52nd Rencontres de Moriond

Electroweak Interactions and Unified Theories

Experimental summary

Tim Gershon
University of Warwick

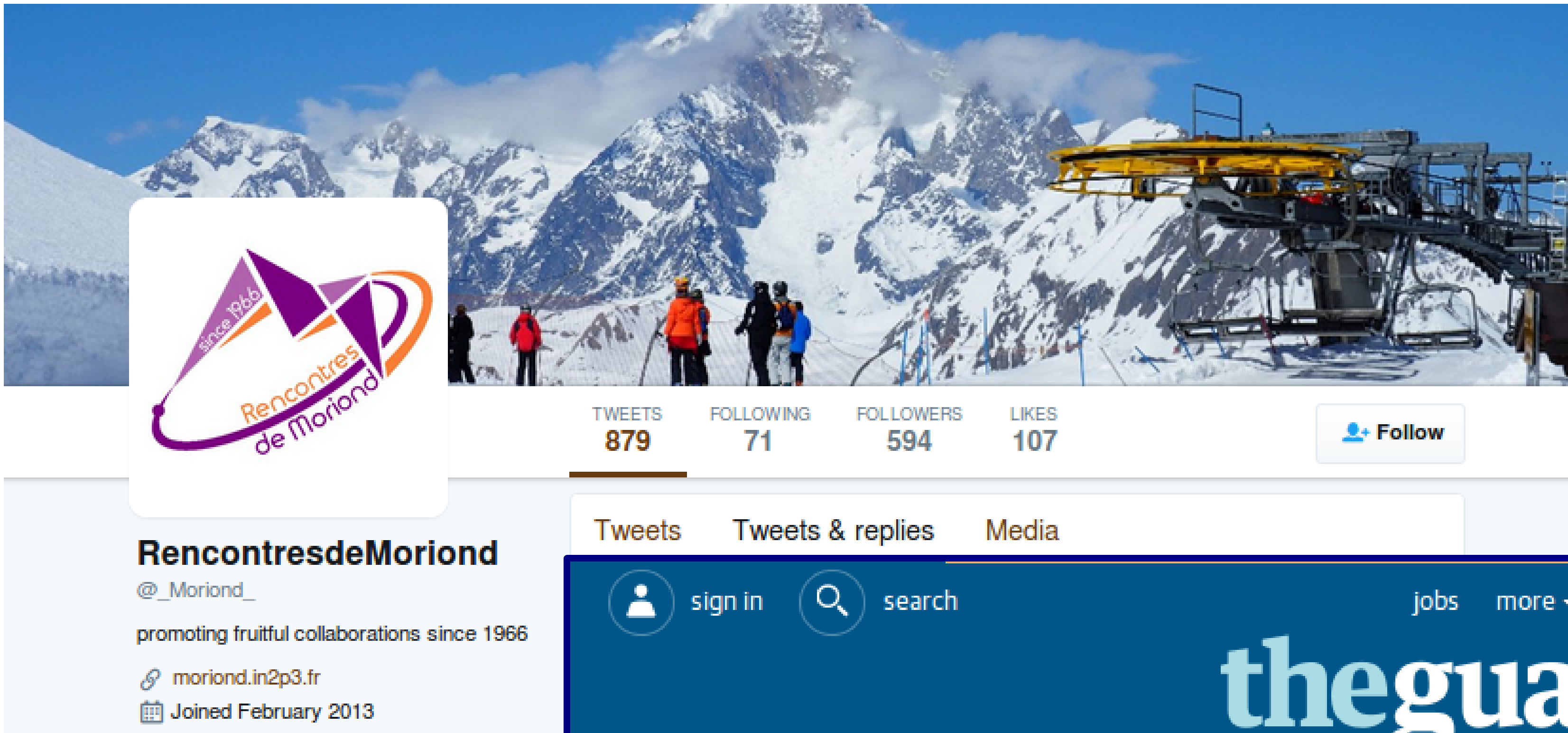
25th March 2017

WARWICK
THE UNIVERSITY OF WARWICK

Most importantly ...

- Another vibrant and stimulating meeting, in the Moriond tradition
- Wonderful talks, containing many many new results
- Thanks to the organisers for the exciting programme
  - and to the secretariat & computing support for taking good care of us all
- Many thanks to the speakers and to others who have patiently answered my dumb questions
- I cannot attempt to cover everything, so will be selective
  - apologies for omissions & mistakes

@Moriond

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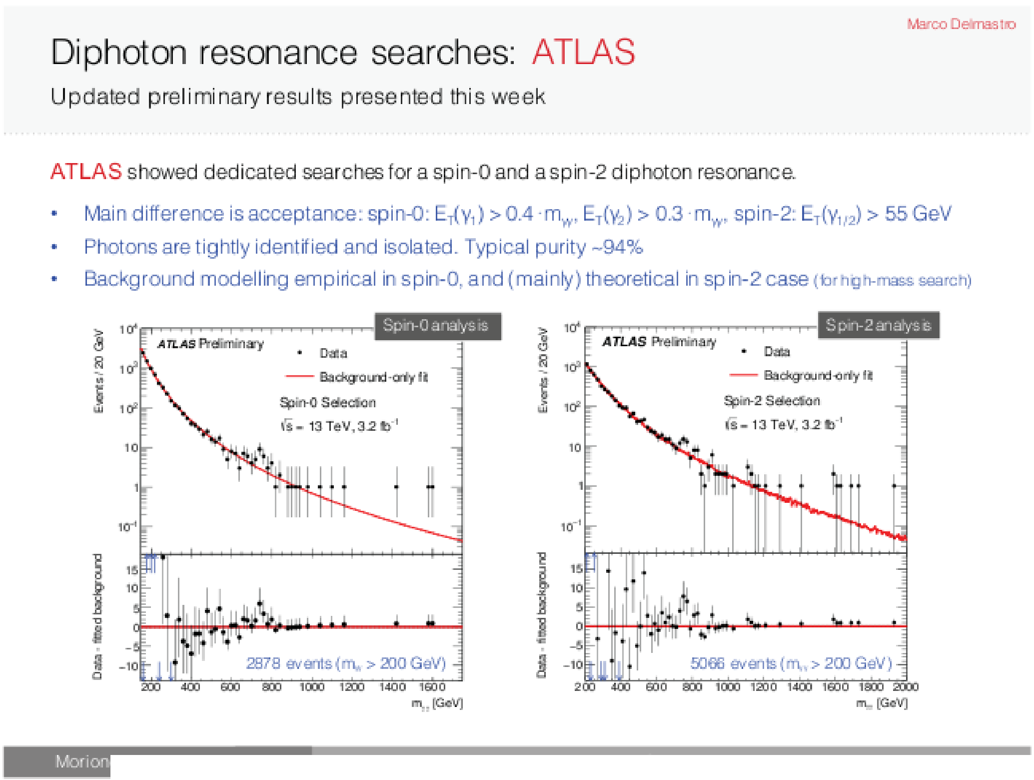
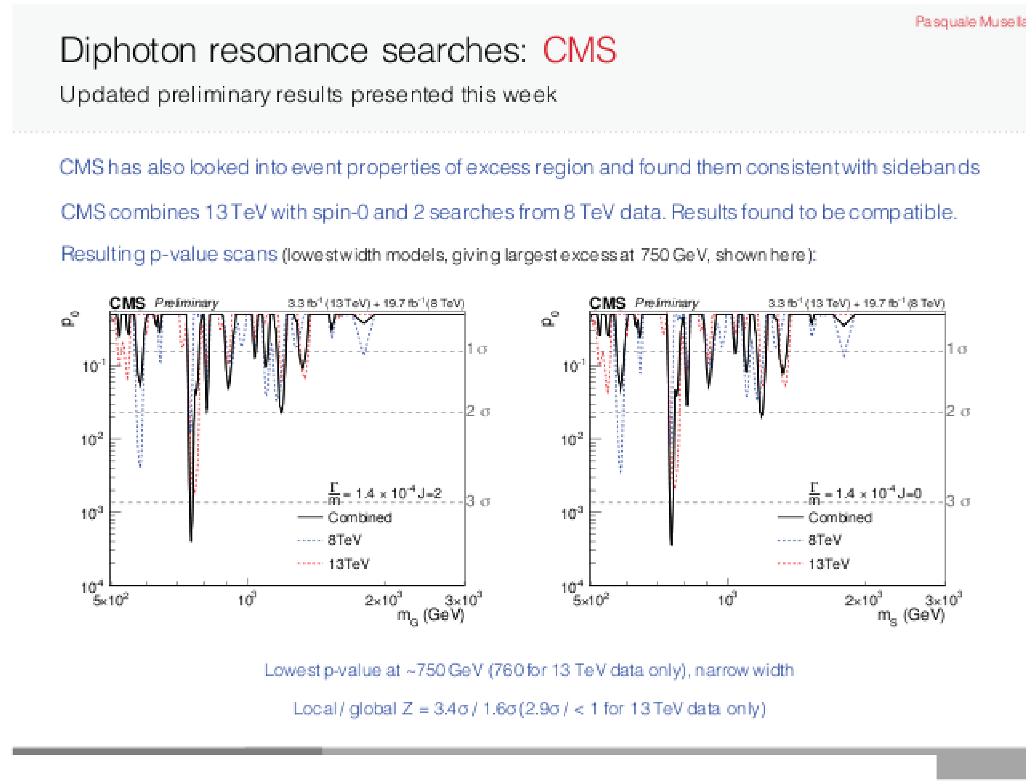
Physics Life and Physics

From gravity to the Higgs we're still waiting for new physics

Annual physics jamboree Rencontres de Moriond has a history of revealing exciting results from colliders, and this year new theories and evidence abound

One year ago ...
(from Andreas Hoecker's summary slides)





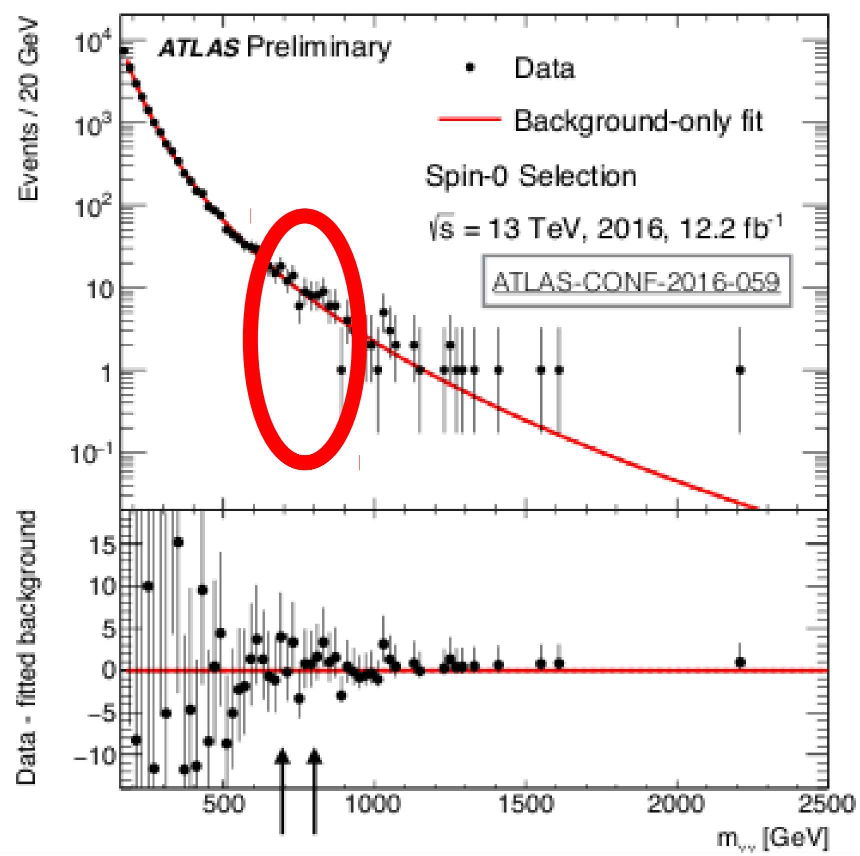
Alessandro Strumia:

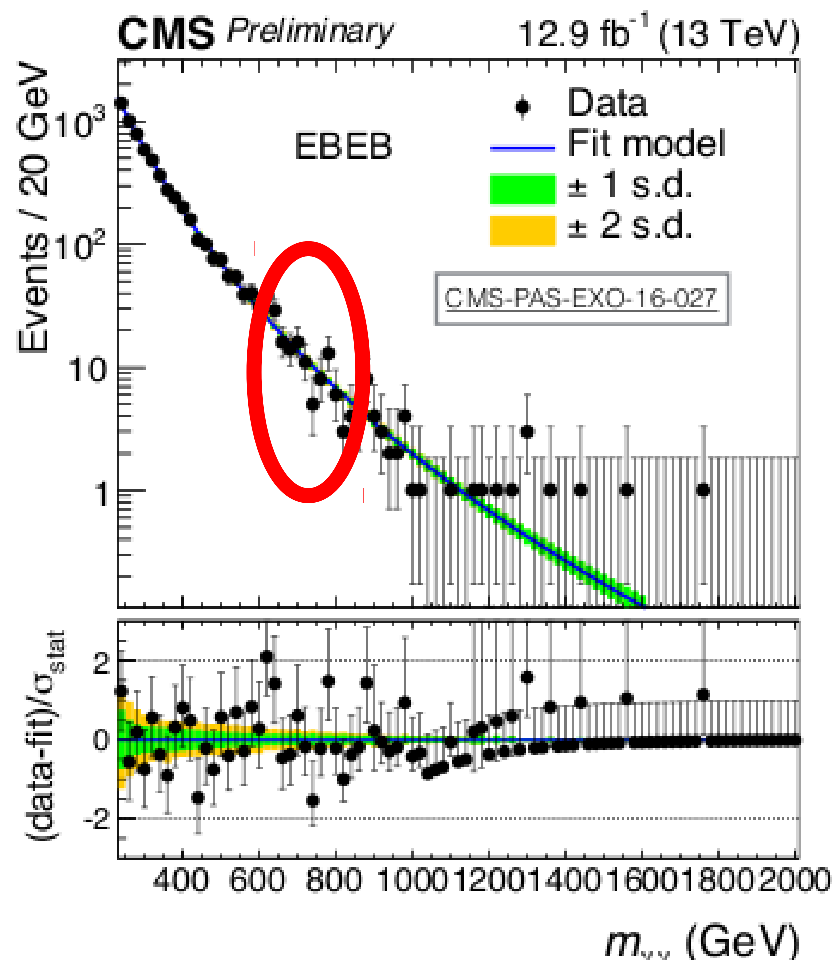
Today it could be everything, including nothing.

Then at ICHEP 2016 ...

(from Shih-Chieh Hsu's plenary talk)

Excesses not confirmed in 2016 data

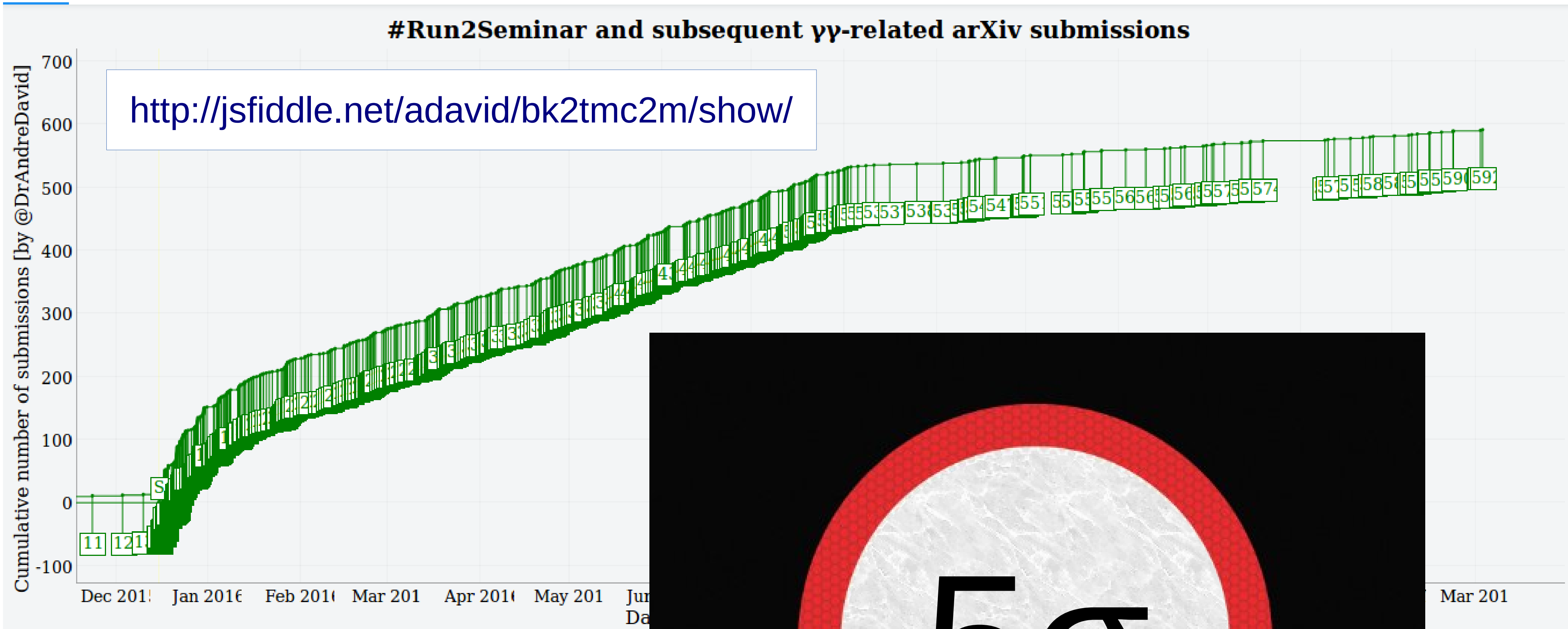




Significance in 2015+2016:

m=710 GeV (Γ/M=10%)
2.3σ(local)/<1σ (global)

m=760 GeV ($\Gamma/M=1.4\times10^{-4}$)
<1σ(local)



worth remembering when discussing other anomalies … as I am about to do

Fake news!

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Fifth fundamental force has NOT been found: LHC search for particle that would rewrite laws of physics comes up empty

- **In December, data suggested a particle six times heavier than Higgs**
- **It would not be described by Standard Model of particle physics**
- **More collisions started in April 2016, to collect more data**
- **CERN scientist told MailOnline these collisions did not find the particle**

By ABIGAIL BEALL FOR MAILONLINE
PUBLISHED: 12:15 GMT, 29 July 2016 | **UPDATED:** 14:53 GMT, 29 July 2016

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The first signs of a particle heavier than the Higgs boson was seen at the Large Hadron Collider (LHC) back in December

Unexplained by current models, its existence might lead to the discovery of a whole new set of particles and possibly even a fifth fundamental force.

But the first results were not enough to confirm the particle exists, and now a second run of tests have failed to find this mysterious particle, MailOnline has learned.

WIRED

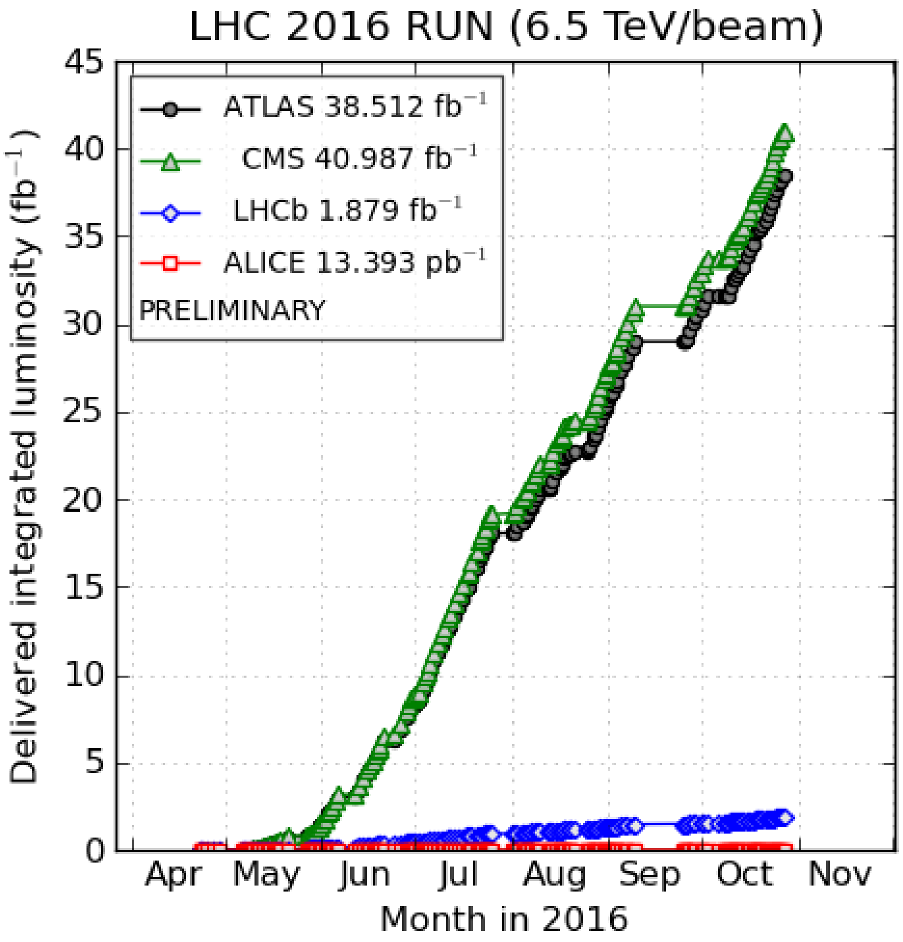
BRENDAN COLE SCIENCE 08.05.16 8:02 AM

SORRY, FOLKS. THE LHC DIDN'T FIND A NEW PARTICLE AFTER ALL

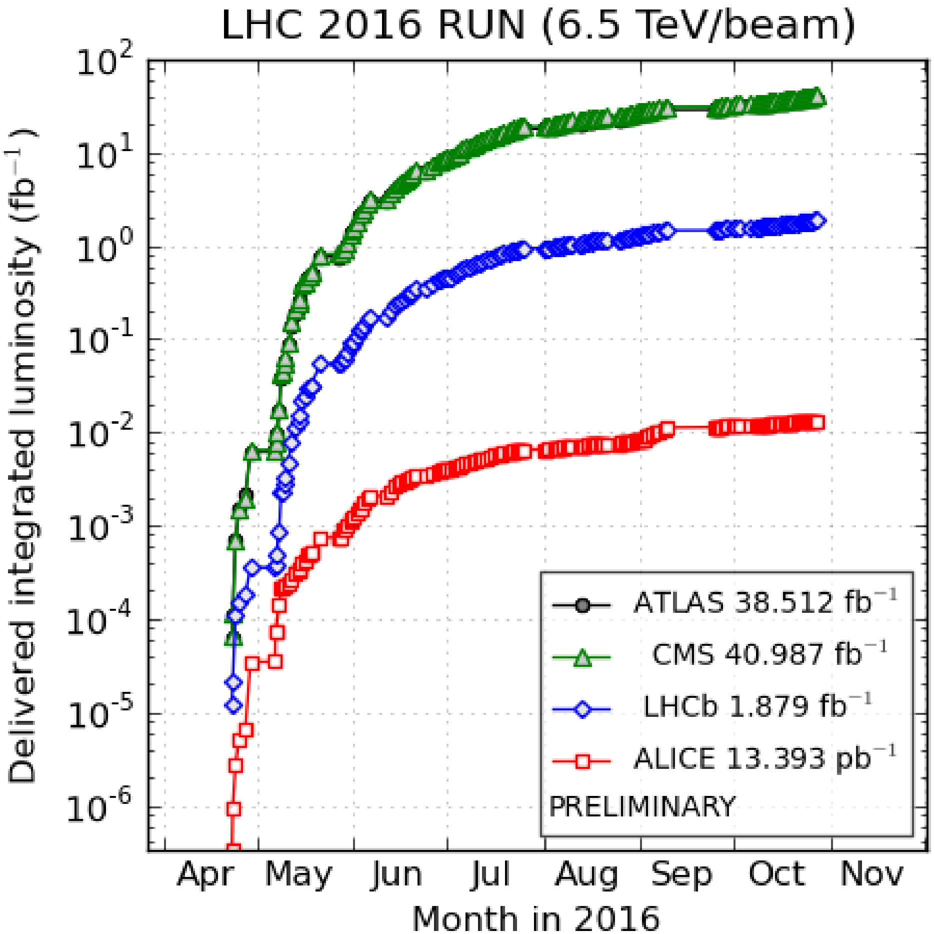
THE LAST THIRTY years of particle physics have been a little disappointing. A scientist's job is to prove themselves wrong, but despite their best efforts, despite recreating the conditions of the Big Bang, particle physicists just keep being correct. Aside from a few unexplained observations (meddling neutrinos!), the Standard Model, which describes interactions between all known particles, has exactly predicted the outcome of every experiment in the history of particle physics. Physicists try to prove it wrong, and they keep failing.

(just two examples)

The spectacular success of the LHC



(2017-02-25 21:50 including fill 5456; scripts by C. Barschel)



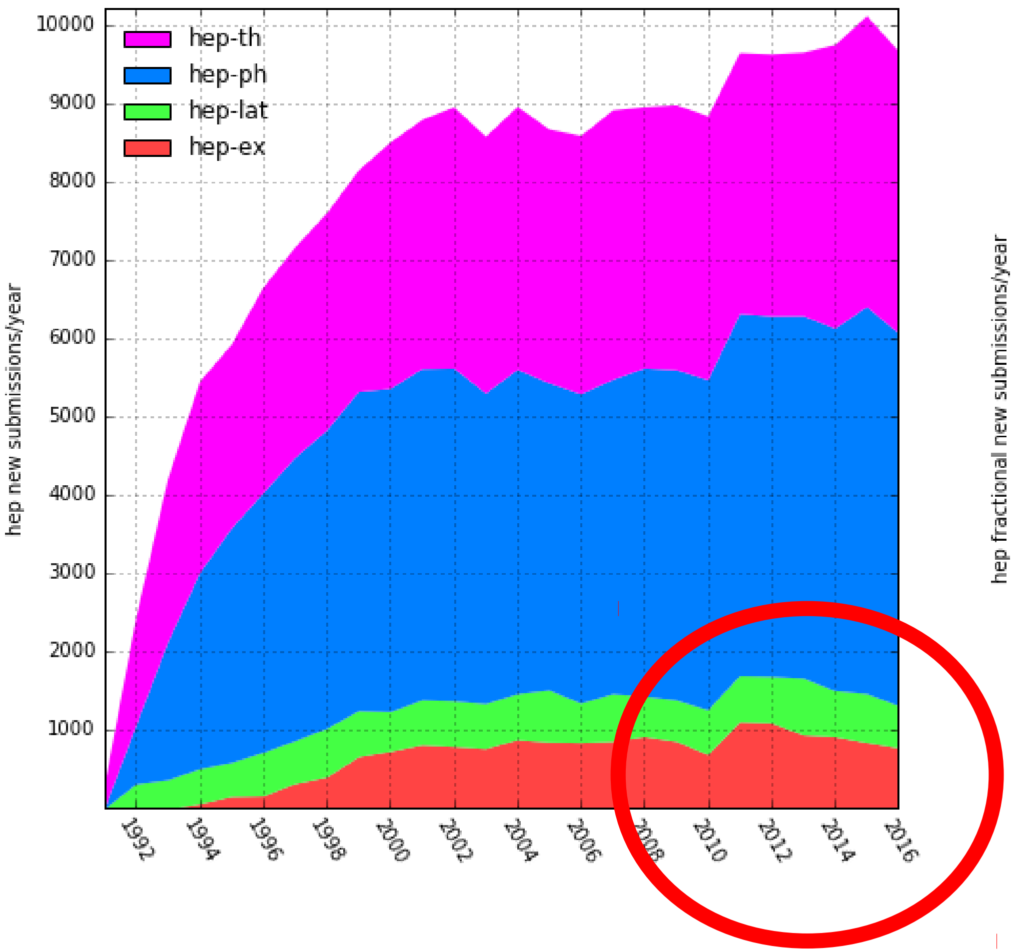
(2017-02-25 21:50 including fill 5456; scripts by C. Barschel)

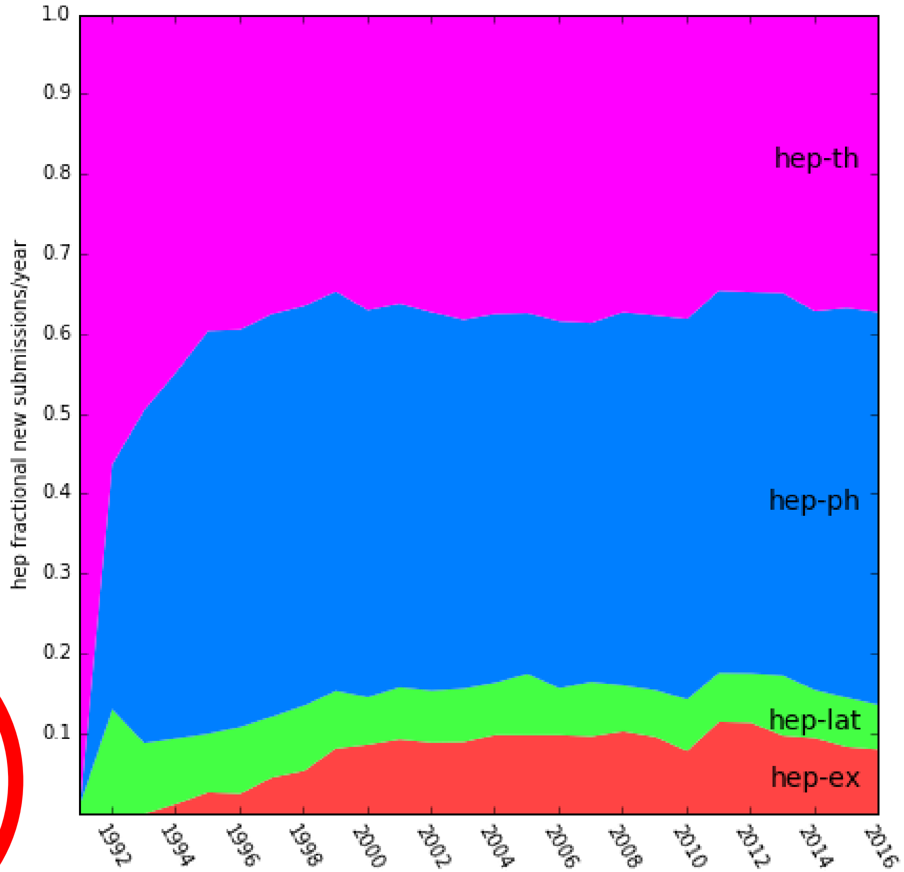
Astonishing machine availability during 2016

Is it possible to have too much data? (No, but it causes issues...)

The health of hep-ex

https://arxiv.org/help/stats/2016_by_area/index

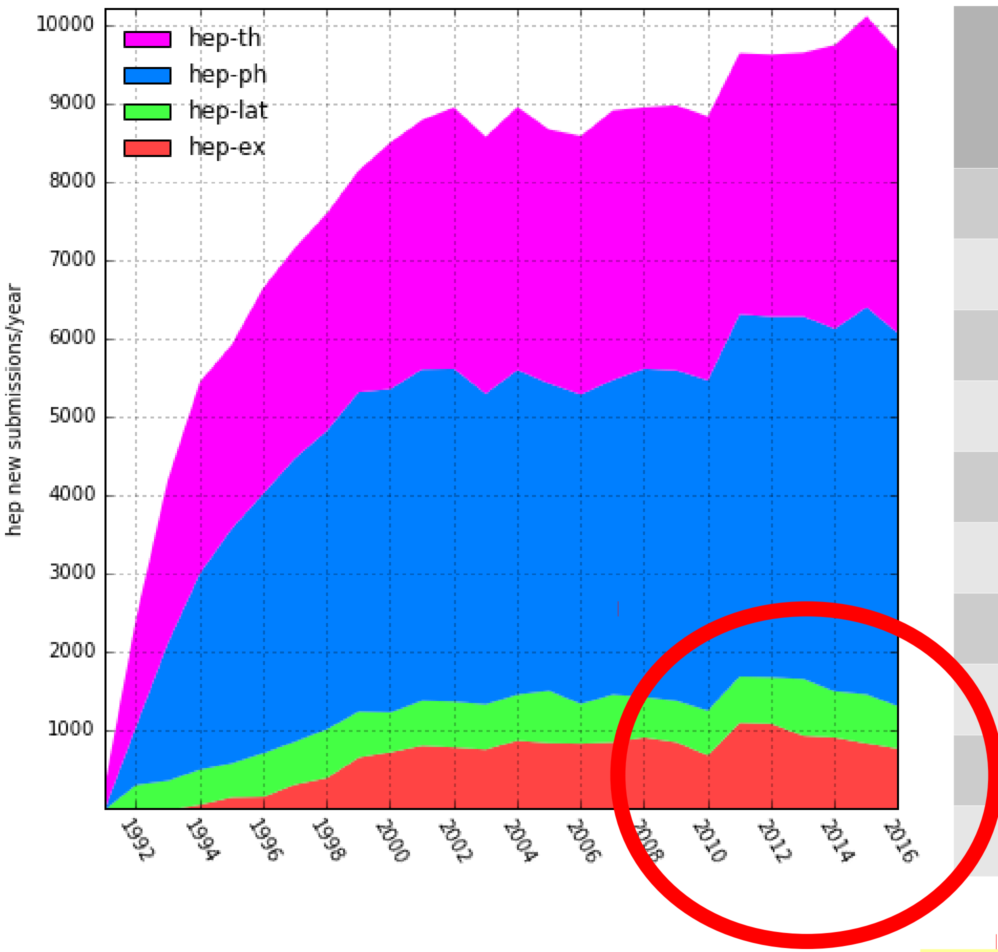




is this a cause for concern?

The health of hep-ex

https://arxiv.org/help/stats/2016_by_area/index



Statistics from INSPIRE

	Total hep-ex	Without conference reports & proceedings (tc c or tc proceedings)
2007	706	321
2008	926	414
2009	865	390
2010	696	369
2011	1111	617
2012	1100	690
2013	945	500
2014	924	544
2015	849	573
2016	779	535

O(500) new papers in 12 months
Roughly ½ from LHC …
so roughly ½ from elsewhere

Probably not
(instead, are we becoming more selective about putting material on arXiv?)

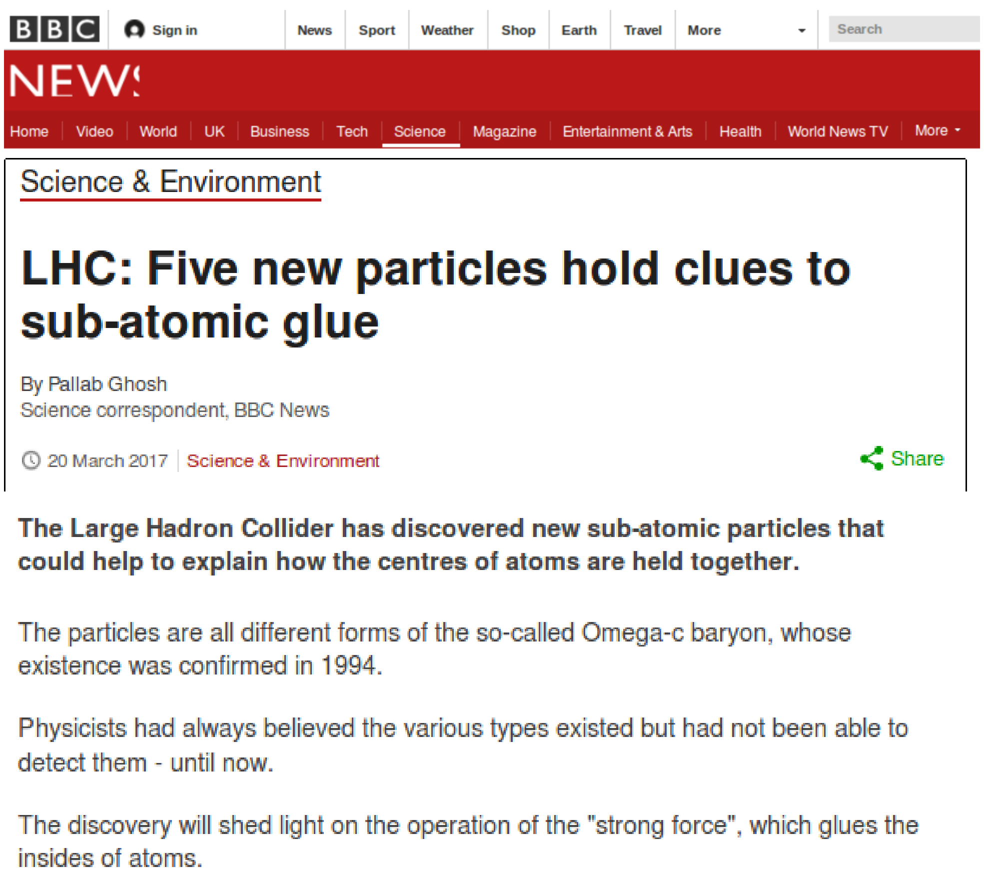
Success or failure?

- Any suggestion that we have “failed” to discover new physics should be rejected
- Our job is to explore nature, without bias
- However …
  - possible that signals are waiting to be found
  - but we are not looking in the right place
  - good new ideas are (always) needed
- We have not succeeded as much as we would like, yet

Morello

Some good (and accurate) news

- Many discoveries being made
  - just not the ones we want the most, perhaps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Science & Environment

LHC: Five new particles hold clues to sub-atomic glue

By Pallab Ghosh
Science correspondent, BBC News

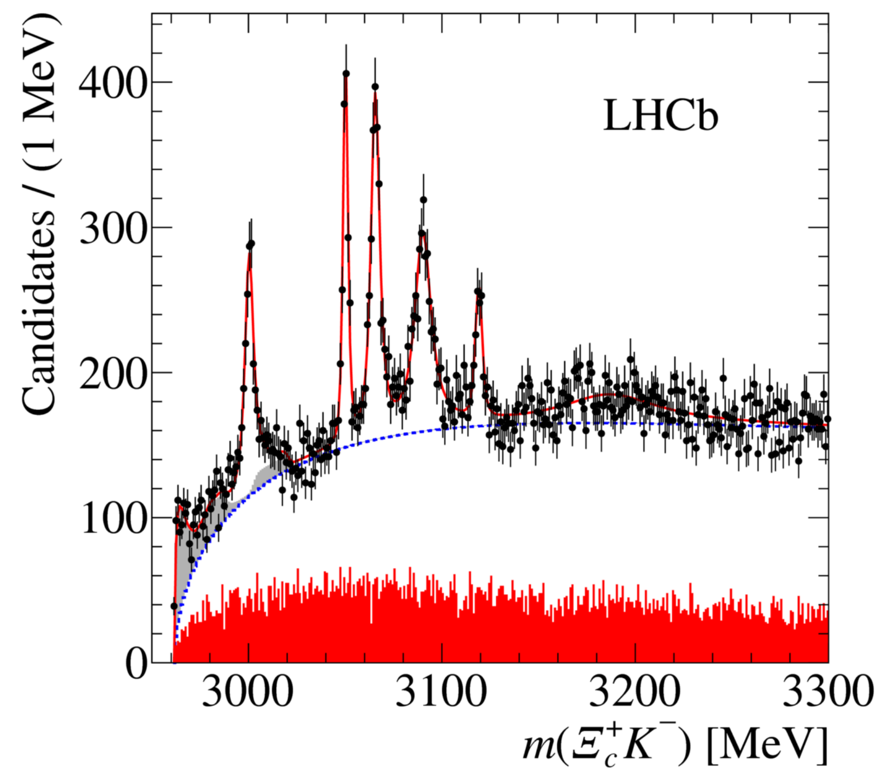
20 March 2017 | Science & Environment | Share

The Large Hadron Collider has discovered new sub-atomic particles that could help to explain how the centres of atoms are held together.

The particles are all different forms of the so-called Omega-c baryon, whose existence was confirmed in 1994.

Physicists had always believed the various types existed but had not been able to detect them - until now.

The discovery will shed light on the operation of the "strong force", which glues the insides of atoms.



The Standard Model scalar
BEH boson is (nearly) 5

Main features (mass, spin) now established
But developments still happening at a rapid rate

In case the analogy is useful ...

- gravitational waves: 1 (baby)
- BEH boson: 5 (child)
- neutrino oscillations: 15 (teenager)
- top quark: 22 (young adult)
- W & Z bosons: 34 (prime of life)
- dark matter: 37 (identity crisis)
- beauty quark: 40 (middle aged but still life in the old dog)
- Moriond series: 51 (can teach the young bucks a thing or two)
- muon: 80 (keeper of the family secrets?)

