COFUND. A project supported by the European Union

Highlights from ICHEP 2018

Birmingham HEP Seminar

31st October 2018

Andy Chisholm
(CERN and University of Birmingham)

Introduction

ICHEP2018 SEOUL

XXXIX INTERNATIONAL CONFERENCE ON high Energy PHYSICS

JULY 4 - 11, 2018
COEX, SEOUL

Introduction - Seoul, South Korea

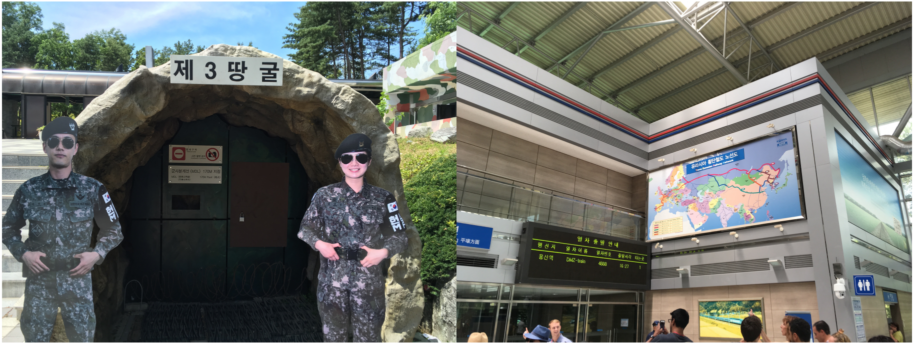
"Seoul is a fast-moving modern metropolis and one of the largest cities in the world. Home to over 10 million citizens, it is a friendly city that is easy to get around."

Introduction - Venue

COEX Mall (containing COnvention centers and EXhibition halls)

Gangnam District (widely known for its heavily concentrated wealth and very high standard of living, compared to cities such as Beverly Hills, California)

Introduction - Tour



Korean Demilitarized Zone (DMZ)

- Established by the provisions of the Korean Armistice Agreement to serve as a buffer zone between North Korea and South Korea following the Korean War (1950-1953)
- Visited “Third Tunnel of Aggression”, Dorasan Railway Station and obervation tower looking out to North Korea

Introduction - View into North Korea

Introduction - View into North Korea

View of North Korean city of Kaesong

Introduction - View into North Korea

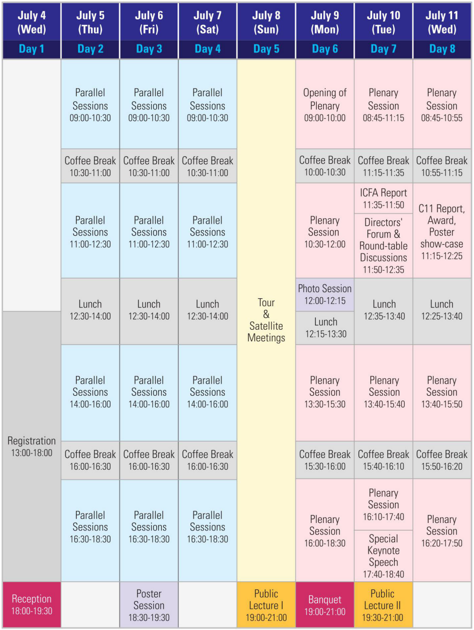
View of North Korean "peace village" and 160m propaganda flagpole

Introduction - Scale

A conference on a huge scale!

- 1119 participants
- 835 parallel talks and 41 plenary talks
- 226 posters

Introduction - Agenda



July 4 (Wed) Day 1	July 5 (Thu) Day 2	July 6 (Fri) Day 3	July 7 (Sat) Day 4	July 8 (Sun) Day 5	July 9 (Mon) Day 6	July 10 (Tue) Day 7	July 11 (Wed) Day 8
	Parallel Sessions 09:00-10:30	Parallel Sessions 09:00-10:30	Parallel Sessions 09:00-10:30	Tour & Satellite Meetings	Opening of Plenary 09:00-10:00	Plenary Session 08:45-11:15	Plenary Session 08:45-10:55
	Coffee Break 10:30-11:00	Coffee Break 10:30-11:00	Coffee Break 10:30-11:00		Coffee Break 10:00-10:30	Coffee Break 11:15-11:35	Coffee Break 10:55-11:15
	Parallel Sessions 11:00-12:30	Parallel Sessions 11:00-12:30	Parallel Sessions 11:00-12:30		Plenary Session 10:30-12:00	ICFA Report 11:35-11:50	C11 Report, Award, Poster show-case 11:15-12:25
						Directors' Forum & Round-table Discussions 11:50-12:35	
Registration 13:00-18:00	Lunch 12:30-14:00	Lunch 12:30-14:00	Lunch 12:30-14:00		Photo Session 12:00-12:15	Lunch 12:35-13:40	Lunch 12:25-13:40
					Lunch 12:15-13:30		
	Parallel Sessions 14:00-16:00	Parallel Sessions 14:00-16:00	Parallel Sessions 14:00-16:00		Plenary Session 13:30-15:30	Plenary Session 13:40-15:40	Plenary Session 13:40-15:50
	Coffee Break 16:00-16:30	Coffee Break 16:00-16:30	Coffee Break 16:00-16:30		Coffee Break 15:30-16:00	Coffee Break 15:40-16:10	Coffee Break 15:50-16:20
	Parallel Sessions 16:30-18:30	Parallel Sessions 16:30-18:30	Parallel Sessions 16:30-18:30		Plenary Session 16:00-18:30	Plenary Session 16:10-17:40	Plenary Session 16:20-17:50
						Special Keynote Speech 17:40-18:40	
Reception 18:00-19:30		Poster Session 18:30-19:30		Public Lecture I 19:00-21:00	Banquet 19:00-21:00	Public Lecture II 19:30-21:00	

Parallel Sessions

- Three very dense days of parallel talks!
- Around 25 talks per session per day
- 9 simultaneous sessions each day
- Impossible to follow anything but a single corner of a single field!

Plenary Sessions

- Summary talks spanning all main pillars of modern experimental and theoretical HEP
- Very effective to learn about what's going on outside of your specialism

Extras

- Poster sessions, public lectures, committee reports (ICFA, IUPAP) and awards

Overview

Sorry...

- My “highlights” are obviously biased towards my own interests...
- However, they do cover many of the new results prepared for the conference and the talks which received most attention from the audience
- Many talks (which I won’t discuss) which will be of great interest to specialists, I’d encrourage you to browse the slides! (https://indico.cern.ch/event/686555/)

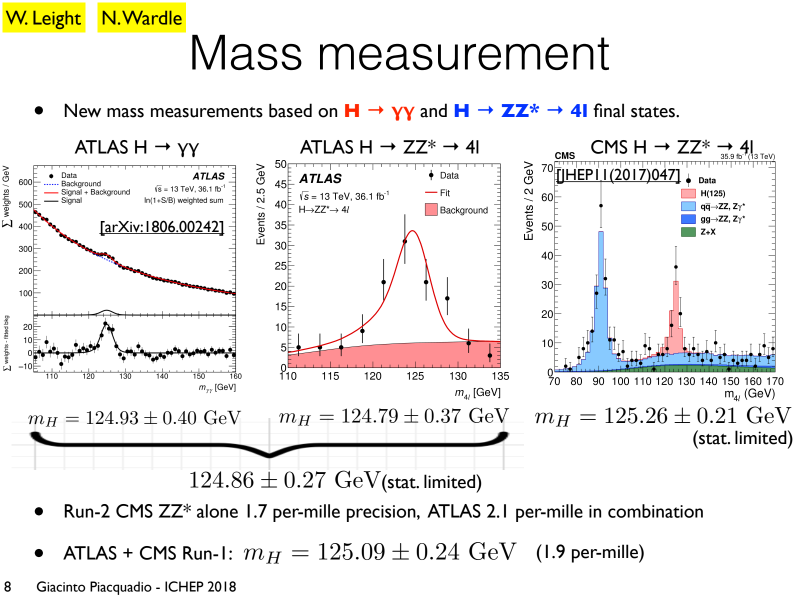
I will concentrate on the following selected highlights

- Latest results from the LHC (SM, Higgs, SUSY)
- Commissioning of new experiments (Belle II and FNAL $g-2$)
- Status of Lattice QCD calculations
- Selected results from neutrino experiments
- Latest results from AMS and a look at “multi-messenger astronomy”

Latest measurement of Higgs boson production and properties

- Several important new results from ATLAS and CMS
- New measurements of m_H and Γ_H
- Unprecedented precision in differential cross-section measurements
- Excitement surrounding $H \to b\bar{b}$ decays, VH and $t\bar{t}H$ production

Measurements of m_H (Higgs Summary - G. Piacquadio)



W. Leight **N.Wardle**

Mass measurement

- New mass measurements based on **H → γγ** and **H → ZZ* → 4l** final states.

ATLAS H → γγ

ATLAS H → ZZ* → 4l

CMS H → ZZ* → 4l

$$\underbrace{m_H = 124.93 \pm 0.40\ \mathrm{GeV} \qquad m_H = 124.79 \pm 0.37\ \mathrm{GeV}}_{124.86 \pm 0.27\ \mathrm{GeV}}$$ (stat. limited)

$$m_H = 125.26 \pm 0.21\ \mathrm{GeV}$$ (stat. limited)

- Run-2 CMS ZZ* alone 1.7 per-mille precision, ATLAS 2.1 per-mille in combination
- ATLAS + CMS Run-1: $m_H = 125.09 \pm 0.24\ \mathrm{GeV}$ (1.9 per-mille)

Measurements of Γ_H (Higgs Summary - G. Piacquadio)

[HIGG-2017-06]

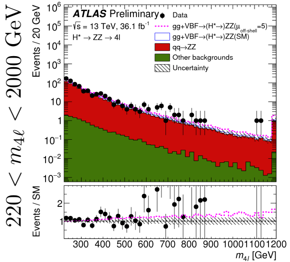
Higgs boson width

- SM Higgs boson width (4 MeV) too small to be measured directly.
- Best direct limit from **CMS** H → ZZ* → 4l ($\Gamma_H < 1.10$ GeV @ 95% CL)
- Or can measure the ratio of on-shell to off-shell cross section in H → ZZ*/WW*

$$\sigma_{\mathrm{off-shell}} \propto \kappa^2_{g,\mathrm{off-shell}} \cdot \kappa^2_{Z,\mathrm{off-shell}}$$

$$\sigma_{\mathrm{on-shell}} \propto \frac{\kappa^2_{g,\mathrm{on-shell}} \cdot \kappa^2_{Z,\mathrm{on-shell}}}{\Gamma_H/\Gamma_H^{SM}}$$

- **ATLAS** Run-2 measurement of off-shell cross-section for H → ZZ* → 4l / 2l 2ν



$$\mu_{\mathrm{off-shell}} = \frac{\sigma_{\mathrm{off-shell}}}{\sigma_{\mathrm{off-shell,SM}}} < 3.8\ (3.4\mathrm{exp.})$$

Assumption:
$$\kappa_{\mathrm{off-shell}} = \kappa_{\mathrm{on-shell}}$$

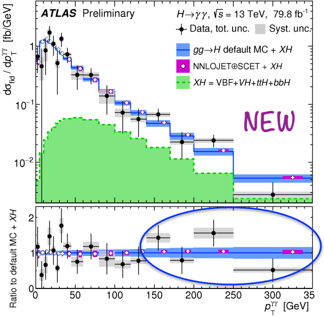
NEW $\Gamma_H < 14.4\ \mathrm{MeV}\ (15.2\ \mathrm{MeV\ exp.})$

- Uses NLO K factors for gg → (H* →) ZZ* as function of m(ZZ) [Caola et al, Phys. Rev. D **92** (2015) 18]
- Improves on Run-I ATLAS and CMS expected limits by almost factor 2

L. Mijovic V. Tavolaro

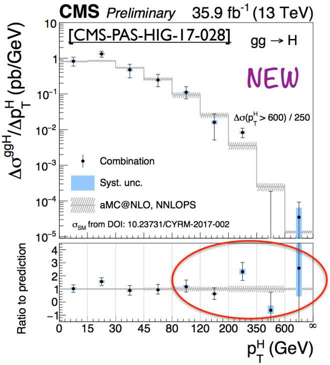
Precise differential measurements

[ATLAS-CONF-2018-028]



- Unprecedented precision on Higgs p_T spectrum
- Good agreement with predictions.
- No sign of New Physics in $p_T(H)$ tail yet!

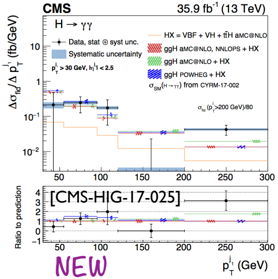
- New **ATLAS H → γγ** measurement with 80 fb^{-1} of Run-2 data.
- New **CMS** combined measurement of **H → γγ, H → ZZ *and* H → *bb*** with 36 fb^{-1} of Run-2.



