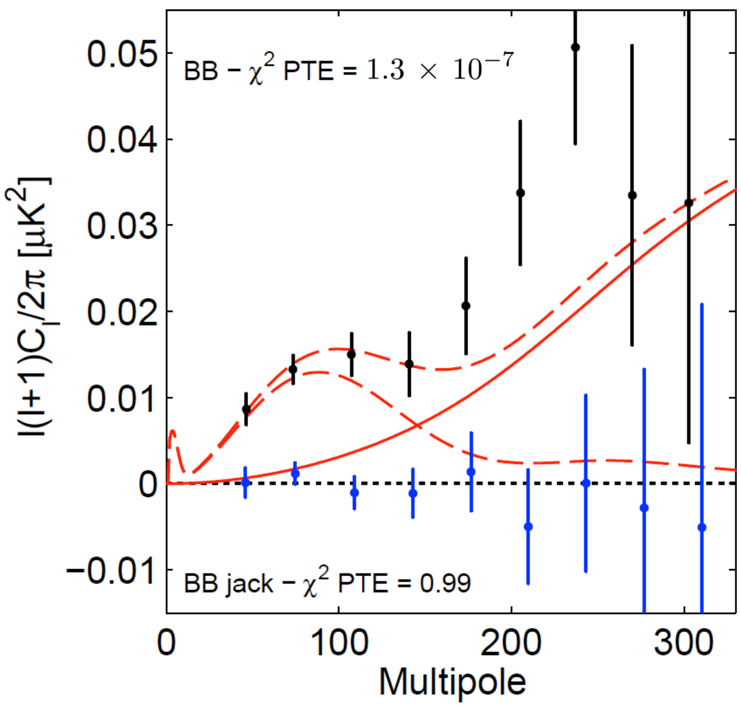
Selected for a Viewpoint in Physics
PRL 113, 101101 (2014)
PHYSICAL REVIEW LETTERS
week ending 5 SEPTEMBER 2014
Observation of High-Energy Astrophysical Neutrinos in Three Years of IceCube Data
• Added one more year of data and 8 new events
• Reject purely background hypothesis at 5.7 σ
• The data are consistent with expectations for equal fluxes of all three neutrino flavors
• And with isotropic arrival directions, suggesting either numerous or spatially extended sources
ICECUBE
XXXIV PHYSICS IN COLLISION, SEPTEMBER 16-20, 2014, BLOOMINGTON, IN, USA
37
UNIVERSITY OF WISCONSIN River Falls



Background Atmospheric Muon Flux
Bkg. Atmospheric Neutrinos (π/K)
Background Uncertainties
Atmospheric Neutrinos (90% CL Charm Limit)
Bkg.+Signal Best-Fit Astrophysical (best-fit slope E^-2.3)
Bkg.+Signal Best-Fit Astrophysical (fixed slope E^-2)
Data
Events per 988 Days
Deposited EM-Equivalent Energy in Detector (TeV)
Southern Sky (downgoing)
Northern Sky (upgoing)
E_dep > 60 TeV
sin(Declination)

Ogburn

BICEP2 B-mode Power Spectrum



B-mode power spectrum
temporal split jackknife
lensed-ΛCDM
r=0.2

B-mode power spectrum estimated directly from Q&U maps, including map based "purification" to avoid E→B mixing

Consistent with lensing expectation at higher l.

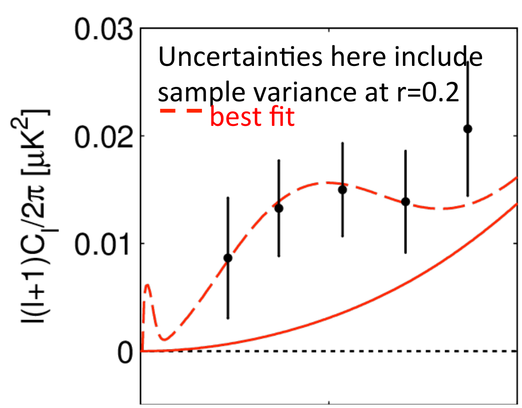
At low l excesses over lensed-ΛCDM at high signal-to-noise.