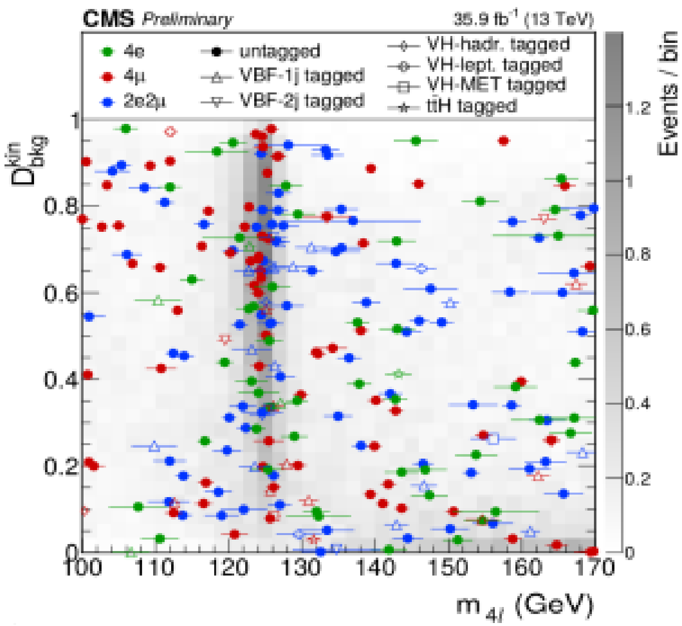
(date of birth and, in some cases, {p,m}aternity open to discussion)

Oda Mei

BEH mass

H → ZZ* → 4l

CMS-PAS-HIG-16-041

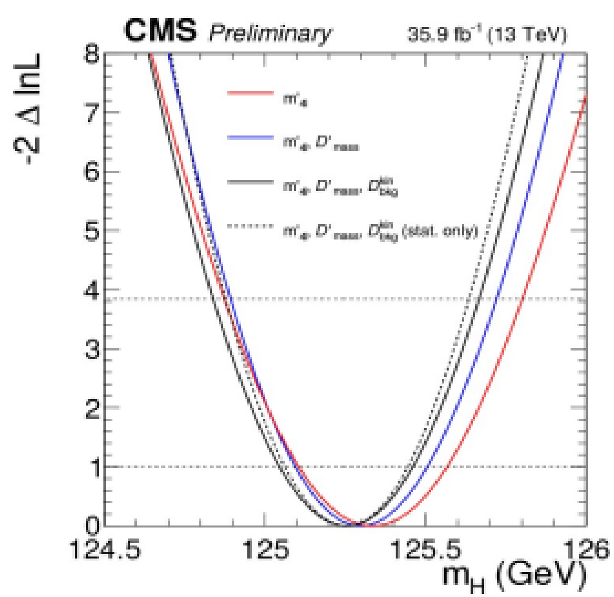


about 2‰ precision

Use per event mass uncertainty + ME-based kinematic discriminant + Z_1 mass constraint:

125.26 ± 0.20 (stat.) ± 0.08 (sys.) GeV

Run I ATLAS+CMS (4l, γγ) combination: 125.09 ± 0.21(stat.)± 0.11(sys.) GeV



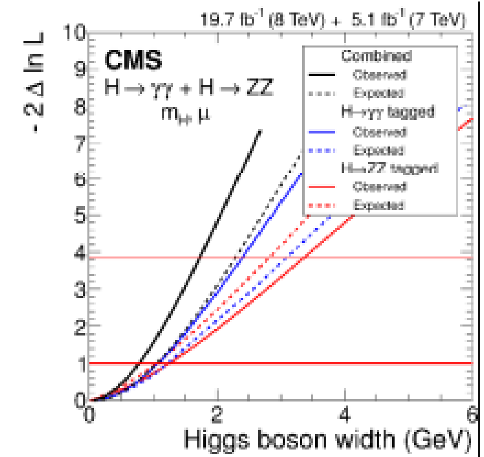
Precision gain in mass measurement:

- Use m4l alone: $L(m_{4l})$
- + per-event mass uncertainty: $L(m_{4l}, D_{mass})$ — 9.8%
- + ME-based kinematic discriminant (CMS Run1 style): $L(m_{4l}, D_{mass}, D^{kin}_{bkg})$ — 3.1%
- + Z_1 mass constraint: $L(m'_{4l}, D'_{mass}, D^{kin}_{bkg})$ — 8.1%

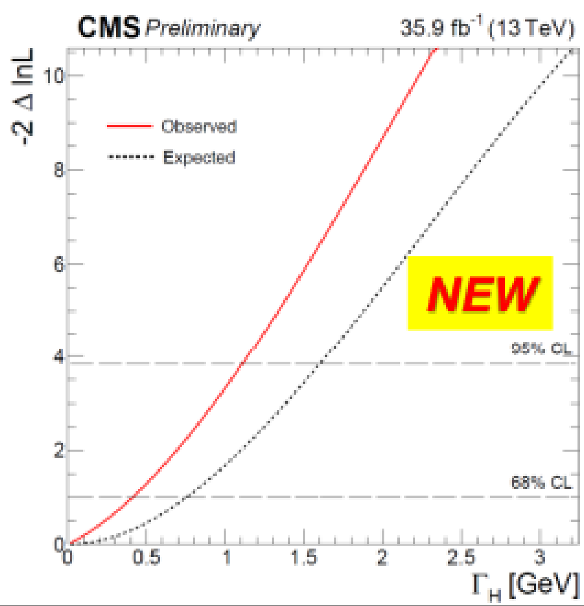
21.0%

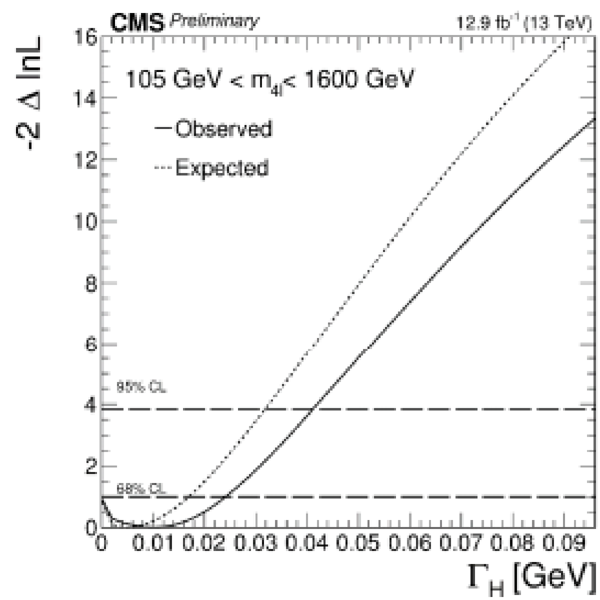
BEH width

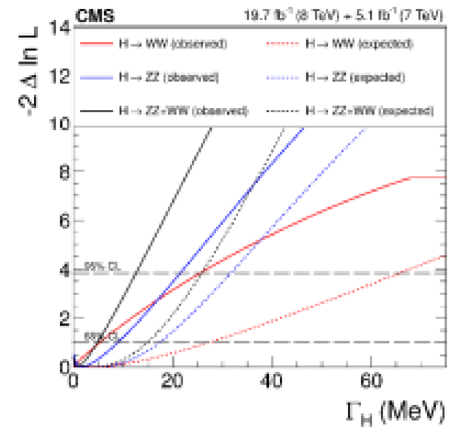
- Mass width is measured with two very different methods.
- $\Gamma_H = 0.00^{+0.41}_{-0.00}$ GeV with only on-shell
  - Tighter limit than Run 1
- $\Gamma_H = 10^{+14}_{-10}$ MeV with both on-shell and off-shell
  - With strong theory assumptions
  - With only 12.9 fb^{-1}



EPJC 75 (2015) 212

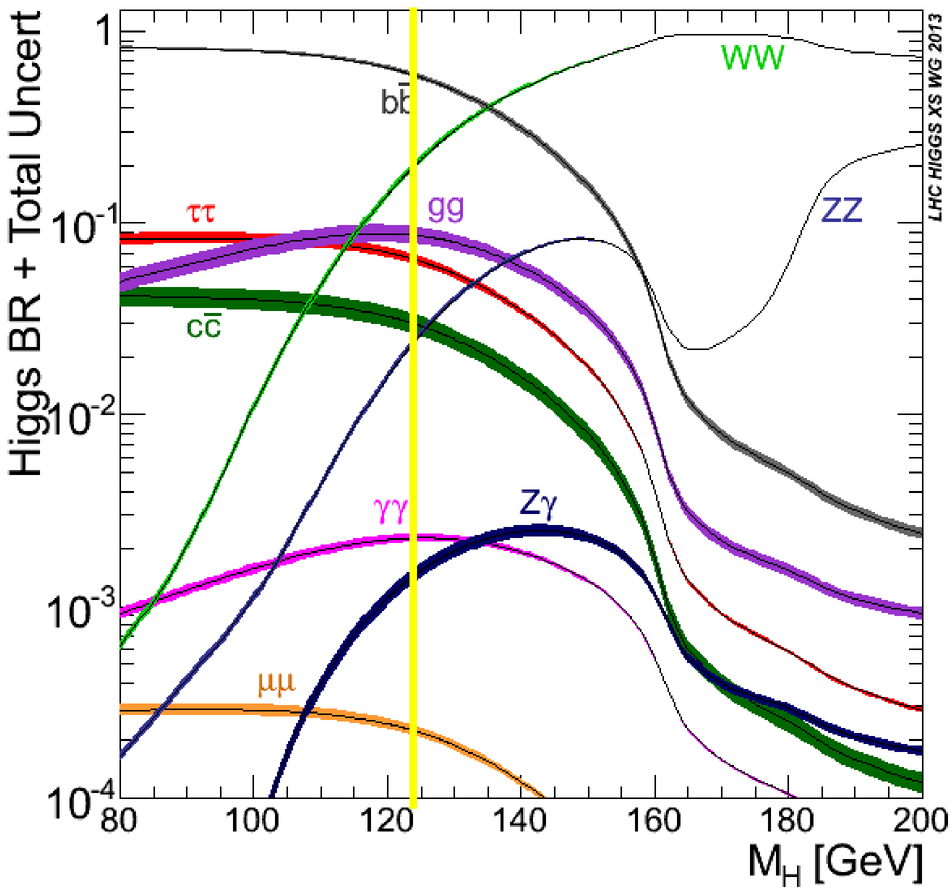


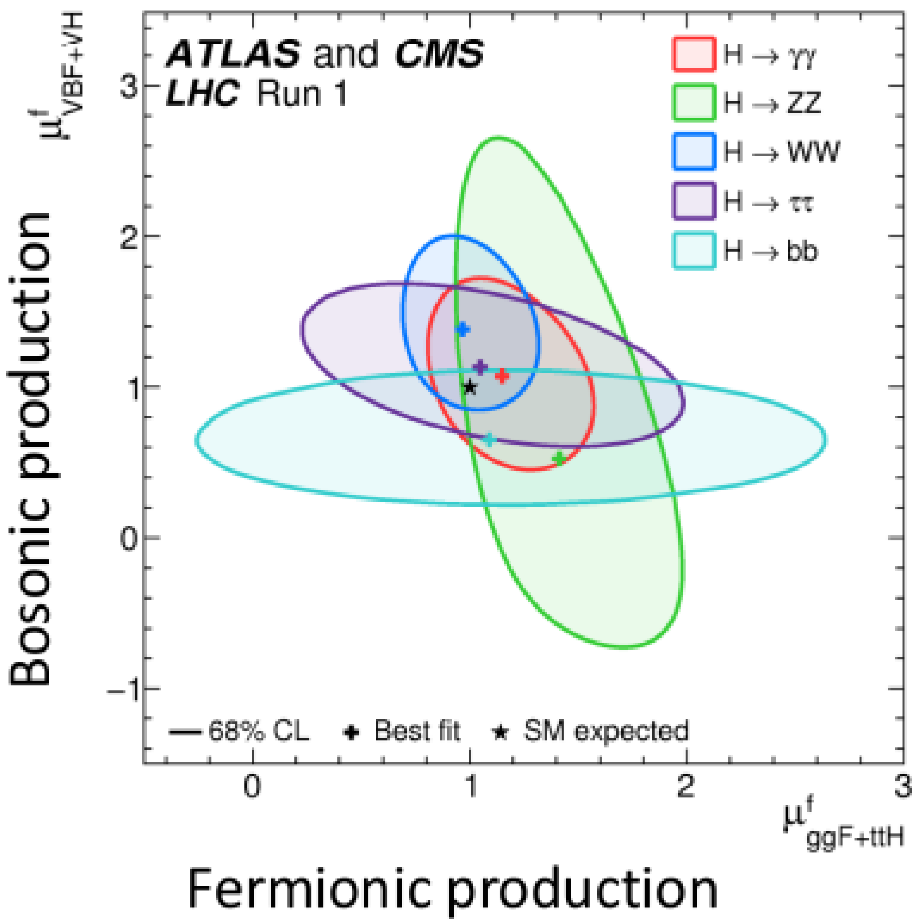




JHEP 09 (2016) 051

BEH couplings



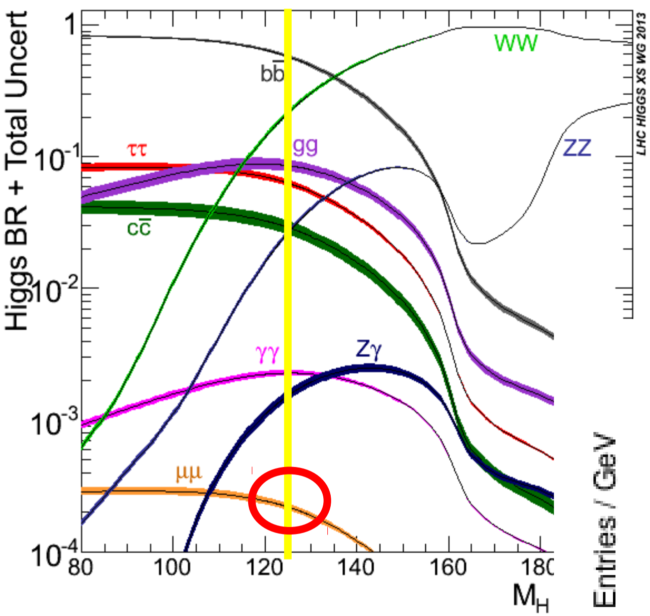


Gaycken

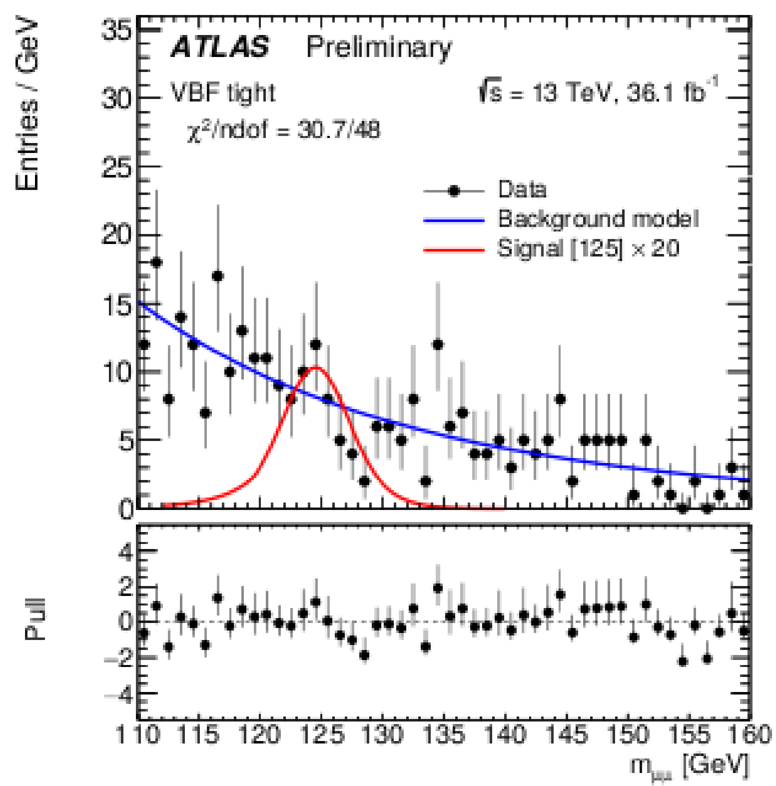
BEH couplings

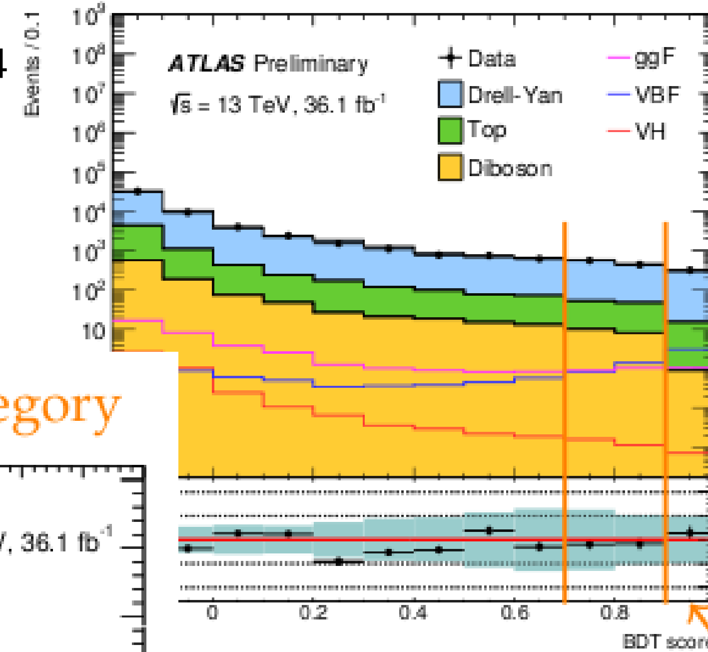
H → μμ

ATLAS-CONF-2017-014



$m_{\mu\mu}$ in VBF tight category

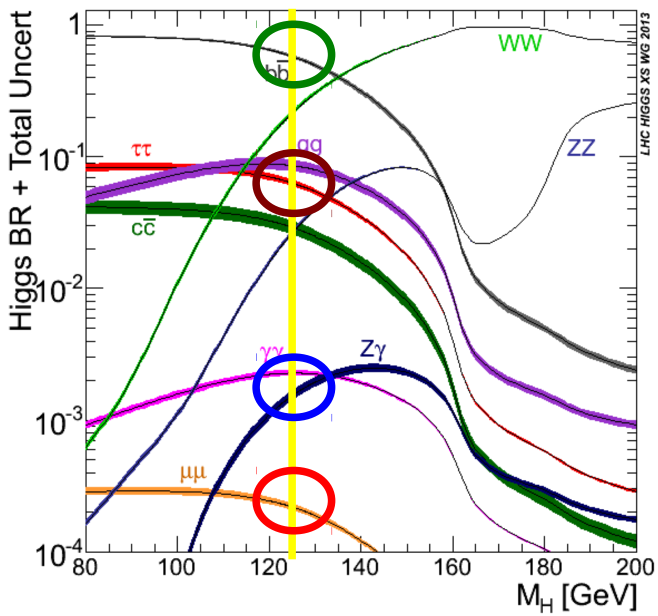




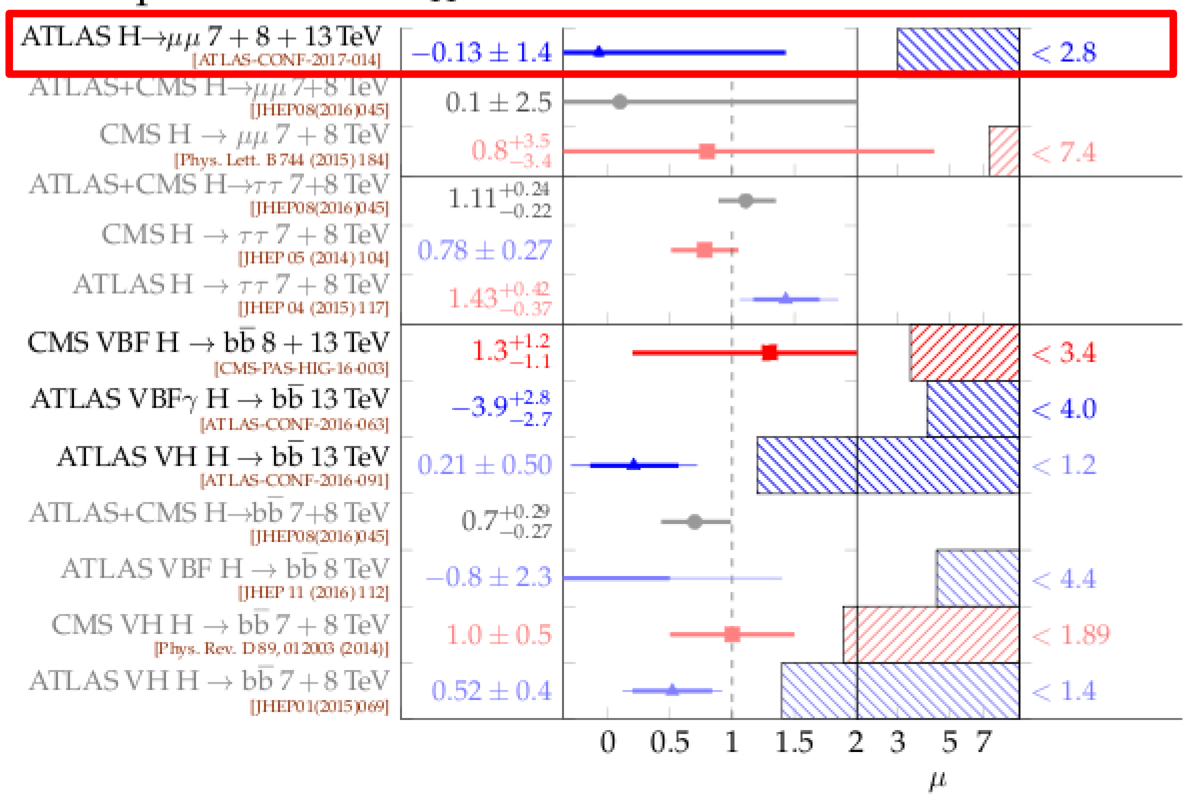
VBF loose tight

Gaycken

BEH couplings



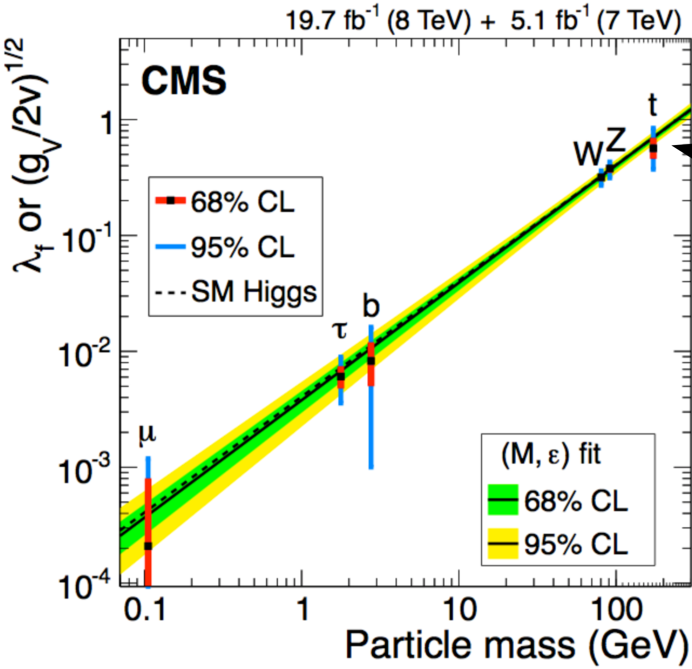
Measured signal strength μ and 95% CL limit on $\sigma \times$ Br relative to the SM expectation for $m_H = 125\,\text{GeV}$:



Exciting prospects for improved H → bb̄, ττ & Zγ results soon

Readioff

BEH couplings

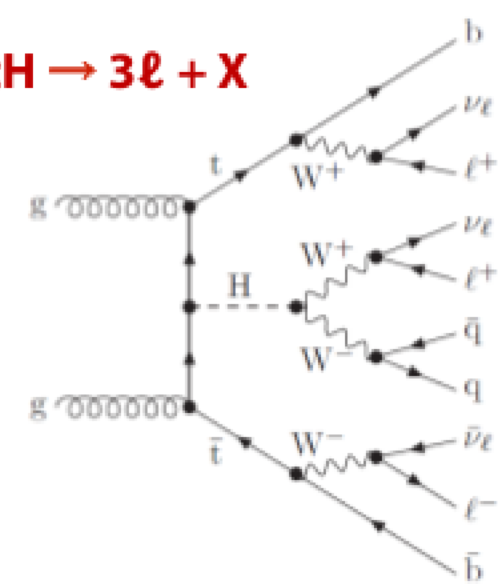


$t\bar{t}H$ production

CMS-PAS-HIG-17-004

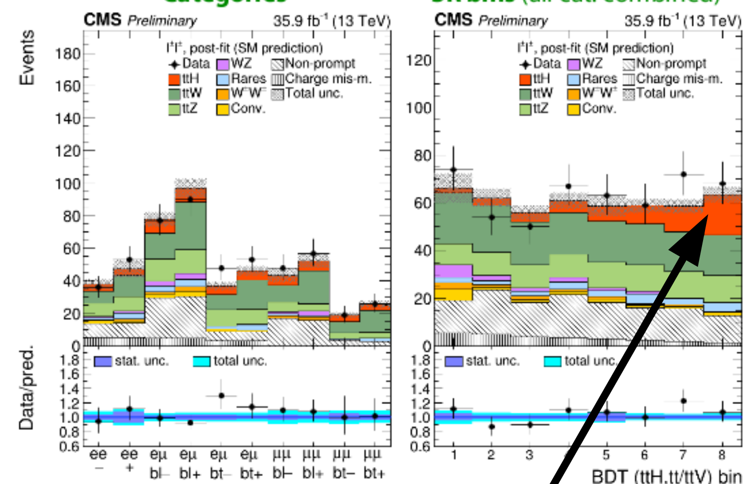
$t\bar{t}H$ coupling known through loops
Ideal to compare with tree-level determination

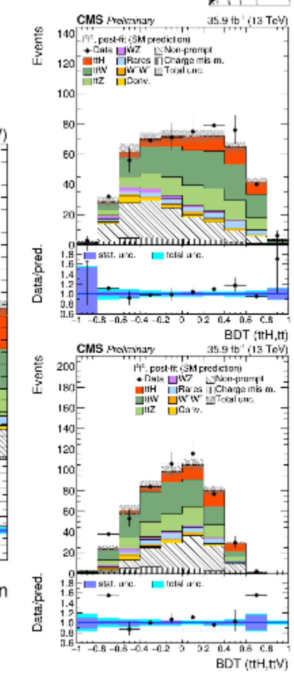
ttH → 3ℓ + X



CMS data, 2ℓ

Categories — **SR bins** (all cat. combined)





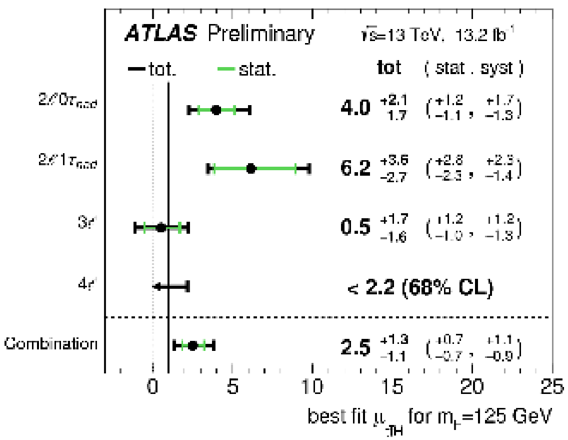
post-fit plots with μ(ttH) constrained to SM predictions

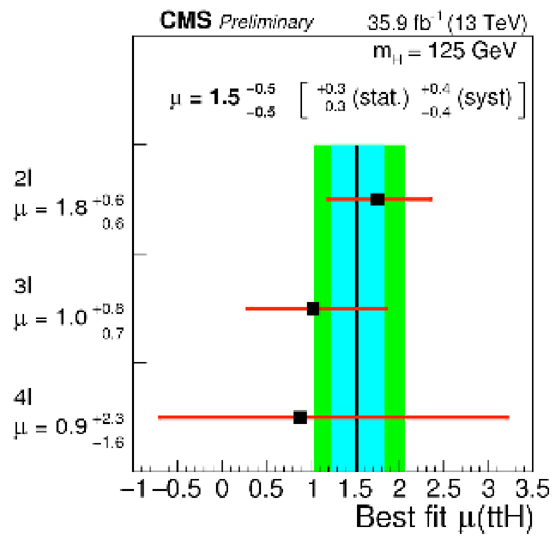
visible excess

Petrucciani

$t\bar{t}H$ coupling

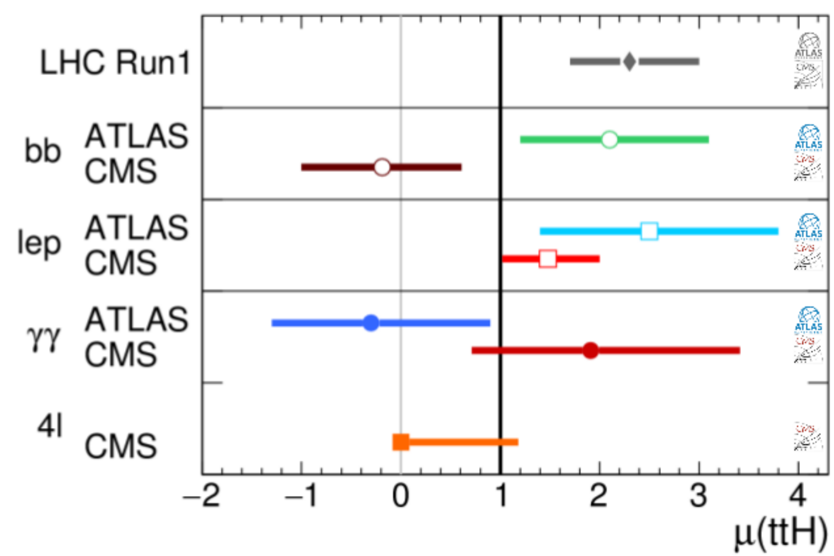
multilepton results





- Both results compatible with SM within about 1σ.
- Significance wrt μ(ttH) = 0 hypothesis:
  - ATLAS: 2.2 σ (expected for SM ttH: 1.0 σ)
  - CMS: 3.3 σ (expected for SM ttH: 2.5 σ)

all results



Cadamuro

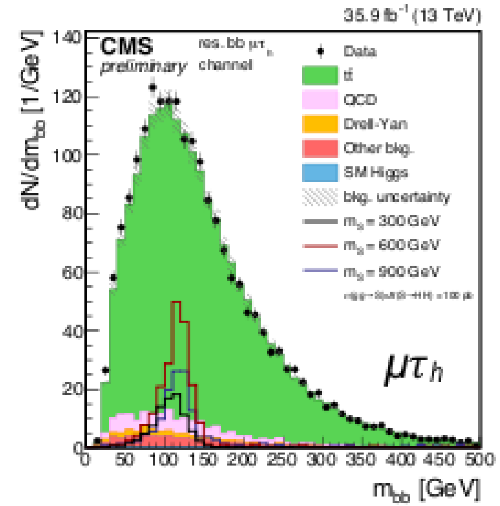
BEH self-coupling

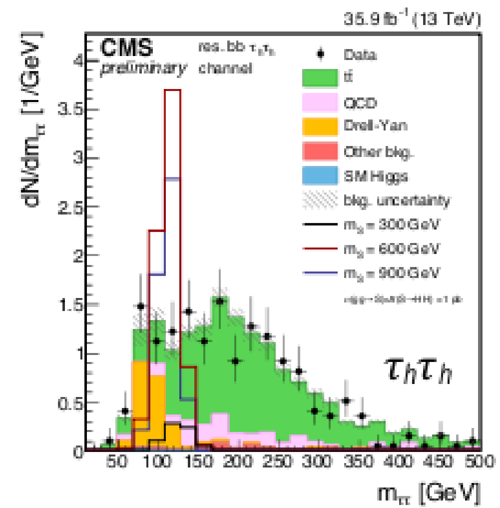
$b\bar{b}\tau\tau$ mode

CMS-PAS-HIG-17-002

Crucial to test shape of V_H & thus test origin of electroweak symmetry breaking

- 3 $\tau\tau$ final states: $\mu\tau_h$, $e\tau_h$, $\tau_h\tau_h$
  - require the presence of μ, e, τ_h candidates and 2 jets in the event
  - $m_{\tau\tau}$ (from likelihood technique) and m_{bb} must be compatible with m_H = 125 GeV
- Main backgrounds:
  - tt : from MC simulation
  - Drell-Yan : MC simulation corrected in data Z→μμ sideband
  - multijet : from data sideband
- Categorization on the selected H→bb jet candidates
  - 2b-tagged jet category
  - 1b-tagged jet + 1 untagged jet category
  - “boosted” category with a R=0.8 jet to improve reconstruction H decays at high m_X

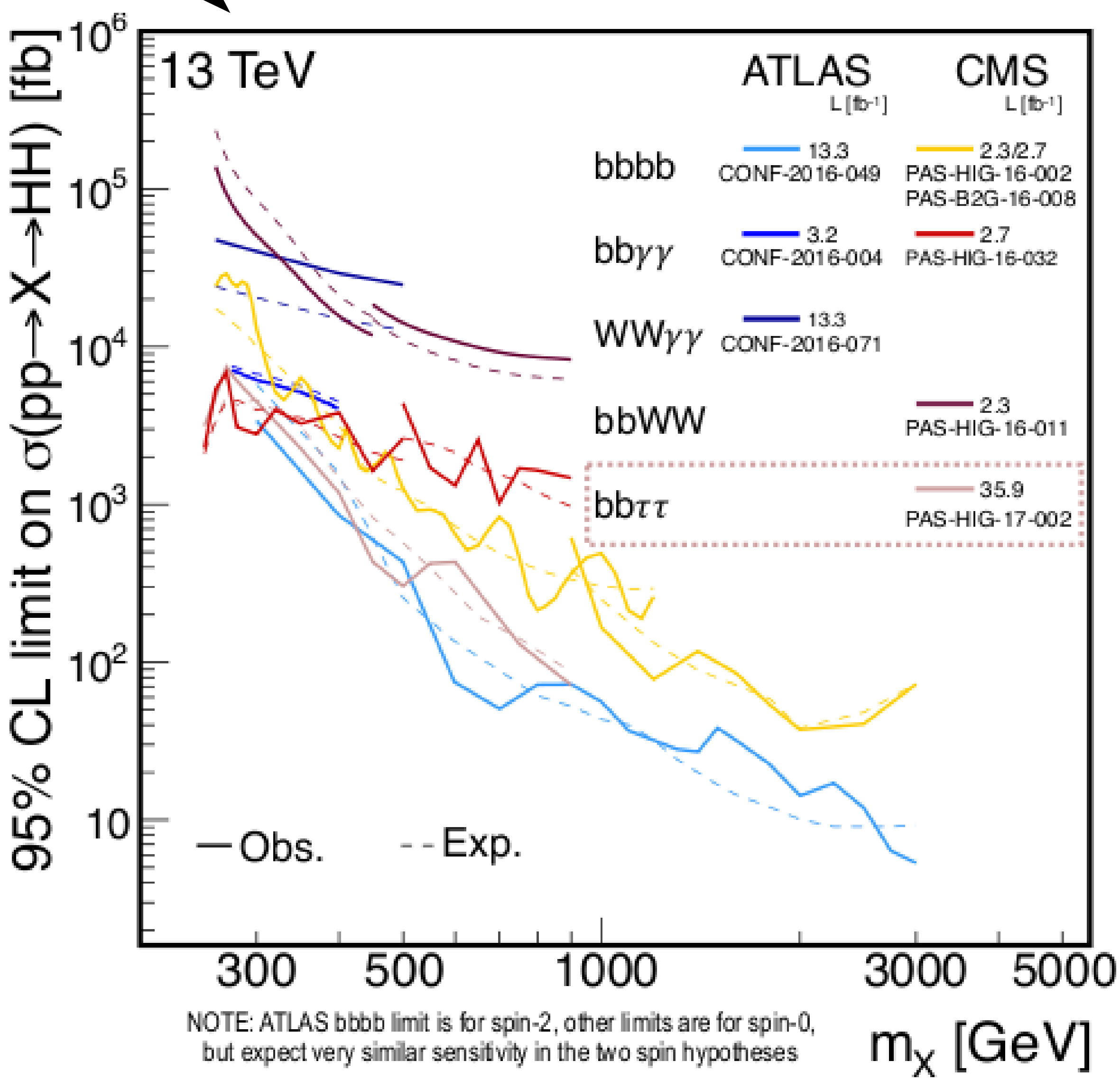




Cadamuro

BEH self-coupling

Resonant (BSM) search



Non-resonant (SM) search

Chan.	Obs. (exp.) 95% C.L. limit on σ/σ_{SM} ATLAS	CMS
bbbb	29 (38)	342 (308)
bbWW	-	410 (227) ⊡
bbττ	-	28 (25) ⊡
bbγγ	117 (161)	91 (90)
WWγγ	747 (386)	-

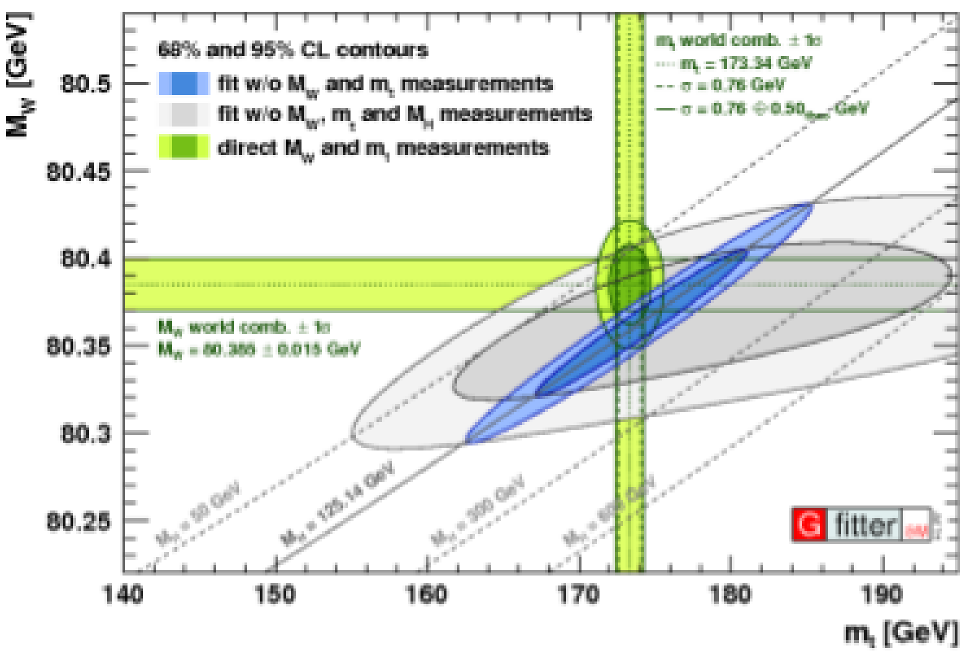
2.3-3.2 fb⁻¹ | 13.3 fb⁻¹ | 35.9 fb⁻¹

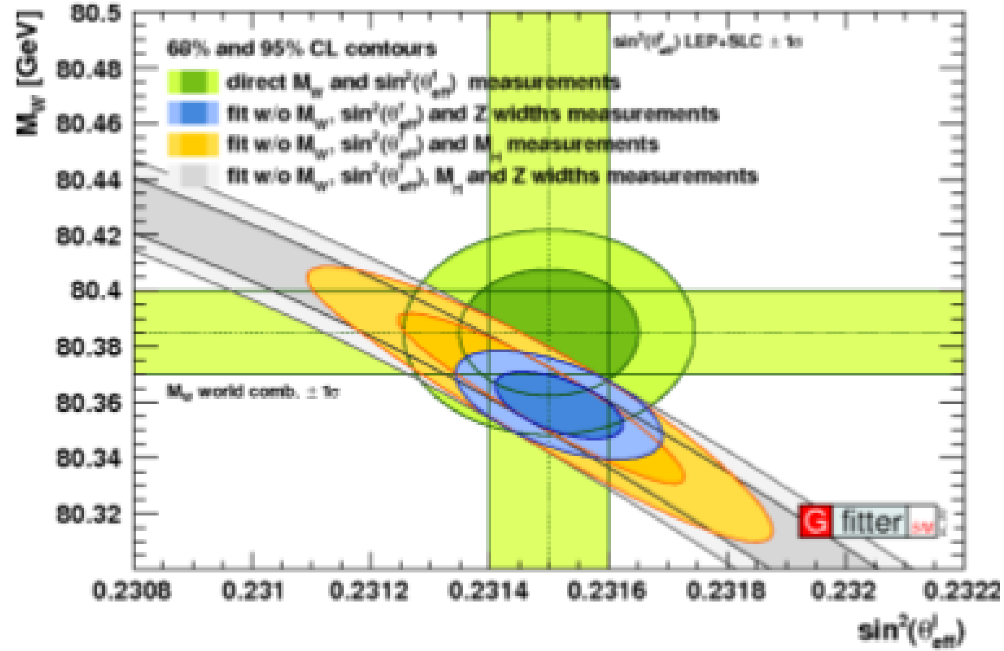
⊡ : Test of anomalous HH couplings

Observation will require full HL-LHC statistics & ATLAS+CMS combination

Han
Erler

Electroweak fits





Over-constrained parameters:

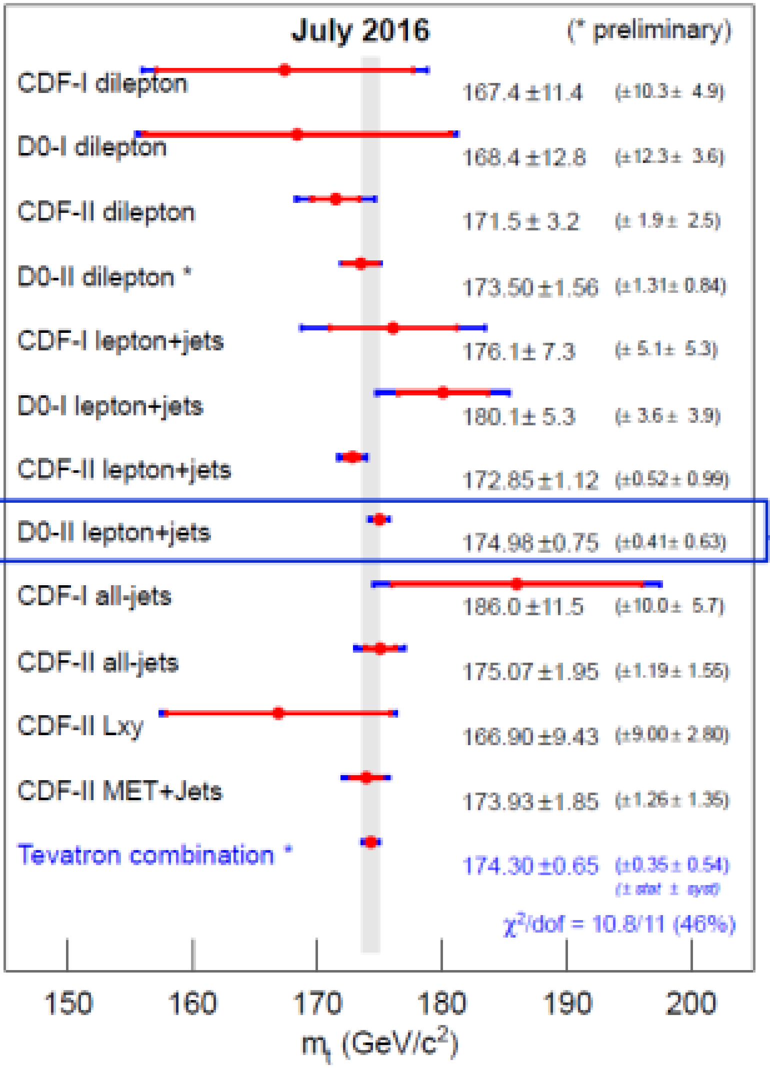
$$\alpha_{em}, G_F, M_Z, M_W, \sin^2\theta_W, m_{top}, M_H$$

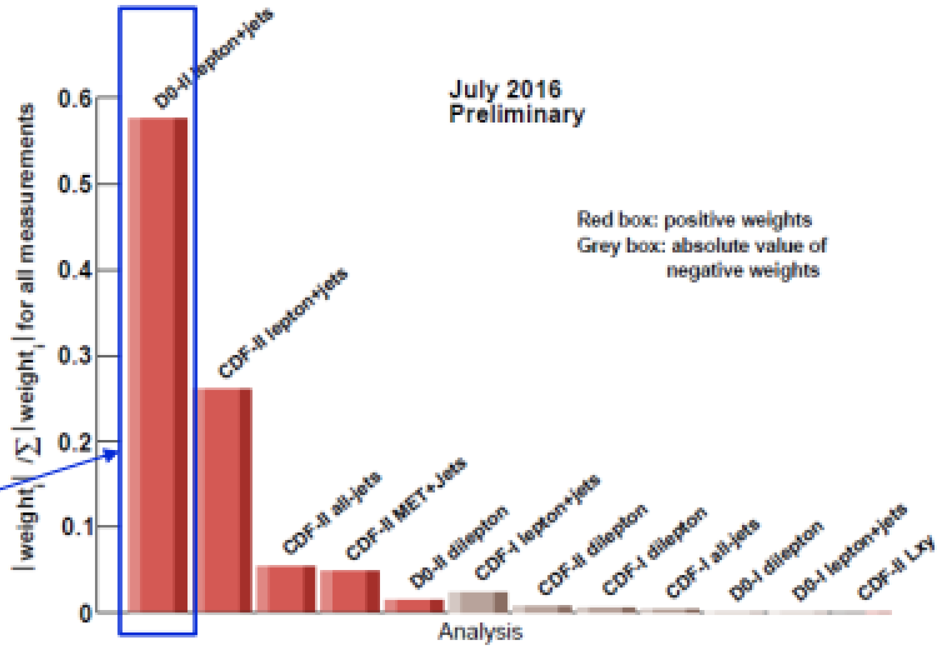
let's look at these in reverse order

Han Bartoš

top mass (Tevatron)

- Combination of 12 CDF and D0 results, with the same uncertainty and correlation definition





174.30 ± 0.65 GeV

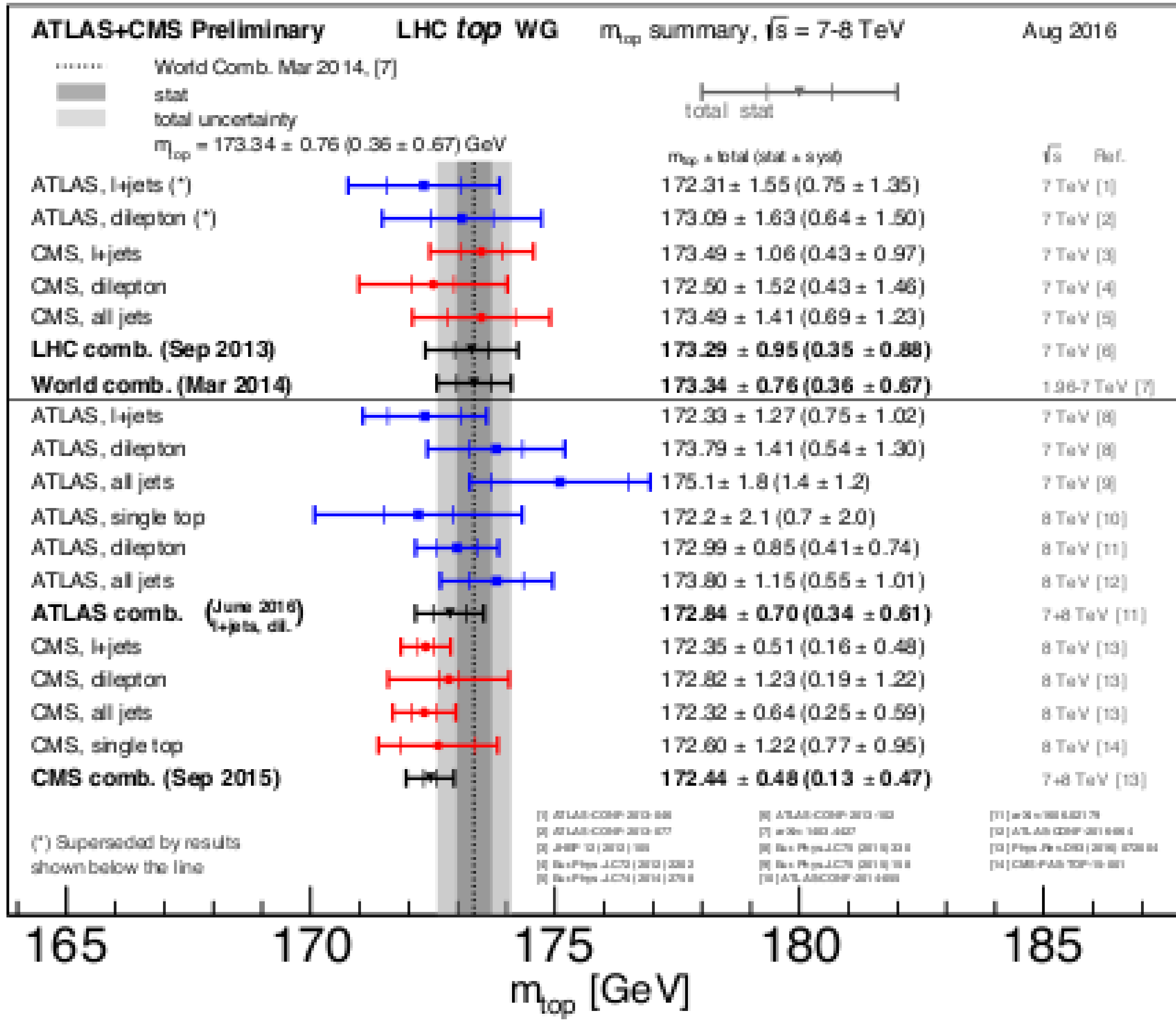
arXiv:1608.01881

D0 combination: 174.95 ± 0.40 (stat) ± 0.64 (syst) GeV arXiv:1703.06994

Owen

top mass (LHC)

Measurements systematics limited, but many systematics uncorrelated between analyses → still room for improvement with more data



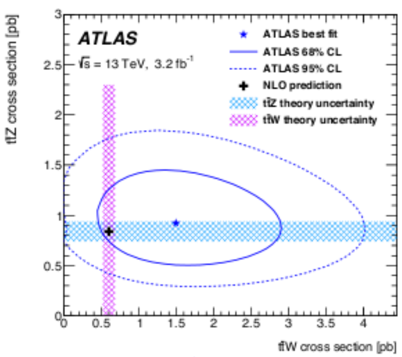
m_{top} = 173.34 ± 0.76 (0.36 ± 0.67) GeV

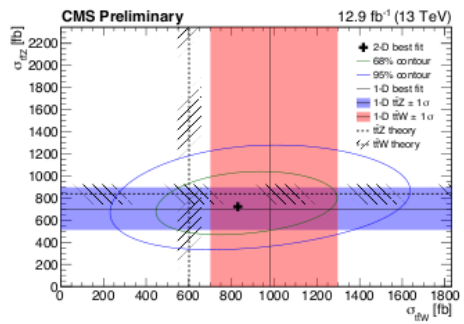
Owen Dobur

(Aside: top production)

$t\bar{t}V$ coupling

- Fit to the many signal-regions to simultaneously extract ttW and ttZ cross-sections:





$t\bar{t}W: 2.2\sigma$ (expected: 1.0σ)

$t\bar{t}Z: 3.9\sigma$ (expected: 3.4σ)

$t\bar{t}W: 3.9\sigma$ (expected: 2.6σ)

$t\bar{t}Z: 4.6\sigma$ (expected: 5.8σ)

Measurements still statistics limited - looking forward to results with higher statistics.