E. Scott O. Kortner T. Sculac

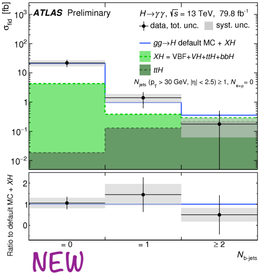
Precise differential measurements

H → γγ (36 fb-1)



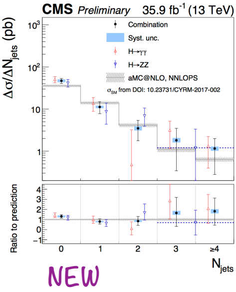
NEW

H → γγ (80 fb-1)



NEW

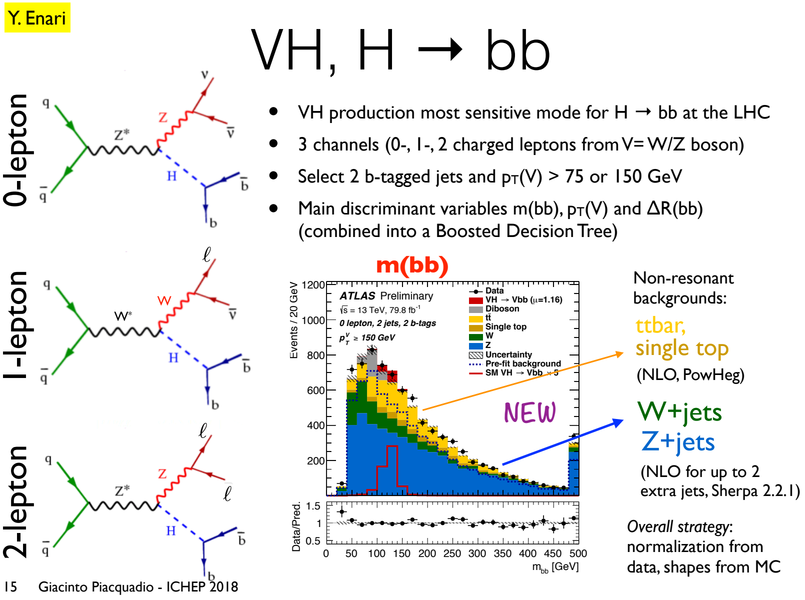
H → γγ + ZZ (36 fb-1)



NEW

- Many many new differential distributions measured.
- All distributions in agreement with expectations.

$H \to b\bar{b}$ decays I (Higgs Summary - G. Piacquadio)



Y. Enari

VH, H → bb

- VH production most sensitive mode for H → bb at the LHC
- 3 channels (0-, 1-, 2 charged leptons from V= W/Z boson)
- Select 2 b-tagged jets and p_T(V) > 75 or 150 GeV
- Main discriminant variables m(bb), p_T(V) and ΔR(bb) (combined into a Boosted Decision Tree)

Non-resonant backgrounds:

ttbar,
single top

(NLO, PowHeg)

W+jets
Z+jets

(NLO for up to 2 extra jets, Sherpa 2.2.1)

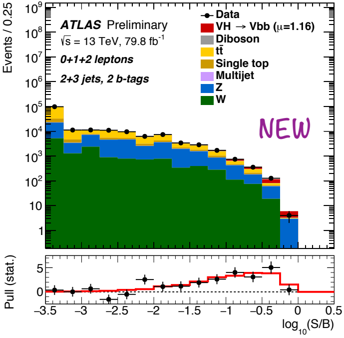
Overall strategy: normalization from data, shapes from MC

15 Giacinto Piacquadio - ICHEP 2018

$H \to b\bar{b}$ decays II (Higgs Summary - G. Piacquadio)

Run-2 VH, H → bb results

[ATLAS-CONF-2018-036]



Fit result with 79.8 fb^{-1} of Run-2 data

$$\mu = \sigma_{\text{meas}}/\sigma_{\text{SM}} = 1.16^{+0.27}_{-0.25}$$

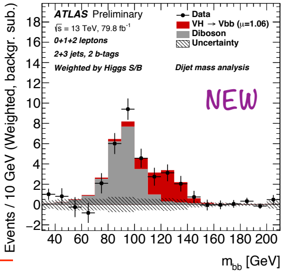
Significance: **4.9σ** (4.3σ expected)

Combination with Run-1:

$$\mu = 0.98 \pm 0.14(\text{stat.})^{+0.17}_{-0.16}(\text{syst.})$$

Significance: **4.9σ** (5.1σ expected)

- Detailed validation of analysis:
  - Fit to diboson VZ, Z → bb: $\mu = 1.20^{+0.20}_{-0.18}$ (9.6σ)
  - m(bb) fit for VH, H → bb: $\mu = 1.06^{+0.36}_{-0.33}$ (**3.6σ**)



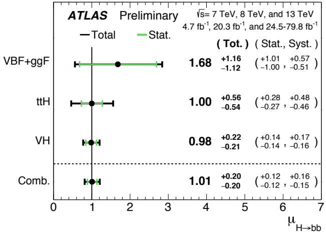
$H \to b\bar{b}$ decays III (Higgs Summary - G. Piacquadio)

[ATLAS-CONF-2018-036]

- Run-1+Run-2
  - VH, H → bb
  - VBF(+ggF), H → bb
  - ttH, H → bb

H → bb combination

NEW



Significance:
5.4σ observed
(5.5σ expected)

Observation of H → bb!!

- Run-2
  - VH, H → bb
  - VH, H → γγ
  - VH, H → ZZ*

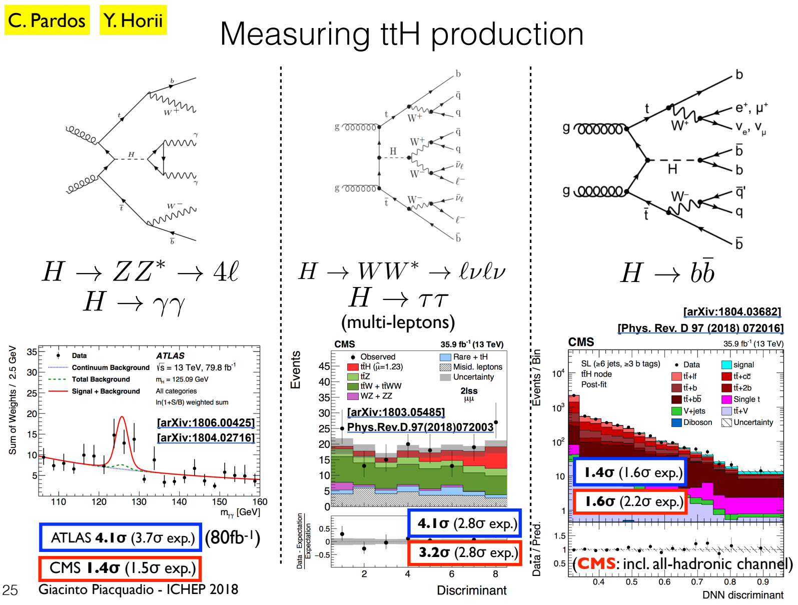
VH combination

NEW

Significance:
5.3σ observed (4.8σ expected)

Observation of VH production!!

$t\bar{t}H$ production I (Higgs Summary - G. Piacquadio)



C. Pardos **Y. Horii**

Measuring ttH production

$H \to ZZ^* \to 4\ell$
$H \to \gamma\gamma$

$H \to WW^* \to \ell\nu\ell\nu$
$H \to \tau\tau$
(multi-leptons)

$H \to b\bar{b}$

[arXiv:1806.00425]
[arXiv:1804.02716]

ATLAS **4.1σ** (3.7σ exp.) (80fb⁻¹)

CMS **1.4σ** (1.5σ exp.)

[arXiv:1803.05485]
Phys.Rev.D.97(2018)072003

4.1σ (2.8σ exp.)

3.2σ (2.8σ exp.)

[arXiv:1804.03682]
[Phys. Rev. D 97 (2018) 072016]

1.4σ (1.6σ exp.)

1.6σ (2.2σ exp.)

(**CMS**: incl. all-hadronic channel)

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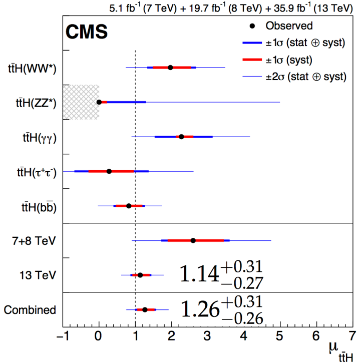
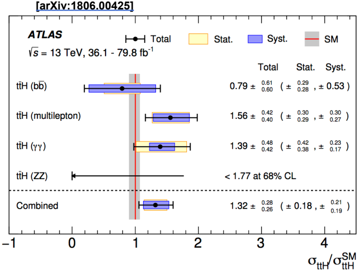
$t\bar{t}H$ production II (Higgs Summary - G. Piacquadio)

C. Pardos Y. Horii

Combination of ttH measurements



[arXiv:1806.00425]



Observation of ttH production!

CMS
Run-1+Run-2: **5.2σ** (4.2σ exp.)

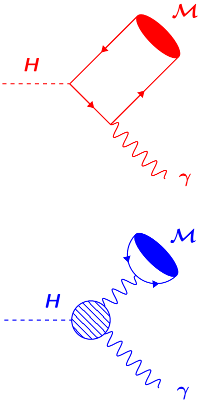
ATLAS (up to 80 fb⁻¹)
Run-2: **5.8σ** (4.9σ exp.)
Run-1+Run-2: **6.3σ** (5.1σ exp.)

$H \to \psi(nS)\gamma$ I (Higgs Parallel - A. Chisholm)

$H \to \mathcal{M}\gamma$ Decays - Motivation

$H \to \mathcal{M}\gamma$ decays provide a clean probe of the charm and light quark Yukawa couplings at the LHC

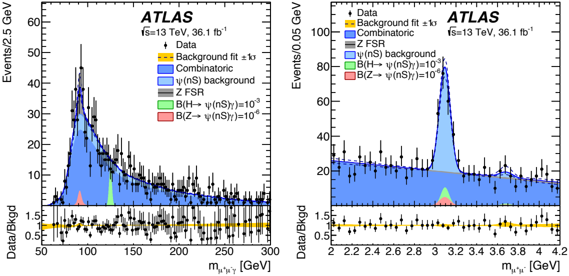
- $\mathcal{M}$ is a vector ($J^{PC} = 1^{--}$) light meson or quarkonium state such as $J/\psi, \psi(2S), \Upsilon(nS)$, $\phi(1020)$, $\rho(770)$
- **Interference** between **direct** ($H \to q\bar{q}$) and **indirect** ($H \to \gamma\gamma^*$) contributions
- **Direct** amplitude (upper) provides **sensitivity to the magnitude and sign of the $Hq\bar{q}$ couplings** (e.g. $\mathcal{M} = J/\psi$ sensitive to $Hc\bar{c}$ coupling)
- **Indirect** amplitude (lower) makes dominant contribution to decay width, **but not sensitive to Yukawa couplings**



$$\mathcal{B}(H \to J/\psi\,\gamma) = (2.99 \pm 0.16) \times 10^{-6} \quad \dagger$$
$$\mathcal{B}(H \to \psi(2S)\,\gamma) = (1.03 \pm 0.06) \times 10^{-6} \quad \dagger$$
$$\mathcal{B}(H \to \Upsilon(1S)\,\gamma) = (5.2^{+2.0}_{-1.7}) \times 10^{-9} \quad \dagger$$
$$\mathcal{B}(H \to \phi\,\gamma) = (2.3 \pm 0.1) \times 10^{-6} \quad \ddagger$$
$$\mathcal{B}(H \to \rho\,\gamma) = (1.7 \pm 0.1) \times 10^{-5} \quad \ddagger$$

† Phys. Rev. D 90, 113010 (2014) (arXiv:1407.6695) ‡ JHEP 1508 (2015) 012 (arXiv:1505.03870)

$H/Z \to \psi(nS)\gamma$ Decays - Results (arXiv:1807.00802)



- Projections of fit ↑ to $\mu^+\mu^-\gamma$ (left) and $\mu^+\mu^-$ (right) invariant mass distributions

Observable	95% CL Upper Limit	
	Expected	Observed
$\mathcal{B}(H \to J/\psi\,\gamma)$	$(3.0^{+1.4}_{-0.8}) \times 10^{-4}$	3.5×10^{-4}
$\mathcal{B}(H \to \psi(2S)\,\gamma)$	$(15.6^{+7.7}_{-4.4}) \times 10^{-4}$	19.8×10^{-4}
$\mathcal{B}(Z \to J/\psi\,\gamma)$	$(1.1^{+0.5}_{-0.3}) \times 10^{-6}$	2.3×10^{-6}
$\mathcal{B}(Z \to \psi(2S)\,\gamma)$	$(6.0^{+2.7}_{-1.7}) \times 10^{-6}$	4.5×10^{-6}

World's first limit on $H/Z \to \psi(2S)\gamma$ decays!
Limit on $\mathcal{B}(H \to J/\psi\,\gamma)$ improved by factor ≈ 4× w.r.t. Run 1 result!