For the hypothesis that the measured band powers come from lensed-ΛCDM we find:

χ^2 PTE	1.3×10^{-7}
significance	$5.2\,\sigma$

Tests of inflation

- Flatness
- Very large-scale features (horizon problem)
- Scale invariance
- Adiabatic perturbations
- Nongaussianity



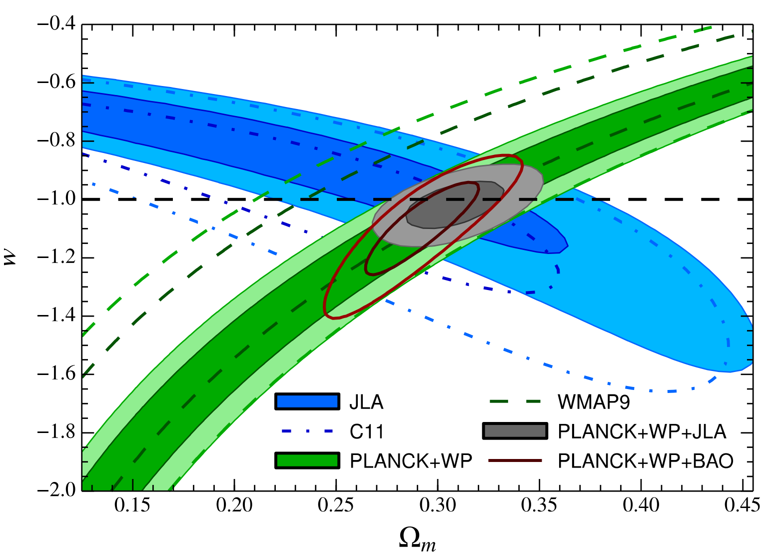
tensor-to-scalar ratio r

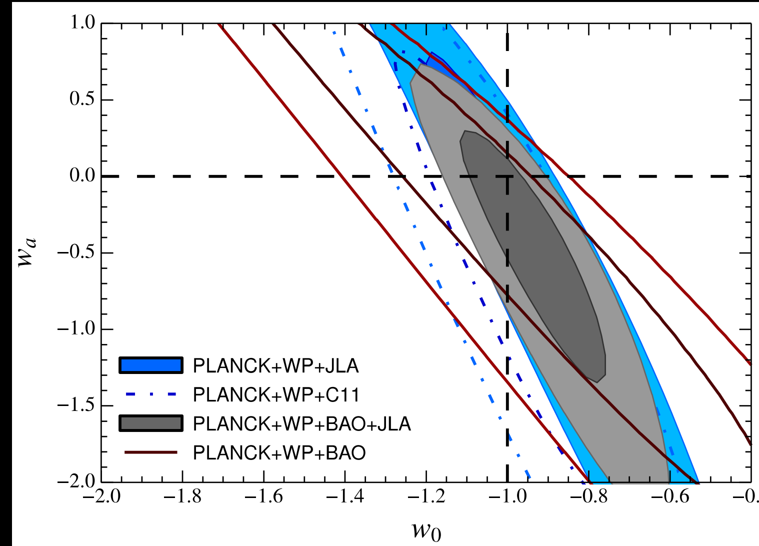
Gerdes

Current Dark Energy Constraints from Supernovae, CMB, and Large-scale Structure

Assuming constant w

Assuming $w=w_0+w_a(1-a)$





Betoule et. al 2014

Consistent with vacuum energy (Λ): $w_0=-1$, $w_a=0$

Dark Energy Survey will provide a detailed study of DE properties

Many possible Extensions of the Standard Model

Physics Explanations have different properties.

Is this bad ?

Reasons for Proposal and Later Solutions to 4 Puzzles (1932)

- 1) Klein Paradox --apparent violation of unitarity (solution:positron existence- pair production possible)
- 2) Wrong Statistics in Nuclei--N-14 nucleus appeared to be bosonic--(solution: neutron not a proton-electron bound state)
- 3) Beta Ray Emission-apparent Energy non conservation (solution:neutrino)
- 4) Energy Generation in Stars (solution: nuclear forces, pep chain, carbon cycle etc.----pion)

The Near Future

- The current decade will see the full development of the LHC program, which will provide detailed information of physics at the TeV scale.
- Origin of fermion and gauge boson masses (electroweak symmetry breaking dynamics) expected to be revealed by these experiments. Higgs Discovery is the first step.
- Missing energy signatures at the LHC may reveal one or more dark matter candidates. Direct and indirect detection experiments will reach maturity, and may lead to additional evidence of Dark Matter. Dark Energy equation of state may be determined.
- Tevatron, LHC, LHCb and super B-factories will provide accurate information on flavor physics, leading to complementary information on new physics.

The Near Future

- Search for charged lepton number violation, g-2 of the muon and neutrino-less double beta decay experiments could shed light on the nature of neutrinos, and new dynamics at the TeV scale.
- Neutrino oscillation experiments lead to the observation of CP-violation or, indirectly, to the existence of additional sterile neutrinos.
- Electric dipole moments may reveal the existence of new CP-violating sources, perhaps connected to baryogenesis at the weak scale.

The next 10 to 20 years can mark the beginning of a genuine new era in physics, similar to the one that led to the successful SMs of particle physics and cosmology, which arguably started about 100 years ago.

Stay Tuned for PIC 2015 !