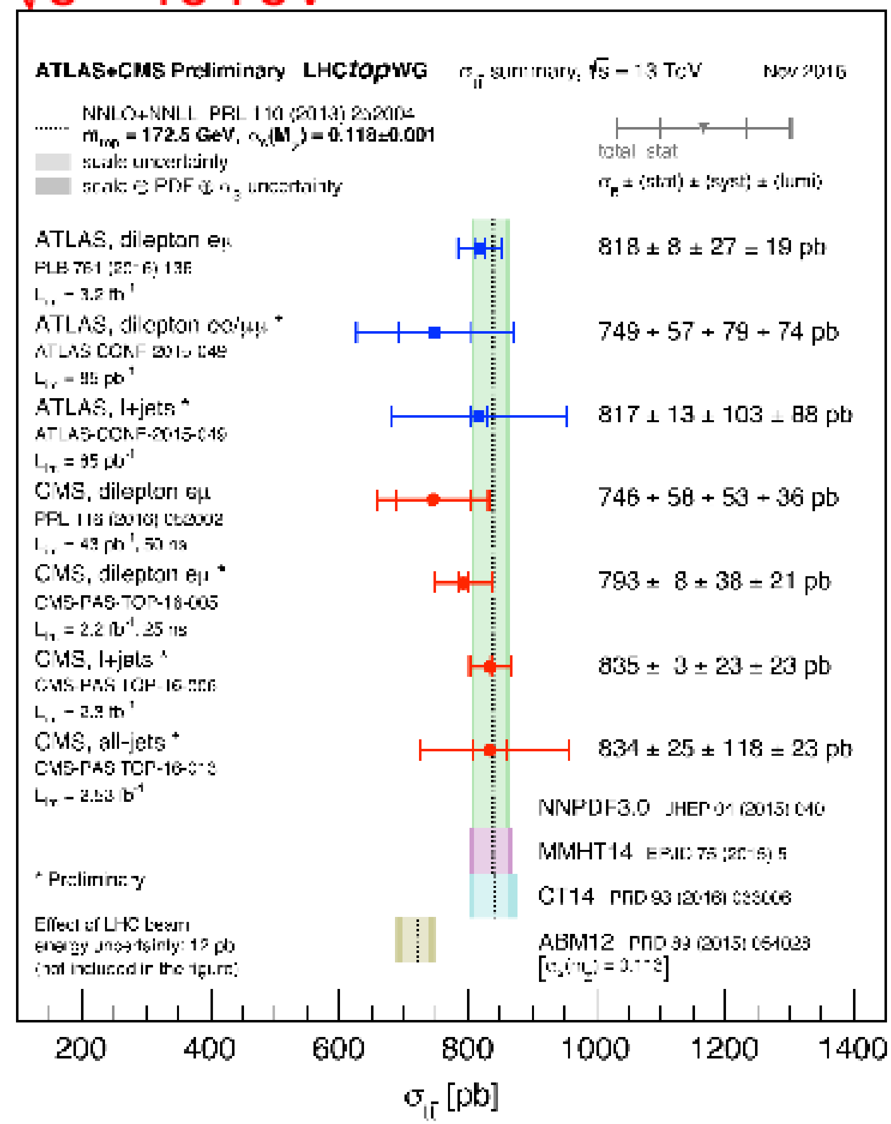
arXiv:1609.01599

CMS-PAS-TOP-16-017

Also

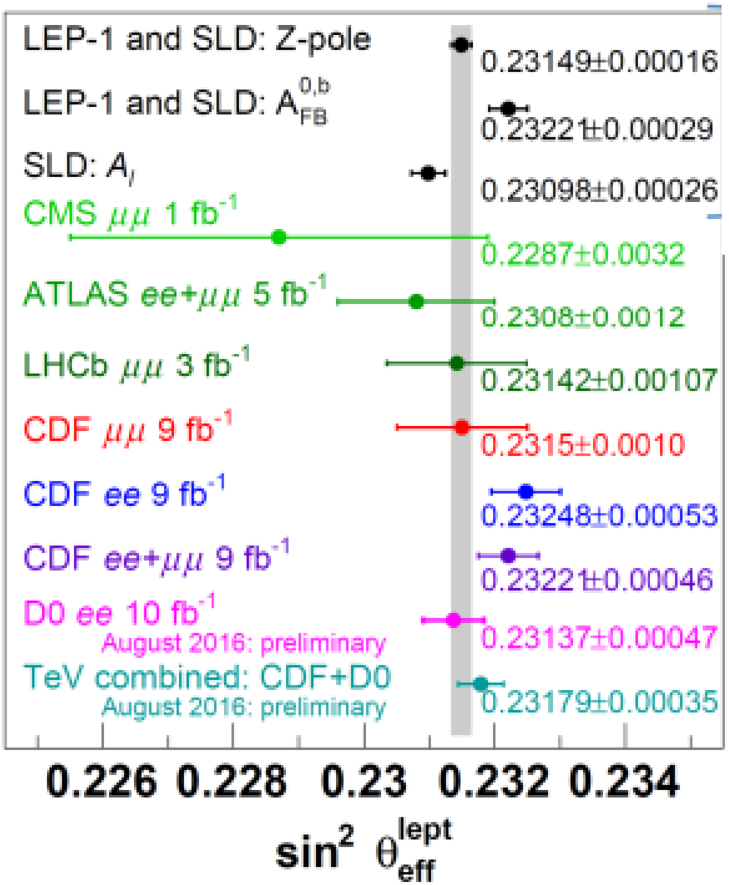
- Double differential $t\bar{t}$ production
- Improved p_T modelling
- Top polarisation
- Boosted tops
- Single top production – measure $|V_{tq}|$
- Search for $t\bar{t}t\bar{t}$

$\sqrt{s} = 13\,\text{TeV}$

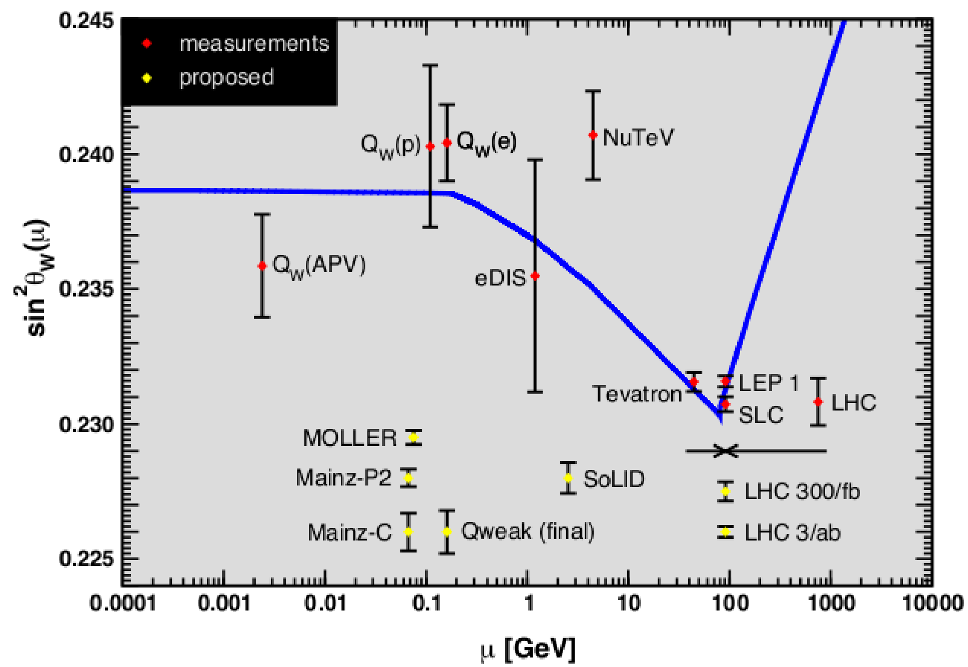


$\sin^2\theta_W$

Han Apyan Erler



good scope for improvement at LHC



Tevatron combination (D0 Z $\rightarrow \mu\mu$ preliminary results not yet included)

$$\sin^2\theta_{eff}^{lept} = 0.23179 \pm 0.00030 \pm 0.00017$$

New experiments & improved measurements will allow to better measure the running (Belle II?)

Han

W mass @ Tevatron

- Strategy:
  - Kinematic variable p_T^l, $E\!\!\!/_T^\nu$, m_T^l distributions in W→*lν* (*l*=*e*/*μ*) channels
  - Likelihood fits of M_W-parameterized simulation templates
  - Lepton E/p scale and recoil calibration with J(ψ)/Y/Z→*ll* data

- Results:

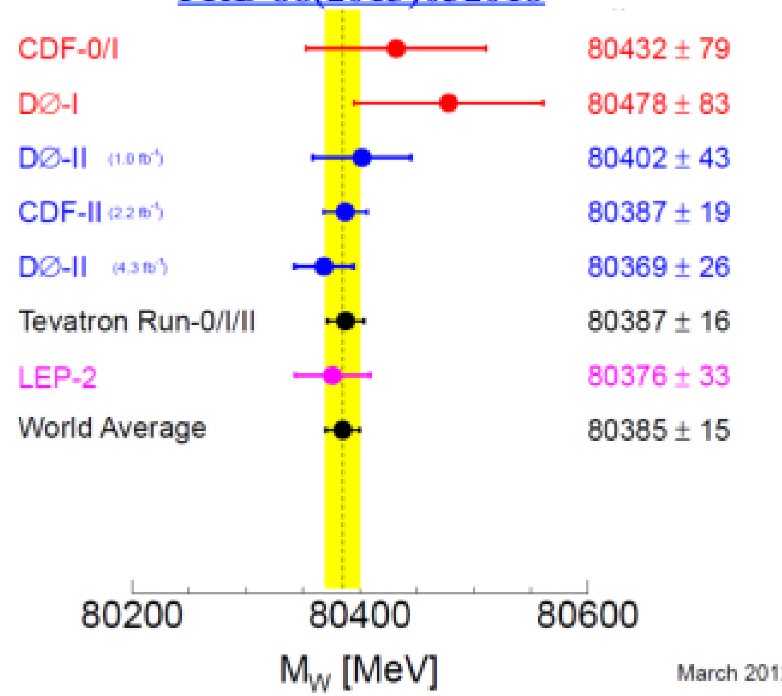
	M_W (MeV)
CDF Run II 2.2fb^{-1} (l=e/μ)	80 387 ± 12 ± 15
D0 Run II 5.3fb^{-1} (l=e)	80 375 ± 11 ± 20

  - Dominant systematic as lepton E/p scale and PDF
  - Tevatron combined with BLUE

M_W = 80387 ± 16 MeV

Consistent with the latest ATLAS result of 80370±19 MeV
arXiv:1701.07240

PRD 88(2013)052018

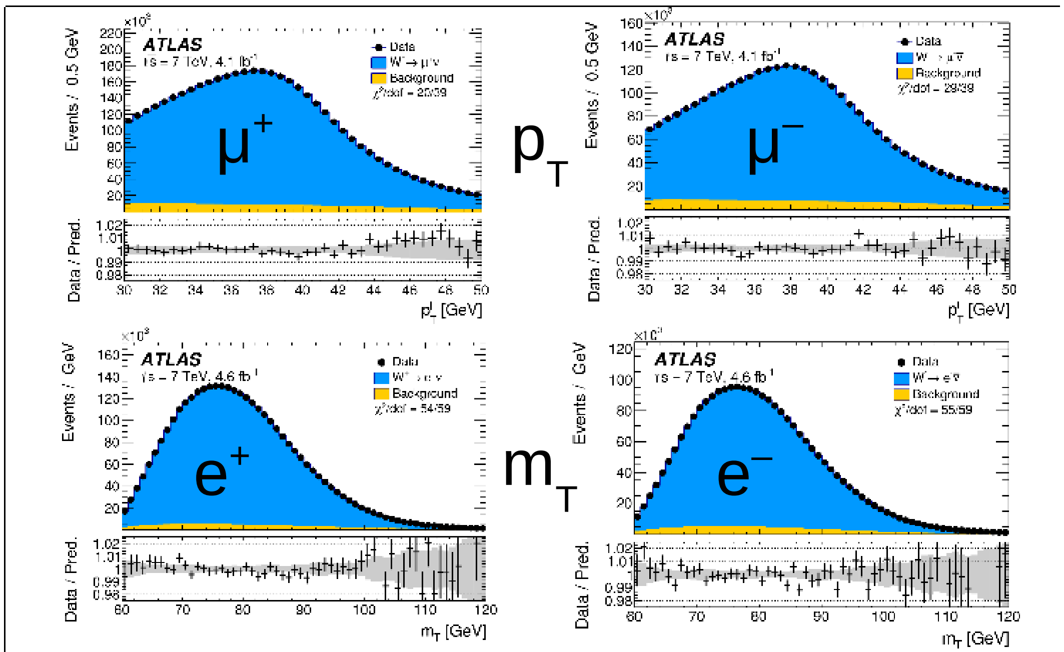


- Status: analysis with full data set of both CDF and D0 are being finalized respectively

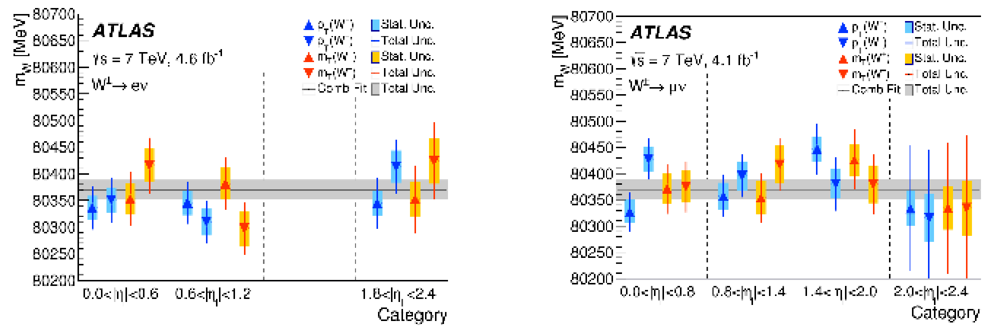
Andari
Rolandi

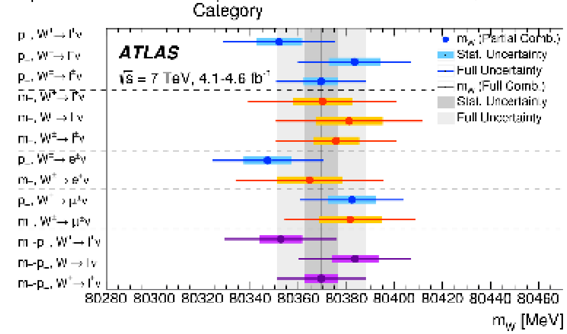
W mass @ ATLAS

arXiv:1701.07240



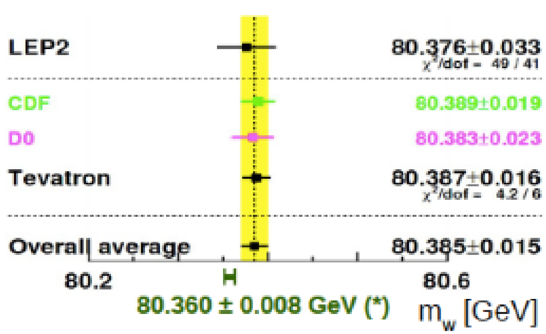
The consistency of the results was checked in the different categories but also in different pileup, u_T and $u_{||}$ bins



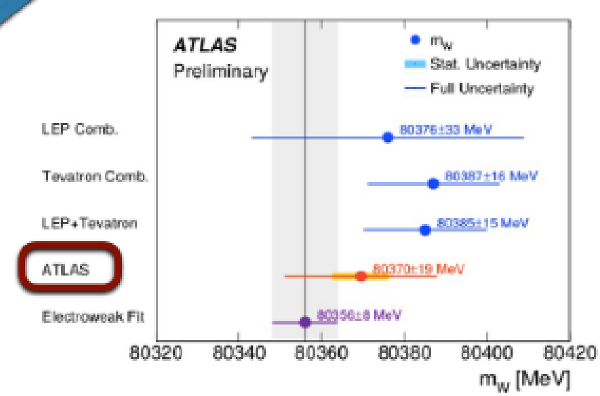


Fitting ranges:
$32<p_T^l<45$ GeV,
$66<m_T<99$ GeV

2012



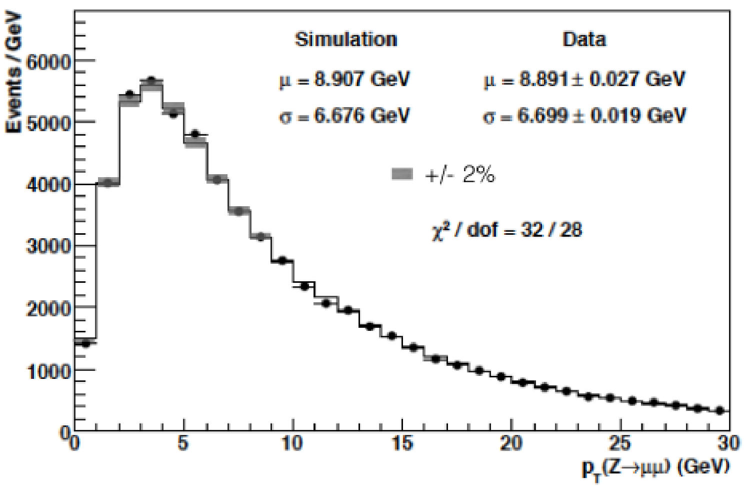
2016

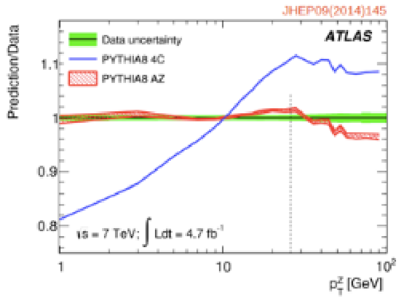


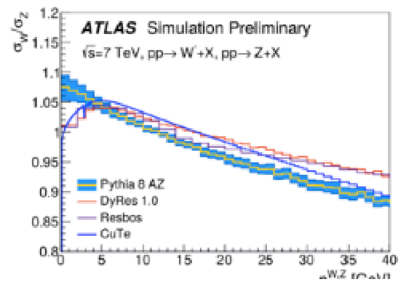
Andari Rolandi

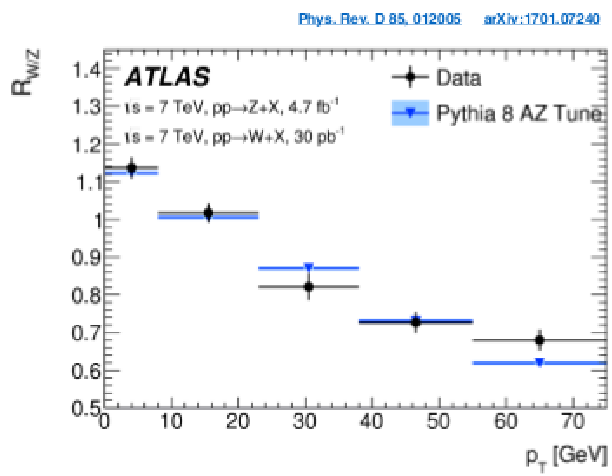
W p_T modelling

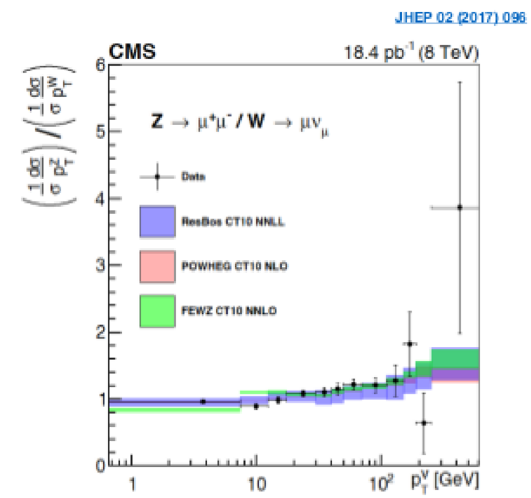
Agreement ~ 2%











Limited precision of the data (~3%), and broad bin width (~8 GeV) limit the impact of these measurements on the systematic uncertainty.

Further measurements would be useful, ideally with low pile-up, targeting bin width <5 GeV and a precision about ~1%.

Constraining the PDFs

Apyan
Forte
Rolandi

W charge asymmetry at LHC

- Constraints on the valence and sea quark distributions
- General good agreement with theory predictions

$$A_e \equiv \frac{\sigma_{W^+\to e^+\nu_e} - \sigma_{W^-\to e^-\bar{\nu}_e}}{\sigma_{W^+\to e^+\nu_e} + \sigma_{W^-\to e^-\bar{\nu}_e}}$$

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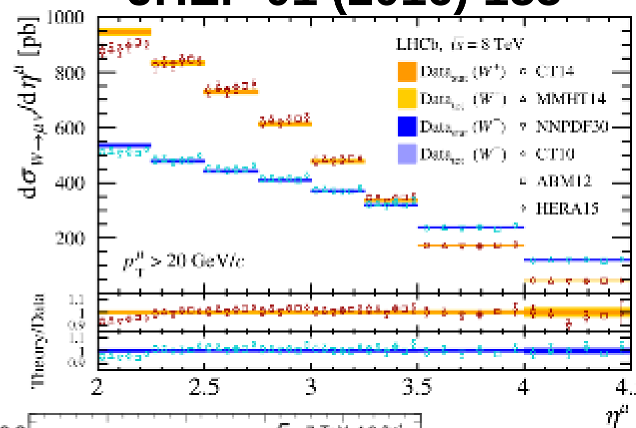
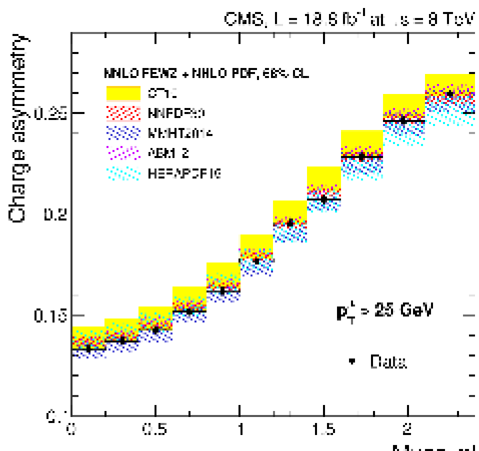
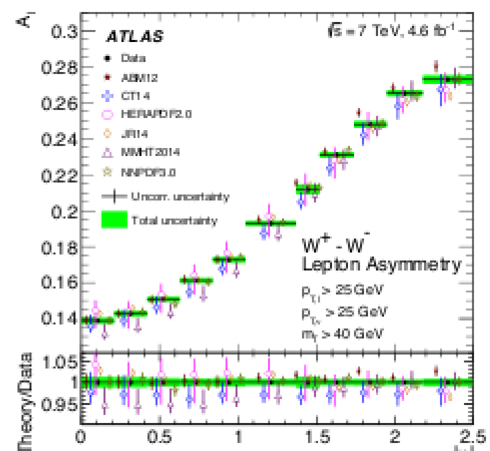


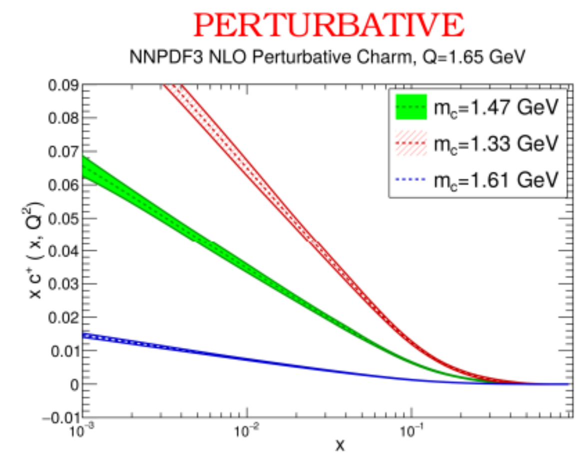


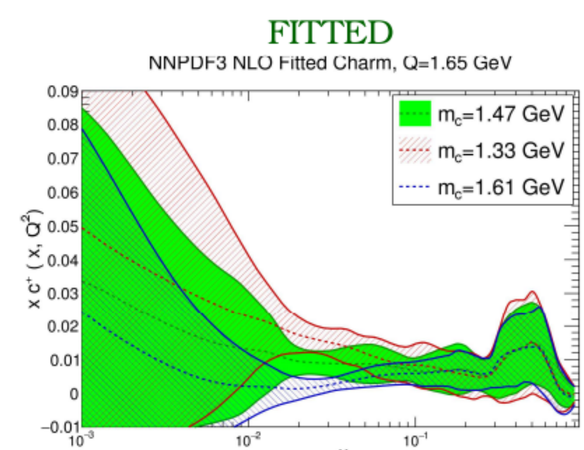
EPJC 76 (2016) 469



Arxiv:1612.03016

Impact of charm mass

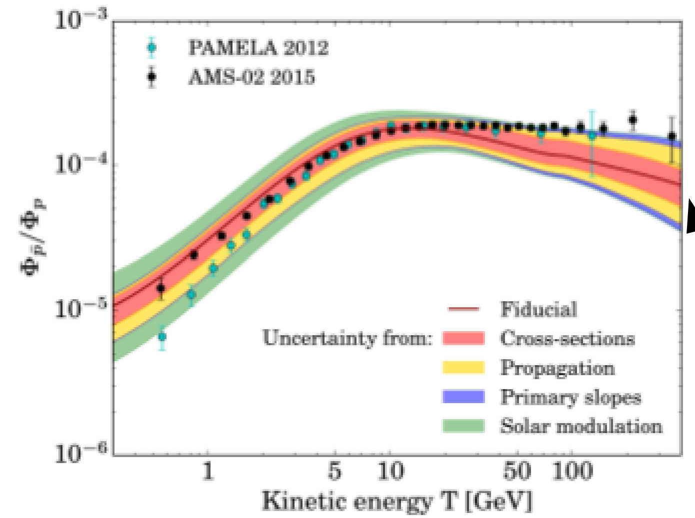




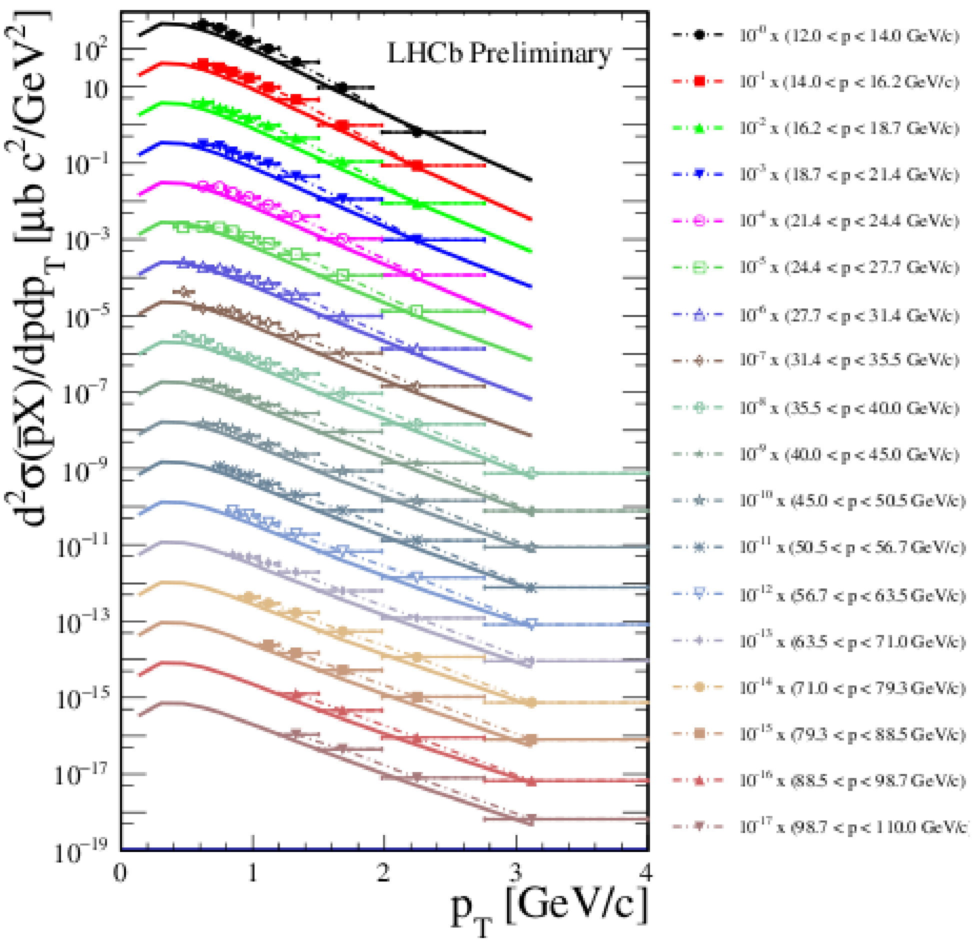
Good prospects for data-driven progress

Graziani

$\bar{p}$ production in pHe collisions



LHCb-CONF-2017-002



Result for **prompt** production (excluding weak decays of hyperons)

The total inelastic cross section is also measured to be

$$\sigma_{inel}^{\text{LHCb}} = (140 \pm 10) \text{ mb}$$

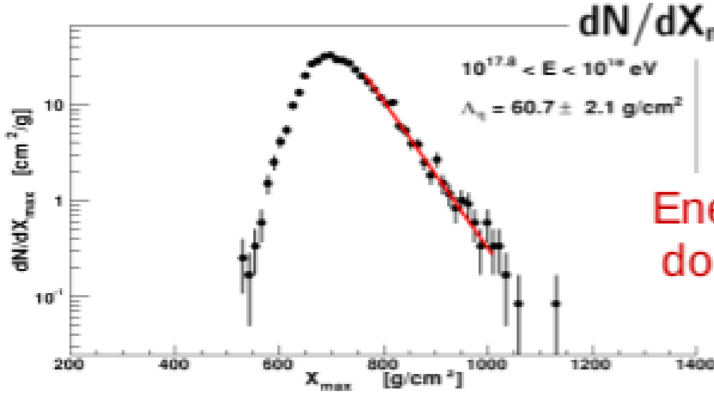
The EPOS LHC prediction [T. Pierog at al, Phys. Rev. C92 (2015), 034906] is 118 mb, ratio is 1.19 ± 0.08.

LHCb results will help to constrain this uncertainty

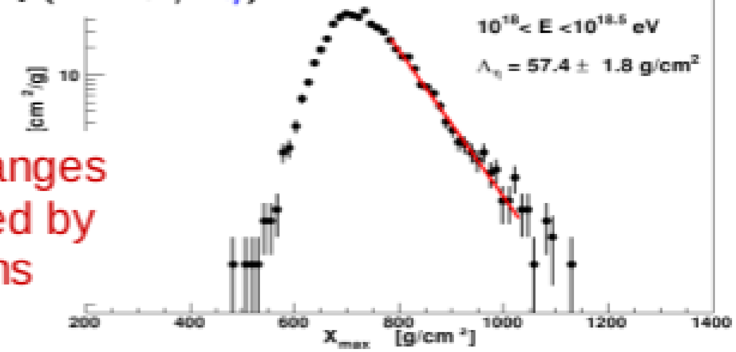
Colalillo

Proton-air cross-section with Pierre Auger

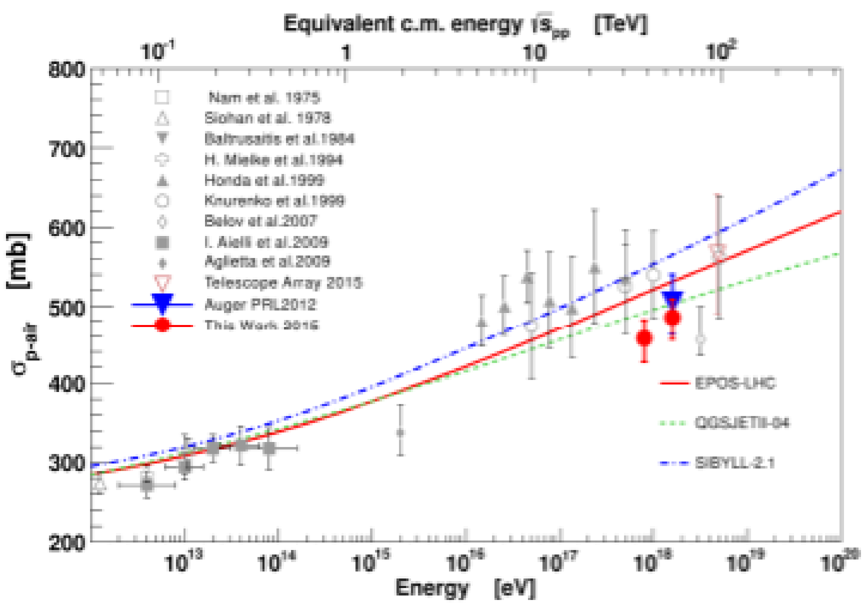
$$dN/dX_{max} \propto \exp(-X_{max}/\Lambda_\eta)$$

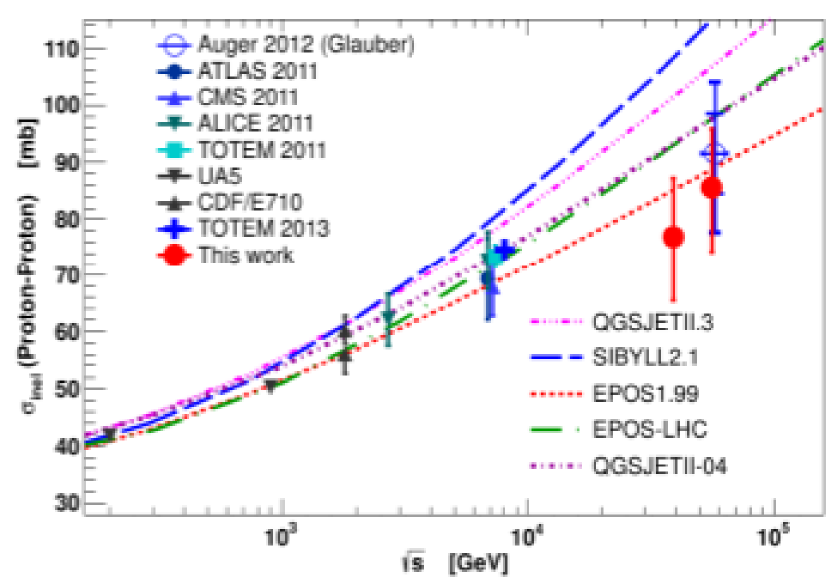


Energy ranges dominated by protons



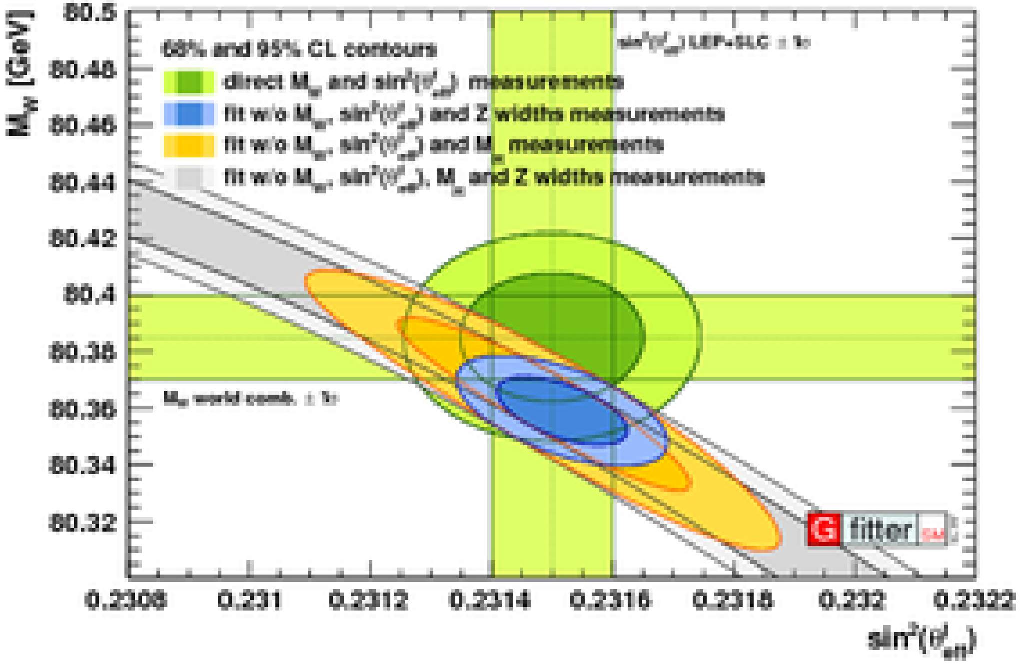
$10^{17.8}$ – 10^{18} eV **10^{18} – $10^{18.5}$ eV**