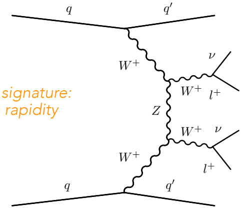
Measurements of rare SM processes with ATLAS and CMS

- New results on vector boson scattering (VBS) processes
- Processes represent direct probes of the heart of EWSB
- Measurements in several new channels now feasible with the LHC Run 2 dataset

VBS Processes I (SM Summary - L. Skinnari)

VBS processes: W±W±

- **Vector-boson scattering (VBS)** processes
  - *Key test of EWSB*
  - *Sensitive to anomalous QGC*
- Enhanced in beyond-SM scenarios (e.g. modified Higgs sector or new resonances)

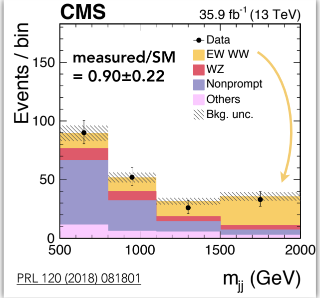


characteristic signature: 2 jets w. large rapidity separation

σ(fid)~4 fb

1st observation @ CMS in 2017

(**5.5σ** observed, 5.7σ expected)

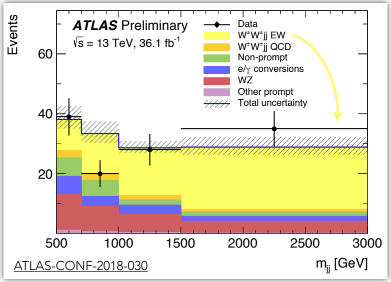


PRL 120 (2018) 081801

Observation @ ATLAS

NEW @ ICHEP

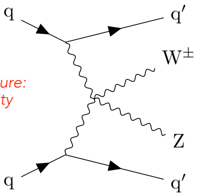
(**6.9σ** observed, 4.6σ expected)



ATLAS-CONF-2018-030

VBS processes: W±Z

- Vector-boson scattering (VBS) processes
    - *Key test of EWSB*
    - *Sensitive to anomalous QGC*
- Enhanced in beyond-SM scenarios (e.g. modified Higgs sector or new resonances)



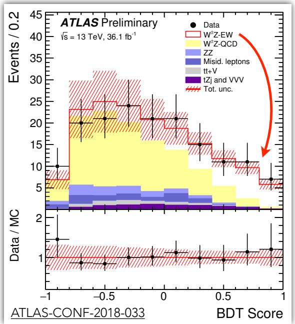
characteristic signature: 2 jets w. large rapidity separation

σ(fid)~1 fb

NEW @ ICHEP

1st observation @ ATLAS

(**5.6σ** observed, 3.3σ expected)



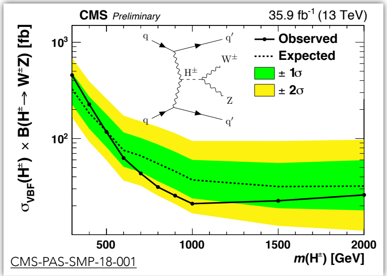
ATLAS-CONF-2018-033

Search @ CMS

(**1.9σ** observed, 2.7σ expected)

NEW @ ICHEP

Limits placed on aTGC & charged Higgs



CMS-PAS-SMP-18-001

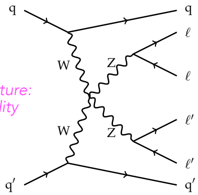
VBS Processes III (SM Summary - L. Skinnari)

VBS processes: ZZ

- Vector-boson scattering (VBS) processes
  - *Key test of EWSB*
  - *Sensitive to anomalous QGC*
- Enhanced in beyond-SM scenarios (e.g. modified Higgs sector or new resonances)

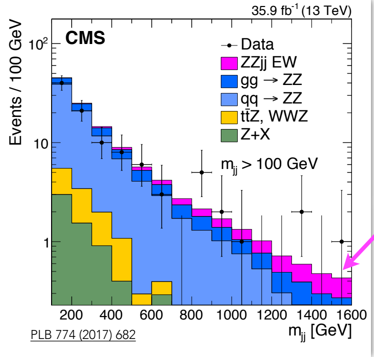
characteristic signature: 2 jets w. large rapidity separation

σ(fid)~0.4 fb



Approaching sensitivity to EW ZZ @ CMS

(**2.7σ** excess, 1.6σ expected)



PLB 774 (2017) 682

electroweak ZZ

Recent measurements of top quark production and properties with ATLAS and CMS

- New single measurements of m_t beginning to approach precision of world average
- Excitement surrounding measurements of spin correlations in $t\bar{t}$ production
- Efforts to measure $t\bar{t}t\bar{t}$ ("four top") production at the LHC

Recent measurements of top quark production and properties with ATLAS and CMS

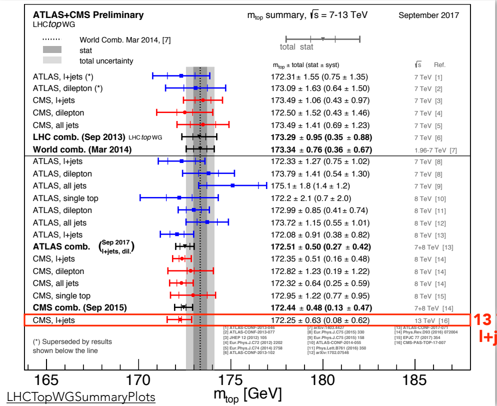
- New single measurements of m_t beginning to approach precision of world average
- Excitement surrounding measurements of spin correlations in $t\bar{t}$ production
- Efforts to measure $t\bar{t}t\bar{t}$ ("four top") production at the LHC

Top properties: *MASS*

- *Key SM parameter*
- *Test EW vacuum stability*

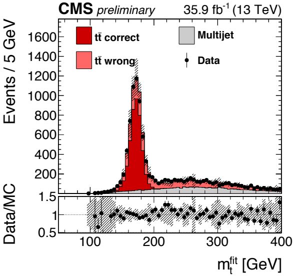
CMS-PAS-TOP-17-008

NEW @ ICHEP



LHCTopWGSummaryPlots

13 TeV, l+jets



CMS all-jet (13 TeV)

172.34 ±0.20 (stat+JSF)

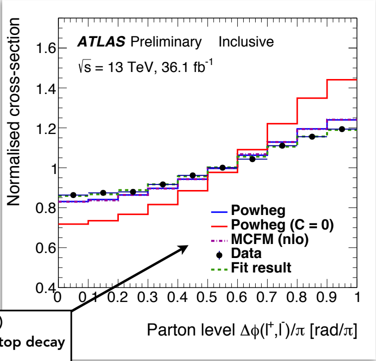
±0.76 (syst) GeV

Top properties: *SPIN CORRELATIONS*

NEW* *@ ICHEP

- Measurement of top quark <u>spin correlations</u> @ 13 TeV
  - Spin properties transferred to decay-leptons (here: eμ)
    - Extract from unfolded normalized cross sections w.r.t. **|Δϕ|** between leptons
    - Could be modified due to different production/decay
  - 3.7σ discrepancy observed (**<u>3.2σ</u>** including uncertainty on the theory prediction)

ATLAS-CONF-2018-027



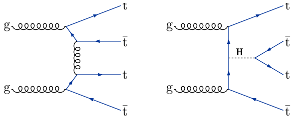
Nominal ttbar sample (NLO QCD)
Nominal w/o spin correlations in top decay
Incl. NLO effects in top decays
Data
Best-fit result

Toward the very rare

ATLAS: Paper in preparation
CMS: EPJC 78 (2018) 140

SM $t\bar{t}t\bar{t}$

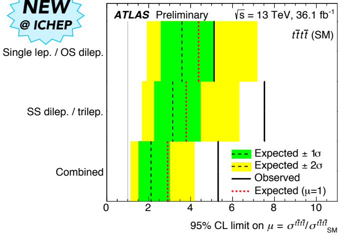
- $\sigma_{tttt,SM} \approx 10^{-5} \times \sigma_{tt,SM}$ @ 13 TeV
- Sensitive to new physics (e.g. high mass scalars), top Yukawa coupling

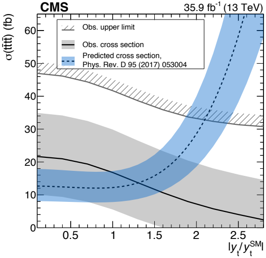


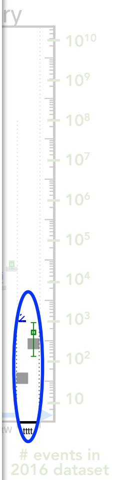
Observed (expected) significance

- ATLAS: **2.8σ** (1.0σ) ← *same-sign/opposite dileptons, l+jets*
- CMS: **1.6σ** (1.0σ) ← *same-sign/trileptons*

NEW @ ICHEP





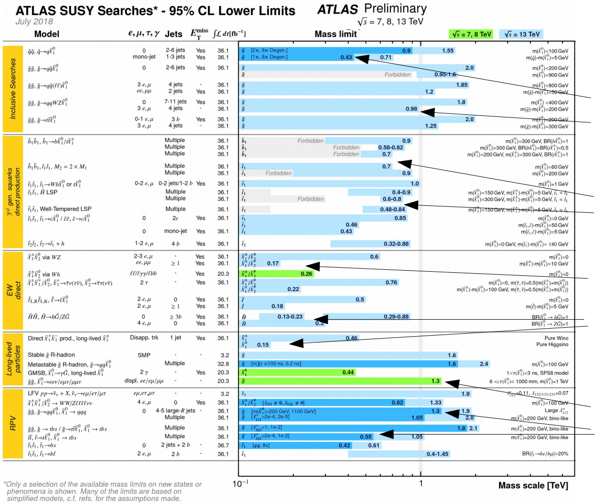


Status of LHC searches for supersymmetry

- Several new results from ATLAS, CMS and LHCb with LHC Run 2 data
- The “low hanging fruit” seems to have already been picked...
- No evidence for SUSY with the broad LHC search programme
- Searches extending to more obscure signatures...

Active SUSY search program

28 publications on SUSY searches with 2015-2016 data (36 fb^{-1}).



Compressed spectrum squark degeneracy:
squarks O(500 GeV)
gluinos O(1 TeV)

Longer decay chain more realistic models:
sbottom O(700 GeV)
stop O(700 GeV)

Low rate, compressed:
winos O(~100 GeV)
sleptons O(~100 GeV)
higgsino O(~100 GeV)

Complexity, long-lived:
gluinos O(1 TeV)
stop O(500 GeV)

Simplified signatures covered to high masses, but plenty of low mass unexplored model space.

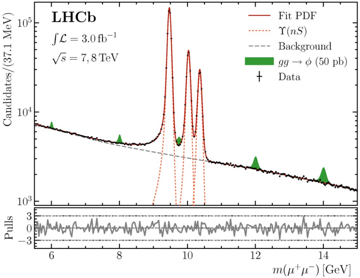
Summary and outlook

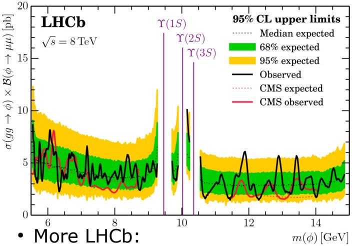
- New results at 13 TeV are being produced at a steady pace.
- Completing the program with 36 fb^{-1} (2015+2016) dataset.
- Start to see first results with 80 fb^{-1} dataset (2015+2016+2017).
- Vast and versatile search program for SUSY.
- No evidence for SUSY yet → strong message from the LHC.
- In most favourable / challenging scenarios we exclude
  - gluinos up to $\mathcal{O}(2)$ / $\mathcal{O}(1)$ TeV.
  - squarks up to $\mathcal{O}(1.5)$ / $\mathcal{O}(0.5)$ TeV.
  - stops and sbottoms up to $\mathcal{O}(1)$ / $\mathcal{O}(0.7)$ TeV.
  - EW produced sparticles up to $\mathcal{O}(0.5\text{-}1)$ / $\mathcal{O}(0.1)$ TeV.
- Regions of parameter space still not well covered.
- Next step is to complete the program with the full Run 2 dataset (150 fb^{-1} expected).
- Ensure we cover all signatures within our reach.

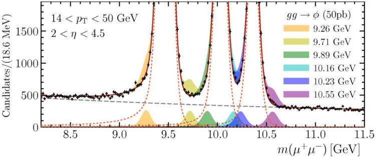
Dimuon resonance in the Υ region

1805.09820

- Search for a scalar resonance decay to a pair of muons.
- Light scalars can appear e.g. in NMSSM scenarios.
- Target difficult region around Υ (5.5-15 GeV).
- Limits comparable to CMS, but extend closer to the Υ mass.