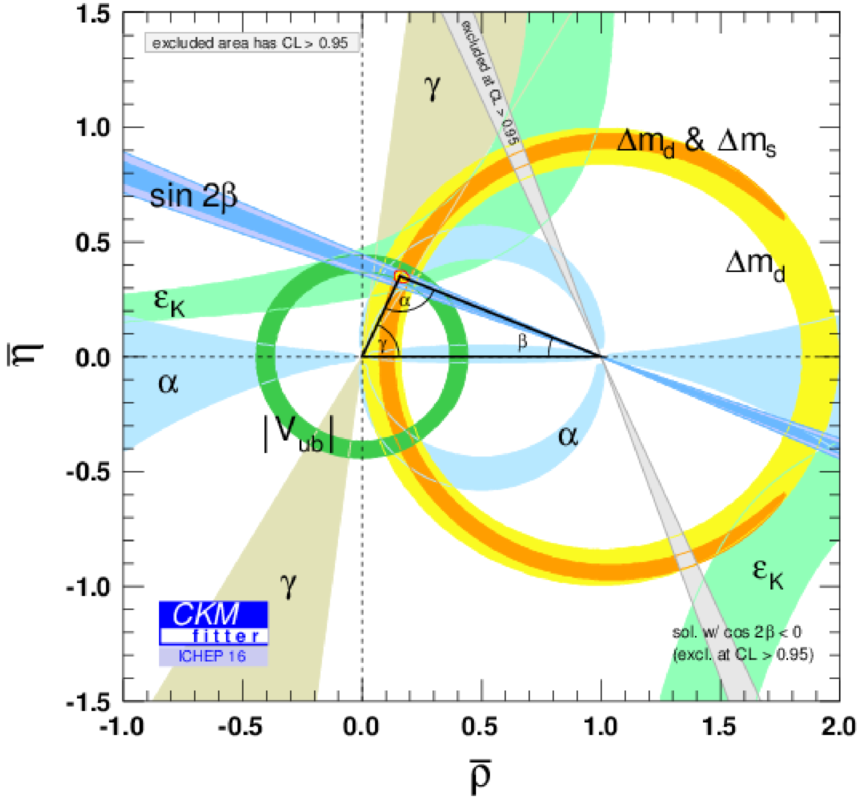




SM fits: EW & CKM

Erler
Zupan



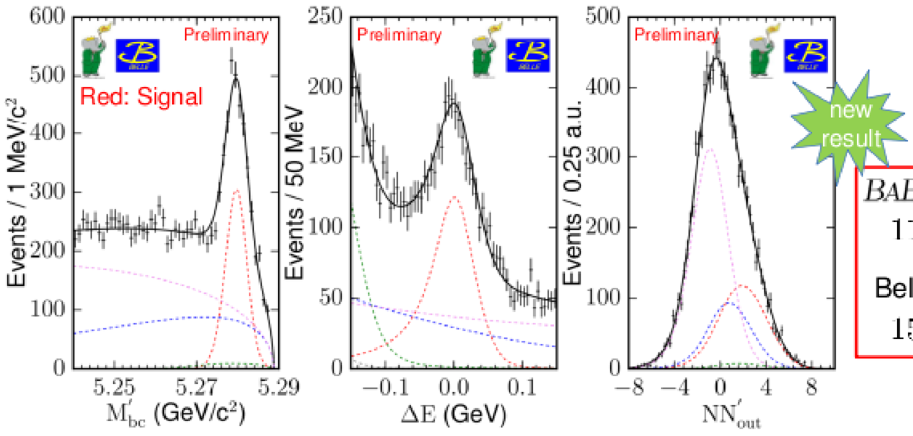


Both sectors overconstrained in the SM – ideal for precision tests
Progress in the EW fit will be challenging
Most measurements in CKM fit statistically limited

Belle II + LHCb phase 2 upgrade: improvement in reach of factor 2.7-4
Like going from 8 TeV to 21-32 TeV!

sin(2β) & cos(2β)

BaBar & Belle preliminary



BABAR :
1129 ± 48 signal events

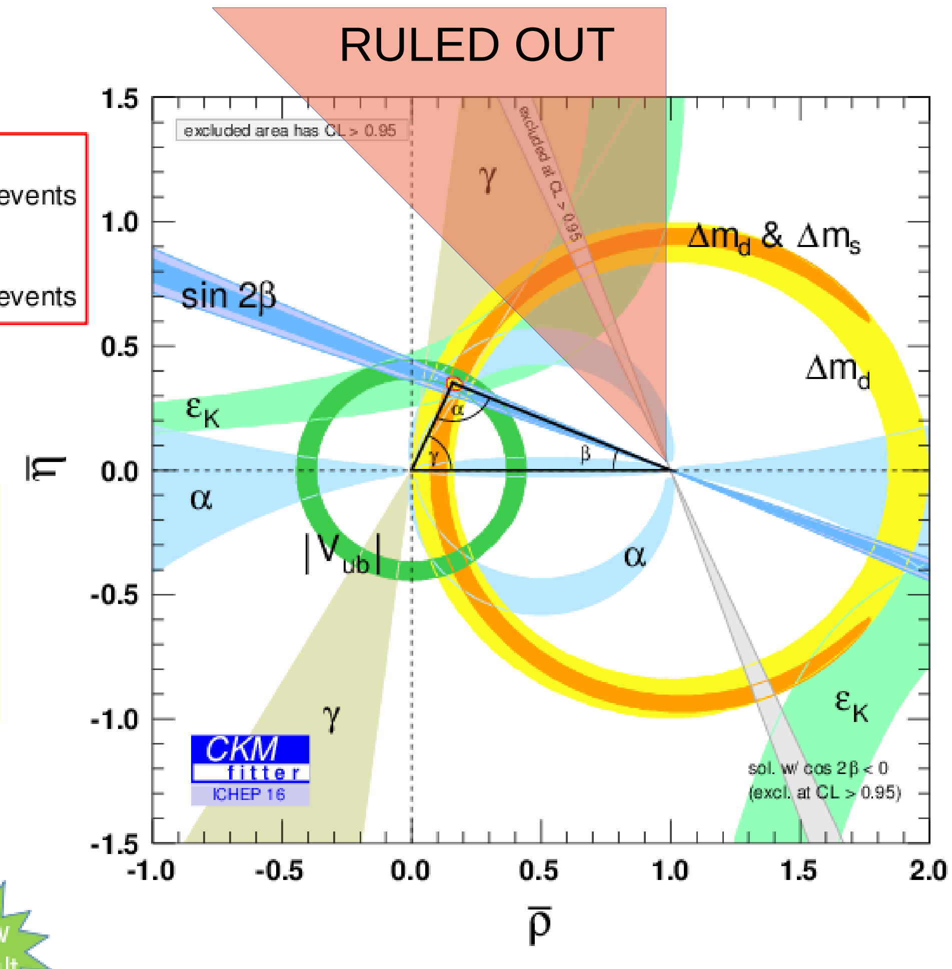
Belle:
1567 ± 56 signal events

Measurement using B → Dh^0 decays
(b→c$\bar{u}$d transition – theoretically clean)
with D → $K_S\pi\pi$ Dalitz plot modelled

BABAR+Belle with 1.1 ab^{-1}: Preliminary

$$\sin(2\beta) = 0.80 \pm 0.14\,(\text{stat.}) \pm 0.06\,(\text{syst.}) \pm 0.03\,(\text{model})$$
$$\cos(2\beta) = 0.91 \pm 0.22\,(\text{stat.}) \pm 0.09\,(\text{syst.}) \pm 0.07\,(\text{model})$$
$$\beta = (22.5 \pm 4.4\,(\text{stat.}) \pm 1.2\,(\text{syst.}) \pm 0.6\,(\text{model}))^\circ$$

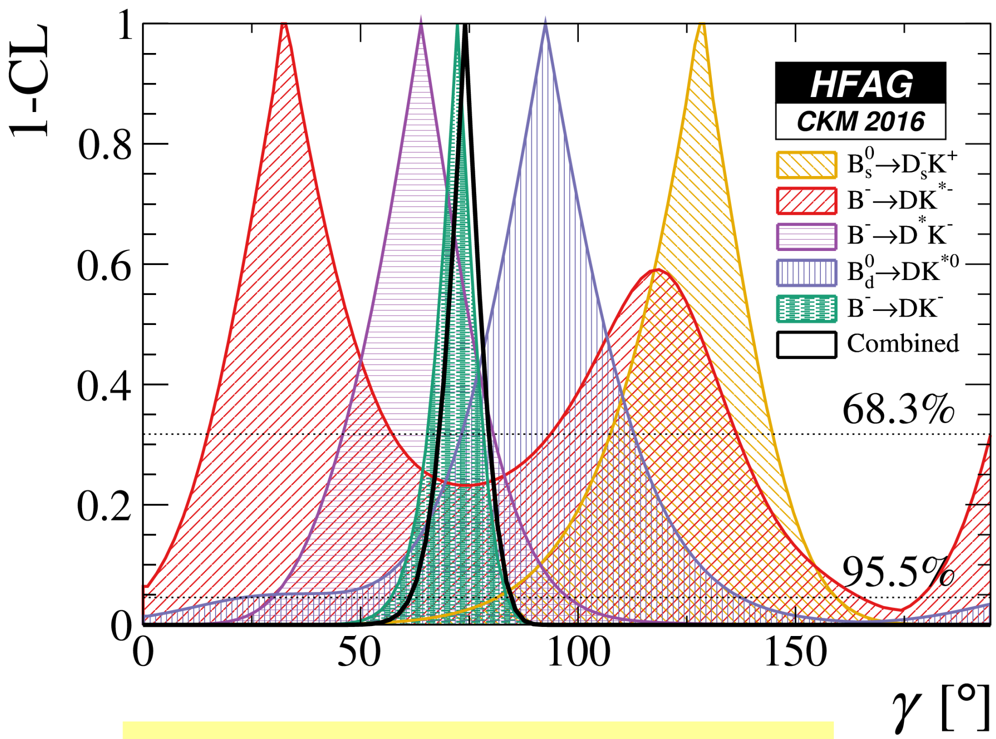
new result



γ – tree-level CP violation

Carson
Eitschberger
Zupan

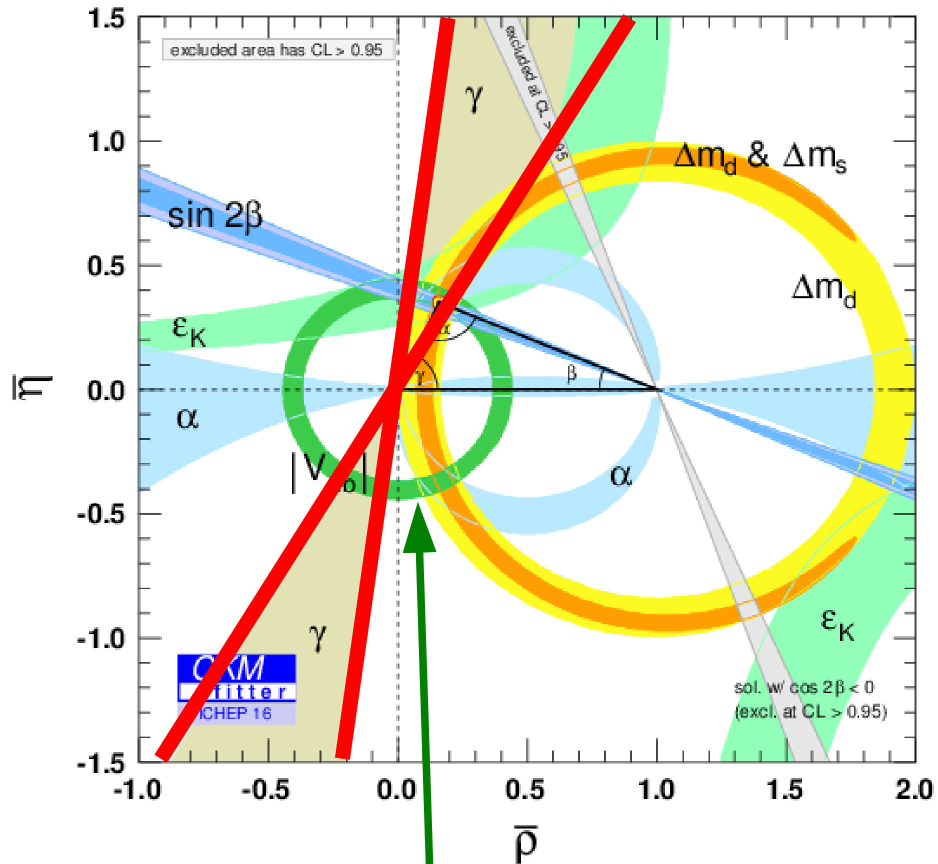
arXiv:1612.07233



Theoretically pristine

$\Gamma = (74.0\,^{+5.8}_{-6.4})°$

Can reach 0.4° with LHCb phase 2 upgrade



Lubej

Good prospects to reduce $\sigma(|V_{ub}|)$ to ~1% at Belle II

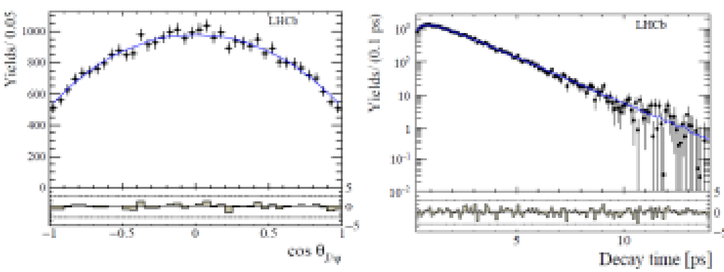
Carson

φ_s from $B_s^0 \to J/\psi K^+K^-$

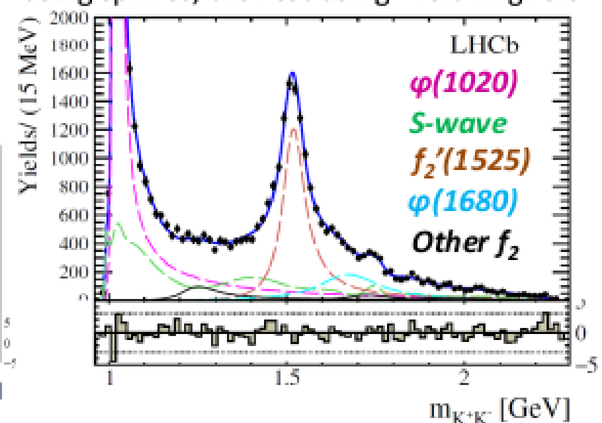
LHCb-PAPER-2017-008

- The fit to $m(J/\psi K^+K^-)$ is used to provide *sWeights* that are then used in a multi-dimensional fit to the decay time, m_{KK} and helicity angles.
- The flavour tagging uses both opposite-side (OS) and same-side Kaon (SSK) taggers.

Fit projections in $\cos\theta_{J/\psi}$ and in decay time, for m_{KK} > 1.05 GeV



Fit projection in m_{KK}. S-wave is modelled using splines, the rest using Breit-Wigners

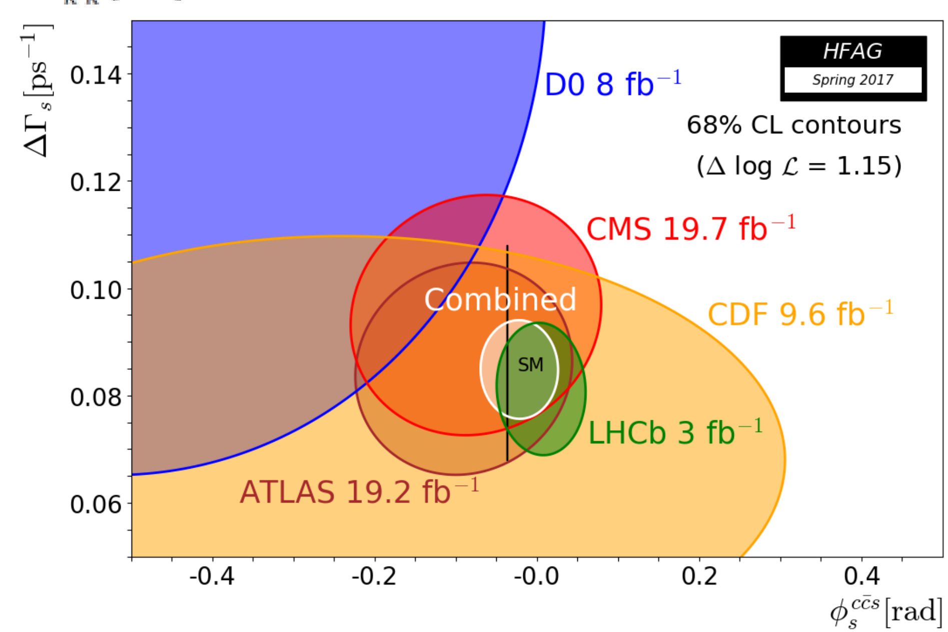


- For m_{KK} > 1.05 GeV, we measure $\boldsymbol{\phi_s}$ **= 0.12±0.11±0.03 rad**.

LHCb average
($J/\psi\varphi$, $J/\psi\pi^+\pi^-$, $D_s^+D_s^-$, $J/\psi K^+K^-$)
φ_s = 0.001±0.037 rad.

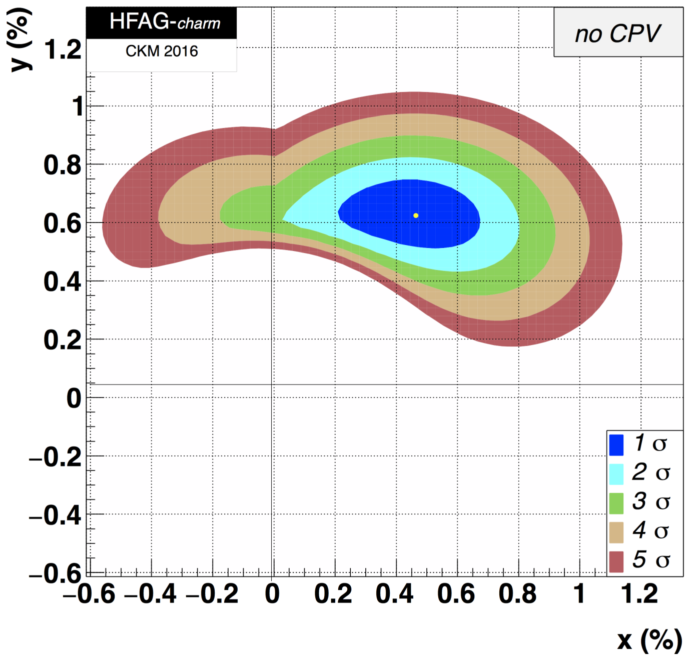
Sensitivity to CP violation at the SM value with LHCb upgrade

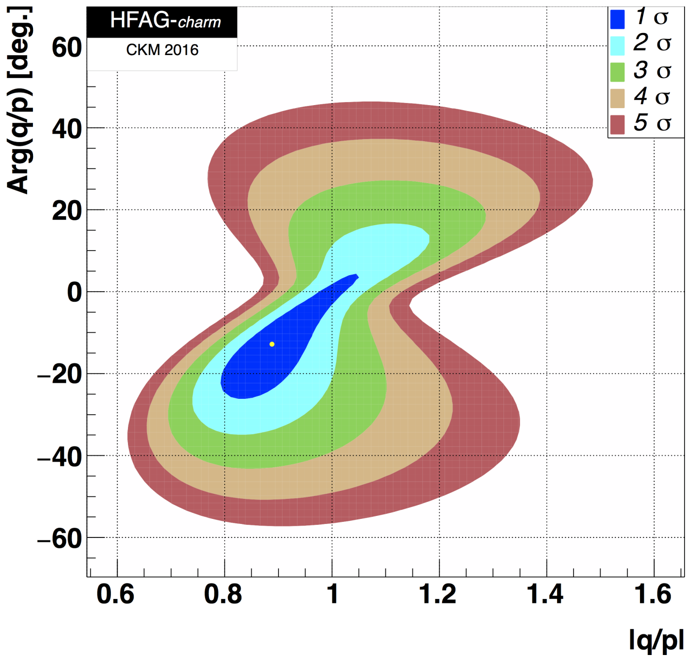
PRELIMINARY



Morello
Weidenkaff

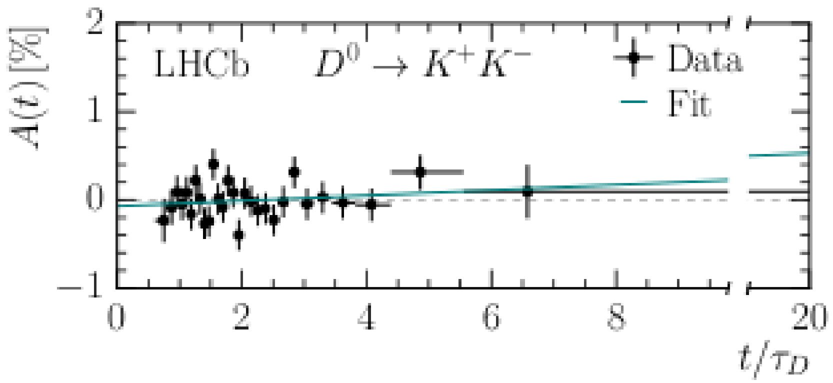
CP violation in charm oscillations

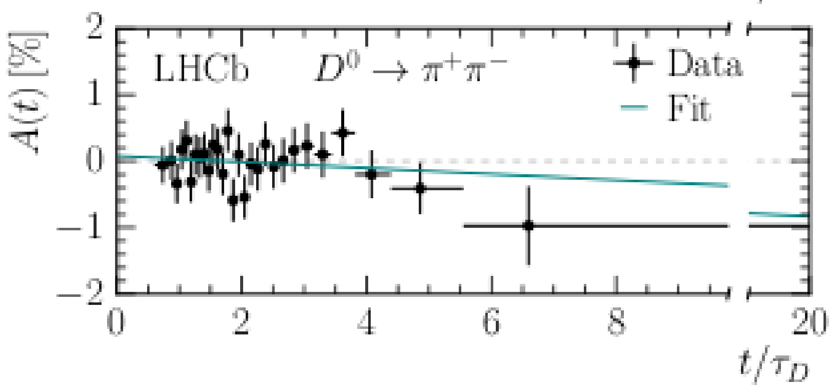




$x = \Delta m/\Gamma$ only 2σ from zero
essential to improve

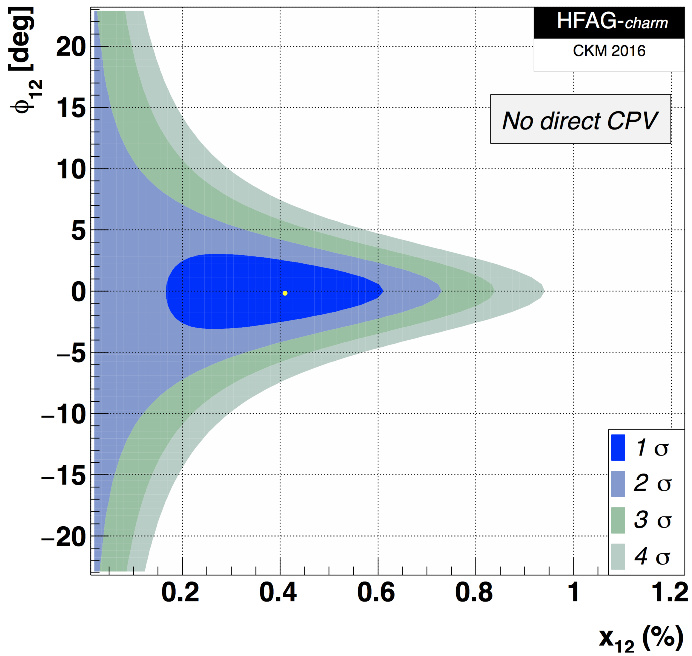
arXiv:1702.06490 [hep-ex]. Submitted to PRL.

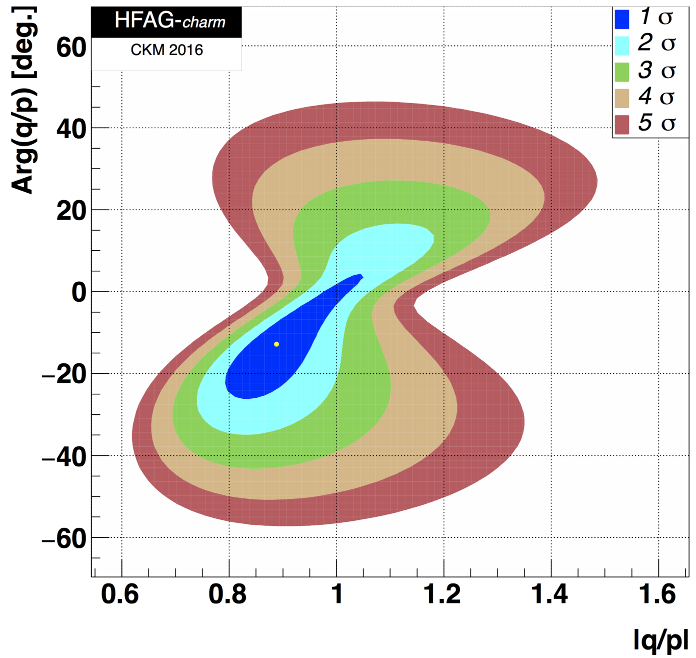




Most precise measurement of
CPV in the charm sector.

CP violation in charm oscillations





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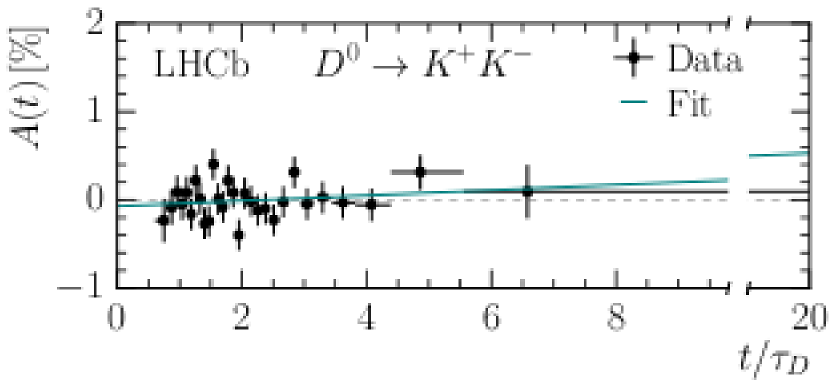
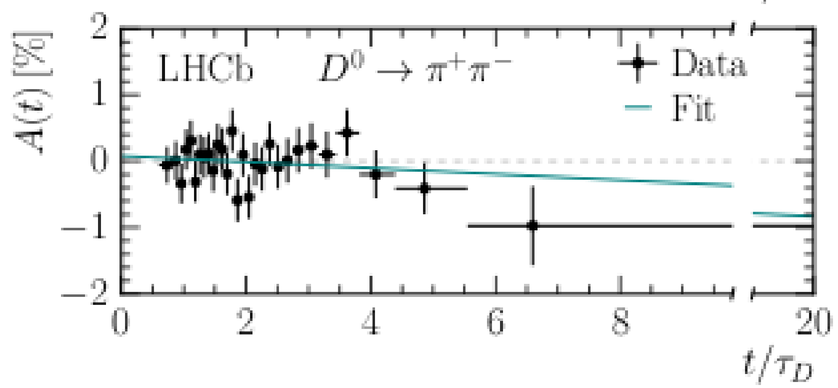
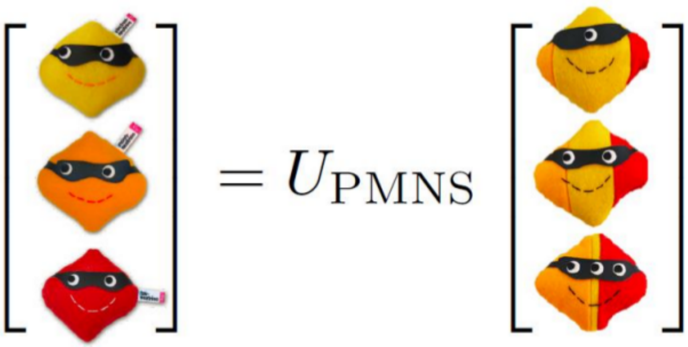


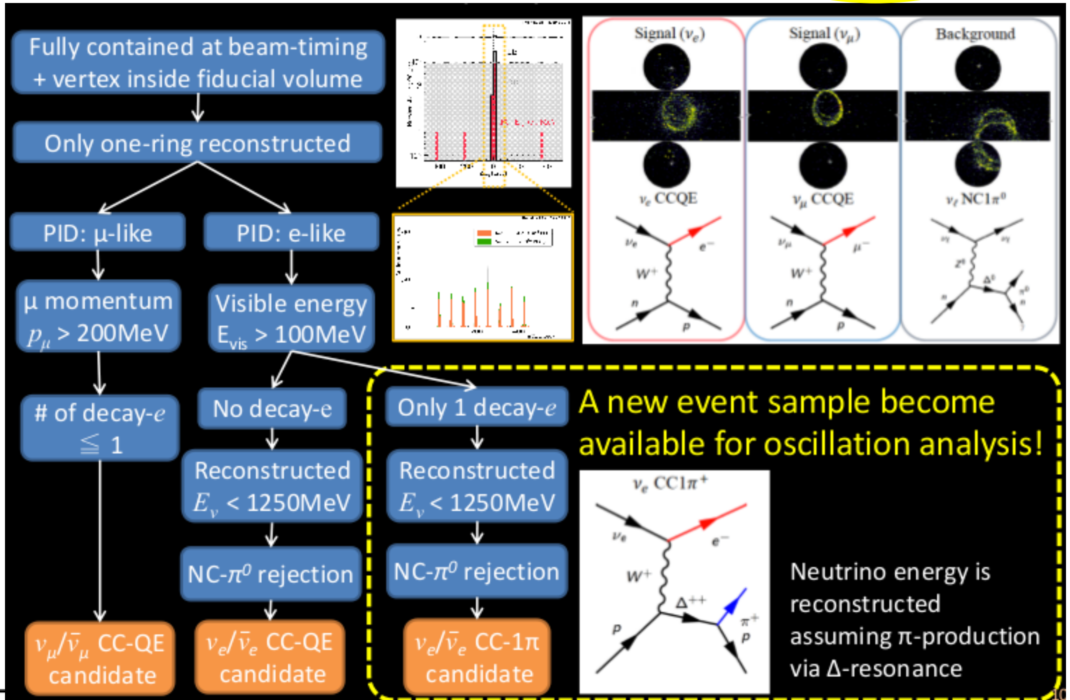


Most precise measurement of
CPV in the charm sector.

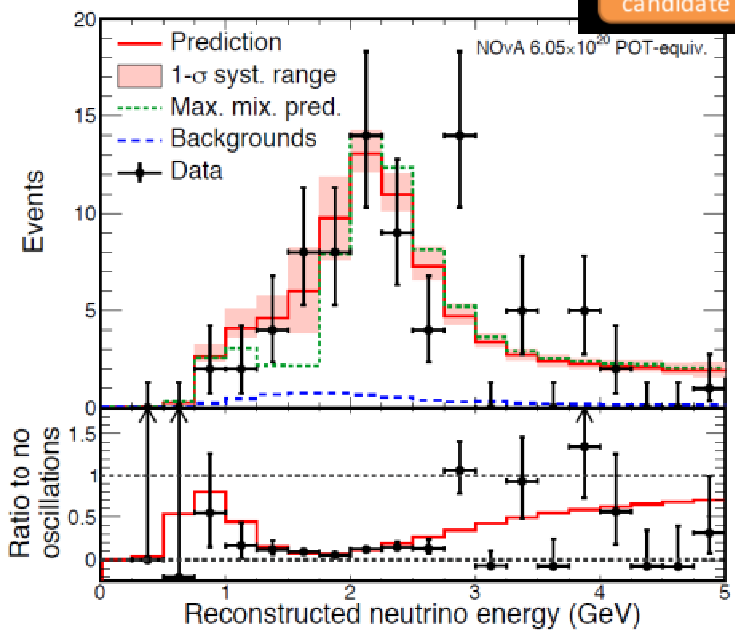
Jediny
Nakadaira
Meregaglia
Carroll

Neutrino oscillations





- 473 ± 30 events predicted in the absence of oscillations
- 78 events observed
- 82 events predicted at the best fit point
  - including 3.7 beam bkg
  - 2.9 cosmic induced



Off-axis detectors

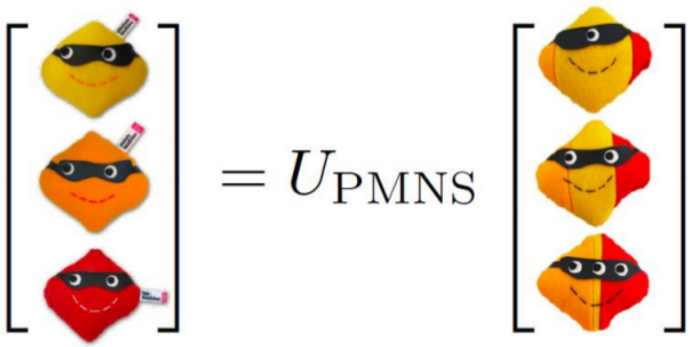
NoνA: ν_μ disappearance

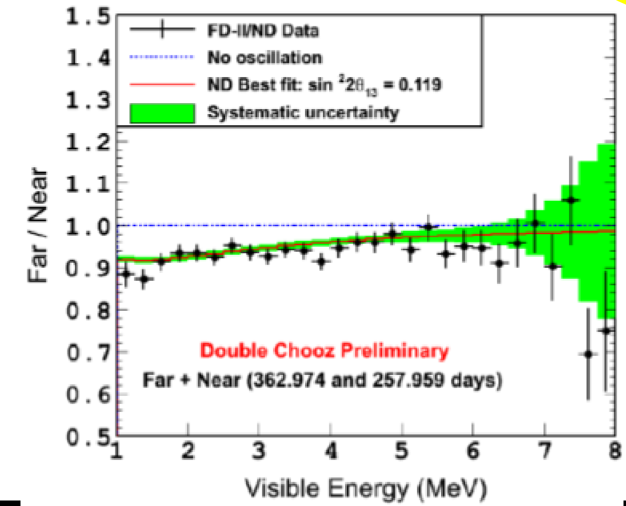
T2K: ν_μ dis- + ν_e appearance

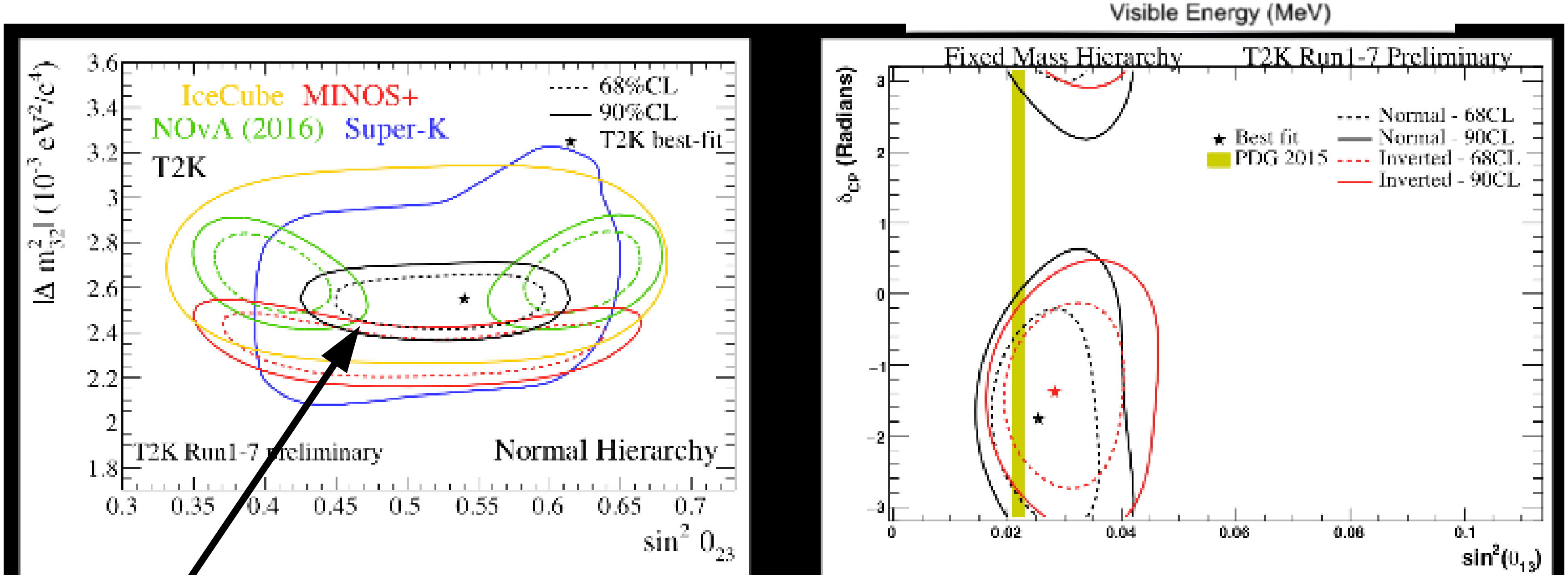
NoνA's longer baseline → better sensitivity to matter effects (mass hierarchy)

Neutrino oscillations

Jediny
Nakadaira
Meregaglia
Carroll







Octant still to be determined

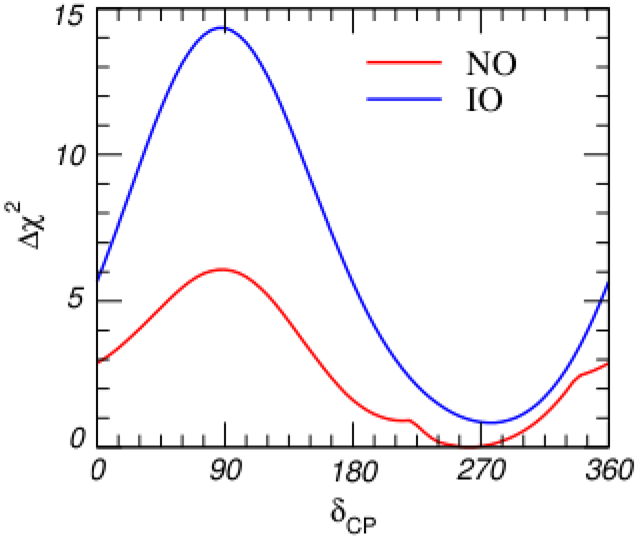
Future prospects excellent

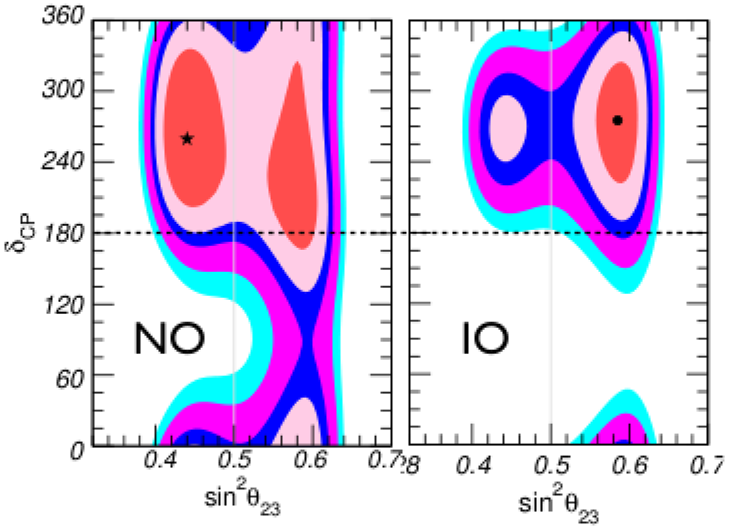
$\sin^2(\theta_{13})$ now the best measured ν parameter!