- More LHCb:

LLPs decaying semileptonically (1612.00945) and to jets (1705.07332)

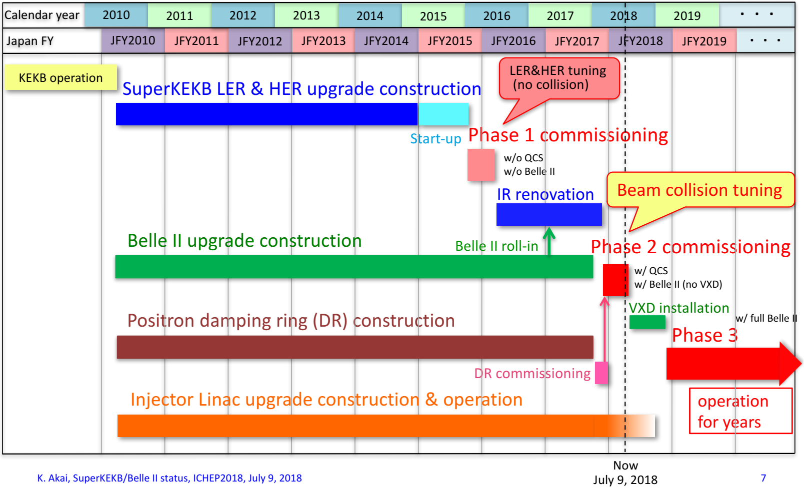
Indirect (1703.05747, 1703.02508, 1609.02032, 1712.08606, 1611.07704)

Commissioning of Belle II + Super KEKB

- Belle + KEKB → Belle II + Super KEKB
- Upgrade accelerator complex to achieve $\mathcal{L} = 8 \times 10^{35}$ cm^{2}s^{-1} (KEKB achieved $\mathcal{L} = 2.1 \times 10^{34}$ cm^{2}s^{-1})
- Upgrade detector with latest technologies + higher radiation tolerance
- Aim to collect a 50 ab^{-1} sample of $B\bar{B}$ events by 2025

Upgrade Schedule (SuperKEKB/Belle II Status - K. Akai)

SuperKEKB / Belle II overall schedule



K. Akai, SuperKEKB/Belle II status, ICHEP2018, July 9, 2018

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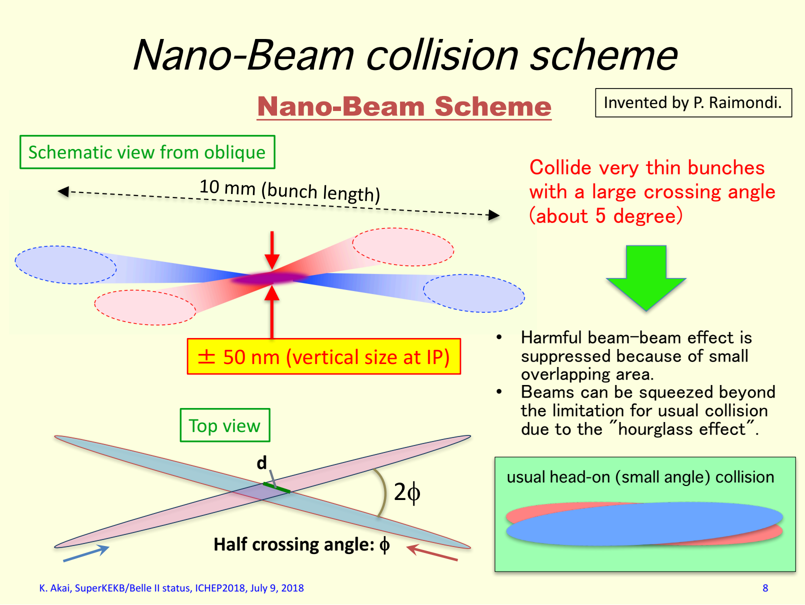
SuperKEKB Upgrade (SuperKEKB/Belle II Status - K. Akai)



Nano-Beam collision scheme

Nano-Beam Scheme

Invented by P. Raimondi.

Schematic view from oblique

10 mm (bunch length)

± 50 nm (vertical size at IP)

Collide very thin bunches with a large crossing angle (about 5 degree)

- Harmful beam–beam effect is suppressed because of small overlapping area.
- Beams can be squeezed beyond the limitation for usual collision due to the "hourglass effect".

Top view

d

2ϕ

Half crossing angle: ϕ

usual head-on (small angle) collision

K. Akai, SuperKEKB/Belle II status, ICHEP2018, July 9, 2018

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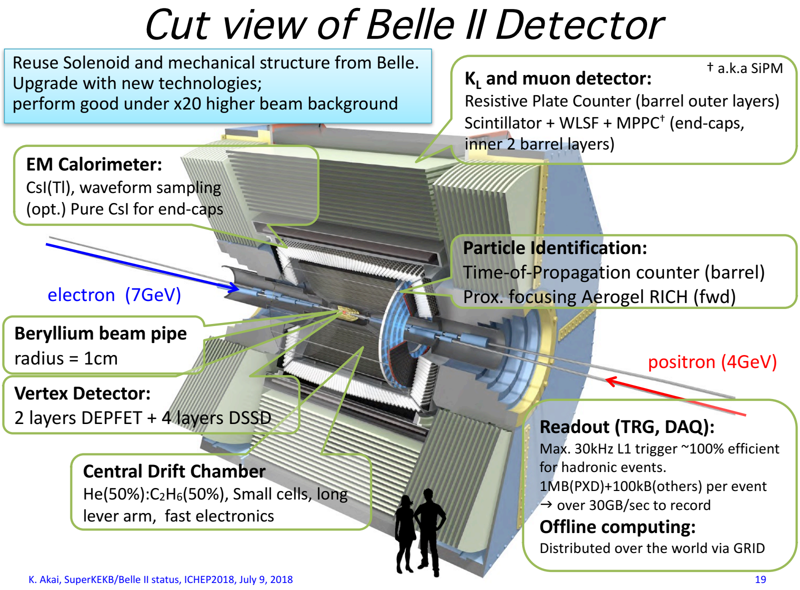


Cut view of Belle II Detector

Reuse Solenoid and mechanical structure from Belle.
Upgrade with new technologies;
perform good under x20 higher beam background

[†] a.k.a SiPM

K_L and muon detector:
Resistive Plate Counter (barrel outer layers)
Scintillator + WLSF + MPPC[†] (end-caps, inner 2 barrel layers)

EM Calorimeter:
CsI(Tl), waveform sampling
(opt.) Pure CsI for end-caps

Particle Identification:
Time-of-Propagation counter (barrel)
Prox. focusing Aerogel RICH (fwd)

Beryllium beam pipe
radius = 1cm

Vertex Detector:
2 layers DEPFET + 4 layers DSSD

Central Drift Chamber
He(50%):C_2H_6(50%), Small cells, long lever arm, fast electronics

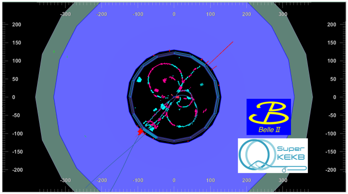
Readout (TRG, DAQ):
Max. 30kHz L1 trigger ~100% efficient for hadronic events.
1MB(PXD)+100kB(others) per event
→ over 30GB/sec to record

Offline computing:
Distributed over the world via GRID

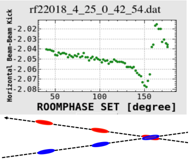
First collision

Apr. 26, 2018

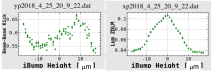
Belle II control room



First hadronic event observed by Belle II



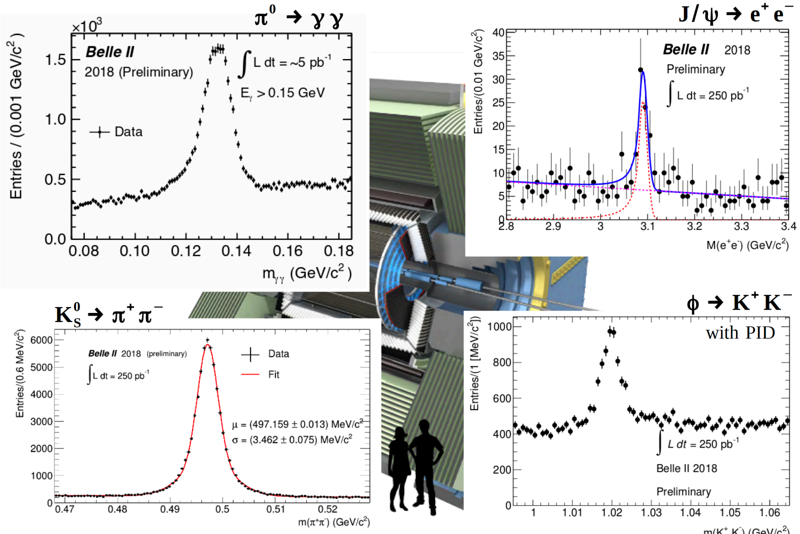
Horizontal beam-beam kick



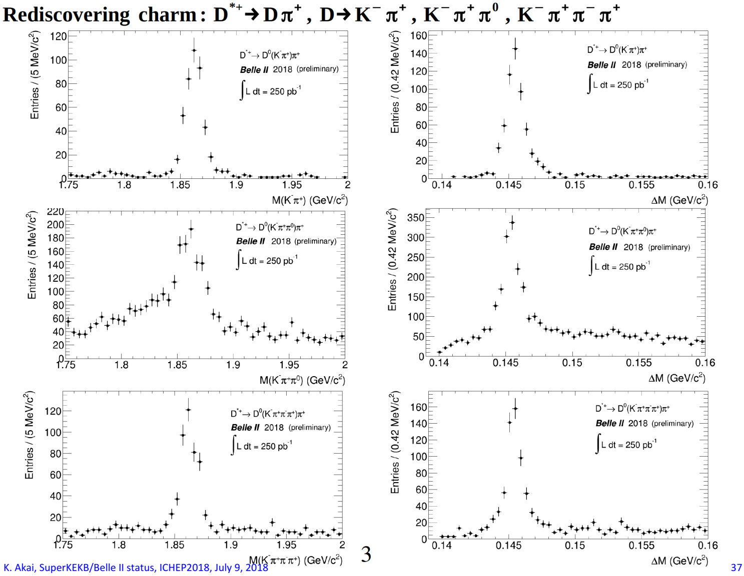
Vertical beam-beam kick

SuperKEKB control room

Physics data obtained at Belle II in Phase 2



Physics Commissioning (SuperKEKB/Belle II Status - K. Akai)



Rediscovering charm : $D^{*+} \to D\pi^+$, $D \to K^-\pi^+$, $K^-\pi^+\pi^0$, $K^-\pi^+\pi^-\pi^+$

K. Akai, SuperKEKB/Belle II status, ICHEP2018, July 9, 2018

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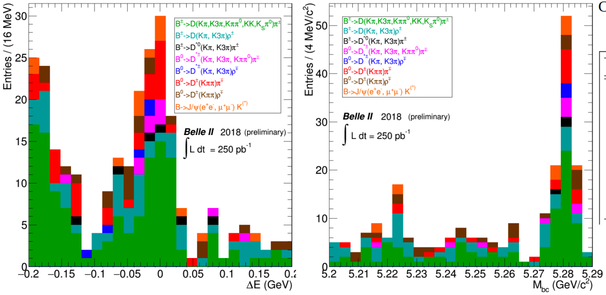
Rediscovering beauty: $B \to D^{(*)} h + B \to J/\psi K^{(*)}$

Gaussian width of signal in M_{bc} is consistent with MC !



Candidates in signal box
($M_{bc} > 5.27$ GeV/c², $|\Delta E| < 0.050$ GeV)

Mode	yield
$B^\pm \to D\pi^\pm$	51
$B^\pm \to D\rho^\pm$	16
$B^\pm \to D^*\pi^\pm$	3
$B^0 \to D^{*\pm}\pi^\mp$	7
$B^0 \to D^{*\pm}\rho^\mp$	3
$B^0 \to D^\pm\pi^\mp$	13
$B^0 \to D^\pm\rho^\mp$	8
$B \to J/\psi K^{(*)}$	8

Show capacity for charm physics in $e^+e^- \to c\bar{c}$

- D^0, D^+, D^*
- Cabibbo favoured and suppressed modes

... for B-physics

- hadronic modes from $b \to c$
- semileptonic decay modes from $b \to c$

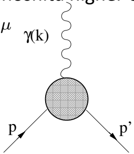
Commissioning of FNAL muon $g - 2$ experiment

Muon anomalous magnetic moment (Flavour Theory - S. Fajfer)

Muon anomalous magnetic moment

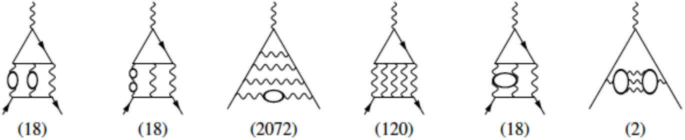
$$ie\bar{u}_\ell(p')\left[\gamma^\mu - \frac{a_\ell}{2m_\ell} i\sigma^{\mu\nu} q_\nu\right] u_\ell(p)\epsilon^*_\mu, \qquad q_\mu = (p-p')_\mu$$

(Schwinger α/π,
Kinoshita higher orders in α)



Dirac equation predicts g=2 $$a = (g-2)/2$$

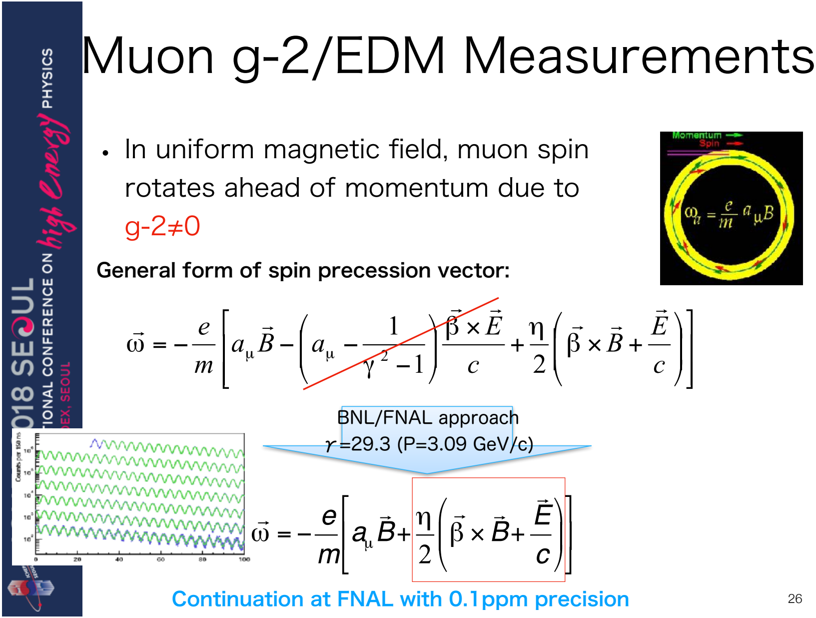
For electron a_e theory and experiment agrees!



$$\boxed{a_\mu^{th} - a_\mu^{exp} = -(3.06 \pm 0.76) \times 10^{-8}}$$ 4 σ

Theory: uncertainty in hadronic contributions to the muon g − 2, (Jägerlehner, 1802.08019).
Lattice QCD great progress light-by-light study (RBC & UKQCD, 1801.07224).