Neutrino CP violation

Jediny
Nakadaira
Carroll
Schwetz

No significant constraint at present
Future prospects excellent



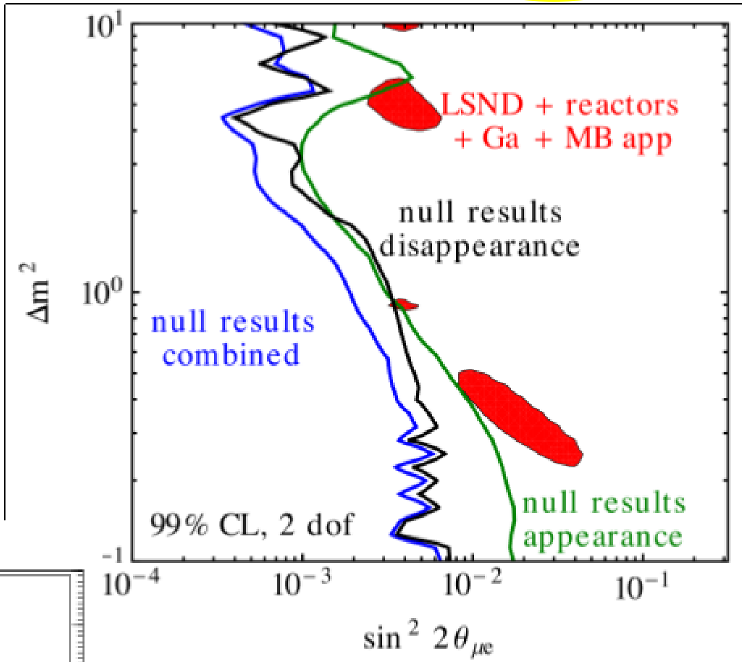


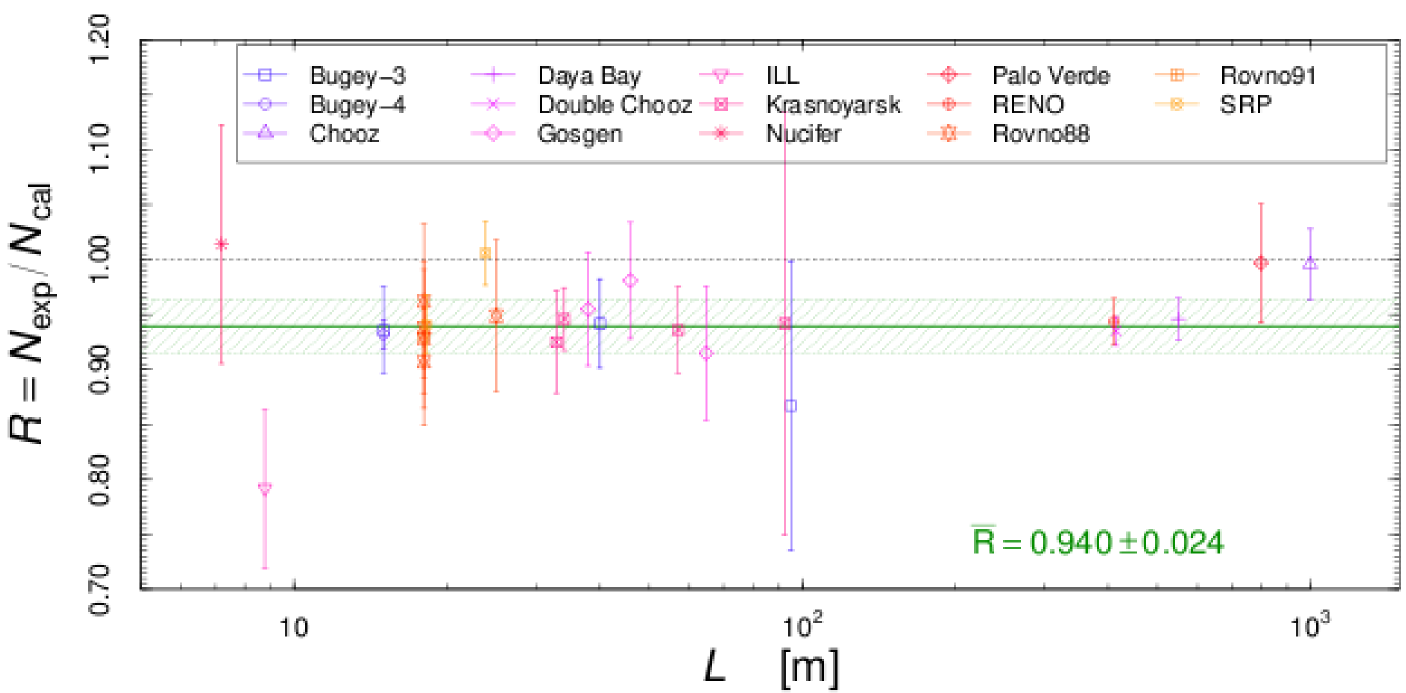
- best fit at $\delta_{CP} \approx 270°$
- correlations with θ_{23}
- CP conservation allowed at 70% CL (NO), 97% CL (IO)
- $\delta_{CP} \approx 90°$ disfavoured with $\Delta\chi^2 \approx 6$ (14) for NO (IO)

Sterile ν ≡ testing PMNS unitarity

Carroll
Danilov
Bonhomme
Giunti
André

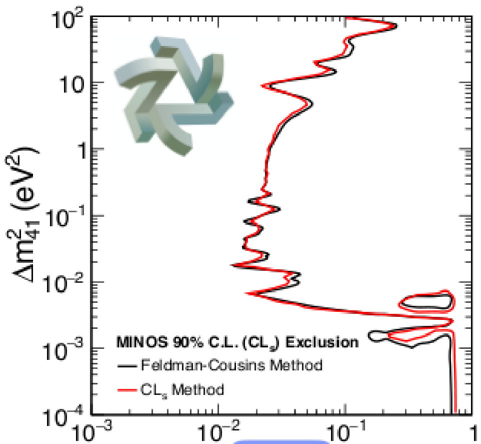
Several hints of anomalous behaviour
Tension with other measurements

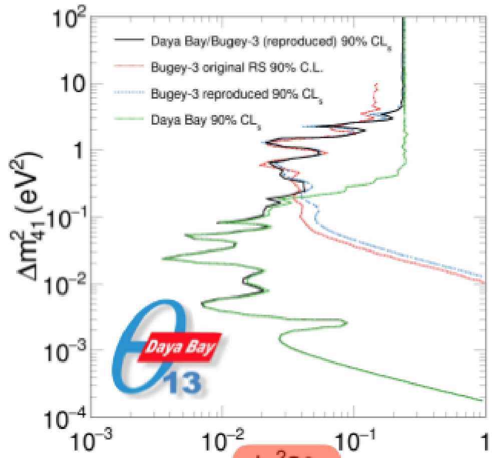




Carroll
André

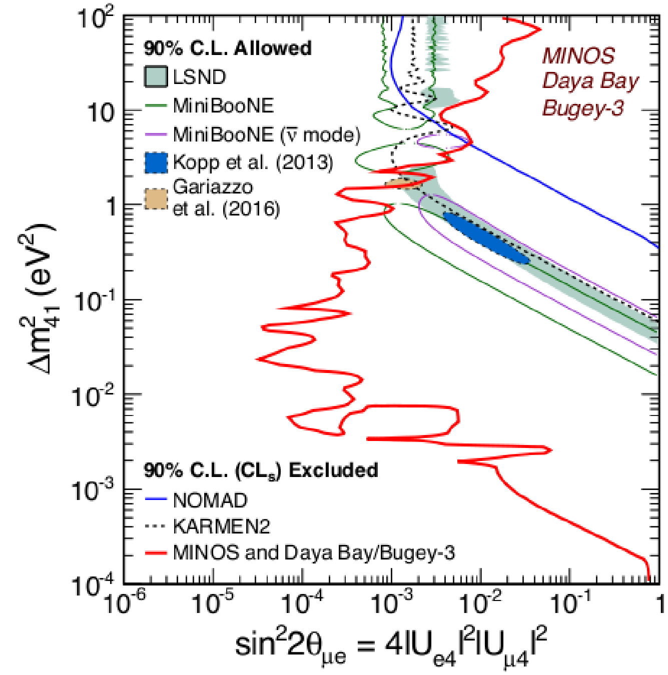
Sterile ν ≡ testing PMNS unitarity



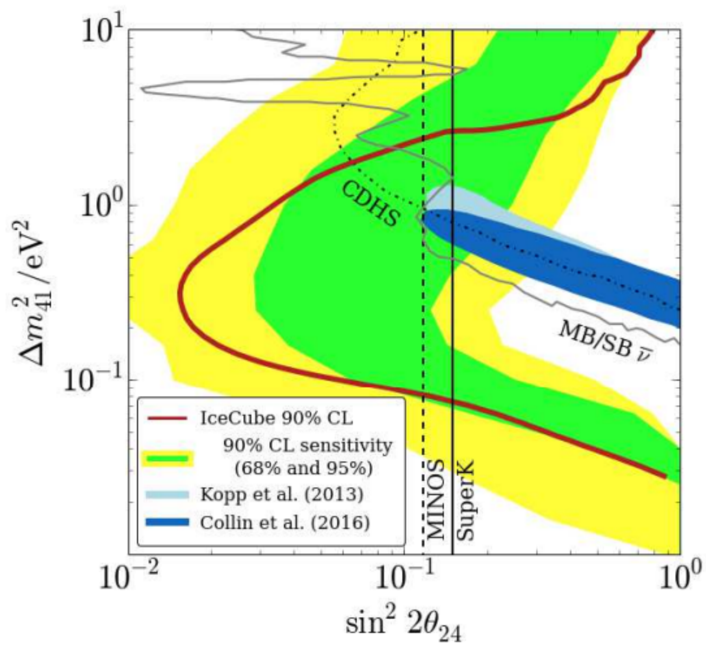


$\sin^2\theta_{24}$ $\sin^2 2\theta_{14}$

LSND & MiniBooNE $4|U_{e4}|^2|U_{\mu4}|^2 = \sin^2\theta_{24}\sin^2 2\theta_{14} \equiv \sin^2 2\theta_{\mu e}$

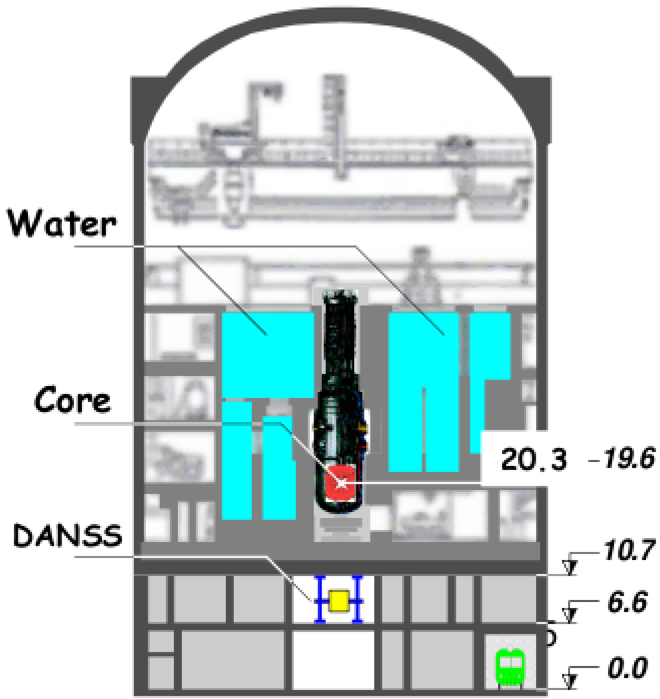


No evidence for sterile νs in MINOS/Daya Bay joint analysis or in IceCube

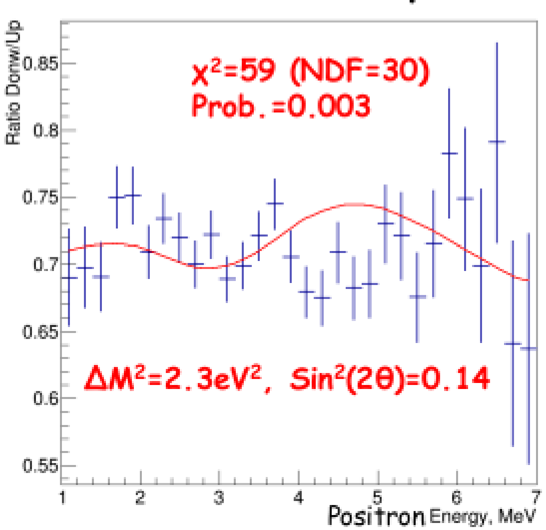


Danilov
Bonhomme

Sterile ν ≡ testing PMNS unitarity



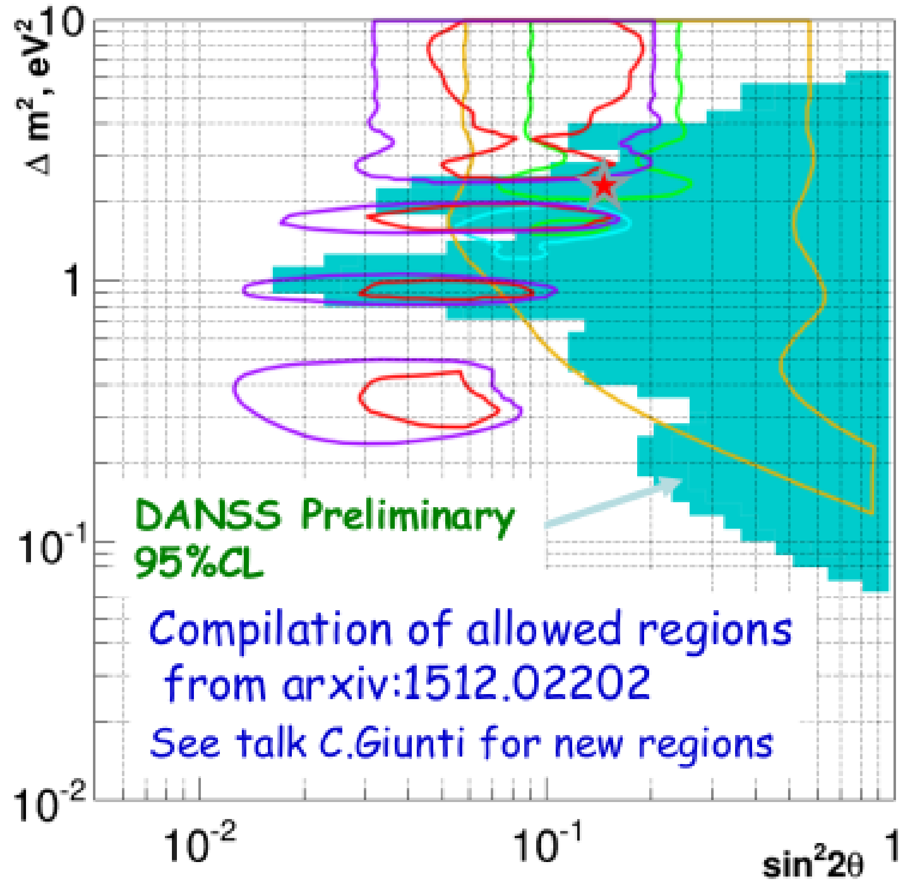
Ratio Down/Up



Fit with constant:
χ^2=32
Prob.=0.39

Most plausible parameter set is excluded

10



No evidence for sterile νs in DANSS
Many other very short baseline experiments coming soon

Hori

Precision measurements with $\bar{p}$

Precision measurements of $\bar{p}He^+$ transition frequencies and companions with QED calculations yields:

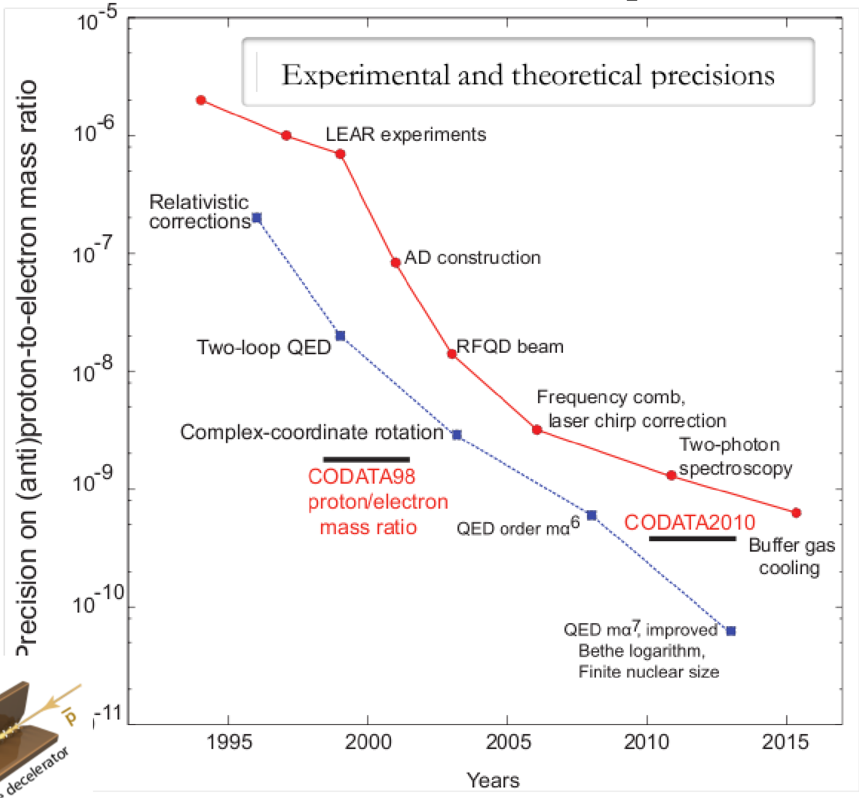
Antiproton-to-electron mass ratio to precision of 8×10^{-10}

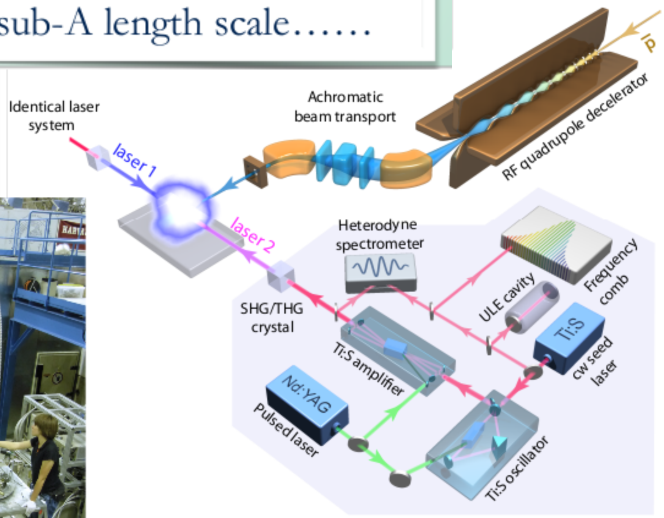
Assuming CPT invariance, **electron mass** to 8×10^{-10}

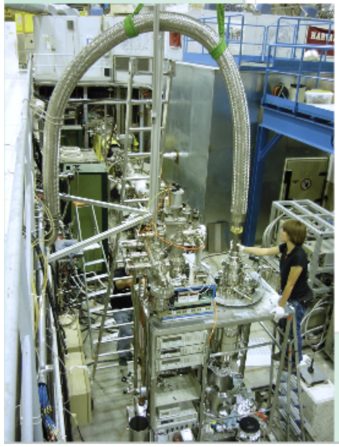
Combined with the cyclotron frequency of antiprotons in a Penning trap by TRAP and BASE collaborations, **antiproton and proton masses and charges** to 5×10^{-10}

→ Consistency test of CPT invariance

Bounds on the 5th force at the sub-A length scale……





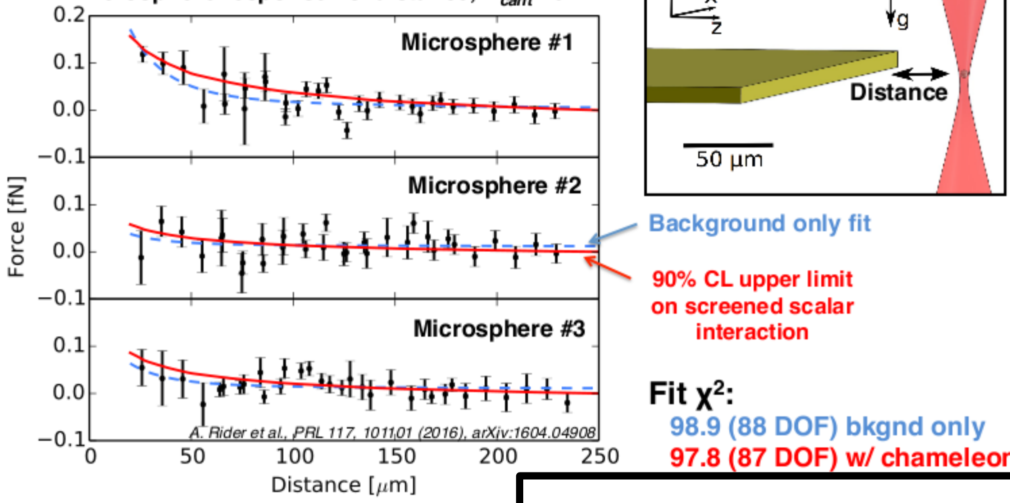


Moore

Precision measurements of g

- Measure electrostatic background with non-zero potential, then set to 0 V
- Residual response consistent with <30 mV contact potentials

Microsphere response vs. distance, V_{cant}= 0V:



Background only fit

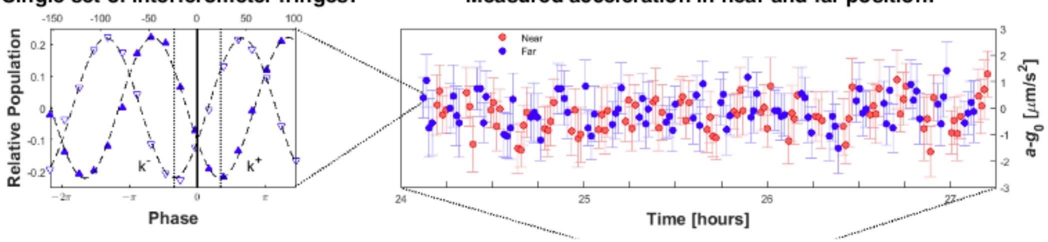
90% CL upper limit on screened scalar interaction

Fit χ^2:

98.9 (88 DOF) bkgnd only

97.8 (87 DOF) w/ chameleon

Single set of interferometer fringes: **Measured acceleration in near and far position:**



- Measure difference in acceleration between near and far position:

$$a_{cyl} = (76 \pm 19_{stat} \pm 16_{syst})\ \mathrm{nm/s^2}$$

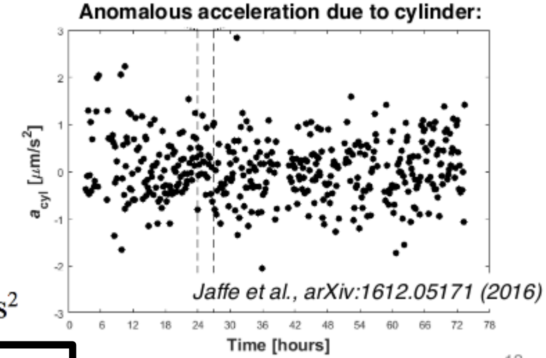
Expected Newtonian acceleration:

$$a_{grav} = (65 \pm 5)\ \mathrm{nm/s^2}$$

Constraint on anomalous acceleration:

$$a_{anomaly} = a_{cyl} - a_{grav} = (11 \pm 24)\ \mathrm{nm/s^2}$$

Anomalous acceleration due to cylinder:



- Additional improvements possible:

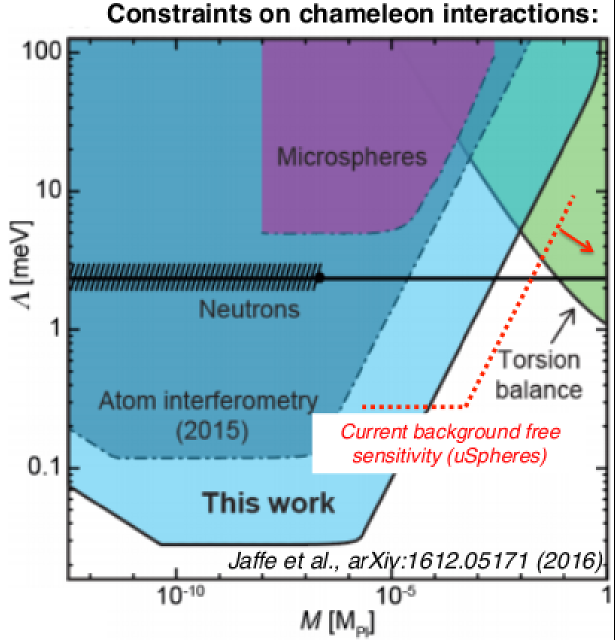
Atom interferometry

- Larger momentum transfer beam splitters
- Optical lattice interferometry

Microspheres

- Cancel contact potentials
- Spin microspheres
- Improve attractor design

Constraints on chameleon interactions:

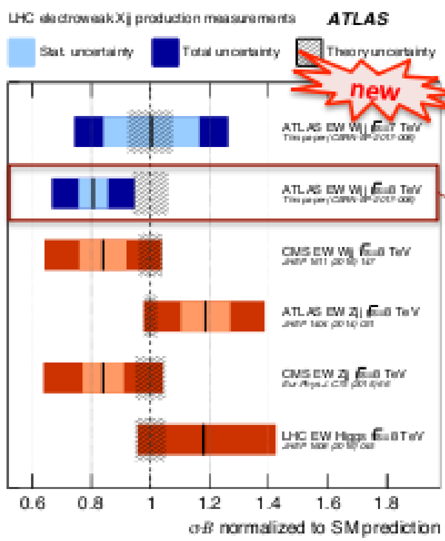


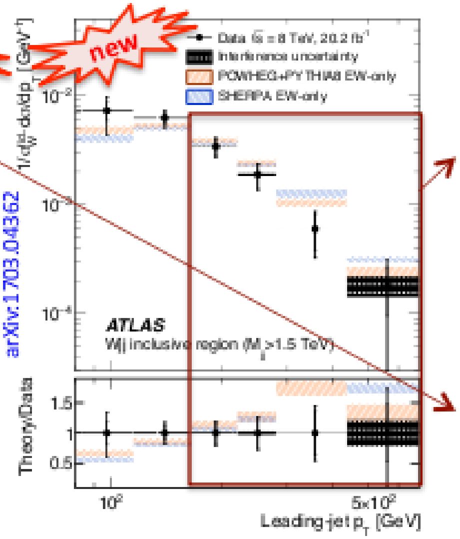
Đurić
Dutta

Electroweak diboson production

ATLAS STDM-2015-021 & arXiv:1703.04362

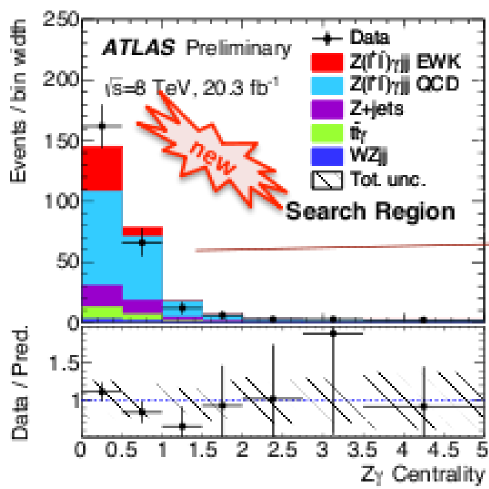
EWK measurements are also going differential!

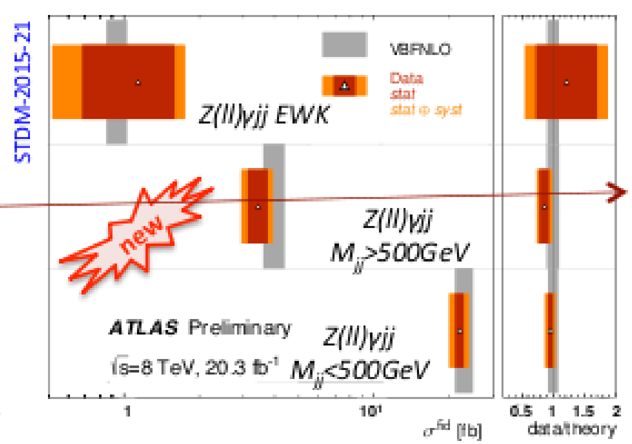




EWK(+QCD) W+2j measurement:

- Unlike QCD+EWK production for EWK production higher masses (M_{jj} > 1.5 TeV) predictions give a harder spectrum than observed in the data
  - Signature of NLO electroweak corrections ?
- Dominant uncertainty is systematic: jet energy scale and resolution, PDF





EWK Zγ+2j measurement:

- Z(ll) and Z(νν) channels included
- Cross section is extracted using a likelihood fit over the centrality of the Zγ two-body system ($\zeta_{Z\gamma}$)
- Measurement statistics dominated

Observations of VV production expected soon (with 13 TeV data)

BSM & Naturalness

+

=

Unnatural!

?

Classic SUSY searches

Kuwertz
Marionneau
Petridis

Huge numbers of new results – astonishing organisational achievement
No significant signals – updated limits. More still to come with 13 TeV.

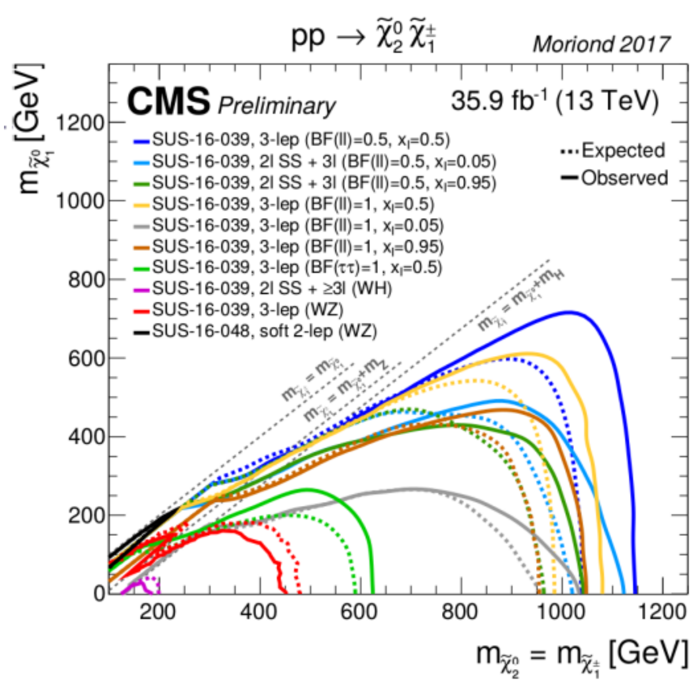
ATLAS SUSY Searches* - 95% CL Lower Limits

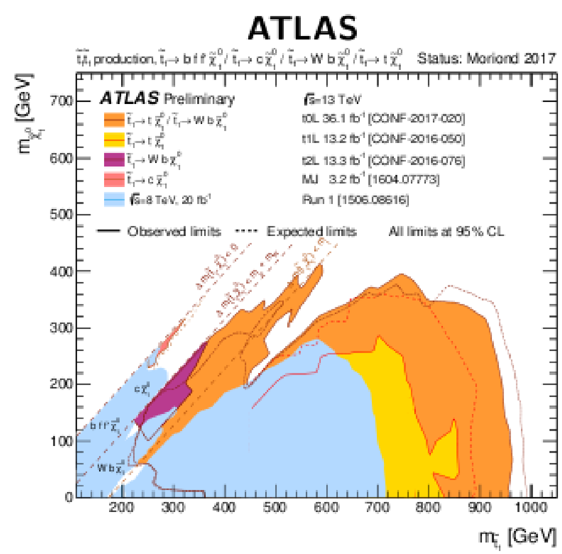
Status: March 2017

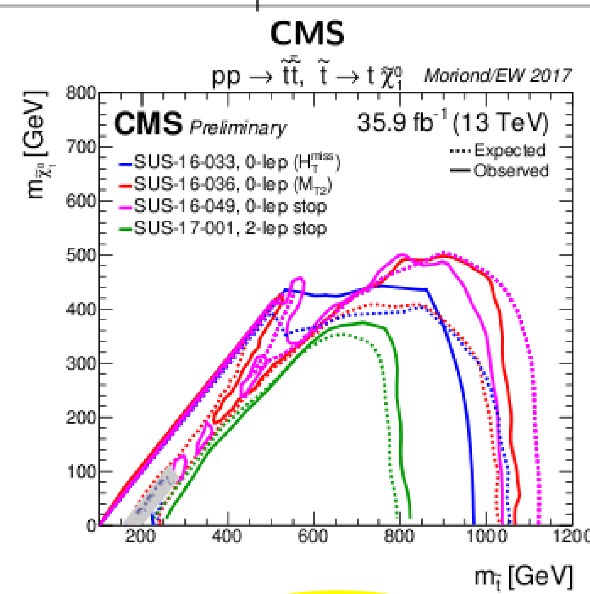
ATLAS Preliminary
$\sqrt{s}$ = 7, 8, 13 TeV

$\sqrt{s}$ = 7, 8 TeV | $\sqrt{s}$ = 13 TeV

	Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\, dt [fb^{-1}]$	Mass limit			Reference
Inclusive Searches	MSUGRA/CMSSM	0-3 e,μ/1-2 τ	2-10 jets/3 b	Yes	20.3	$\tilde{q}, \tilde{g}$	1.85 TeV	$m(\tilde{q})=m(\tilde{g})$	1507.05525
	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	$\tilde{q}$	1.57 TeV	$m(\tilde{\chi}_1^0)$<200 GeV, $m(1^{st}$ gen. $\tilde{q})=m(2^{nd}$ gen. $\tilde{q})$	ATLAS-CONF-2017-022
	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}_1^0$ (compressed)	mono-jet	1-3 jets	Yes	3.2	$\tilde{q}$	608 GeV	$m(\tilde{q})-m(\tilde{\chi}_1^0)$<5 GeV	1604.07773
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	$\tilde{g}$	2.02 TeV	$m(\tilde{\chi}_1^0)$<200 GeV	ATLAS-CONF-2017-022
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}_1^{\pm}\to qqW^{\pm}\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	$\tilde{g}$	2.01 TeV	$m(\tilde{\chi}_1^0)$<200 GeV, $m(\tilde{\chi}^{\pm})=0.5(m(\tilde{\chi}_1^0)+m(\tilde{g}))$	ATLAS-CONF-2017-022
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq(\ell\ell/\nu\nu)\tilde{\chi}_1^0$	3 e,μ	4 jets	-	13.2	$\tilde{g}$	1.7 TeV	$m(\tilde{\chi}_1^0)$<400 GeV	ATLAS-CONF-2016-037
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qqWZ\tilde{\chi}_1^0$	2 e,μ (SS)	0-3 jets	Yes	13.2	$\tilde{g}$	1.6 TeV	$m(\tilde{\chi}_1^0)$ <500 GeV	ATLAS-CONF-2016-037
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ + 0-1 ℓ	0-2 jets	Yes	3.2	$\tilde{g}$	2.0 TeV		1607.05979
	GGM (bino NLSP)	2 γ	-	Yes	3.2	$\tilde{g}$	1.65 TeV	$c\tau$(NLSP)<0.1 mm	1606.09150
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	20.3	$\tilde{g}$	1.37 TeV	$m(\tilde{\chi}_1^0)$<950 GeV, $c\tau$(NLSP)<0.1 mm, μ<0	1507.05493
	GGM (higgsino-bino NLSP)	γ	2 jets	Yes	13.3	$\tilde{g}$	1.8 TeV	$m(\tilde{\chi}_1^0)$>680 GeV, $c\tau$(NLSP)<0.1 mm, μ>0	ATLAS-CONF-2016-066
	GGM (higgsino NLSP)	2 e,μ (Z)	2 jets	Yes	20.3	$\tilde{g}$	900 GeV	m(NLSP)>430 GeV	1503.03290
	Gravitino LSP	0	mono-jet	Yes	20.3	$F^{1/2}$ scale	865 GeV	$m(\tilde{G})>1.8 \times 10^{-4}$ eV, $m(\tilde{g})=m(\tilde{q})=1.5$ TeV	1502.01518







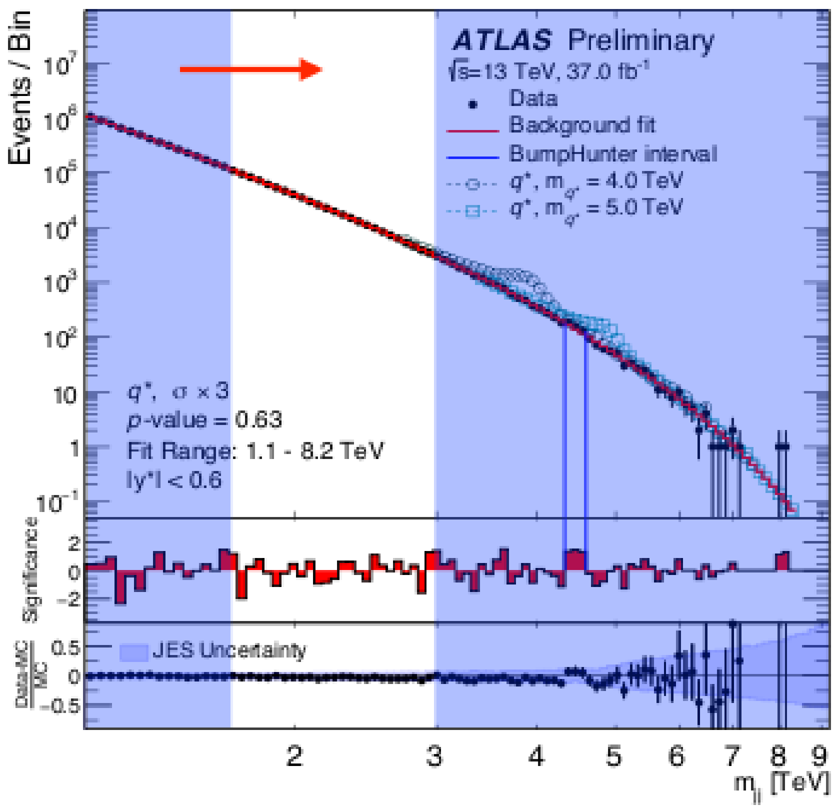
Results also interpreted in context of dark matter

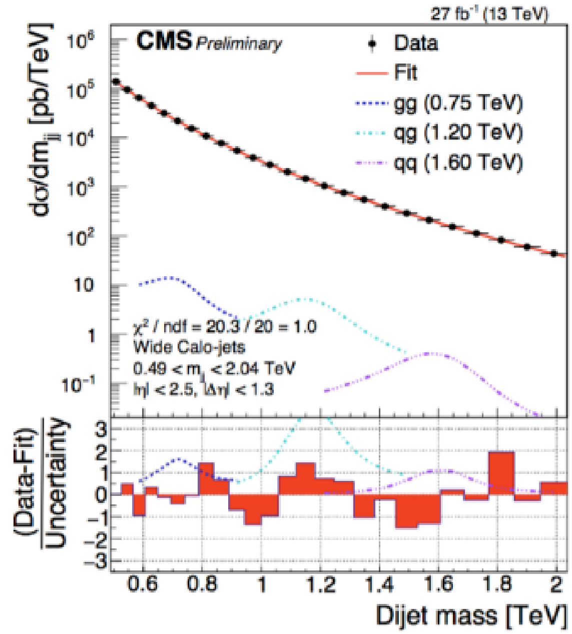
Madsen
Gerosa

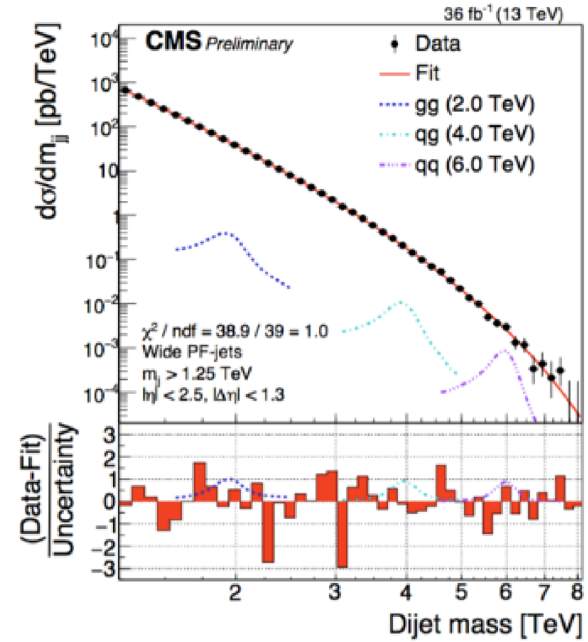
Gao

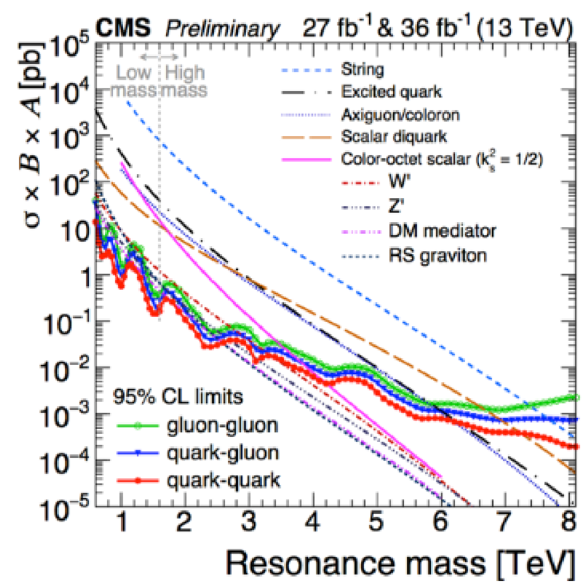
Generic BSM signatures

Dijet resonances







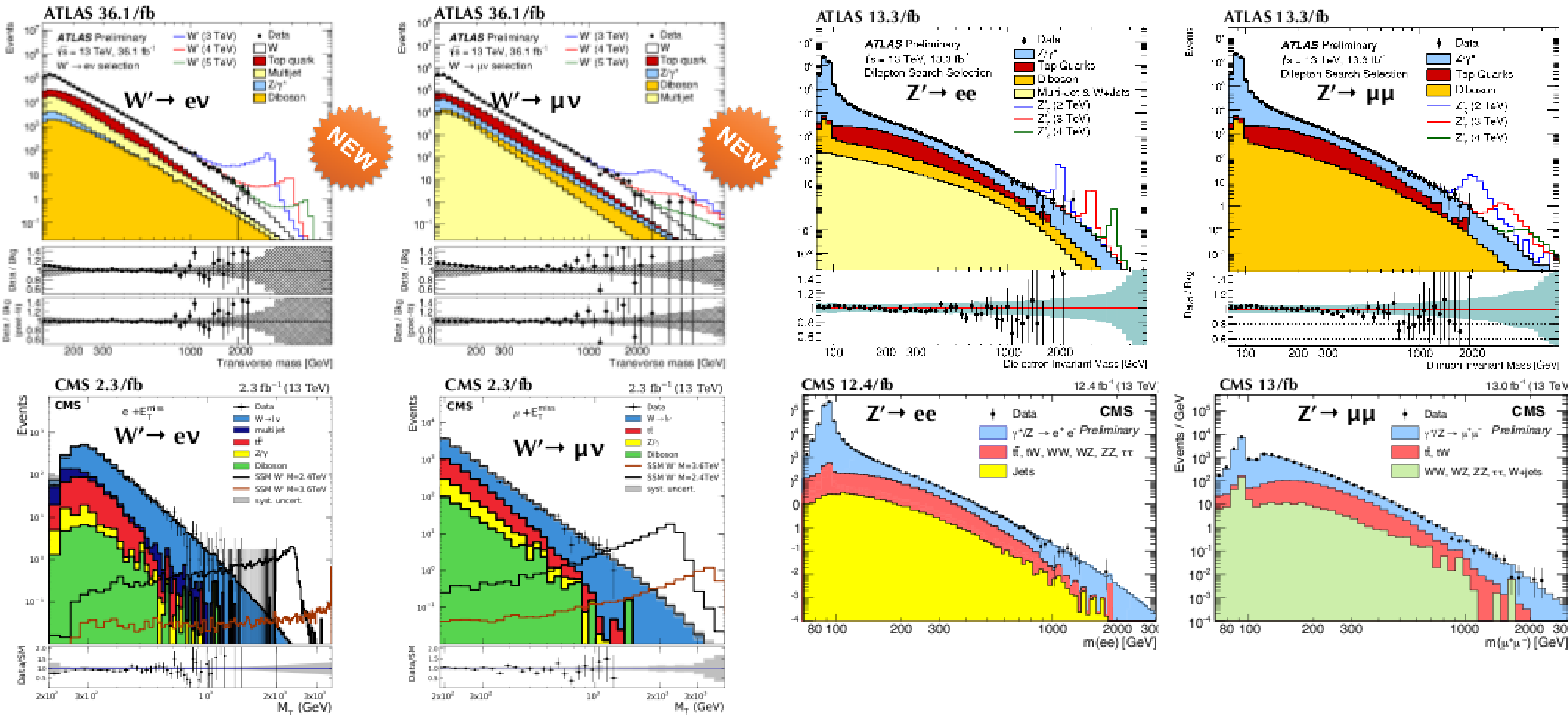


- ATLAS: sliding window mass fit
- ATLAS: angular analysis to limit contact interactions
- CMS: data scouting to reach lower masses