Muon $g-2$ ($g-2$/EDM Summary - S. Mihara)



Muon g-2/EDM Measurements

- In uniform magnetic field, muon spin rotates ahead of momentum due to g-2≠0

General form of spin precession vector:

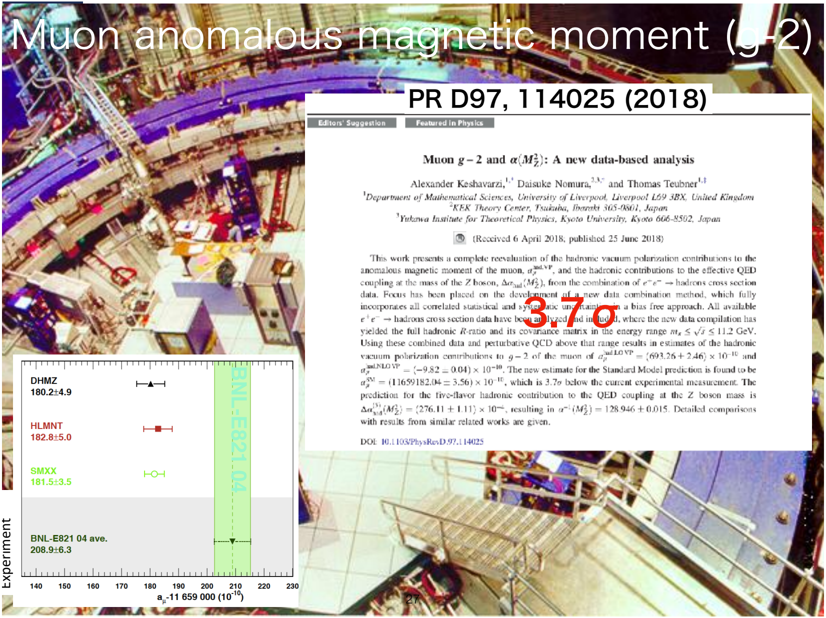
$$\vec{\omega} = -\frac{e}{m}\left[a_\mu \vec{B} - \cancel{\left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta}\times\vec{E}}{c}} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c}\right)\right]$$

BNL/FNAL approach
γ=29.3 (P=3.09 GeV/c)

$$\vec{\omega} = -\frac{e}{m}\left[a_\mu \vec{B} + \boxed{\frac{\eta}{2}\left(\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c}\right)}\right]$$

Continuation at FNAL with 0.1ppm precision

Muon $g-2$ at BNL ($g-2$/EDM Summary - S. Mihara)



Muon anomalous magnetic moment (g-2)

PR D97, 114025 (2018)

Editors' Suggestion | Featured in Physics

Muon $g-2$ and $\alpha(M_Z^2)$: A new data-based analysis

Alexander Keshavarzi,[1,*] Daisuke Nomura,[2,3,†] and Thomas Teubner[1,‡]
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(Received 6 April 2018; published 25 June 2018)

This work presents a complete reevaluation of the hadronic vacuum polarization contributions to the anomalous magnetic moment of the muon, $a_\mu^{\mathrm{had,VP}}$, and the hadronic contributions to the effective QED coupling at the mass of the Z boson, $\Delta\alpha_{\mathrm{had}}(M_Z^2)$, from the combination of $e^+e^- \to$ hadrons cross section data. Focus has been placed on the development of a new data combination method, which fully incorporates all correlated statistical and systematic uncertainties in a bias free approach. All available $e^+e^- \to$ hadrons cross section data have been analyzed and included, where the new data compilation has yielded the full hadronic R-ratio and its covariance matrix in the energy range $m_\pi \leq \sqrt{s} \leq 11.2$ GeV. Using these combined data and perturbative QCD above that range results in estimates of the hadronic vacuum polarization contributions to $g-2$ of the muon of $a_\mu^{\mathrm{had,LO\,VP}} = (693.26 \pm 2.46) \times 10^{-10}$ and $a_\mu^{\mathrm{had,NLO\,VP}} = (-9.82 \pm 0.04) \times 10^{-10}$. The new estimate for the Standard Model prediction is found to be $a_\mu^{\mathrm{SM}} = (11659182.04 \pm 3.56) \times 10^{-10}$, which is 3.7σ below the current experimental measurement. The prediction for the five-flavor hadronic contribution to the QED coupling at the Z boson mass is $\Delta\alpha_{\mathrm{had}}^{(5)}(M_Z^2) = (276.11 \pm 1.11) \times 10^{-4}$, resulting in $\alpha^{-1}(M_Z^2) = 128.946 \pm 0.015$. Detailed comparisons with results from similar related works are given.

DOI: 10.1103/PhysRevD.97.114025

3.7σ

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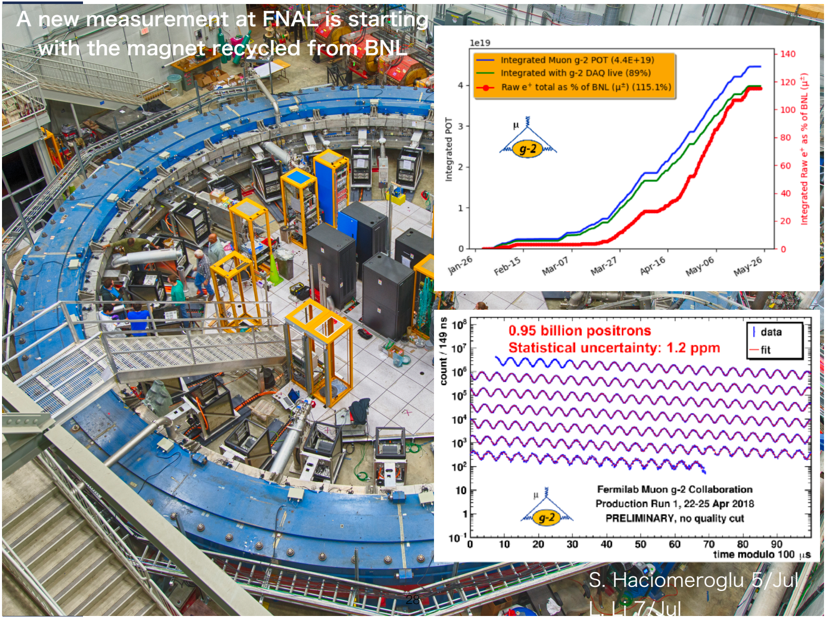
Muon $g-2$ at FNAL ($g-2$/EDM Summary - S. Mihara)



A new measurement at FNAL is starting with the magnet recycled from BNL

S. Haciomeroglu 5/Jul

L. Li 7/Jul

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Review of Lattice QCD in 2018

Lattice QCD
for HEP

We are entering the

- Precision era of lattice QCD for simple systems
- Beginning of reliable lattice QCD results for nuclear matrix elements

I will highlight some new results in these areas since ICHEP2016

Lattice QCD can provide input for

Decay constants, form factors, mixing parameters

Hadronic vacuum polarisation and light-by-light scattering

Neutrino-nucleus interactions

Dark matter-nucleon and DM-nucleus interactions

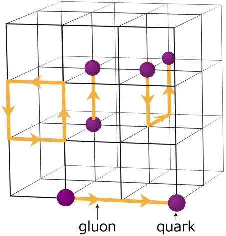
Muon-nucleus cross-sections

Parton distribution functions

Lattice QCD

`Numerical first-principles approach to non-perturbative QCD`

- Discretise QCD onto 4D space-time lattice
- Approximate QCD path integral using Monte-Carlo methods and importance sampling
- Run on supercomputers and dedicated clusters
- Take limit of vanishing discretisation, infinite volume, physical quark masses



Lattice QCD

`Numerical first-principles approach to non-perturbative QCD`

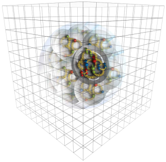
INPUT

Lattice QCD action has same free parameters as QCD: quark masses, α_S

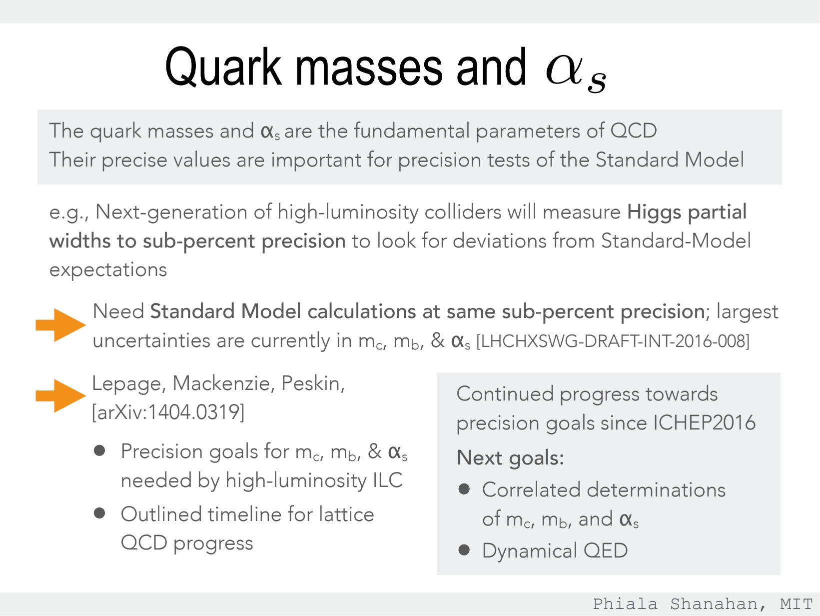
- Fix quark masses by matching to measured hadron masses, e.g., π, K, D_s, B_s for u, d, s, c, b
- One experimental input to fix lattice spacing in GeV (and also α_S), e.g., $2S$-$1S$ splitting in Y, or f_π or Ω mass

OUTPUT

Calculations of all other quantities are QCD predictions



α_s and m_Q from Lattice QCD (Lattice QCD - P. Shanahan)



Quark masses and α_s

The quark masses and α_s are the fundamental parameters of QCD
Their precise values are important for precision tests of the Standard Model

e.g., Next-generation of high-luminosity colliders will measure **Higgs partial widths to sub-percent precision** to look for deviations from Standard-Model expectations

→ Need **Standard Model calculations at same sub-percent precision**; largest uncertainties are currently in m_c, m_b, & α_s [LHCHXSWG-DRAFT-INT-2016-008]

→ Lepage, Mackenzie, Peskin, [arXiv:1404.0319]

- Precision goals for m_c, m_b, & α_s needed by high-luminosity ILC
- Outlined timeline for lattice QCD progress

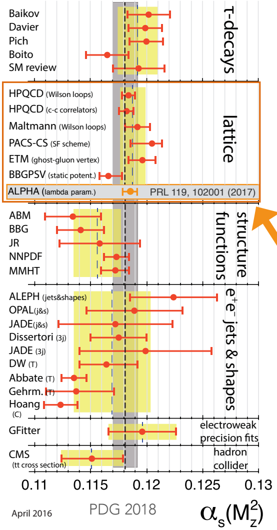
Continued progress towards precision goals since ICHEP2016

Next goals:

- Correlated determinations of m_c, m_b, and α_s
- Dynamical QED

Phiala Shanahan, MIT

m_Q from Lattice QCD (Lattice QCD - P. Shanahan)



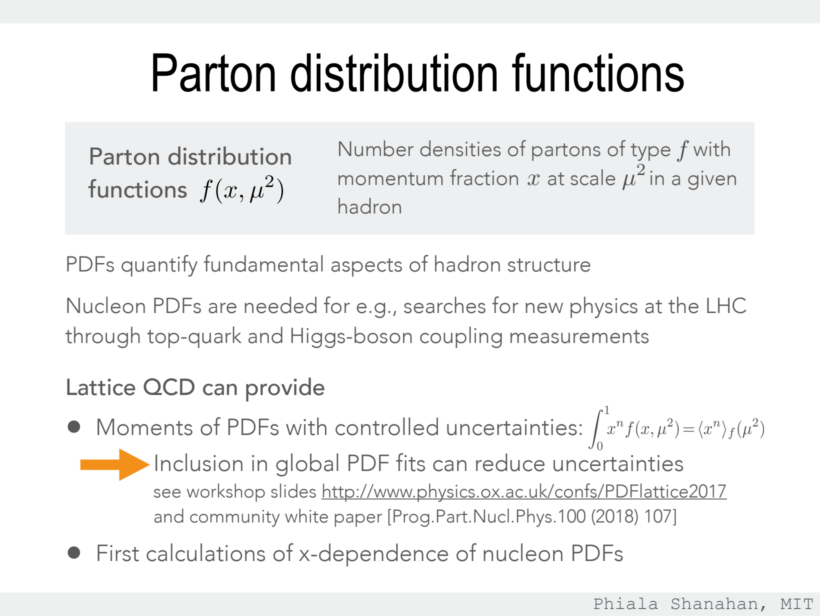
α_s update

Best lattice QCD uncertainties ~0.6-0.7%, approaching ILC target: 0.6%.
Twice as precise as non-lattice world average

- Several independent lattice QCD methods available to obtain α_s
- Results consistent, despite significantly different sources of systematic uncertainty

2017 Highlight:
New lattice QCD determination based on finite size scaling (rather than Wilson Loops and quarkonia) consistent and precise: α_s =0.1185(8)(3) [PRL119, 102001]

PDFs from Lattice QCD (Lattice QCD - P. Shanahan)



Parton distribution functions

Parton distribution functions $f(x,\mu^2)$ — Number densities of partons of type f with momentum fraction x at scale μ^2 in a given hadron

PDFs quantify fundamental aspects of hadron structure

Nucleon PDFs are needed for e.g., searches for new physics at the LHC through top-quark and Higgs-boson coupling measurements

Lattice QCD can provide

- Moments of PDFs with controlled uncertainties: $\int_0^1 x^n f(x,\mu^2) = \langle x^n \rangle_f(\mu^2)$

  ➡ Inclusion in global PDF fits can reduce uncertainties

  see workshop slides http://www.physics.ox.ac.uk/confs/PDFlattice2017
  and community white paper [Prog.Part.Nucl.Phys.100 (2018) 107]

- First calculations of x-dependence of nucleon PDFs

Phiala Shanahan, MIT

Moments of PDFs

Lattice QCD can cleanly access low moments of PDFs (n ≲ 3)

[work to move beyond: Chambers et al., arXiv:1703.01153, Davoudi & Savage, arXiv:1204.4146]

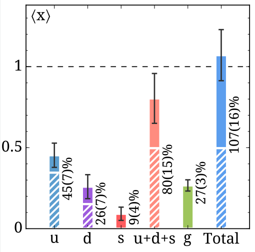
$$\int_0^1 x^n f(x,\mu^2) = \langle x^n \rangle_f(\mu^2)$$

State-of-the-art calculations have:

- Fully-controlled systematic uncertainties competitive with or better than experiment for some quantities
- Separate contributions from
  - Strangeness and light flavours
  - Charge symmetry violation
  - Gluons

2017 Highlight: All terms of nucleon momentum decomposition calculated with controlled uncertainties

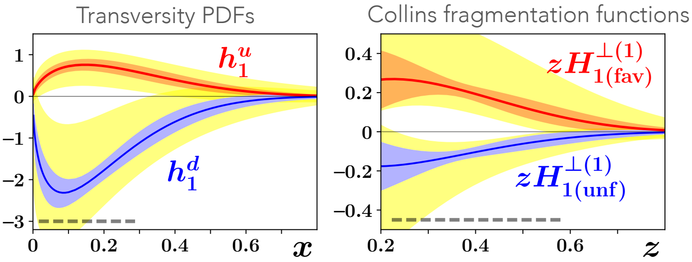
$\overline{\text{MS}}$-scheme at 2 GeV



[C. Alexandrou et al., arXiv:1706.02973]

Constraints on global PDF fits

- Including lattice QCD results for moments in global PDF fits can yield significant improvements

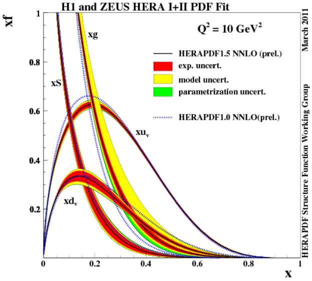


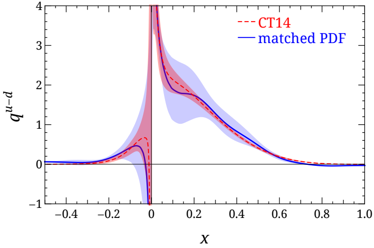
Yellow:	SIDIS data only: direct constraints in region indicated by dashes
Blue/Red:	SIDIS + lattice QCD for tensor charge (zeroth moment)

[H-W. Lin et al., arXiv:1710.09858]

x-dependence of PDFs

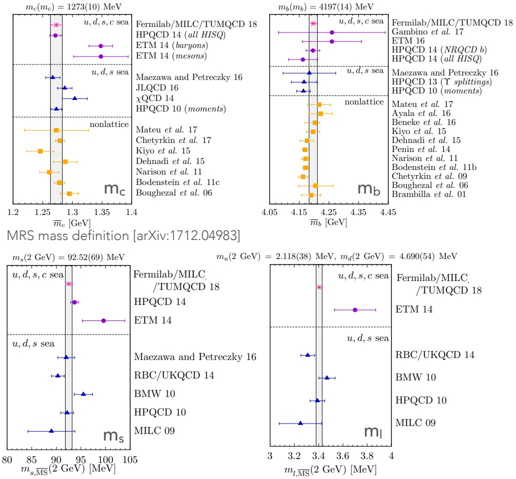
- First calculations of x-dependence of nucleon PDFs undertaken
  Quasi and pseudo-PDF calculations use non-local Euclidean correlators and perturbative QCD matching in high momentum limit [X. Ji, arXiv:1305.1539]
- Extremely rapid progress, but many systematics to be controlled
- Flavour separation is relatively straightforward





[J-W Chen et al., arXiv:1803.04393]

Quark masses update



MRS mass definition [arXiv:1712.04983]

2018 Highlight:
Significant improvement in heavy quark mass determinations using new method based on heavy-quark effective theory [arXiv:1802.04248]

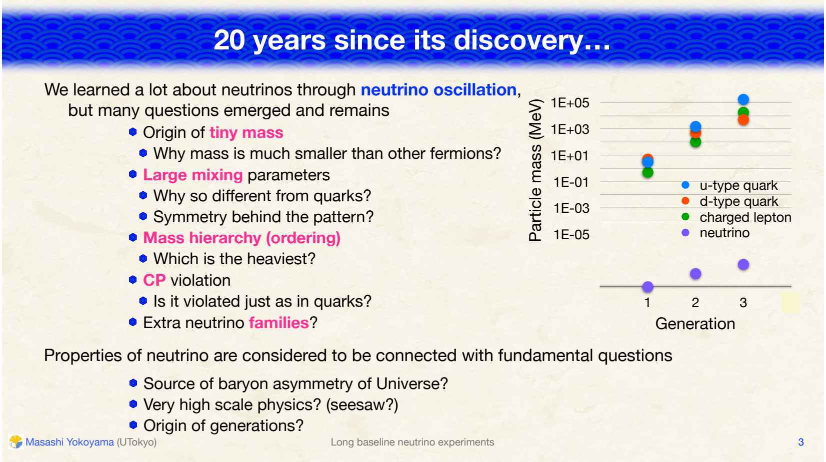
Precision	**ILC goals**
$\delta m_b \sim 0.3$	0.3
$\delta m_c \sim 0.8$	0.7

Will improve further with inclusion of finer lattice spacings

Selected results from neutrino physics experiments

- Measurements of neutrino mixing matrix parameters and mass hierarchy
- Efforts to directly measure neutrino with the KATRIN experiment

Neutrino Oscillation (Long Baseline ν - M. Yokoyama)



20 years since its discovery…

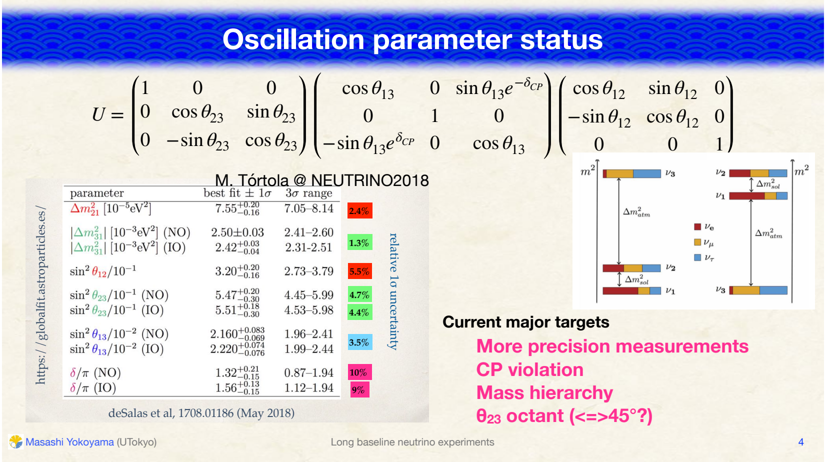
We learned a lot about neutrinos through **neutrino oscillation**, but many questions emerged and remains

- Origin of **tiny mass**
  - Why mass is much smaller than other fermions?
- **Large mixing** parameters
  - Why so different from quarks?
  - Symmetry behind the pattern?
- **Mass hierarchy (ordering)**
  - Which is the heaviest?
- **CP** violation
  - Is it violated just as in quarks?
- Extra neutrino **families**?

Properties of neutrino are considered to be connected with fundamental questions

- Source of baryon asymmetry of Universe?
- Very high scale physics? (seesaw?)
- Origin of generations?

Neutrino Oscillation (Long Baseline ν - M. Yokoyama)



Oscillation parameter status

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-\delta_{CP}} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{\delta_{CP}} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

M. Tórtola @ NEUTRINO2018

https://globalfit.astroparticles.es/

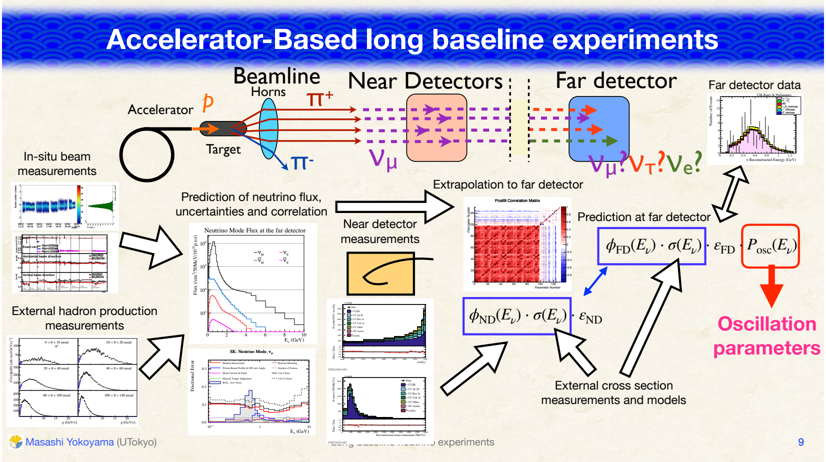
parameter	best fit ± 1σ	3σ range	relative 1σ uncertainty
Δm^2_{21} $[10^{-5}\mathrm{eV}^2]$	$7.55^{+0.20}_{-0.16}$	7.05–8.14	2.4%
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\mathrm{eV}^2]$ (NO)	2.50 ± 0.03	2.41–2.60	1.3%
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\mathrm{eV}^2]$ (IO)	$2.42^{+0.03}_{-0.04}$	2.31-2.51	
$\sin^2\theta_{12}/10^{-1}$	$3.20^{+0.20}_{-0.16}$	2.73–3.79	5.5%
$\sin^2\theta_{23}/10^{-1}$ (NO)	$5.47^{+0.20}_{-0.30}$	4.45–5.99	4.7%
$\sin^2\theta_{23}/10^{-1}$ (IO)	$5.51^{+0.18}_{-0.30}$	4.53–5.98	4.4%
$\sin^2\theta_{13}/10^{-2}$ (NO)	$2.160^{+0.083}_{-0.069}$	1.96–2.41	3.5%
$\sin^2\theta_{13}/10^{-2}$ (IO)	$2.220^{+0.074}_{-0.076}$	1.99–2.44	
δ/π (NO)	$1.32^{+0.21}_{-0.15}$	0.87–1.94	10%
δ/π (IO)	$1.56^{+0.13}_{-0.15}$	1.12–1.94	9%

deSalas et al, 1708.01186 (May 2018)

Current major targets

More precision measurements
CP violation
Mass hierarchy
θ_{23} octant (<=>45°?)

Masashi Yokoyama (UTokyo) Long baseline neutrino experiments 4



Accelerator-Based long baseline experiments

Beamline

Horns

Accelerator p

Target

π^+

π^-

Near Detectors

Far detector

ν_μ

ν_μ? ν_τ? ν_e?