Generic BSM signatures

Radogna

Dilepton resonances



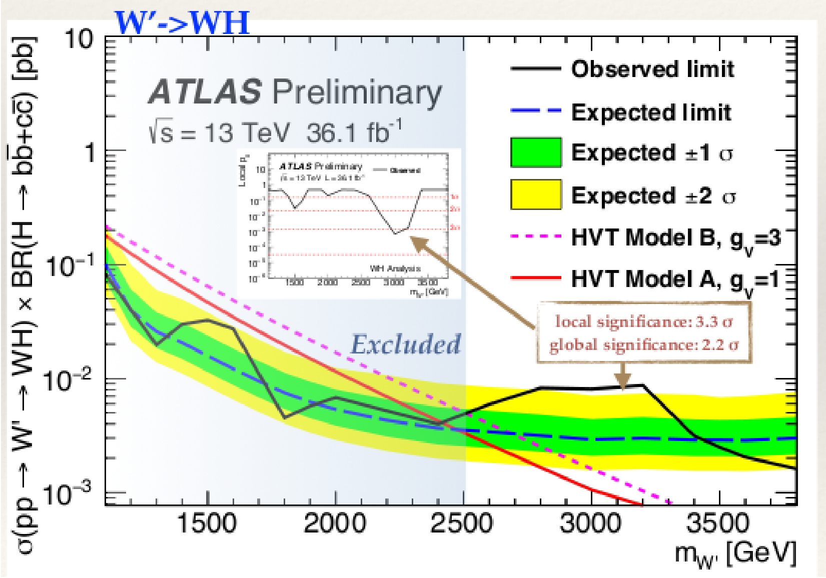
No signals – strong limits

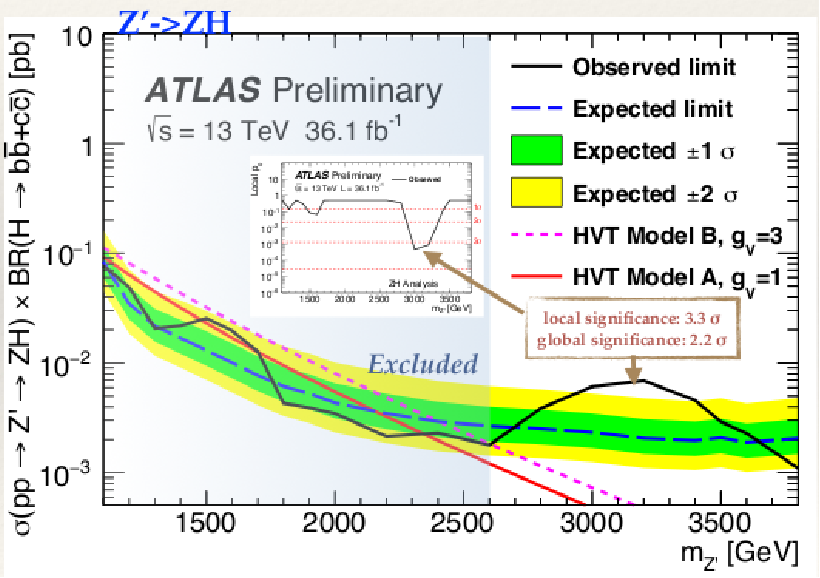
Generic BSM signatures

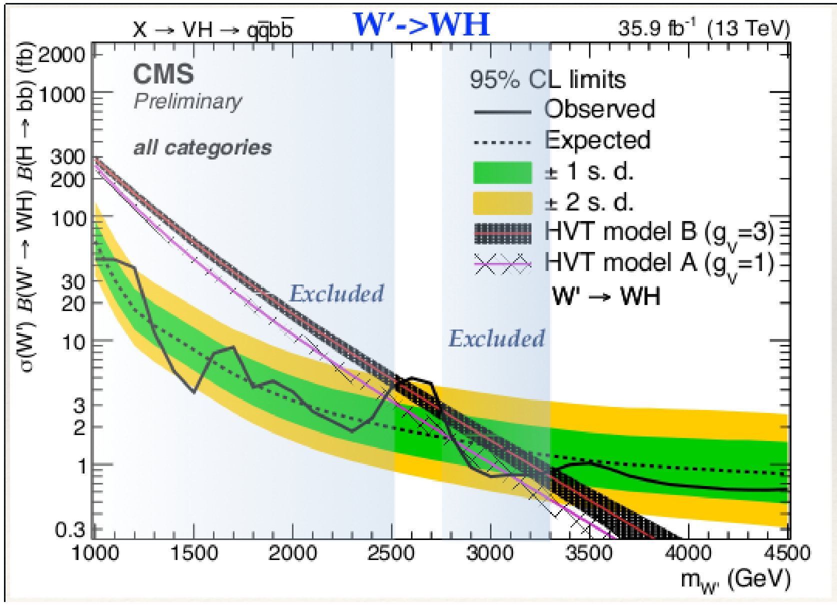
Diboson resonances

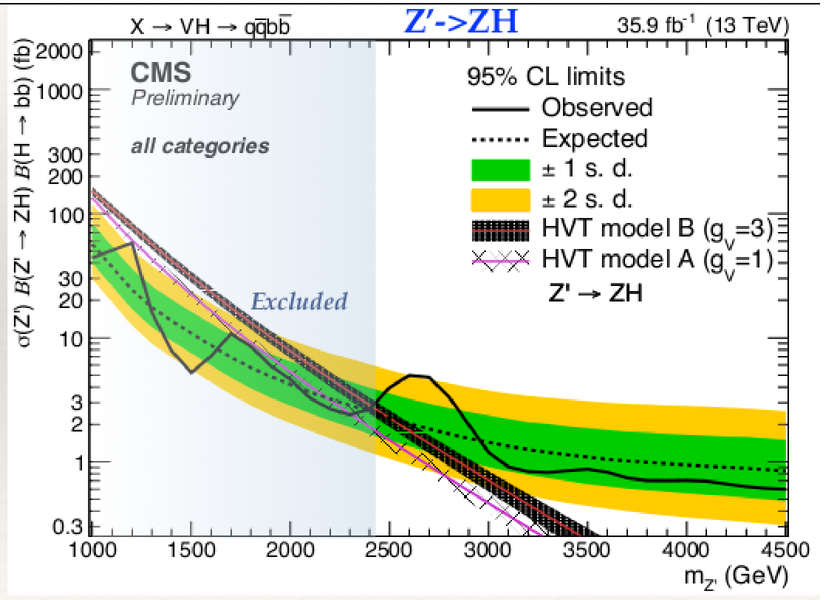
Li

Jet grooming to handle pile-up







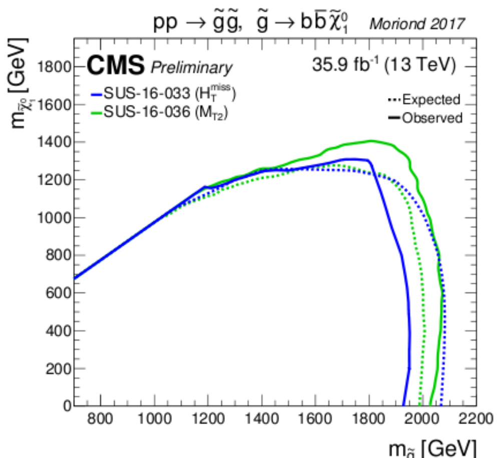


Small excess in ATLAS data at ~3 TeV not seen in CMS

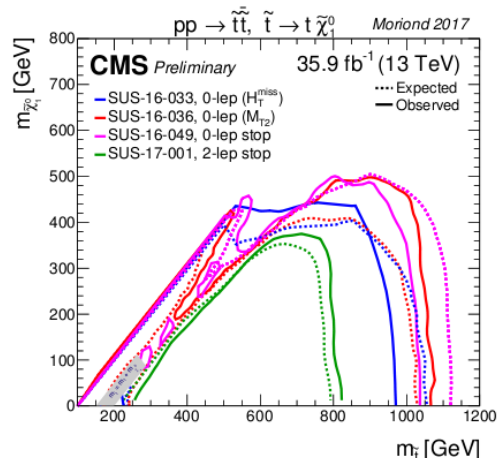
What then?

Shchutska
Radogna
Hod
Genest
Spieza

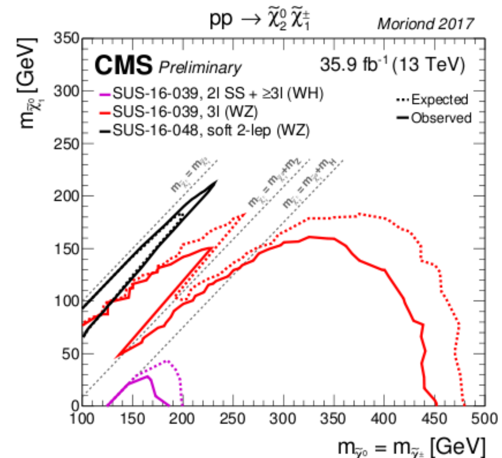
Still plenty of phase space to be explored in Runs 2, 3 & HL-LHC



gluinos 2 TeV now
2.5 TeV @ 300/fb
3 TeV @ 3000/fb



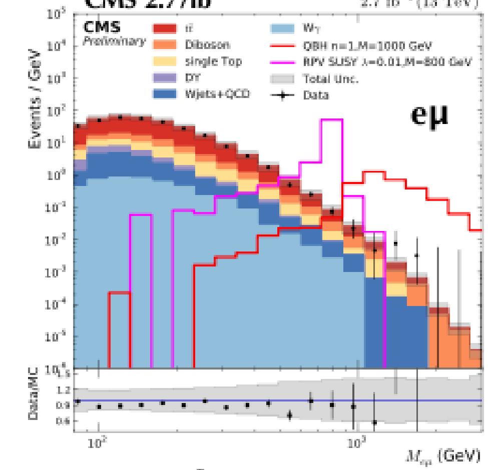
stops: 1.1 TeV now
1.5 TeV @ 300/fb
2 TeV @ 3000/fb



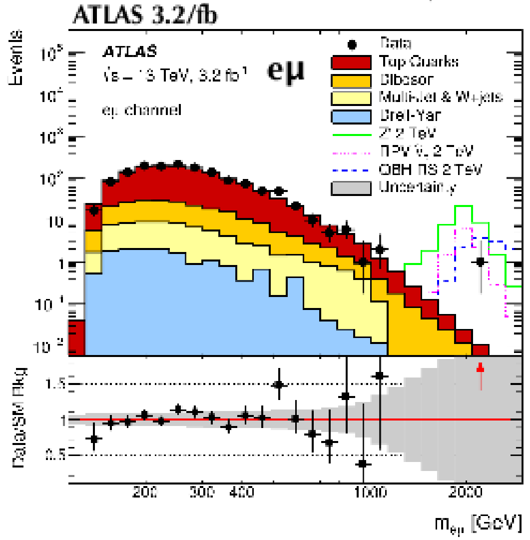
charginos: 0.45 TeV now
0.75 TeV @ 300/fb
1.2 TeV @ 3000/fb

LFV dilepton

CMS 2.7/fb



ATLAS 3.2/fb

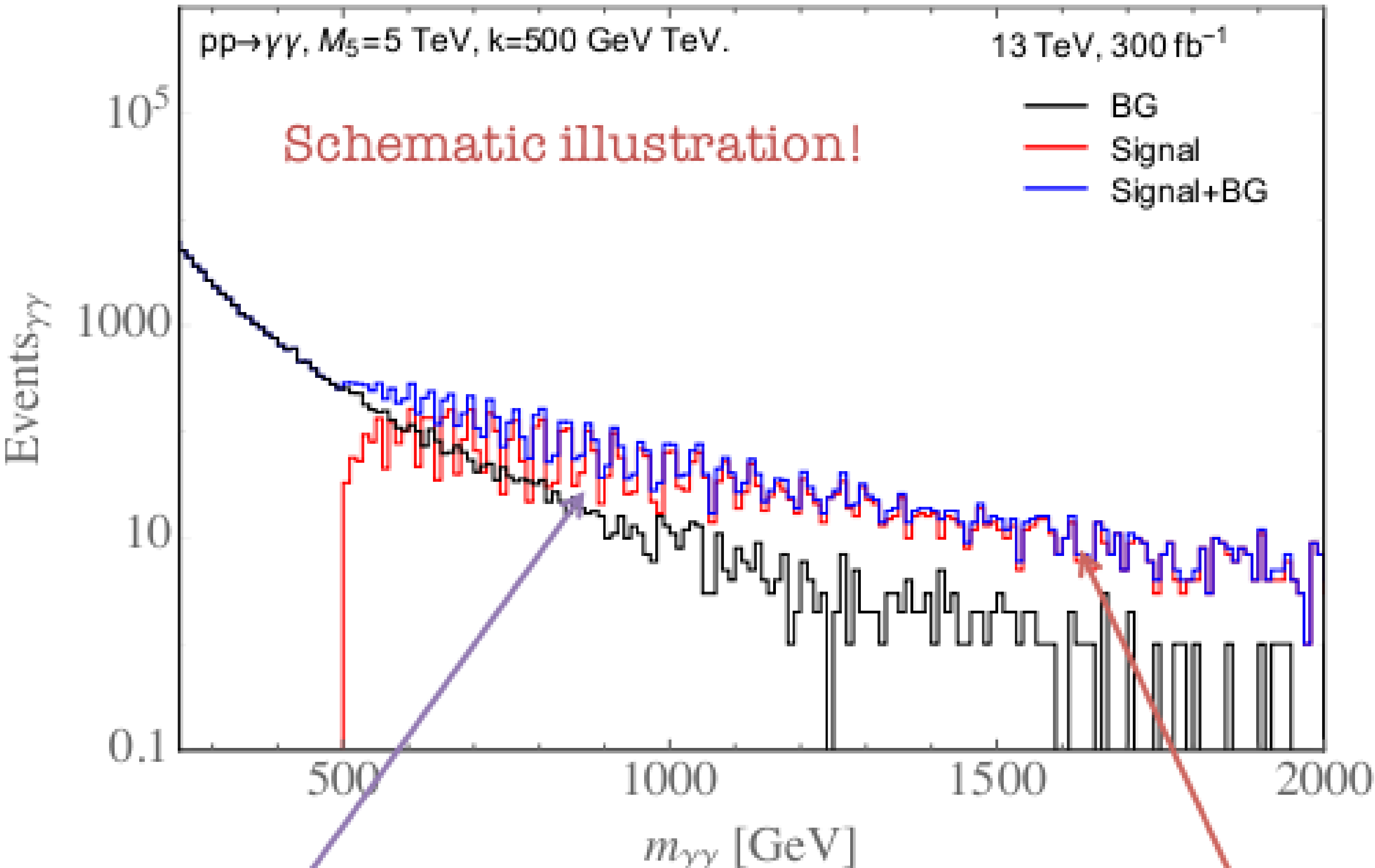


However, stronger limits point to weaker couplings
& to more exotic signatures
New ideas (both theory & experiment) needed

New ideas $\Longrightarrow$ Exponential improvement

McCullough

Example: Fourier analysis



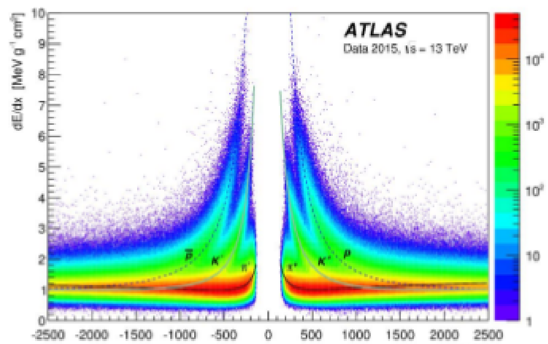
Any obvious signals would have been noticed, but still interesting to explore further

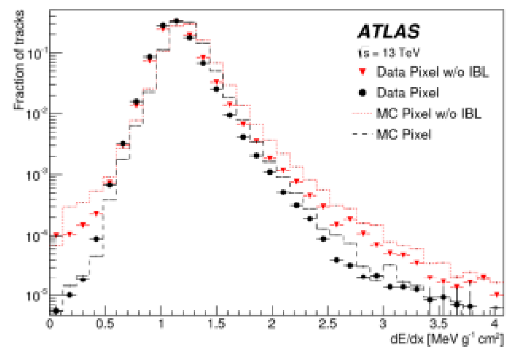
Most interestingly, due to splittings, signal appears to "oscillate". Thus get extra sensitivity by doing spectral analysis... The "power spectrum" of LHC data!

Can search for continuum spectrum at high energies. BG modelling essential...

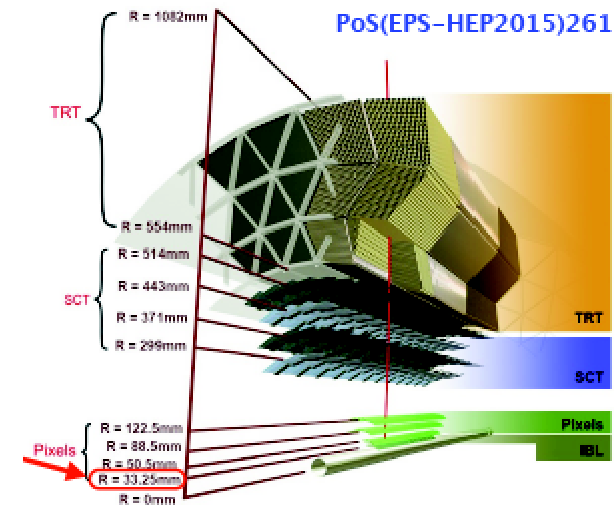
Many types of long lived particles

Spieza
Hulsbergen
Kaji

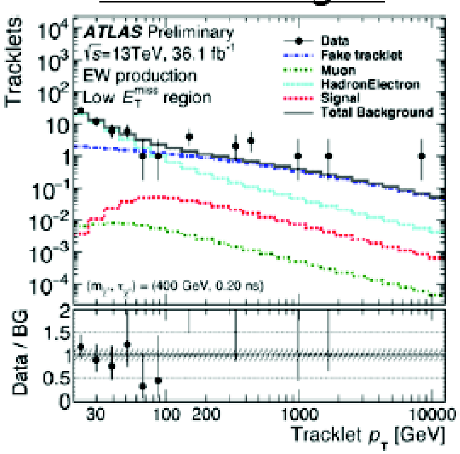




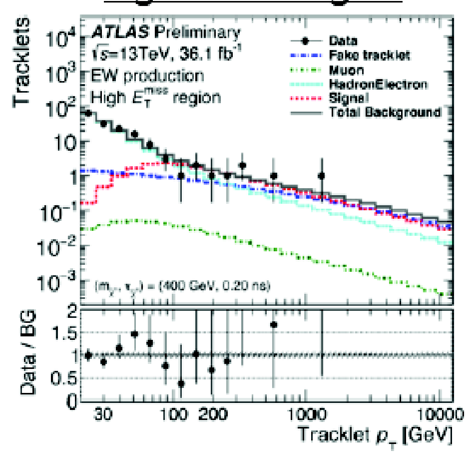
Layout of Inner Detector (ID)

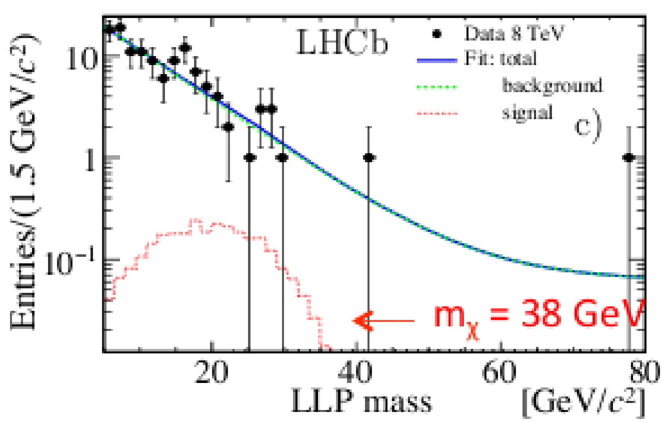


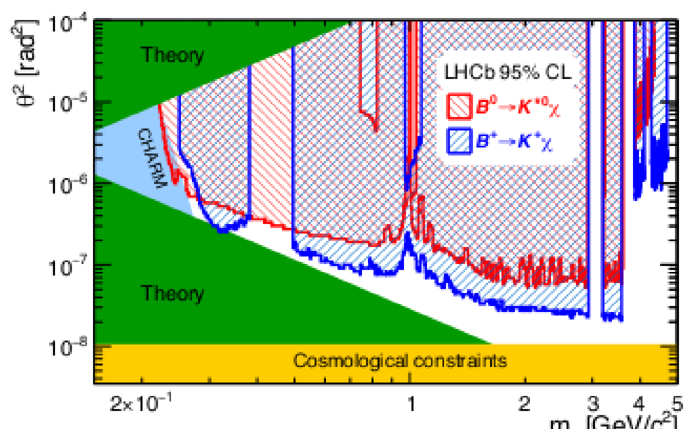
low-E_T^{miss} region



high-E_T^{miss} region





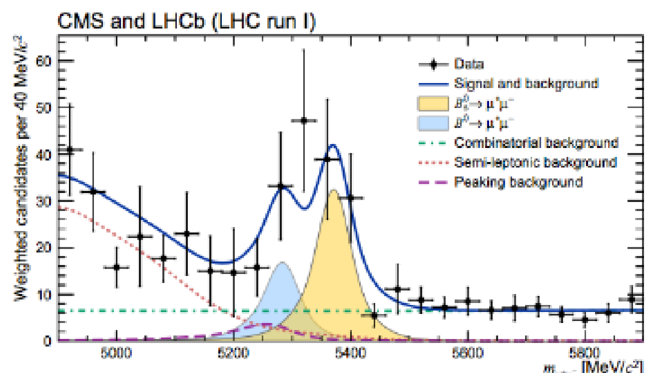


Tolk Mulder

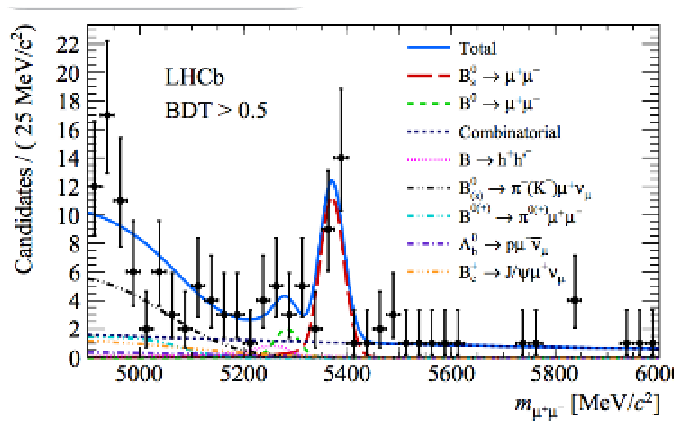
BSM searches in Heavy Flavour

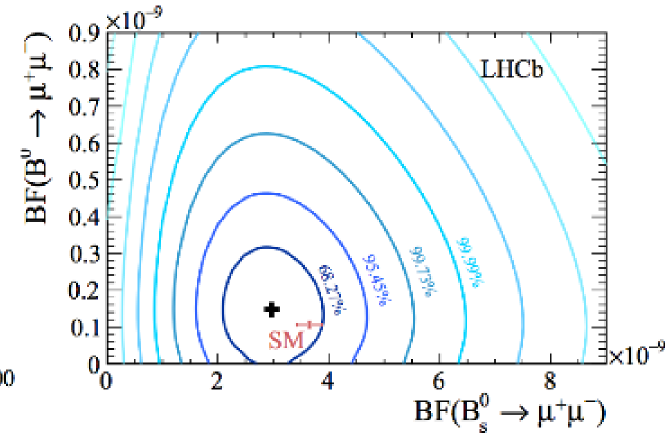
purely leptonic final states are theoretically clean

CMS+LHCb combination (Run I) | LHCb only (including Run II) | arXiv:1703.05747



Nature 522, 68-72 (04 June 2015)





- **The fitted central values**

$$\mathcal{BR}(B_s \to \mu^+\mu^-) = 2.8^{+0.7}_{-0.6} \times 10^{-9}$$
$$\mathcal{BR}(B_d \to \mu^+\mu^-) = 3.9^{+1.6}_{-1.4} \times 10^{-10}$$

Run I results also from ATLAS

- **LHCb Run1 data (3fb^{-1}) + 2015 (0.33fb^{-1}) + 2016 (1.4fb^{-1})**
- Several **improvements** compared to the old analysis:
  - better di-hadron background rejection (50%)
  - exclusive background estimates validated on data
  - new isolation variables with improved geometry
- The most precise results up to date; the **first single experiment $B_s \to \mu\mu$ observation**

$$\mathcal{B}(B_s \to \mu^+\mu^-) = (3.0 \pm 0.6^{+0.3}_{-0.2}) \times 10^{-9}$$
$$\mathcal{B}(B_d \to \mu^+\mu^-) < 3.4 \times 10^{-10}$$

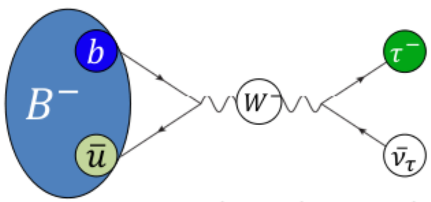
$B_s \to \mu\mu$ (7.8σ) and $B_d \to \mu\mu$ (1.6σ)

LHCb also presented first direct limits on $B_s^0 \to \tau^+\tau^-$ arXiv:1703.02508

Hirose
Weidenkaff

BSM searches in Heavy Flavour

purely leptonic final states are theoretically clean



$$BF(B^- \to \tau^- \bar{\nu}_\tau)_{SM} = \frac{G_F^2 m_B m_\tau^2}{8\pi}\left(1 - \frac{m_\tau^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2 \tau_B$$

- Contains a τ lepton
- Rare decay at O(10^{-4})

} Good probe for NP coupling to τ

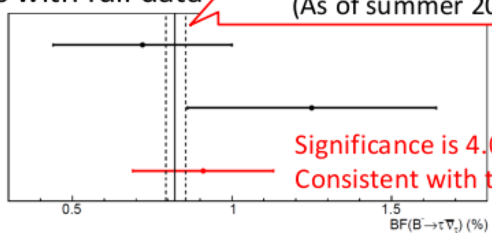
- Two measurements with full data

SM prediction by the CKM fitter (As of summer 2016)

Phys. Rev. Lett. 110, 131801 (2013) (Hadronic tagging)

Phys. Rev. D 92, 051102 (R) (2015) (Semileptonic tagging)

Belle average



Significance is 4.0σ
Consistent with the SM

Results also available from BaBar
Sensitivity close to SM level for $B^+ \to \mu\nu$

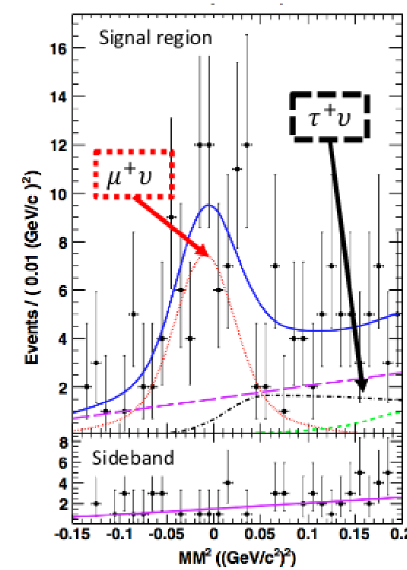
$D_S^+ \to \mu^+ \upsilon \,/\, \tau^+ \upsilon$

- Missing mass of the neutrino

$$MM^2 = (E_{beam} - E_{\mu^+})^2/c^4 - (-\vec{p}_{D_S^-} - \vec{p}_{\mu^+})^2/c^2.$$

- Two fit approaches
  - Constrained $\frac{\Gamma(D_S \to \tau\nu)}{\Gamma(D_S \to \mu\nu)} = 9.76$
  - Unconstrained

Mode	Branching fraction (%)
$D_S^+ \to \mu^+\nu$	$0.495 \pm 0.067 \pm 0.026$
$D_S^+ \to \tau^+\nu$	$4.83 \pm 0.65 \pm 0.26$ constraint fit



incomplete list, see PDG 2014

Experiment	$B[D_S \to \mu\nu]$ (%)	$f_{D_S^+}$ (MeV)
CLEO-c [PRD79, 052001 (2009)]	$0.565 \pm 0.045 \pm 0.017$	$257.6 \pm 10.3 \pm 4.3$
BaBar [PRD82, 091103 (2010)]	$0.602 \pm 0.038 \pm 0.034$	$265.9 \pm 8.4 \pm 7.7$
Belle [JHEP09, 139 (2013)]	$0.531 \pm 0.028 \pm 0.020$	$249.0 \pm 6.6 \pm 5.0$
Experimental average	0.556 ± 0.024	257.5 ± 4.6 $(\mu\nu + \tau\nu)$
This work [PRD 94, 072004 (2016)]	$0.495 \pm 0.067 \pm 0.026$	$241.0 \pm 16.3 \pm 6.6$
Lattice (HPQCD) [PRD86, 054510 (2012)]		$246.0 \pm 0.7 \pm 3.5$
Lattice (FNAL + MILC) [PRD85, 114506 (2012)]		$246.4 \pm 0.5 \pm 3.6$

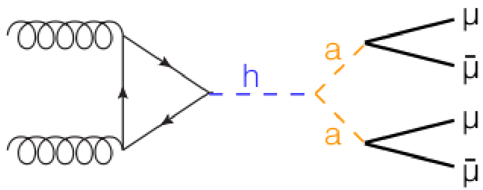
Good agreement with previous measurements and lattice QCD

Outschoorn

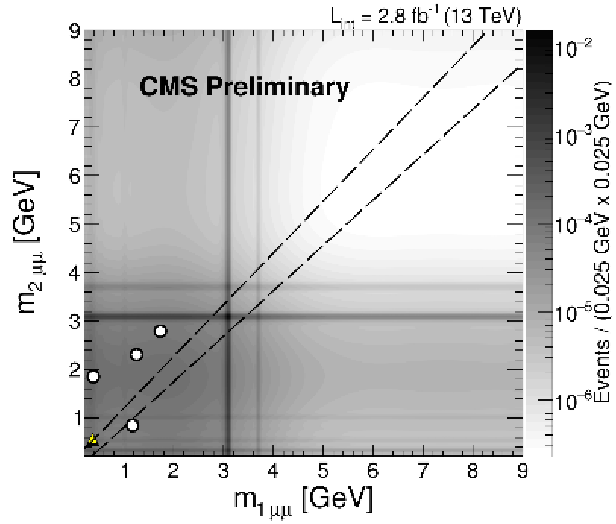
BEH BSM

$H \to a_1 a_1$ CMS-PAS-HIG-16-035

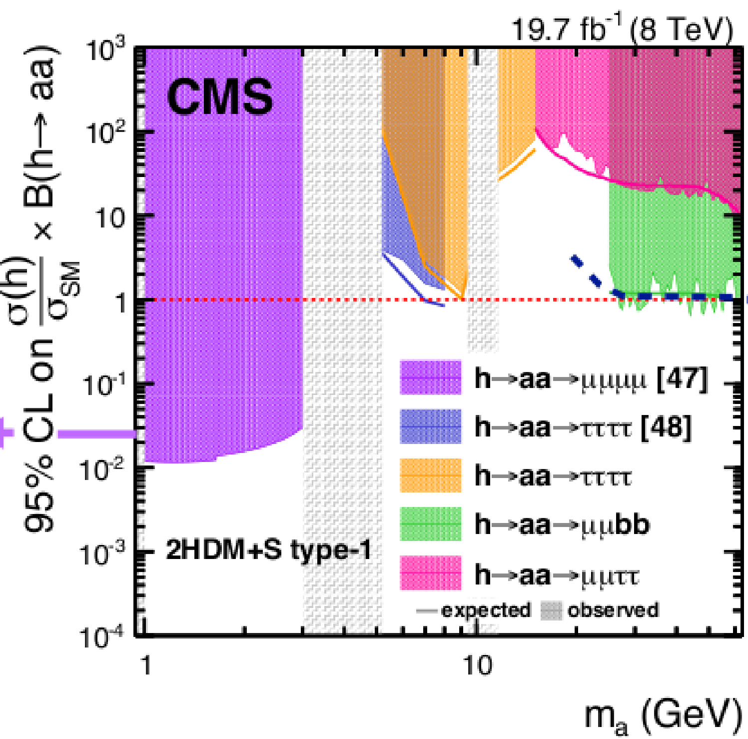
Signal



target $2m_\mu \lesssim m_a \lesssim 2m_\tau$



Also
- H → invisible
- H → LLP
- …



4μ extended to m_a<1 GeV in 13 TeV analysis

results are model dependent → here Yukawa couplings

4b sensitivity with first 13 TeV analysis

Eur. Phys. J. C 76 (2016) 605 arXiv: 1606.08391

8 TeV result from ATLAS for 2τ2μ also available down to $m_{2\tau}$

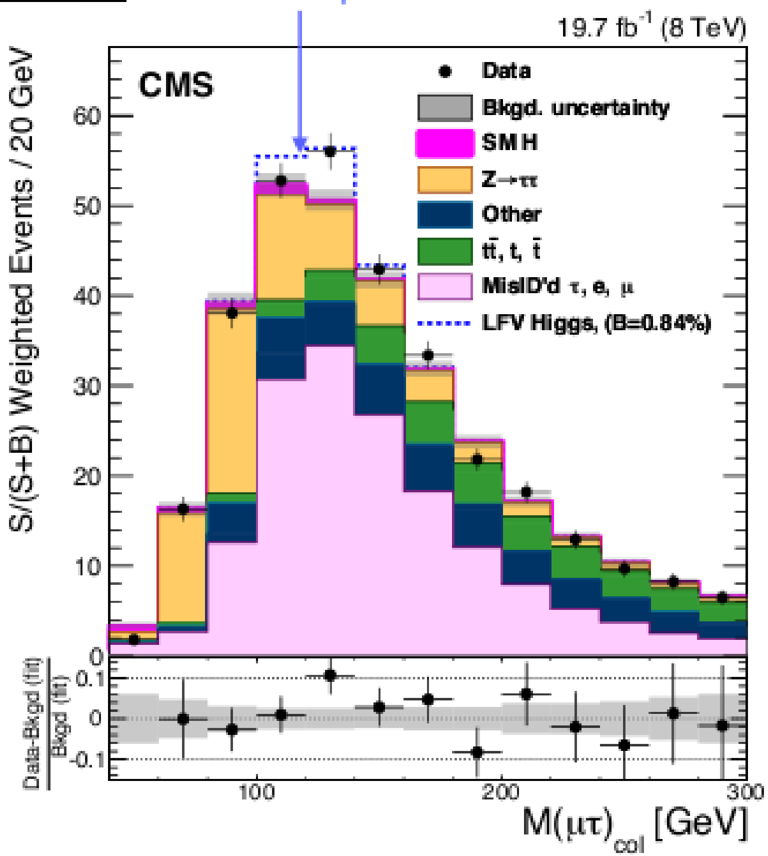
Outschoorn

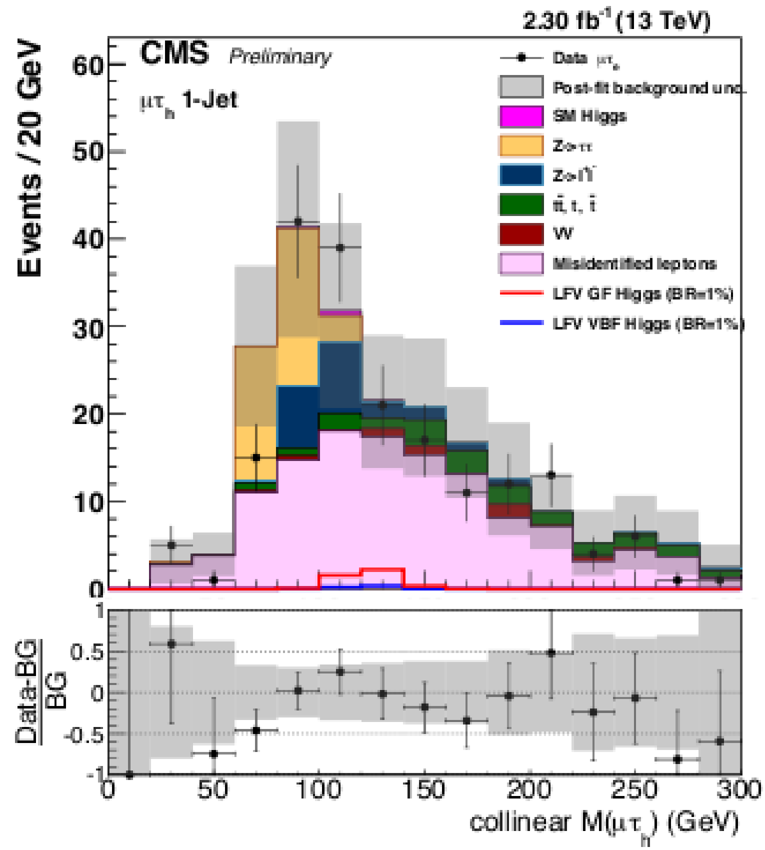
BEH BSM

$H \rightarrow \mu\tau$ arXiv:1502.07400

Excess in $\mu\tau$ at 8 TeV

No excess observed at 13 TeV in 2015 data, but not sensitive enough to exclude the 8TeV result





13 TeV: Br($H \rightarrow \mu\tau$)<1.20% (1.62% expected)

8 TeV: Br($H \rightarrow \mu\tau$)<1.51% (0.75% expected)

Kahlhoefer

Dark matter

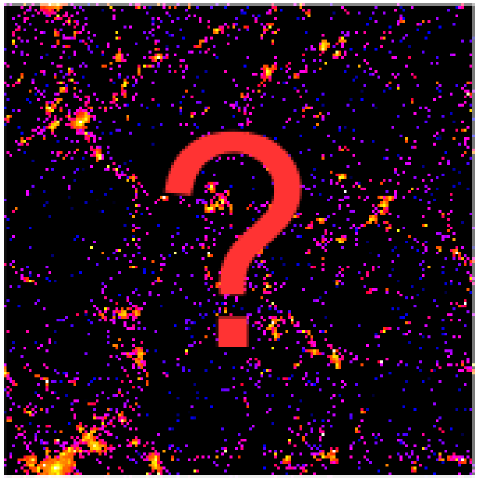
Cold white matter

Known

Hot dark matter

Known

Cold dark matter



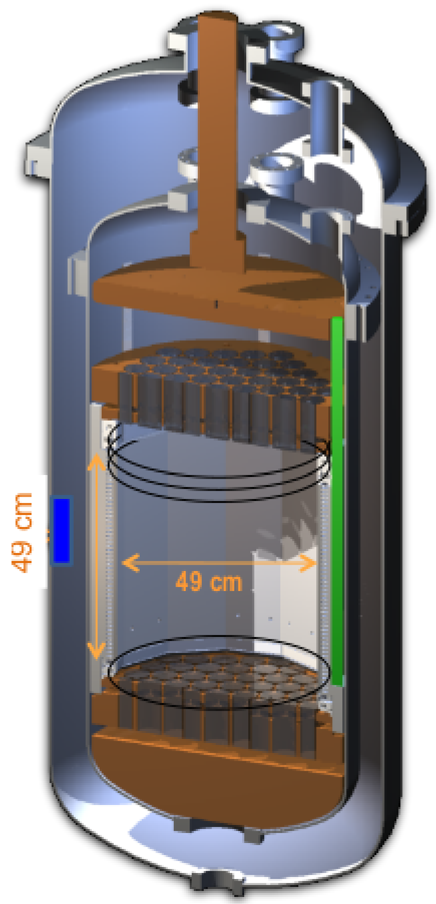
Unknown until today!

Scottish spiced rum
Definitely BSM!