Far detector data

In-situ beam measurements

Prediction of neutrino flux, uncertainties and correlation

Extrapolation to far detector

Near detector measurements

Prediction at far detector

$$\boxed{\phi_{\rm FD}(E_\nu)\cdot\sigma(E_\nu)}\cdot\varepsilon_{\rm FD}\cdot\boxed{P_{\rm osc}(E_\nu)}$$

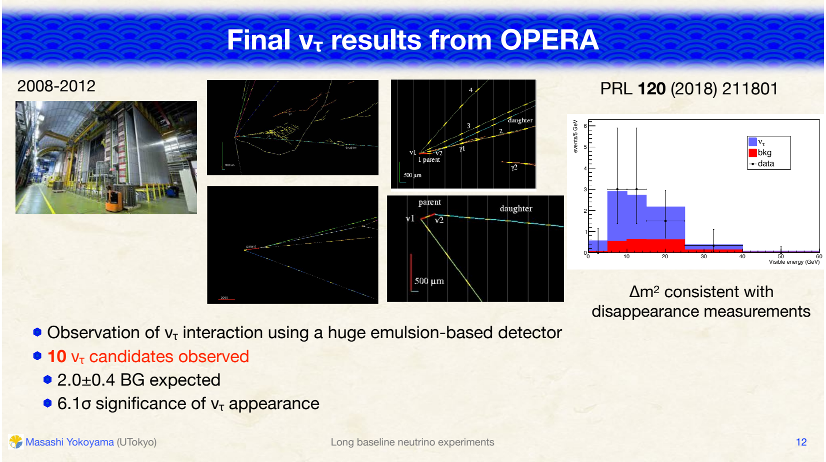
$$\boxed{\phi_{\rm ND}(E_\nu)\cdot\sigma(E_\nu)}\cdot\varepsilon_{\rm ND}$$

Oscillation parameters

External hadron production measurements

External cross section measurements and models

OPERA Results (Long Baseline ν - M. Yokoyama)



Final ν_τ results from OPERA

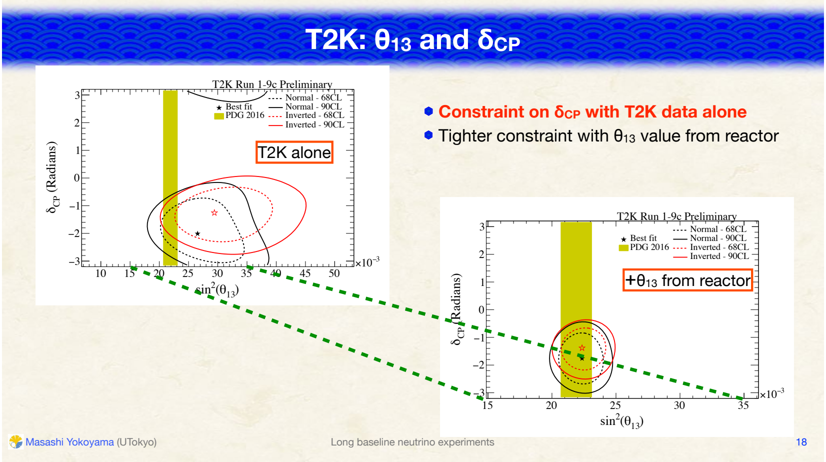
2008-2012

PRL **120** (2018) 211801

Δm² consistent with disappearance measurements

- Observation of ν_τ interaction using a huge emulsion-based detector
- **10** ν_τ candidates observed
  - 2.0±0.4 BG expected
  - 6.1σ significance of ν_τ appearance

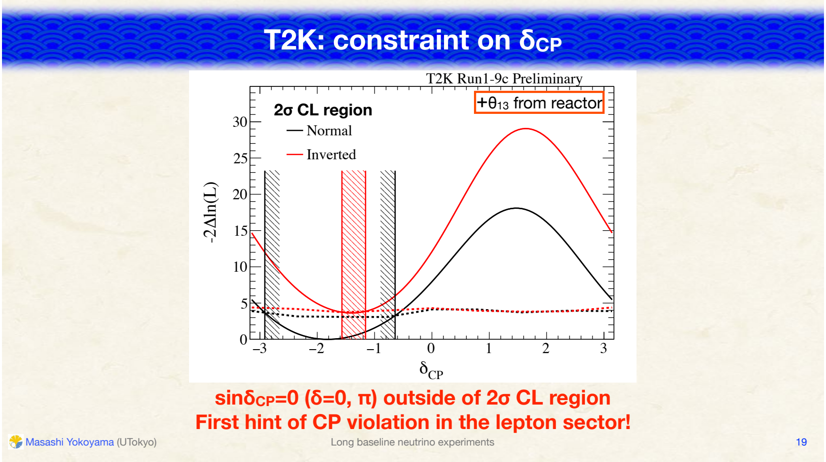
T2K Results (Long Baseline ν - M. Yokoyama)



T2K: θ_{13} and δ_{CP}

- **Constraint on δ_{CP} with T2K data alone**
- Tighter constraint with θ_{13} value from reactor

T2K Results (Long Baseline ν - M. Yokoyama)

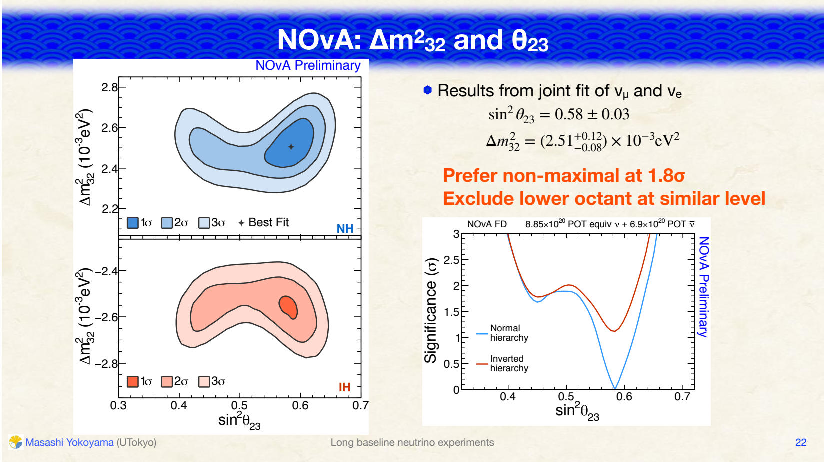


T2K: constraint on δ_{CP}

$\sin\delta_{CP}$=0 (δ=0, π) outside of 2σ CL region

First hint of CP violation in the lepton sector!

NOνA Results (Long Baseline ν - M. Yokoyama)



NOvA: Δm^2_{32} and θ_{23}

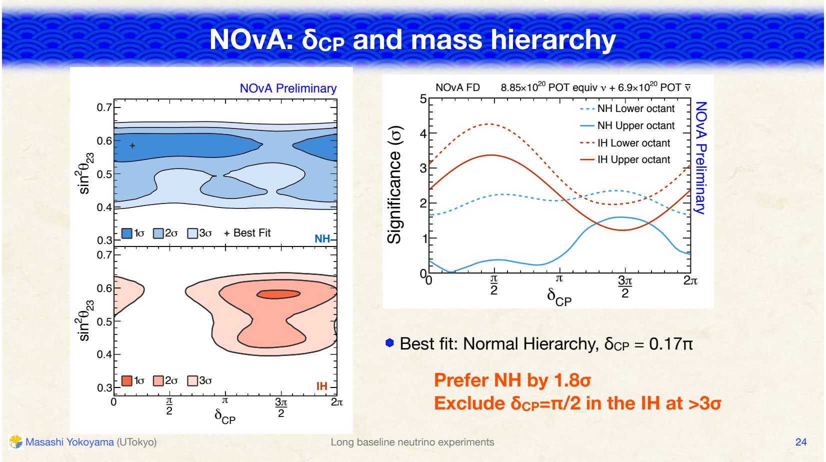
- Results from joint fit of ν_μ and ν_e

$$\sin^2\theta_{23} = 0.58 \pm 0.03$$

$$\Delta m^2_{32} = (2.51^{+0.12}_{-0.08}) \times 10^{-3}\mathrm{eV}^2$$

Prefer non-maximal at 1.8σ
Exclude lower octant at similar level

NOνA Results (Long Baseline ν - M. Yokoyama)

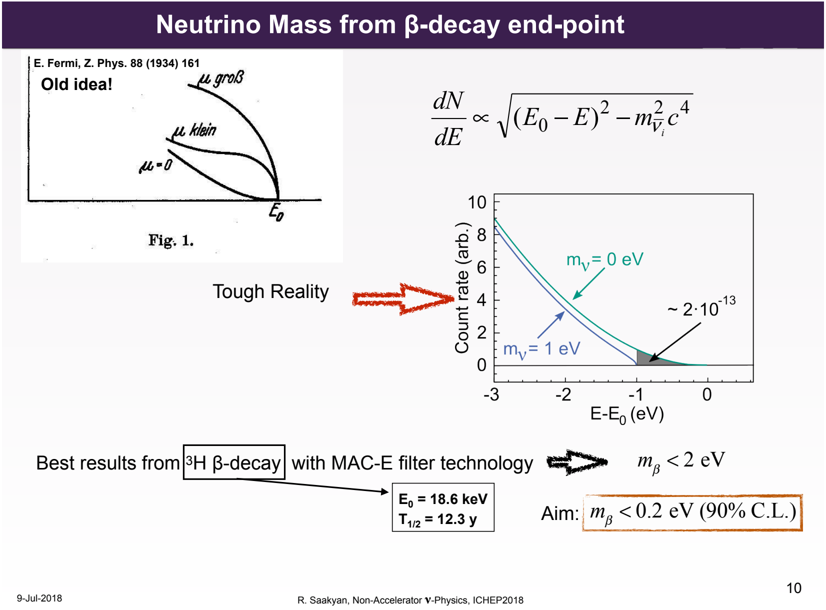


NOvA: δ_{CP} and mass hierarchy

- Best fit: Normal Hierarchy, $\delta_{CP} = 0.17\pi$

Prefer NH by 1.8σ
Exclude $\delta_{CP}=\pi/2$ in the IH at >3σ

KATRIN (Non-accelerator ν - R. Saakyan)



Neutrino Mass from β-decay end-point

E. Fermi, Z. Phys. 88 (1934) 161

Old idea!

Fig. 1.

$$\frac{dN}{dE} \propto \sqrt{(E_0 - E)^2 - m_{\bar{\nu}_i}^2 c^4}$$

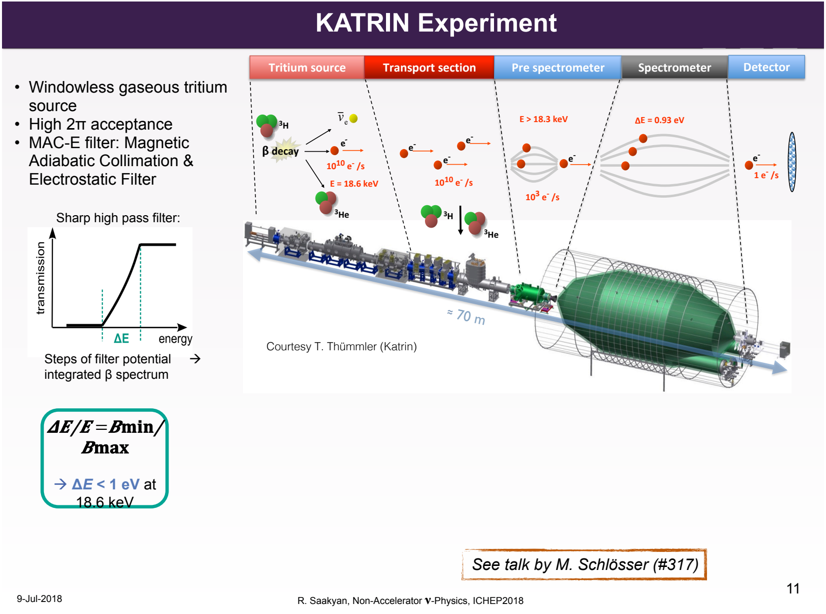
Tough Reality

Best results from ^{3}H β-decay with MAC-E filter technology $m_\beta < 2$ eV

E_0 = 18.6 keV
$T_{1/2}$ = 12.3 y

Aim: $m_\beta < 0.2$ eV (90% C.L.)