(Until now, unable to find gin called “neutrino mass”)

Masbou

Direct DM searches

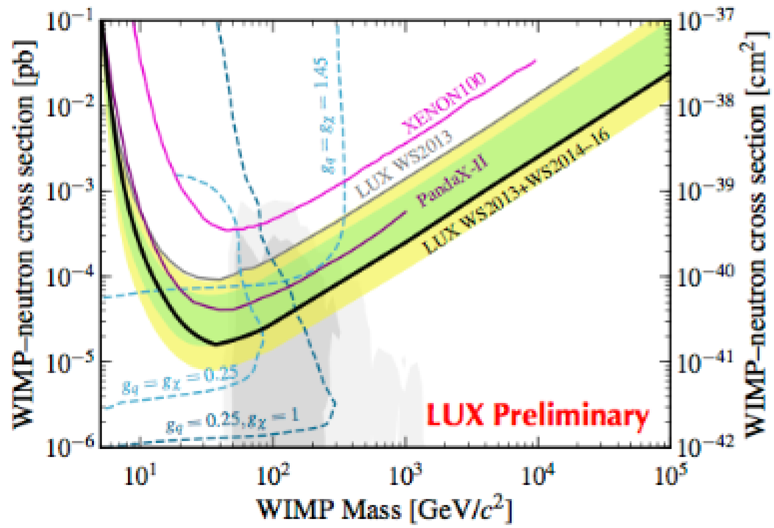


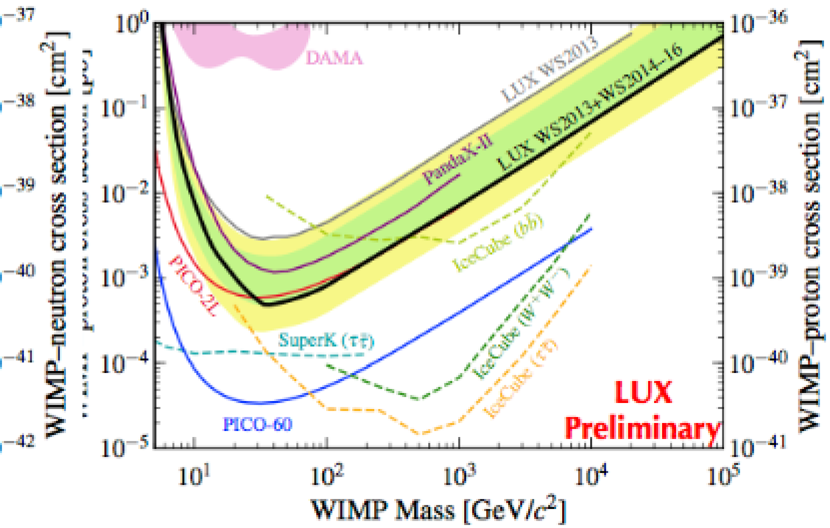
370 kg

New LUX spin-dependent limits

Improvement of a factor of six compared with the results from the first science run – 95 days (PRL, 116, 161302 (2016))

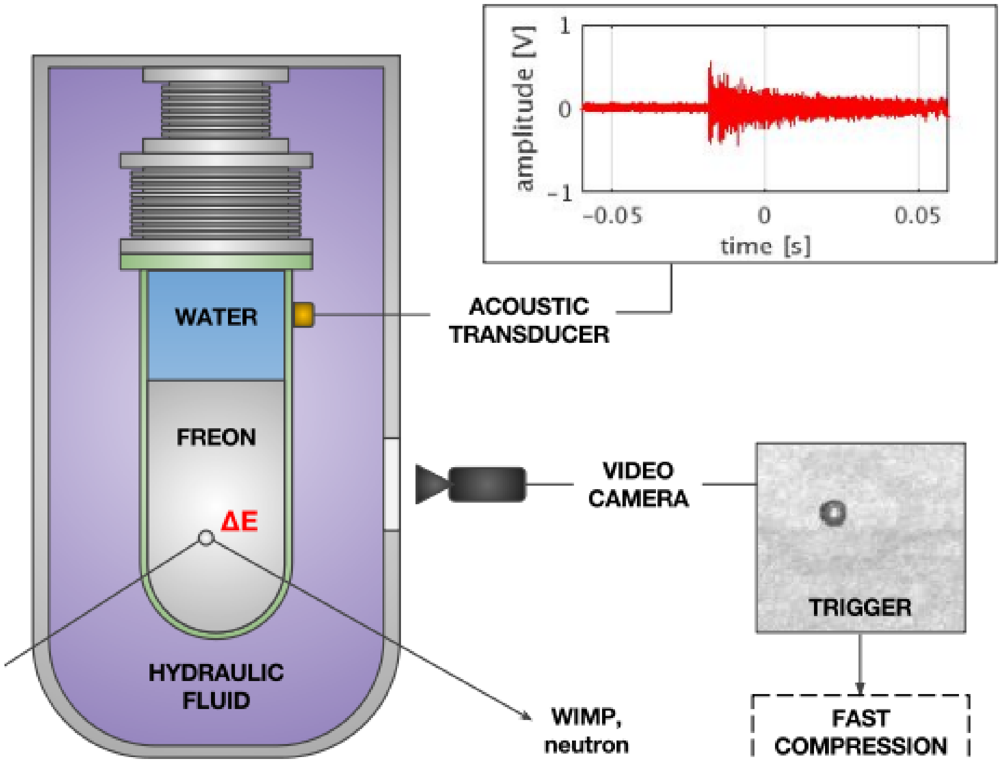
(picture with the courtesy of Cláudio Silva - LUX Collaboration)

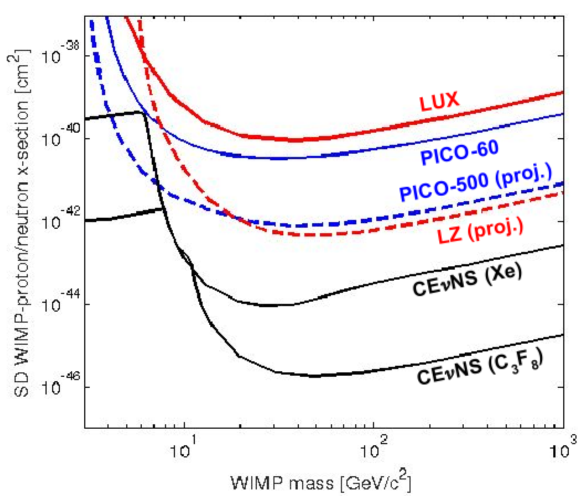




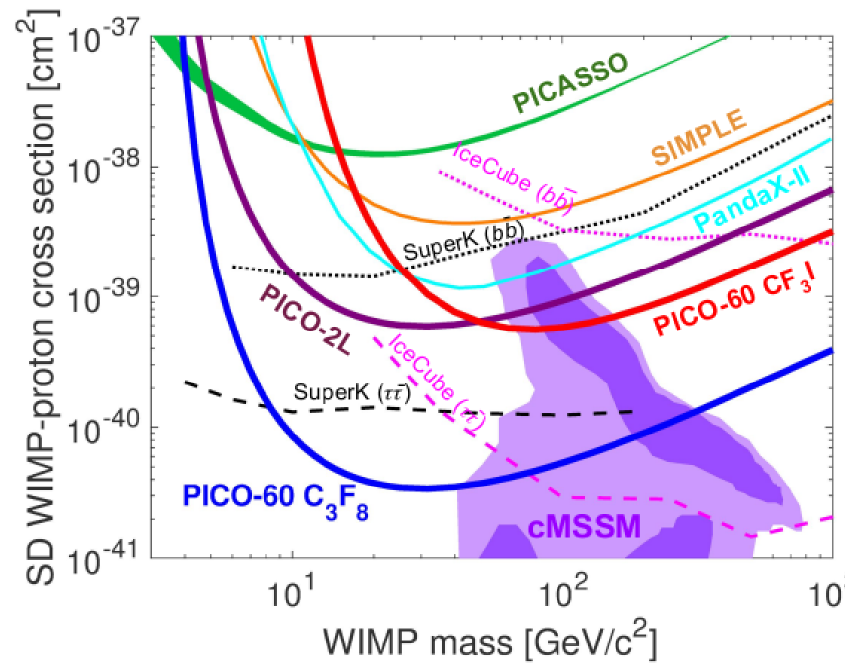
Giroux

Direct DM searches





PIC060
Look and listen for bubbles caused by WIMP interactions in superheated freon

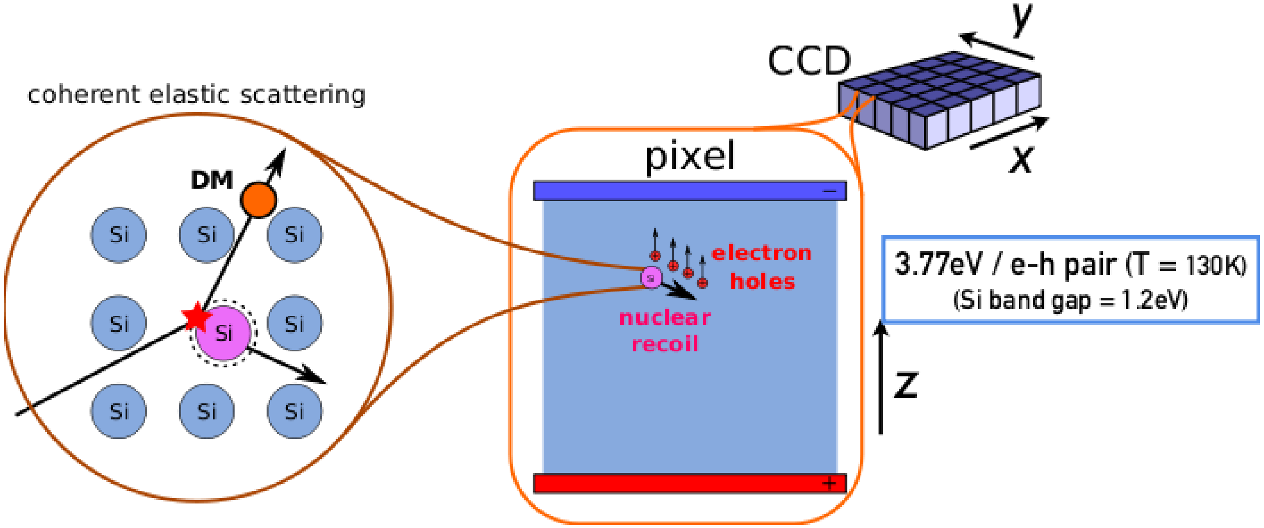


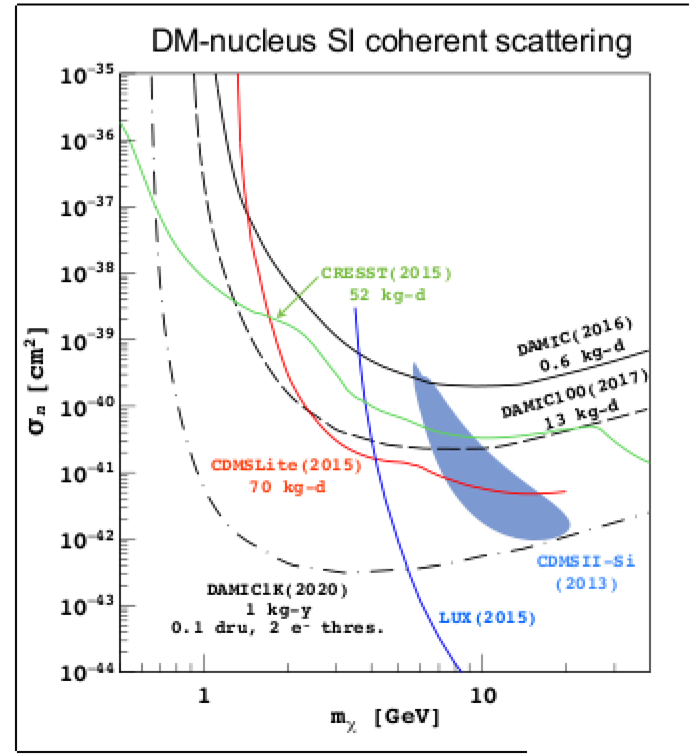
C. Amole *et al.*, arXiv:1702.07666 [astro-ph.CO] 2017

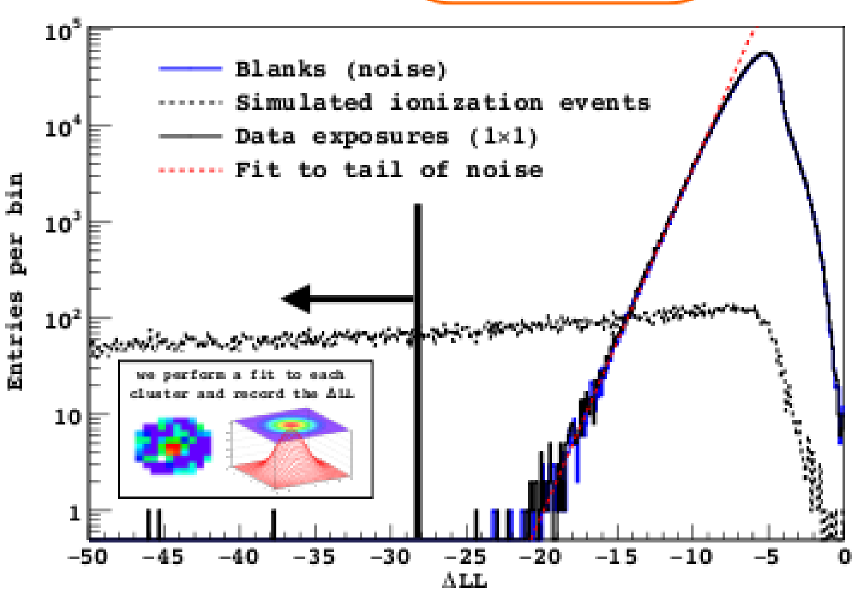
Exciting prospects for improvements in sensitivity

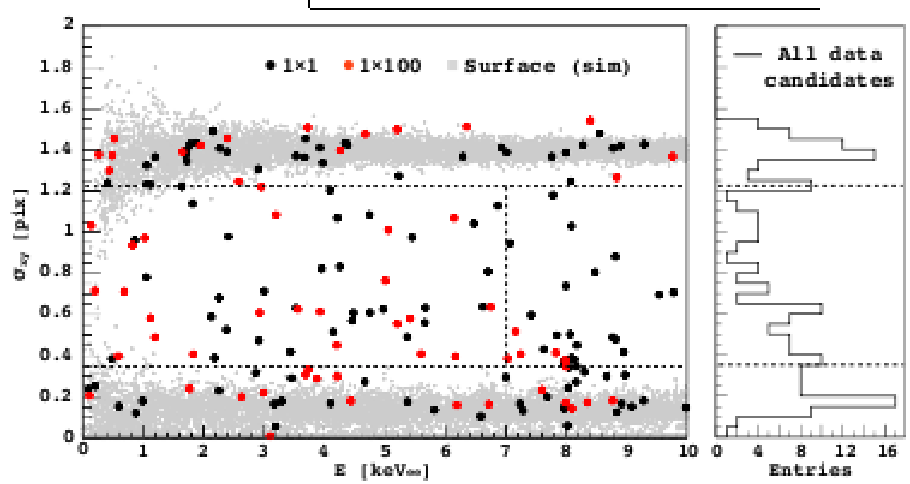
Direct DM searches

DAMIC search for low mass wimps in CCDs





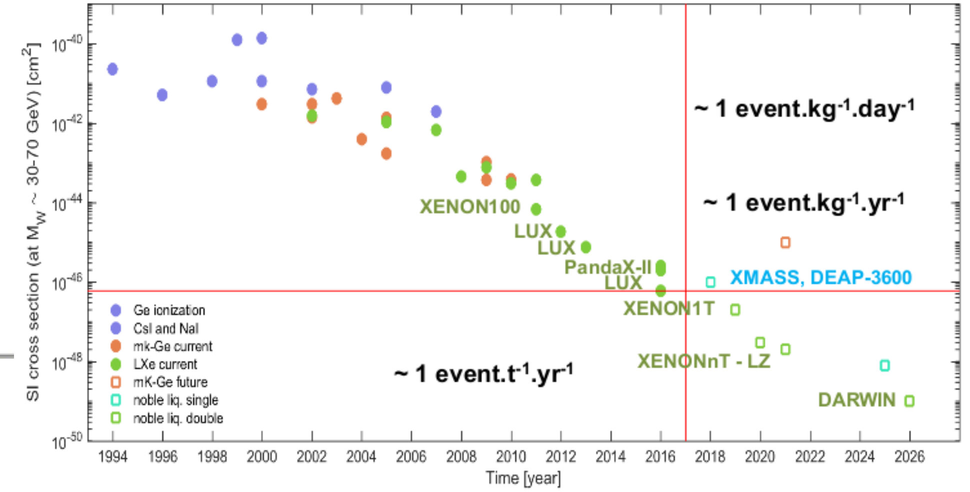


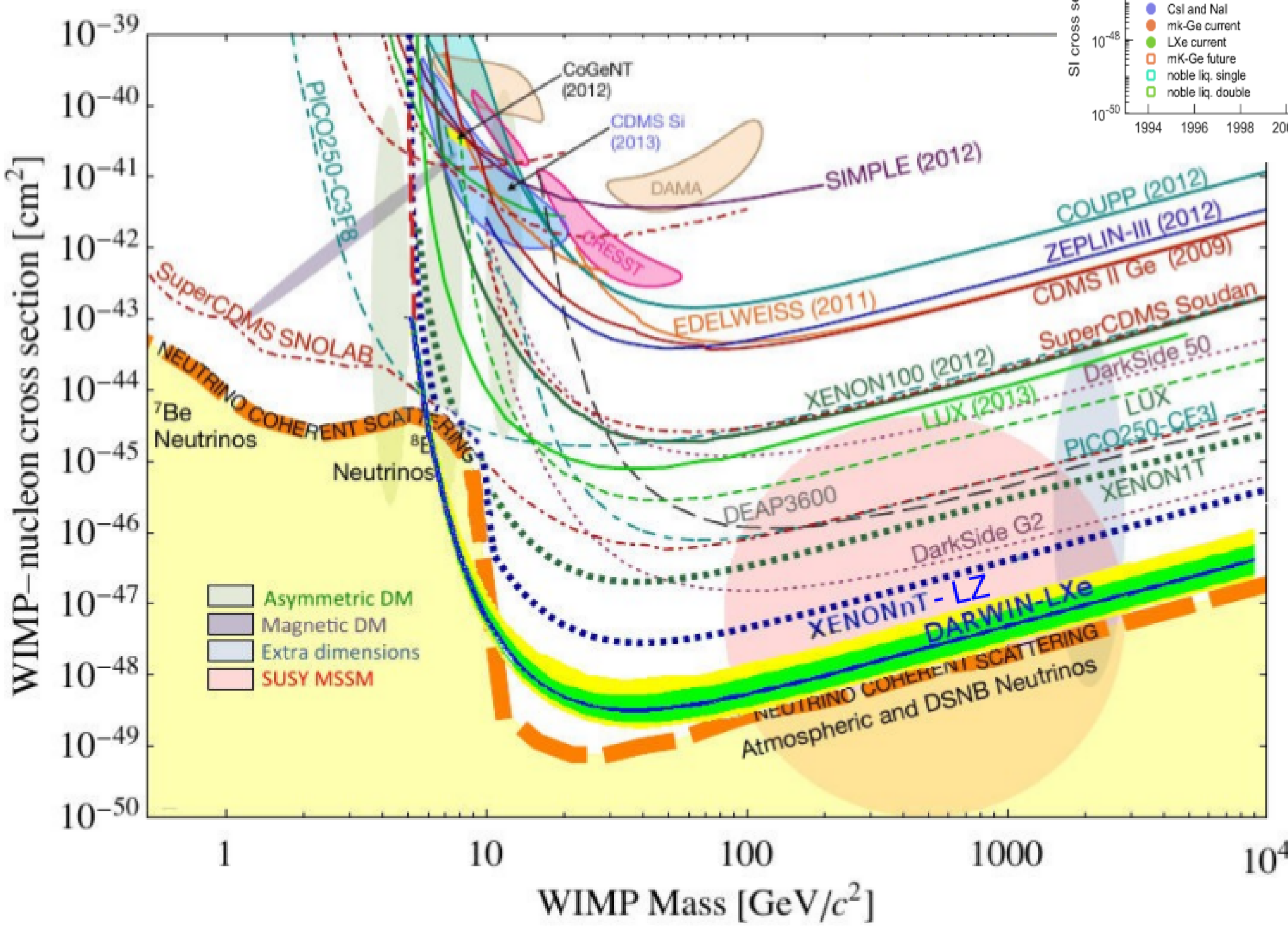


Masbou

Direct DM searches

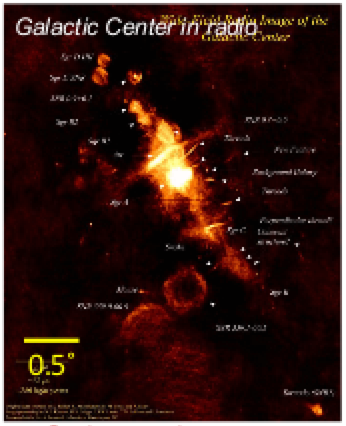
Exciting prospects to cover phase-space down to ν floor





Viana

Astrophysical WIMP searches

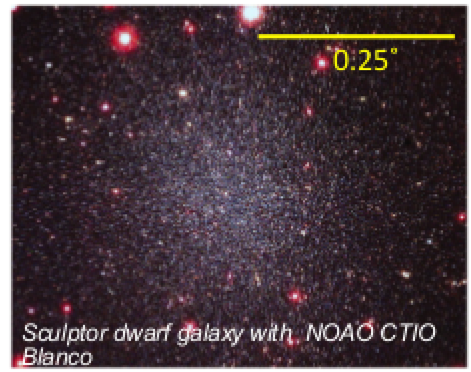


Galactic Centre

- Proximity (~8kpc)
- High (possibly) central DM concentration :
  DM profile : core? cusp?
- High astrophysical background in gamma-rays

Dwarf galaxies of the Milky Way

- Many of them within the 100 kpc from Sun
- Extremely DM-dominated environment
- Potential low astrophysical background

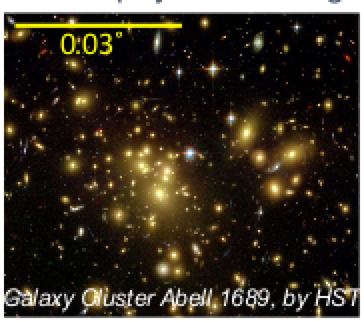


Sculptor dwarf galaxy with NOAO CTIO Blanco

No clear signal for DM in searches by HESS and Fermi

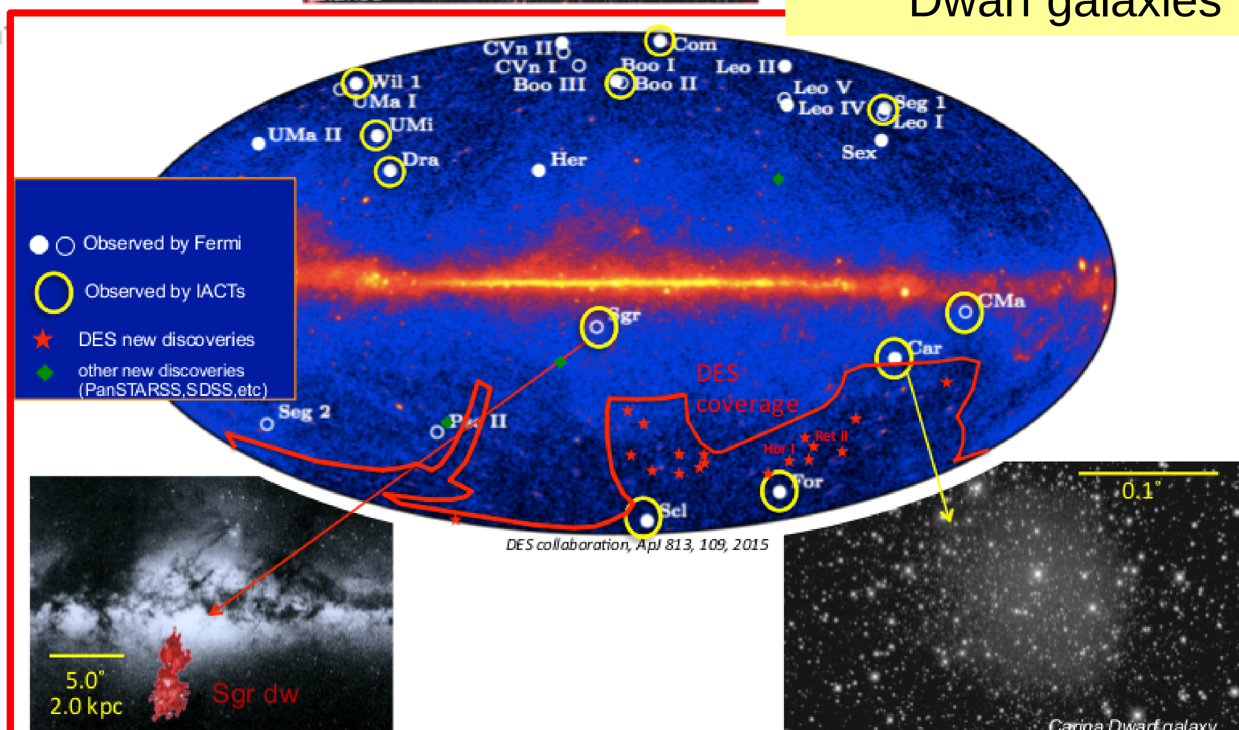
Galaxy clusters

- High DM annihilation luminosity
- Substructures contribution to the overall DM flux
- Astrophysical background may be important



Galaxy Cluster Abell 1689, by HST

Dwarf galaxies

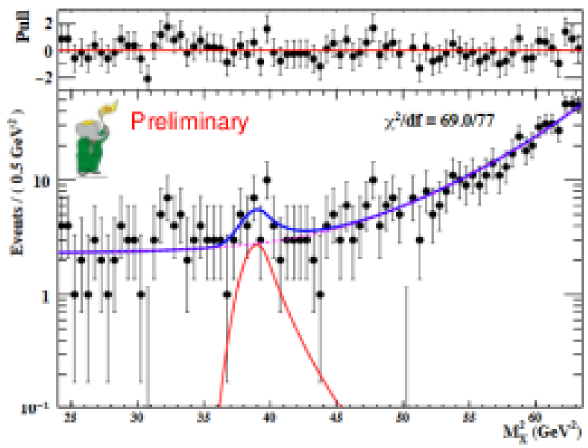


Alternatives to WIMPS

Röhrken
Gavela

Dark photons, axions, ALPS, ...

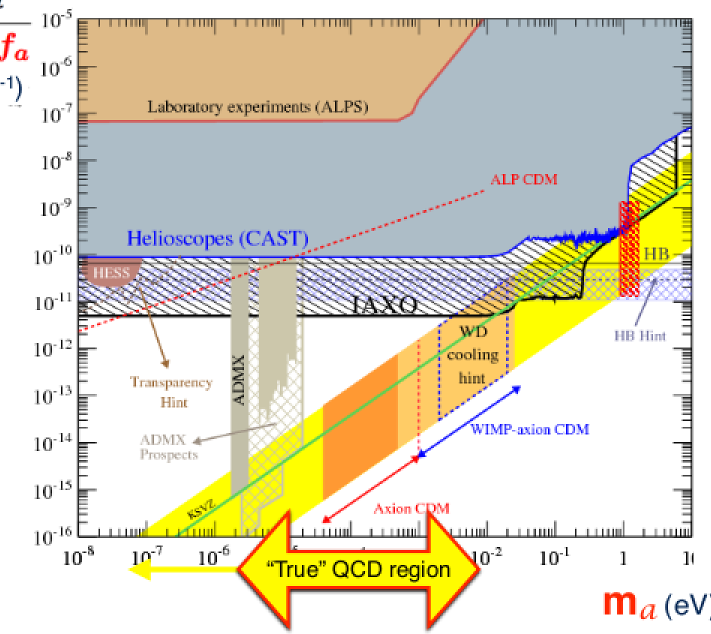
Most significant fit at $m_{A'} = 6.22$ GeV



Local (global) significance: 3.1σ (2.6σ)
Global p-value: ≈1%

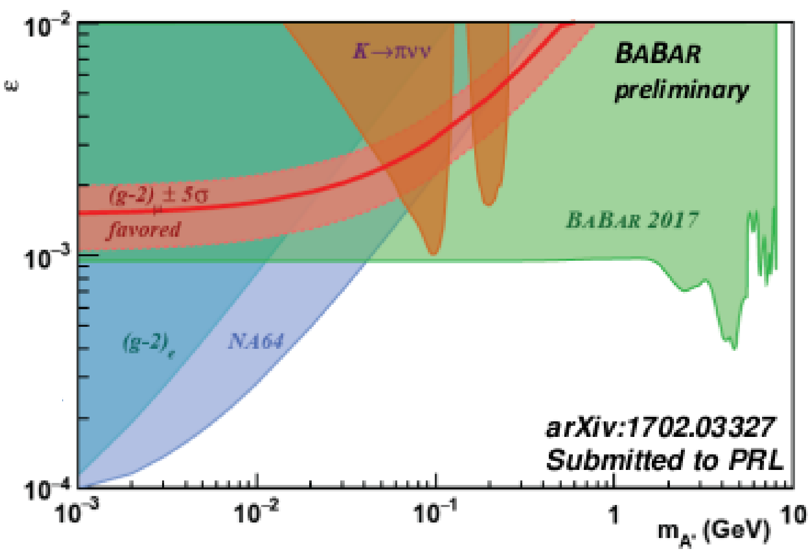
$$g_{a\gamma} \sim \frac{\alpha}{8\pi f_a}$$

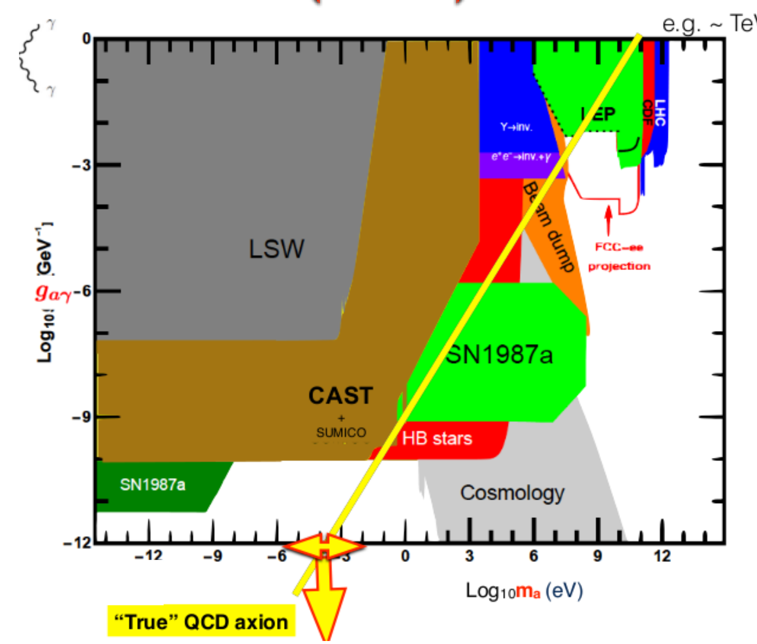
(GeV^{-1})



m_a (eV)

Limits (90% CL) on the mixing parameter ε





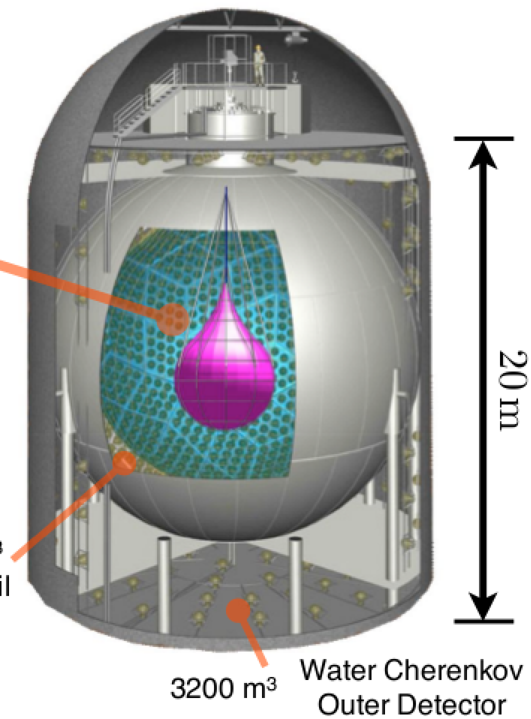
Neutrino mass

Decowski
Wagner
Calvez

Possibly the most fundamental question in particle physics today

Being addressed by several experiments

- 1 kton Scintillation Detector
  - 6.5m radius balloon filled with:
    - 20% Pseudocumene (scintillator)
    - 80% Dodecane (oil)
    - PPO
- 34% PMT coverage
  - ~1300 17" fast PMTs
  - ~550 20" large PMTs
- Water Cherenkov veto
- Operational since 2002

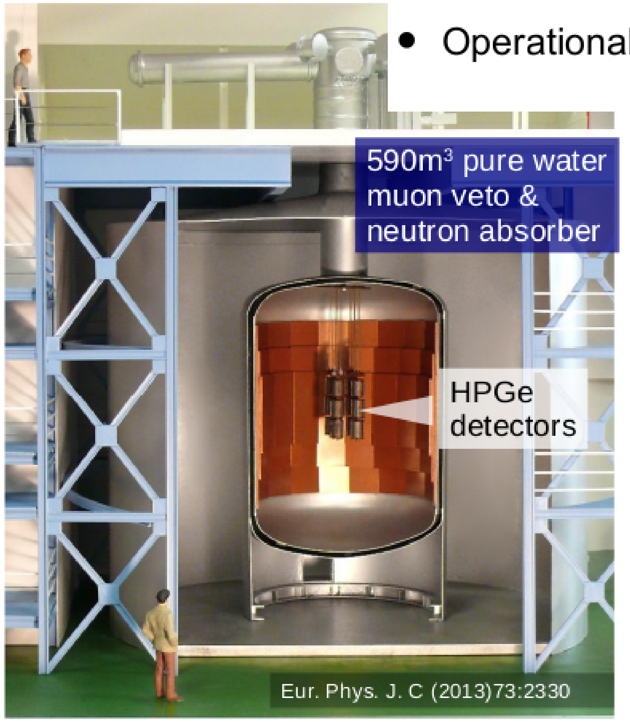


concept:
operate bare HPGe detectors in LAr which serves as coolant & (active) shielding

GERDA Phase I (Nov 2011- May 2013)
- **17.8 kg** enriched semi-coaxial + **3.6 kg** enriched BEGe
- exposure 21.6 kg·y
- BI ~ 10^{-2} counts/(keV·kg·yr)
- $T^{0\nu}_{1/2} > 2.1 \cdot 10^{25}$ yr (90% C.L.)

PRL 111, 122503 (2013)

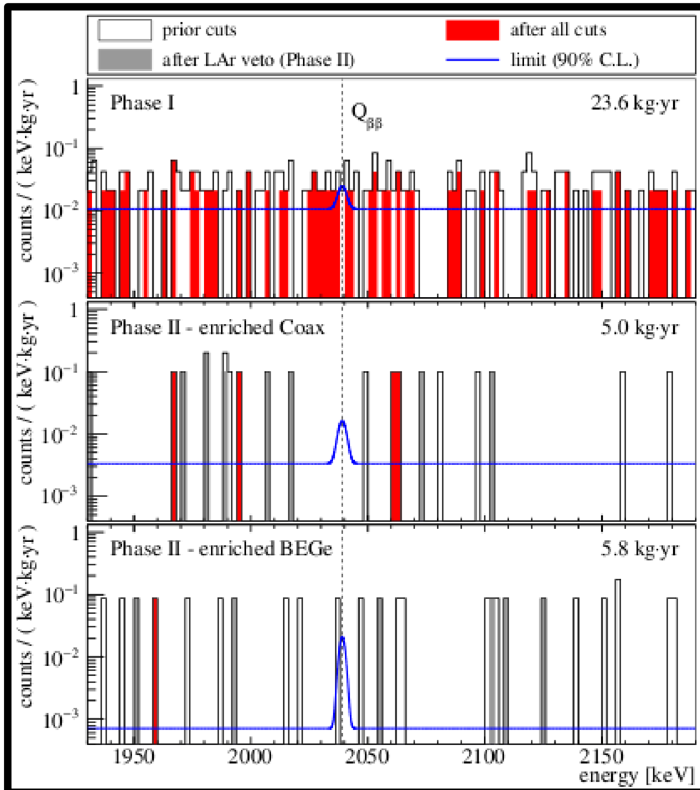
GERDA Phase II (Dec 2015 -)
- **30** enriched **BEGe** (= **20.0 kg**) + 7 enriched semi-coaxial (= **15.6 kg**)
- **LAr instrumentation**
- goal: BI ~ 10^{-3} counts/(keV·kg·yr)



Highly sophisticated background suppression techniques

Decowski
Wagner
Calvez

Neutrino mass

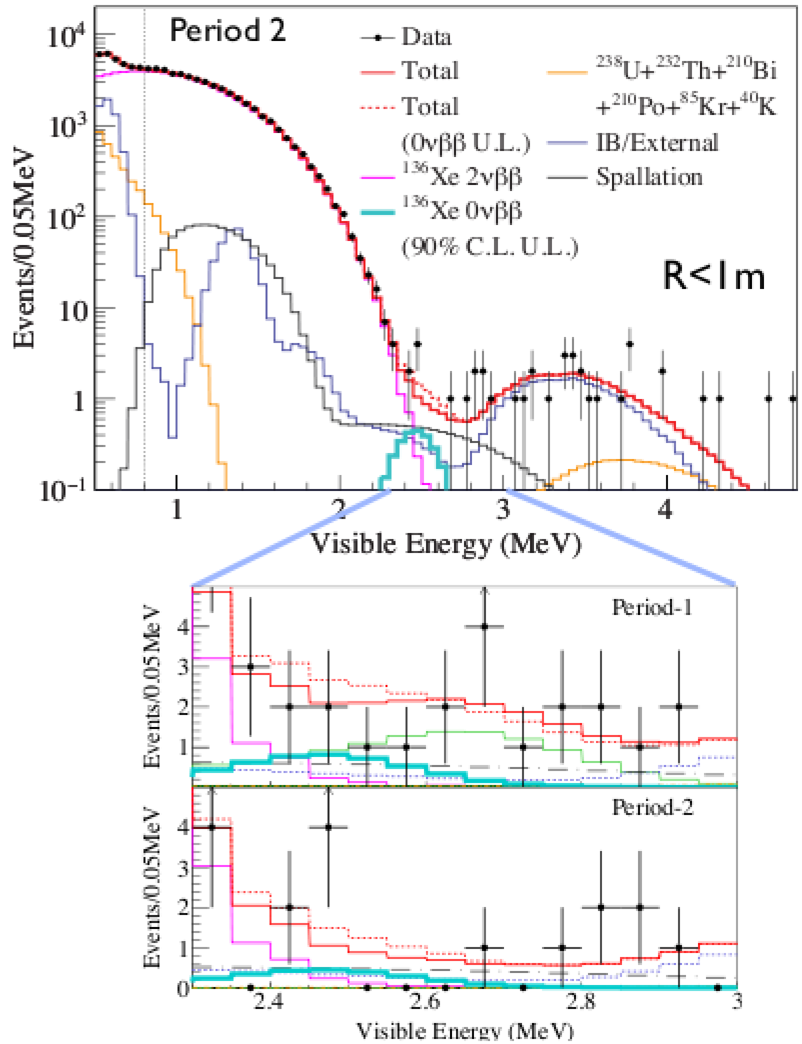


Extended unbinned profile likehood:

- flat background in 1930-2190 keV
- signal = Gaussian with mean at $Q_{\beta\beta}$ and standard deviation σ_E
- 7 parameters: 6 BI + common $T_{1/2}$

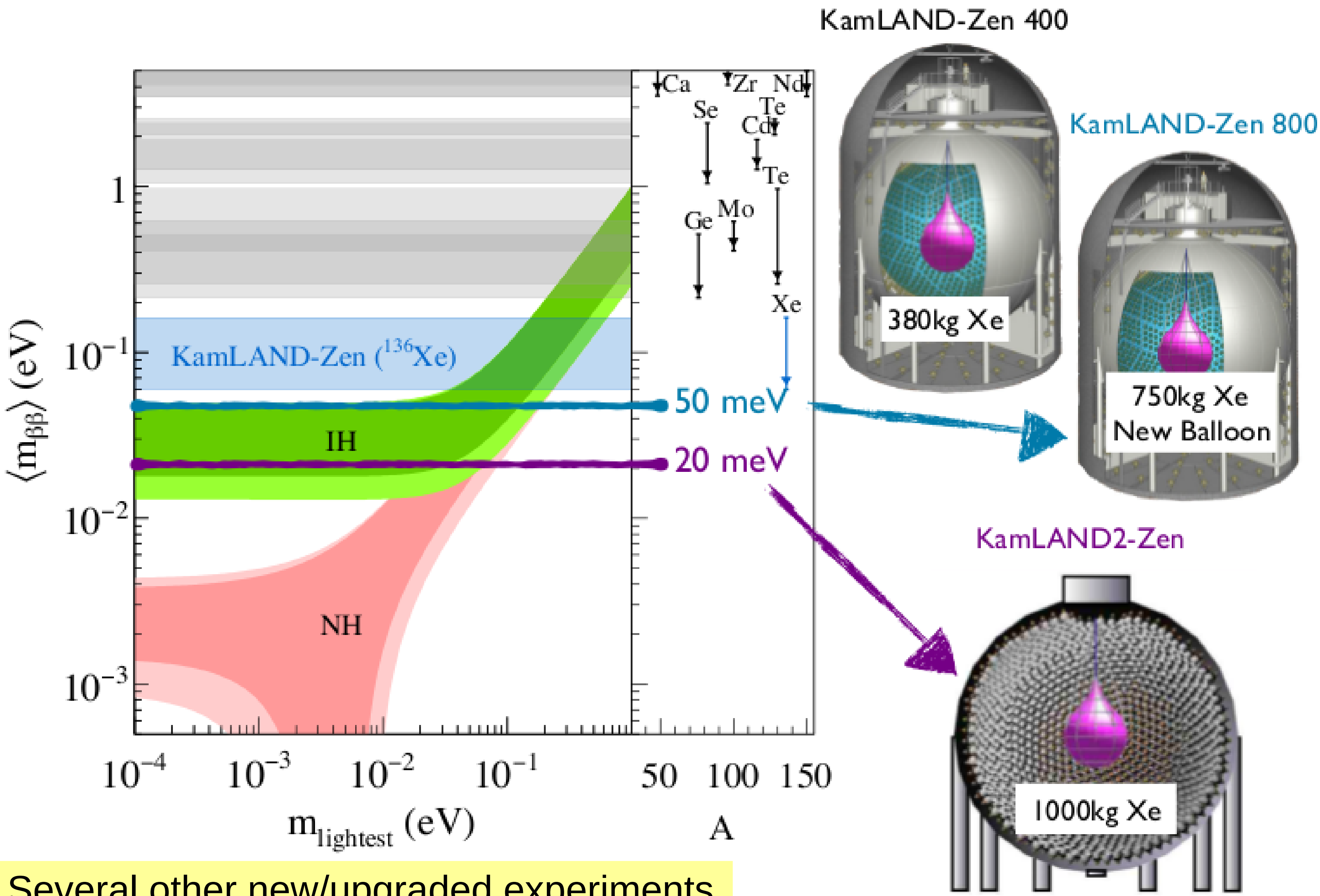
- best fit for $N_{0\nu} = 0$
- lower limit $T_{1/2}^{0\nu} > 5.3 \cdot 10^{25}$ yr $^{+}$ with $T_{1/2}^{0\nu}$ sensitivity $4.0 \cdot 10^{25}$ yr (90 % C.L.)

$^{+}$Frequentist approach after Cowan et al., EPJC 71 (2011) 1554



Neutrino mass

Decowski
Wagner
Calvez



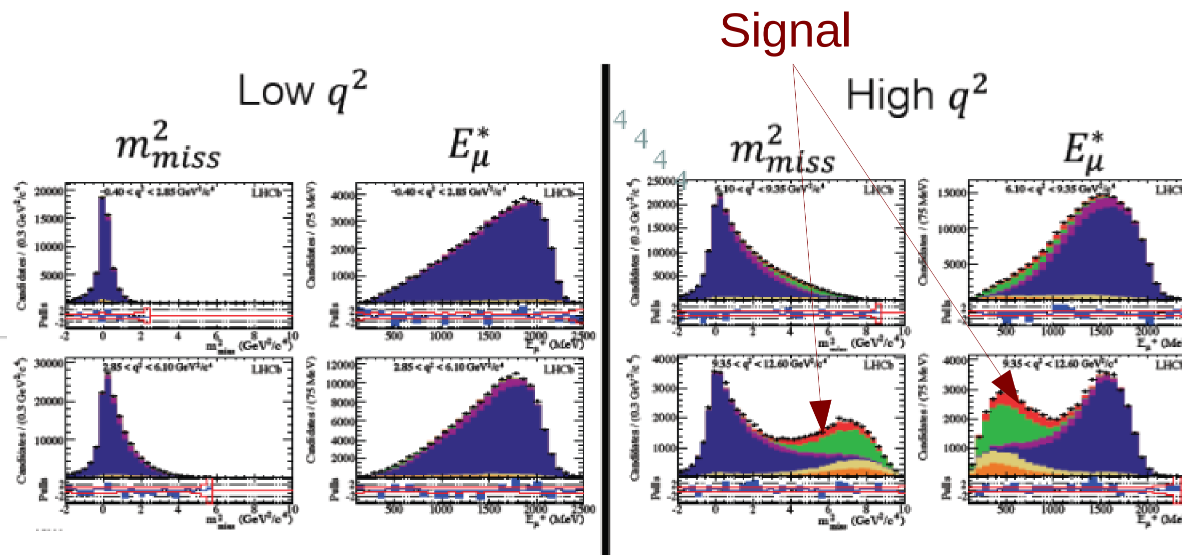
Several other new/upgraded experiments on similar timescales

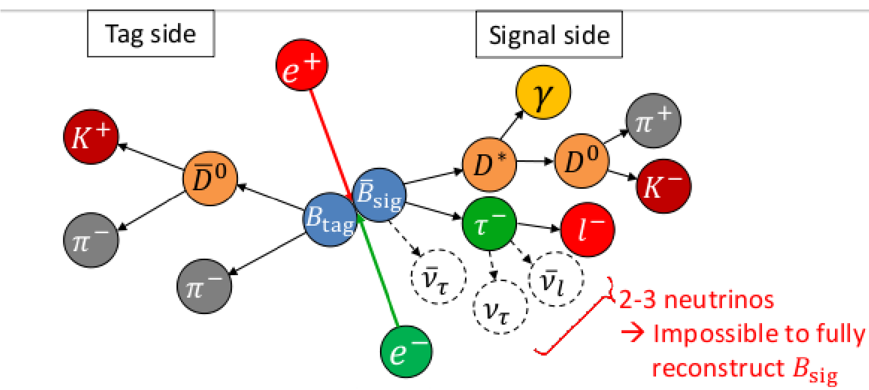
Pink unicorns

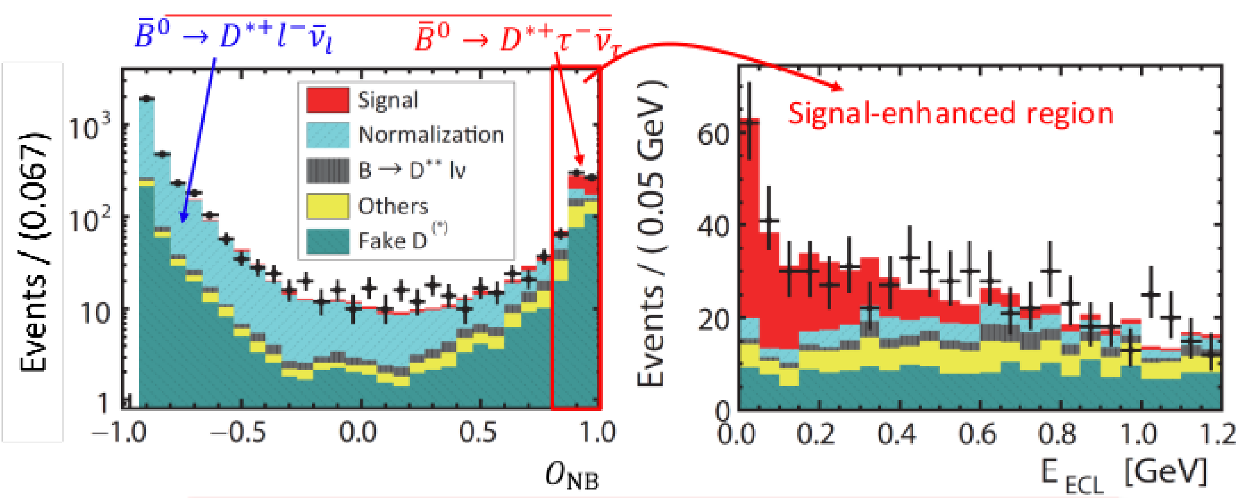
$B \rightarrow D^{(*)}\tau\nu$

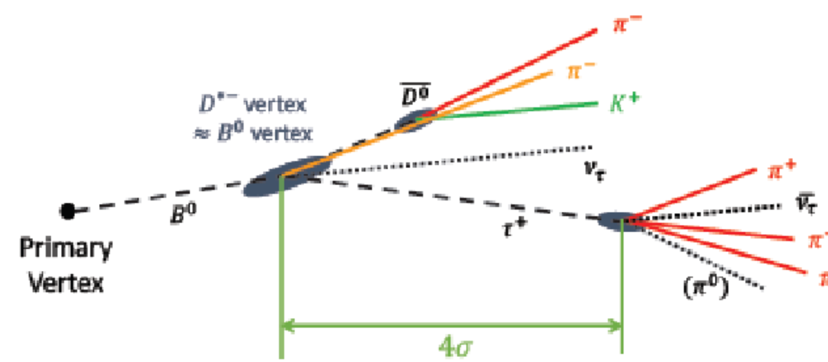
Wormser
Betti
Hirose

More new results “coming soon”





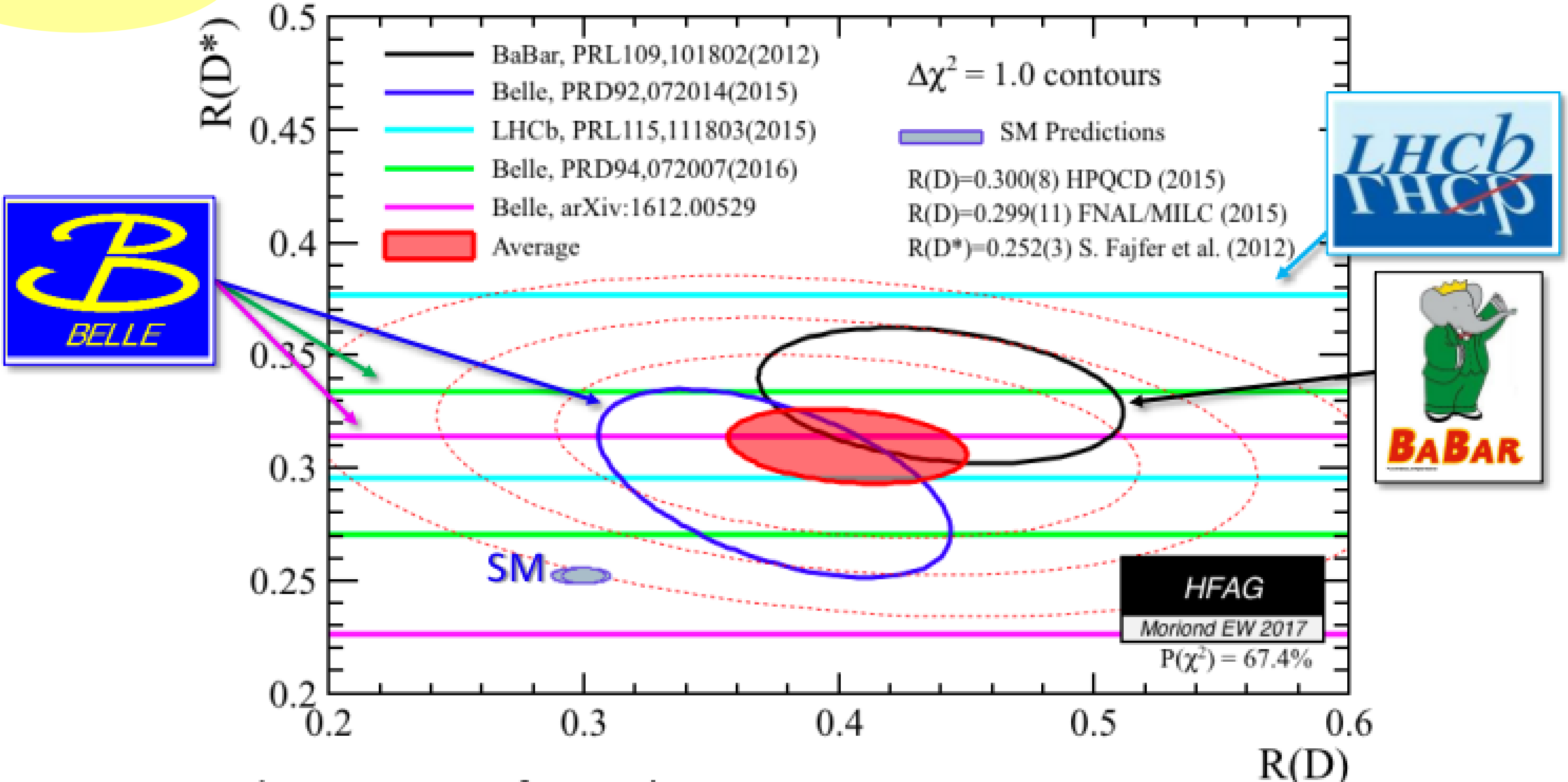




3.9σ

$B \to D^{(*)}\tau\nu$

Wormser
Betti
Hirose



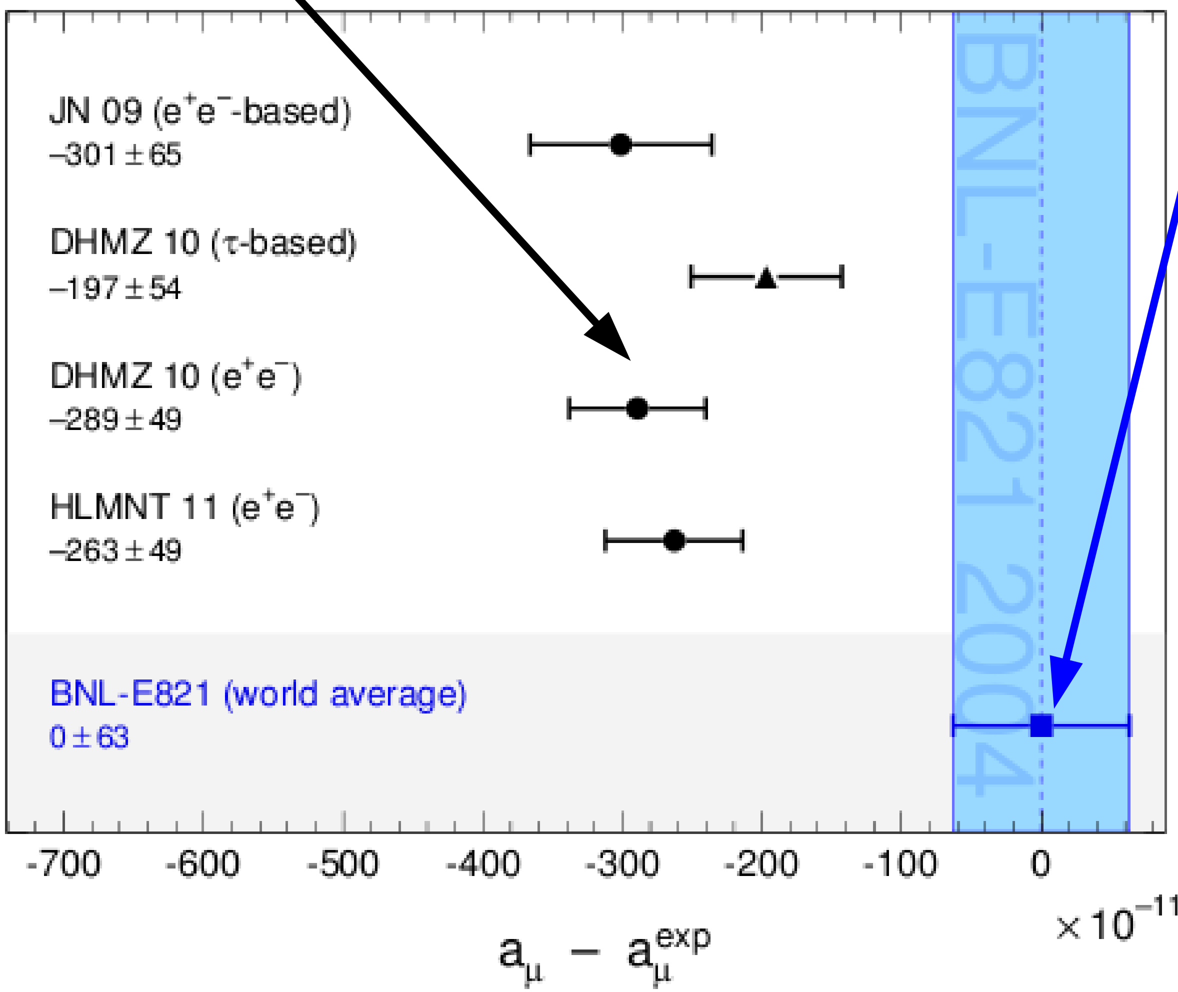
- ~4σ discrepancy from the SM remains
  - All the experiments show the larger $R(D^{(*)})$ than the SM
- More precise measurements at Belle II and LHCb are essential

$(g-2)_\mu$

3.6σ

Theory predictions

Experiment

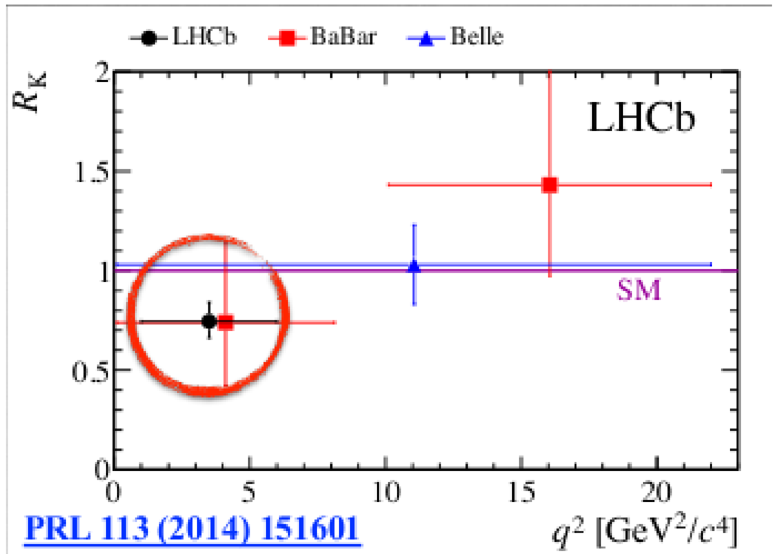


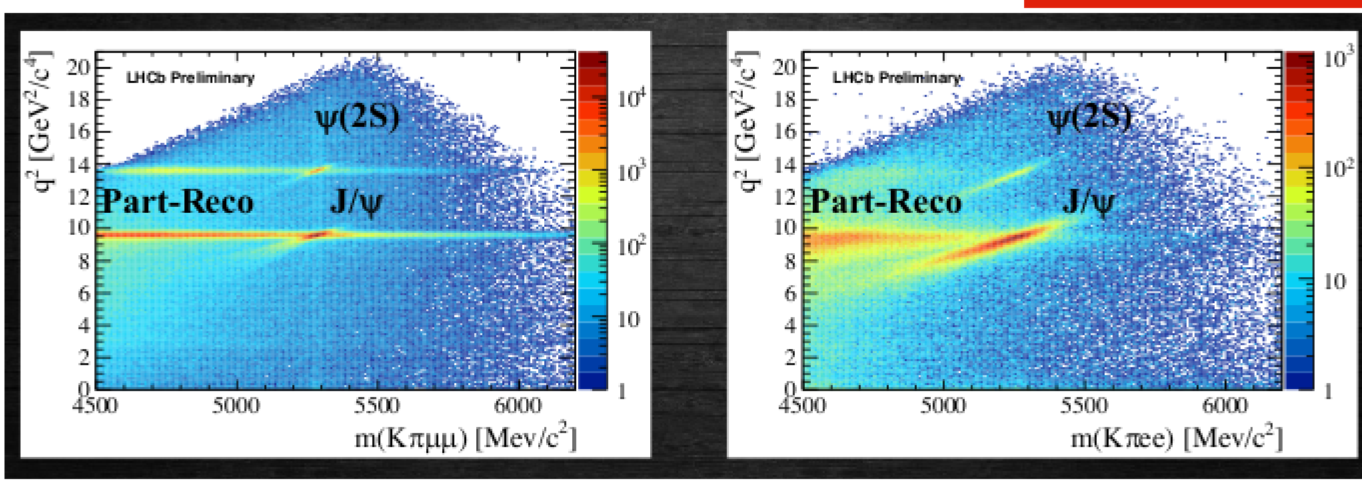
New experiment at FNAL will reduce uncertainty by factor ~2
Improvements in theory uncertainties also anticipated

Bifani

$\mathcal{B}(B \to K^{(*)}\mu\mu)/\mathcal{B}(B \to K^{(*)}ee)$

2.6σ





One important question finally answered:

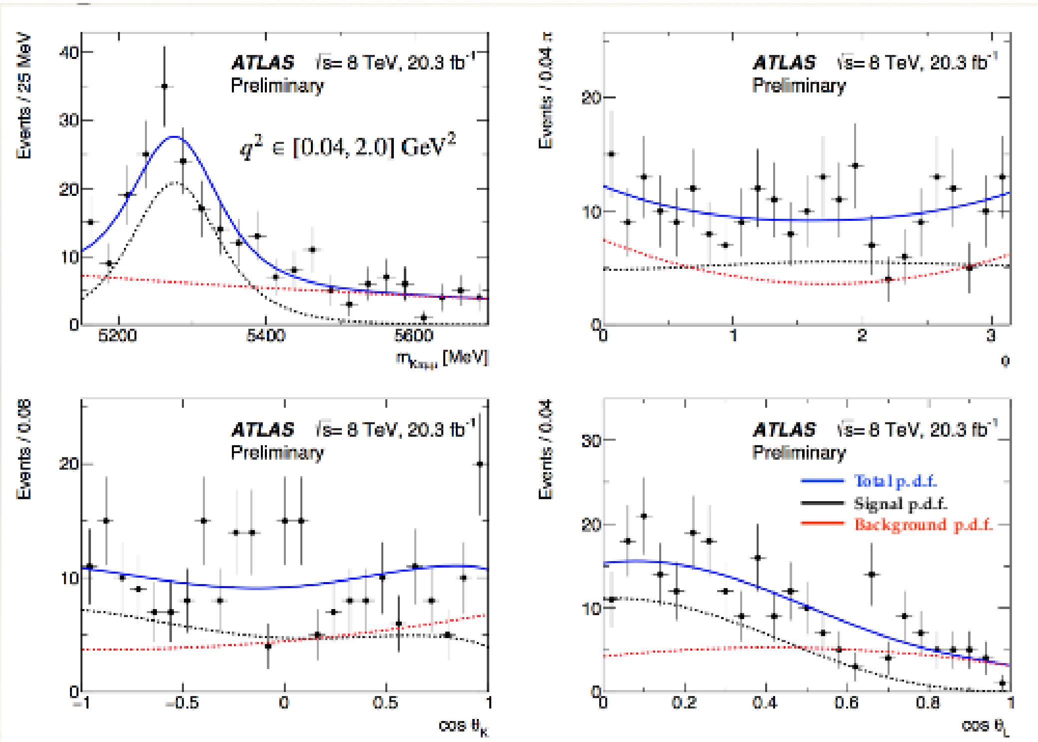
"Will LHCb have results on R(K*) at Moriond?"

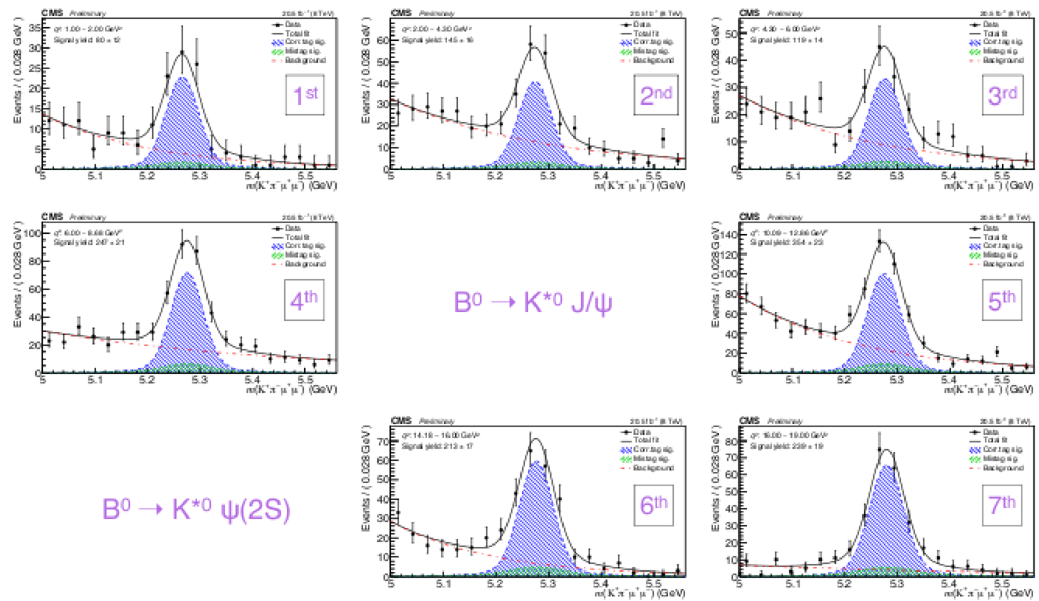
Bevan
Dinardo

P_5' and friends

ATLAS-CONF-2017-023

CMS-PAS-BPH-15-008





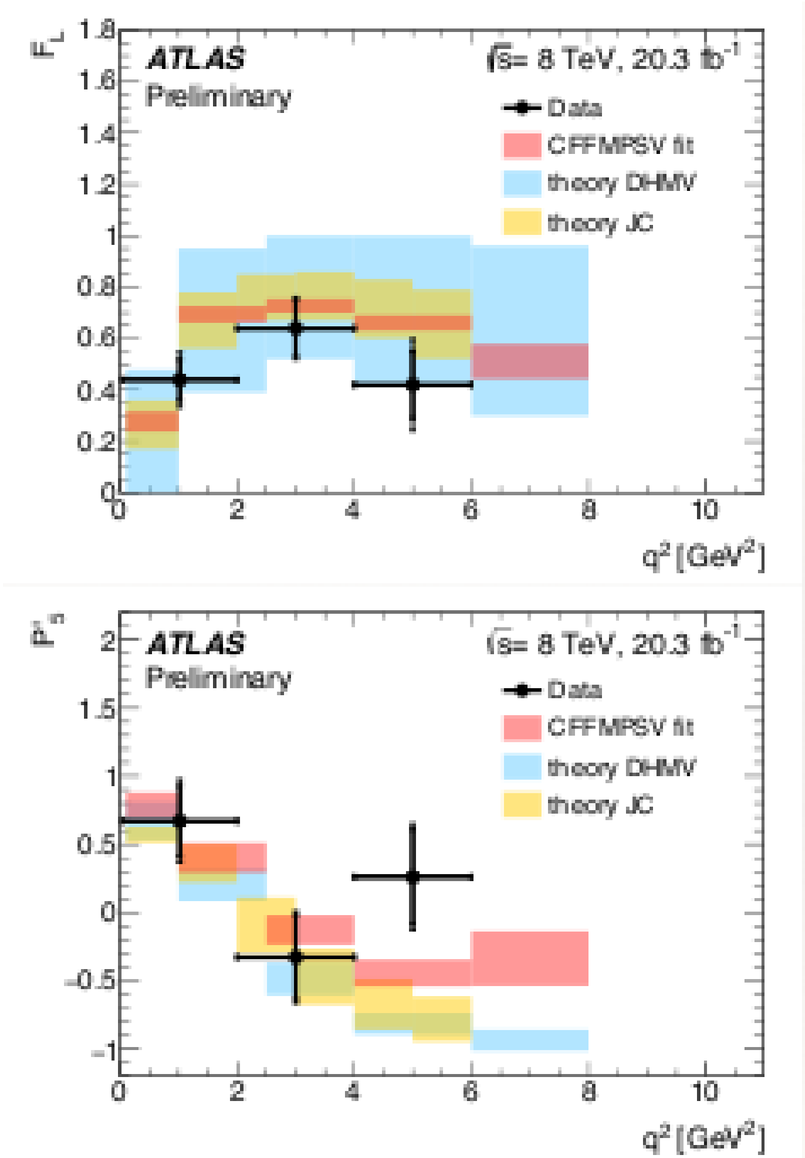
Angular observables in $B^0 \to K^{*0}\mu^+\mu^-$ decays
(not only P_5' – several others measured)

Fits done in several bins of $q^2 = m^2(\mu^+\mu^-)$

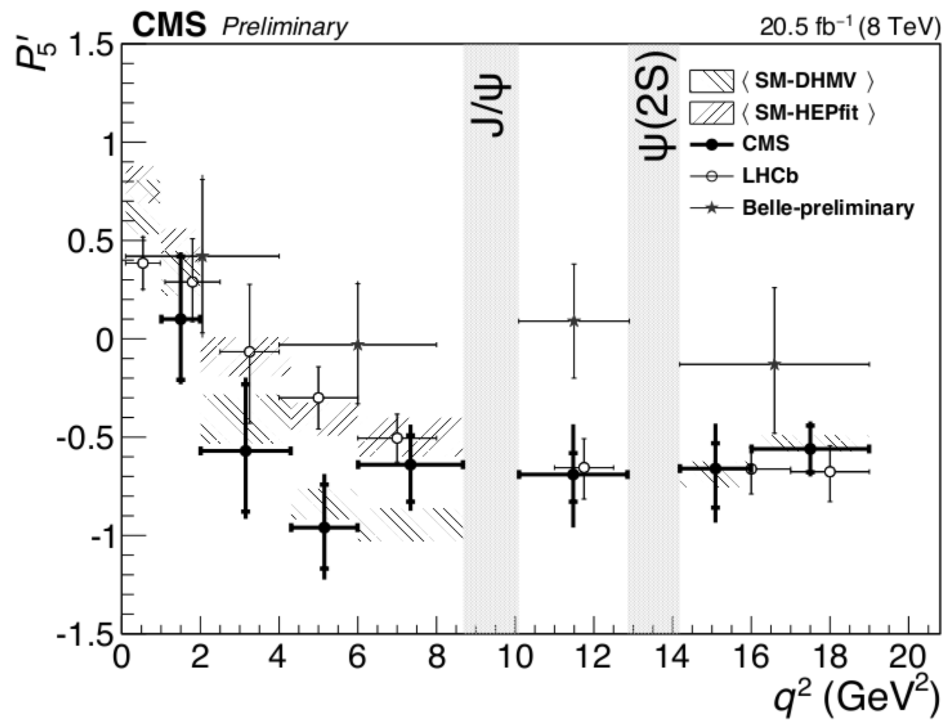
Bevan Dinardo

P_5' and friends

ATLAS-CONF-2017-023



CMS-PAS-BPH-15-008



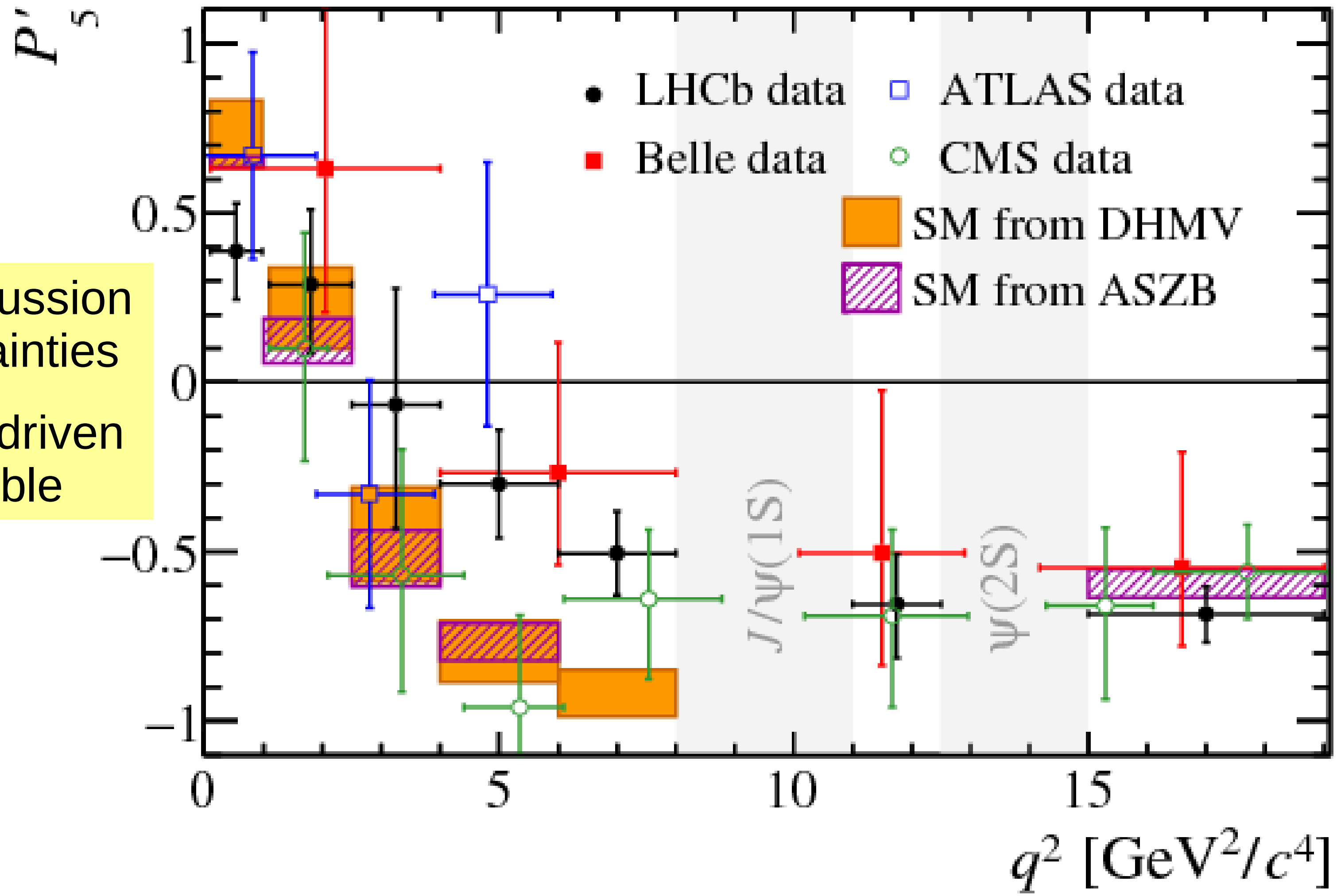
Congratulations to both experiments for completing these difficult but important measurements

Essential to continue with Run 2, and work on triggers for future

X.Xσ

P_5' and friends

Bevan
Dinardo



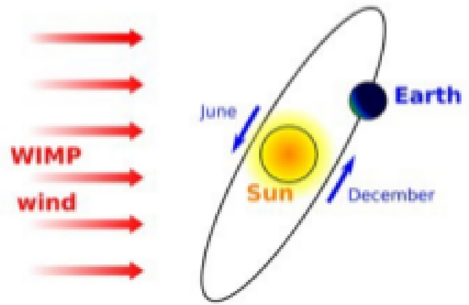
Ongoing theory discussion re: hadronic uncertainties

Important that data-driven progress is possible

No average yet (difficult for many reasons)
Look forward to improved results from LHC Run 2 & Belle II

Masbou

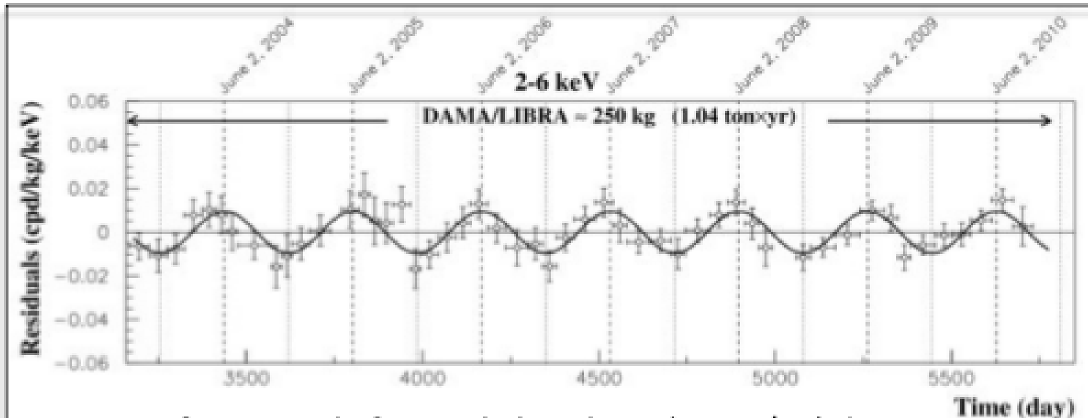
Dark matter annual modulation?



Freese et al., Rev. Mod. Phys. 85, 1561 (2013)

DM signal rate is expected to be annually modulating
Peak phase 152 days (June 1)

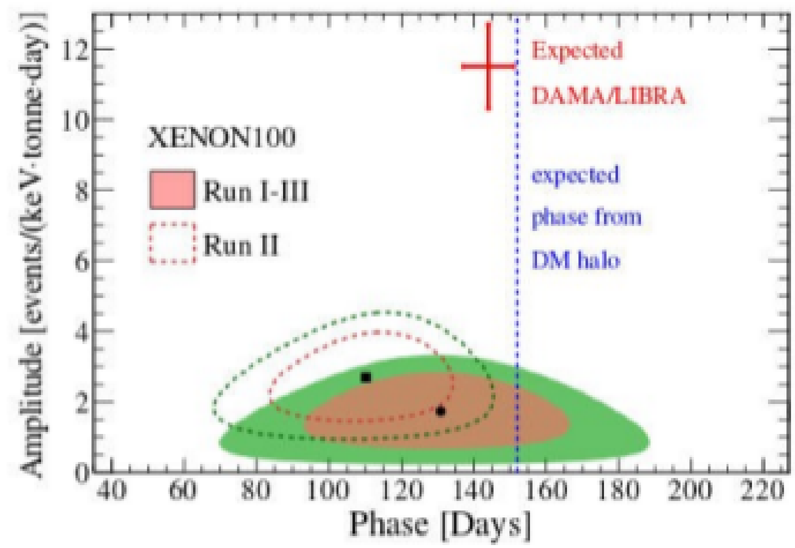
Bernabei et al., Eur. Phys. J. C 73, 12 (2013)



9.3 σ significance only for single hit phase (144 +/- 7) days
No signal above 6 keV, No ER/NR discrimination

arXiv:1701.00769

- The amplitude of is also too small compared with the expected DAMA/LIBRA modulation signal in XENON100.
- The DM interpretation of DAMA/LIBRA annual modulation as being due to WIMPs electron scattering through axial vector coupling is disfavored at 5.7 σ from a PL analysis

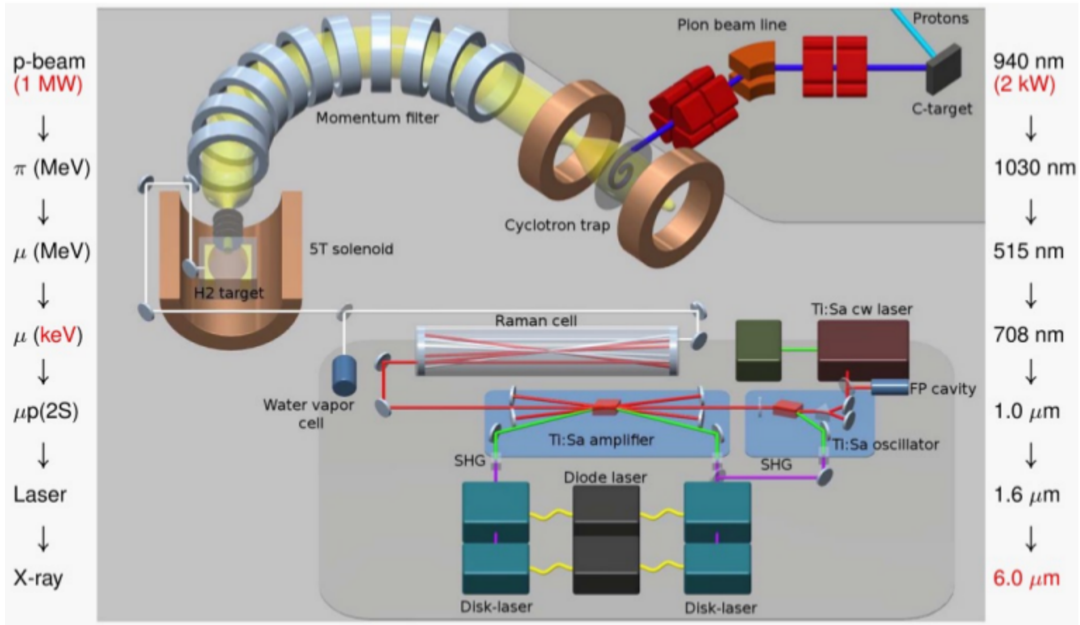


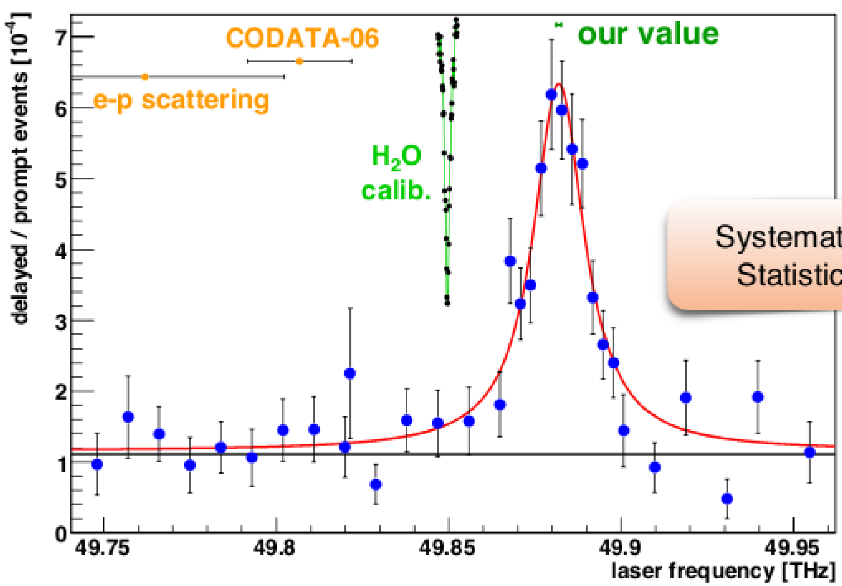
DAMA/LIBRA claim in tension with many other experiments
Still don't know what is causing modulation

Antognini

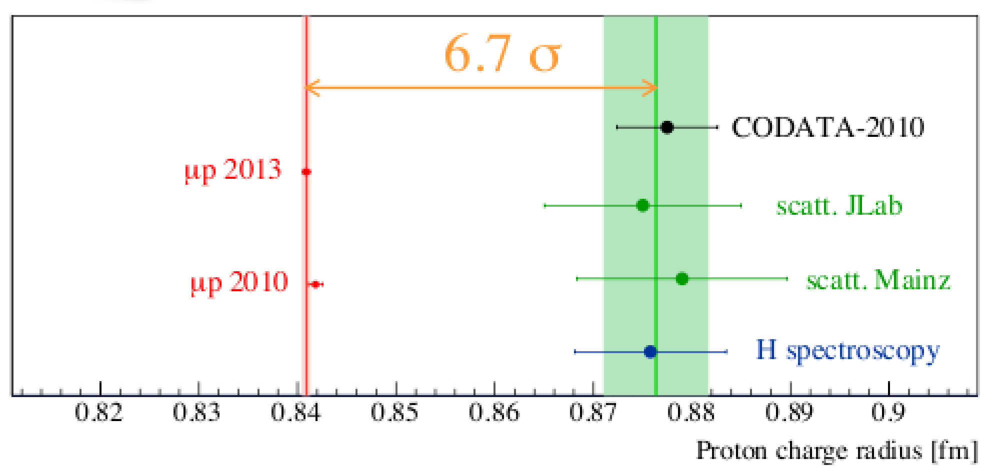
Proton radius puzzle?

Possible experimental explanations need to be investigated





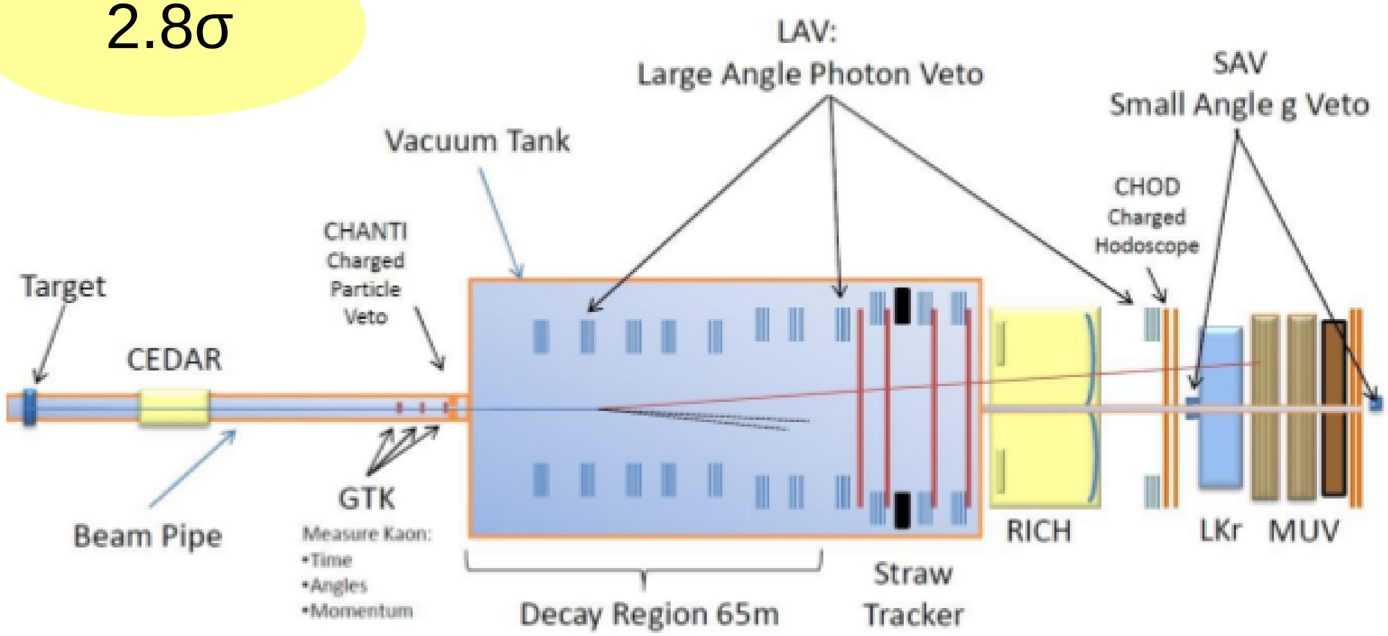
Systematics: 300 MHz
Statistics: 700 MHz

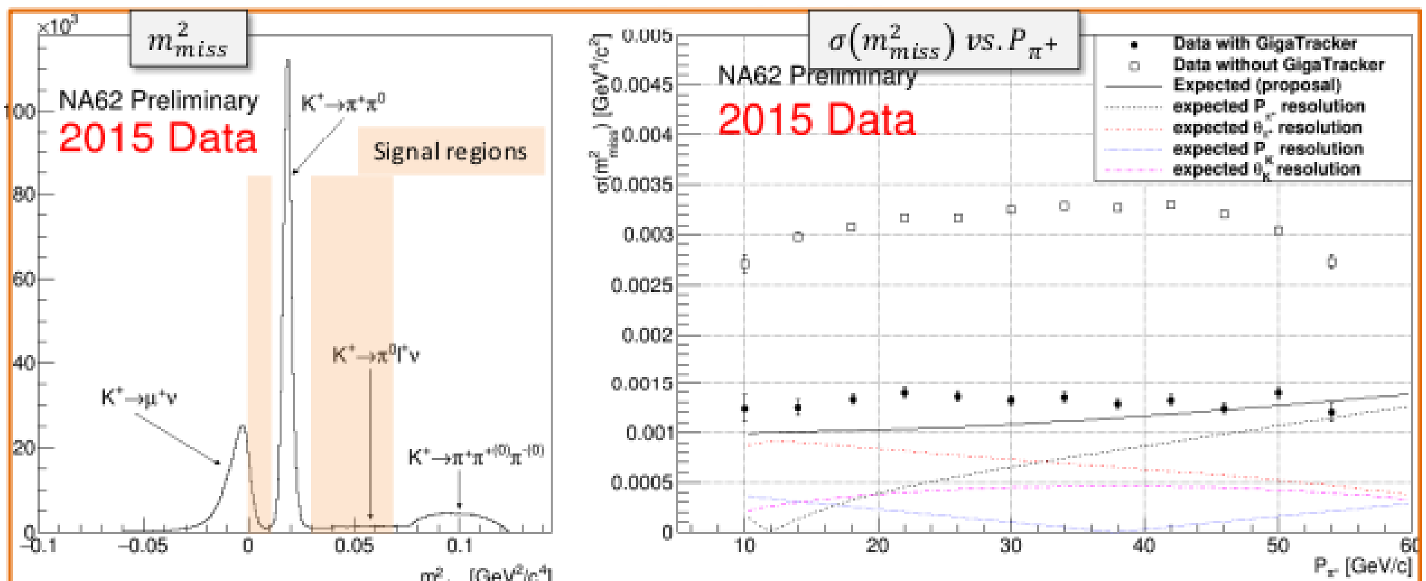


ε'/ε & $B(K \to \pi\nu\bar{\nu})$

Lurkin
Soni
Nierste

2.8σ





Close to design performance

- tracking
- particle identification
- vetoes

More data being analysed (2016) & taken (2017-18)

Options for Run 3 & beyond

K0T0 experiment at J-PARC to measure $B(K_L \to \pi^0\nu\bar{\nu})$

“Science is the new rock and roll” (*)

Prof. Brian Cox

(* probably not an accurate quote)

We do not have, and it is becoming increasingly likely that we will not have, another discovery that allows such a straightforward statement

“Science is the new rock and roll” (*)

Prof. Brian Cox

(* probably not an accurate quote)

“I think we have it”

“You can't always get what you want …
but if you try … you might find …
you get what you need”

So let's keep trying.