KATRIN (Non-accelerator ν - R. Saakyan)



KATRIN Experiment

- Windowless gaseous tritium source
- High 2π acceptance
- MAC-E filter: Magnetic Adiabatic Collimation & Electrostatic Filter

Sharp high pass filter:

Steps of filter potential → integrated β spectrum

$$\Delta E/E = B\text{min}/B\text{max}$$

→ $\Delta E < 1$ eV at 18.6 keV

Courtesy T. Thümmler (Katrin)

See talk by M. Schlösser (#317)

9-Jul-2018

R. Saakyan, Non-Accelerator ν-Physics, ICHEP2018

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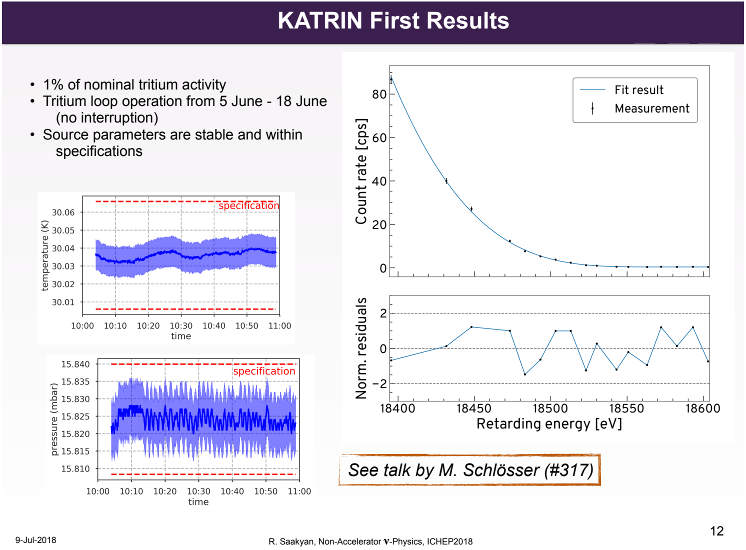
KATRIN (Non-accelerator ν - R. Saakyan)



KATRIN First Results

- 1% of nominal tritium activity
- Tritium loop operation from 5 June - 18 June (no interruption)
- Source parameters are stable and within specifications

See talk by M. Schlösser (#317)

9-Jul-2018

R. Saakyan, Non-Accelerator ν-Physics, ICHEP2018

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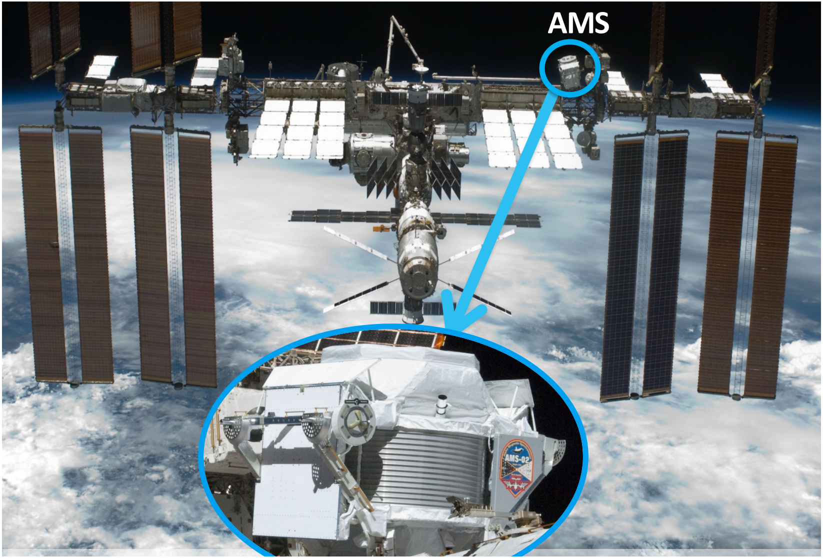
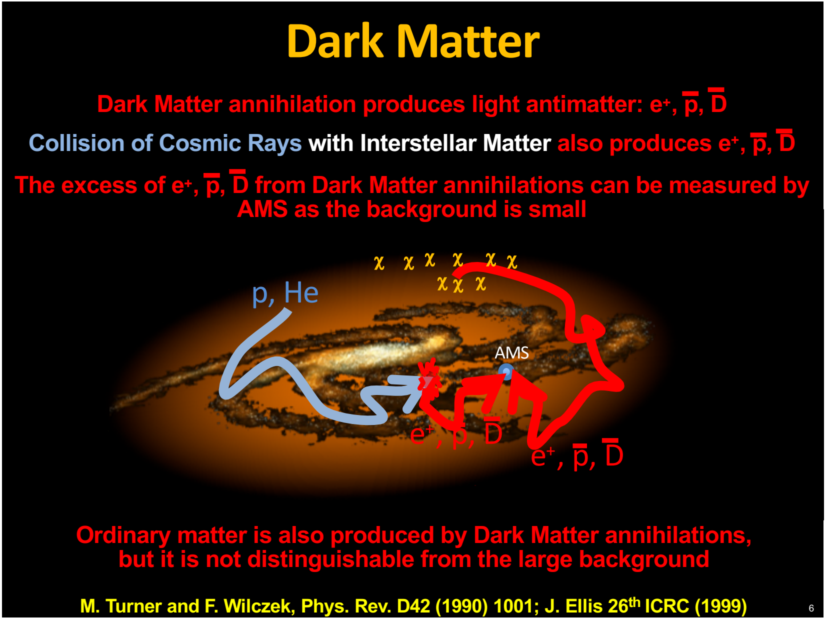
Latest results from the AMS experiment



- Much interest in new AMS results of the cosmic ray flux



Dark Matter

Dark Matter annihilation produces light antimatter: e^+, $\bar{p}$, $\bar{D}$

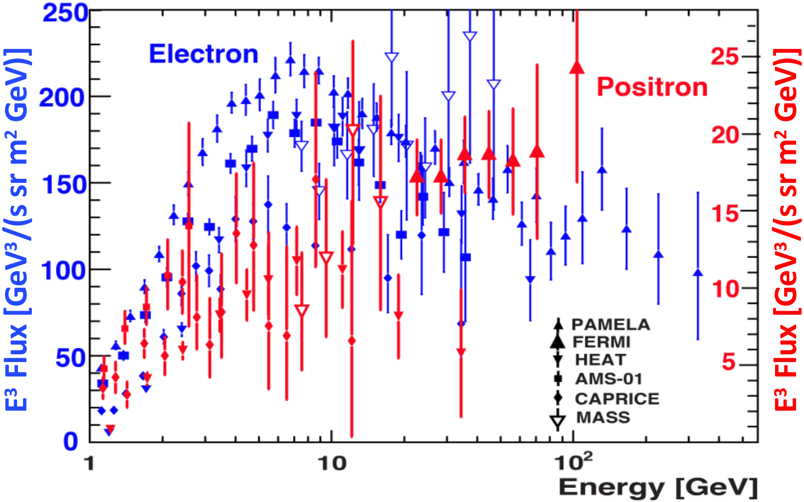
Collision of Cosmic Rays with Interstellar Matter also produces e^+, $\bar{p}$, $\bar{D}$

The excess of e^+, $\bar{p}$, $\bar{D}$ from Dark Matter annihilations can be measured by AMS as the background is small

Ordinary matter is also produced by Dark Matter annihilations, but it is not distinguishable from the large background

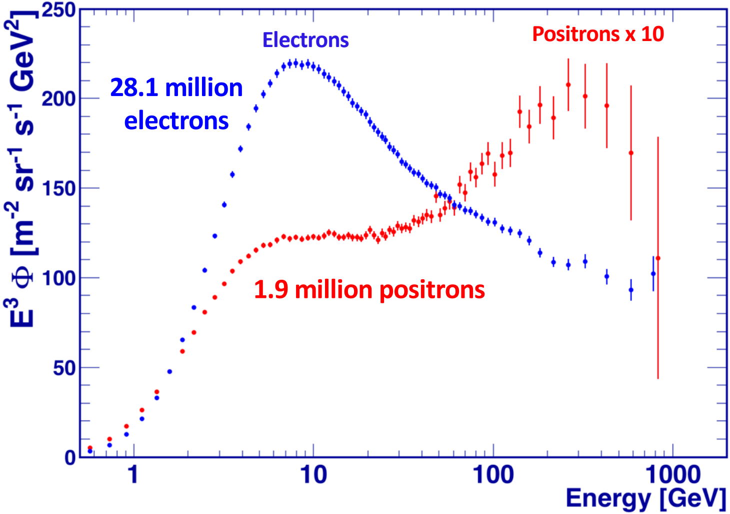
M. Turner and F. Wilczek, Phys. Rev. D42 (1990) 1001; J. Ellis 26th ICRC (1999)

Electron and Positron spectra before AMS

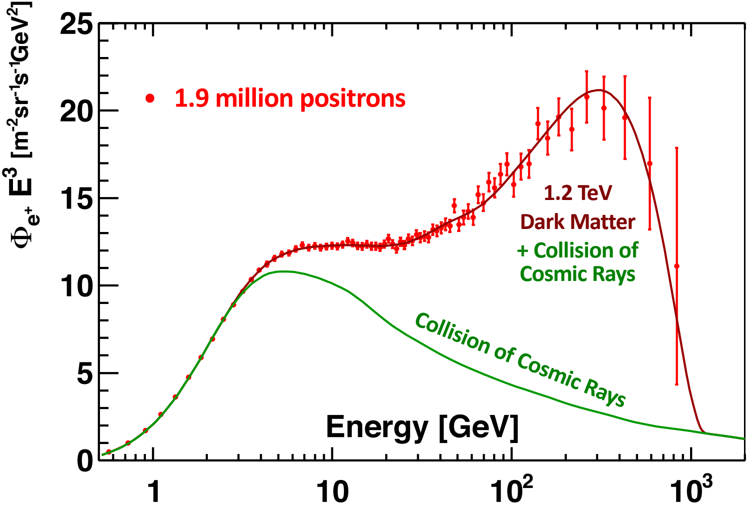


These are very difficult experiments

Latest AMS results on positron and electron fluxes



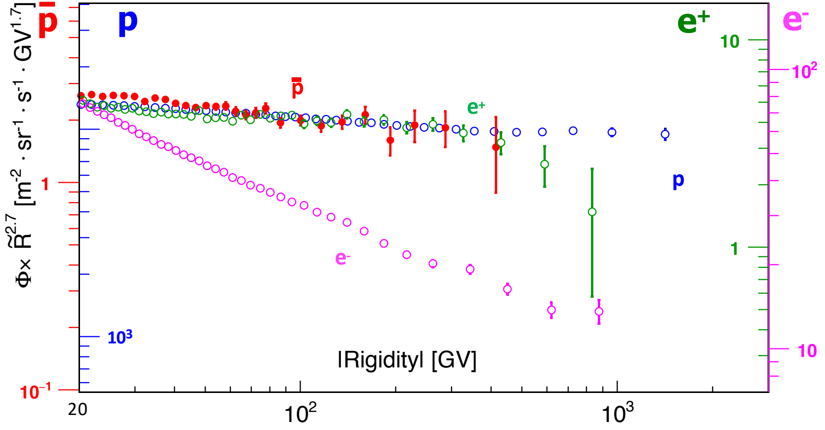
The positron flux appears to be in agreement with predictions from a 1.2 TeV Dark Matter model (J. Kopp, Phys. Rev. D 88, 076013 (2013))



Most surprisingly:

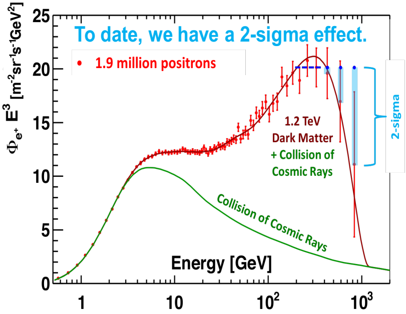
The spectra of positrons, antiprotons, and protons are identical,
but the proton and antiproton mass is 2000 times the positron mass.

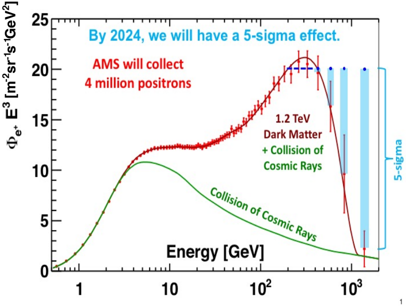
The electron spectrum is different



Physics of AMS on ISS: Positrons and Dark Matter

Extend the measurements to 2 TeV and determine the sharpness of the drop off.





Currently, the approved ISS lifetime is until 2024.
The incremental gain between now and 2024 is from 2-sigma to 5-sigma.

Many models proposed to explain the physics origin of the observed behavior

(>2000 citations of the AMS results)

1) Particle origin: Dark Matter
2) Astrophysics origin: Pulsars, SNRs
3) Propagation of cosmic rays

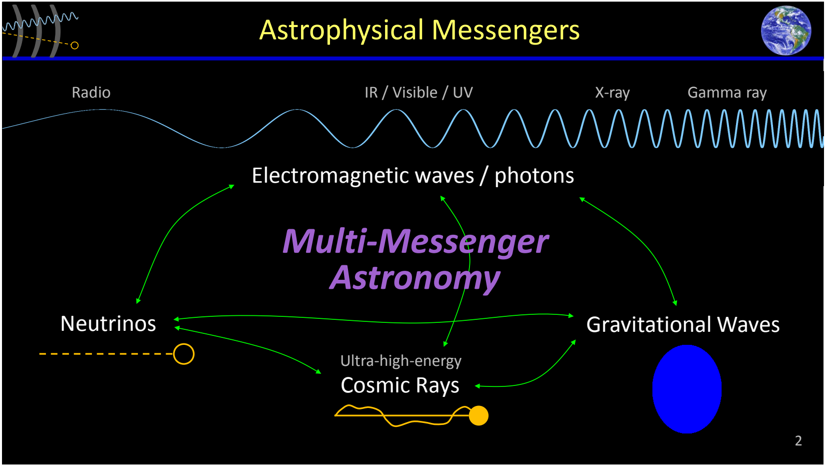
Models based on very different assumptions describe observed trends of a single measurement.

Simultaneous description of several precision measurements is difficult in the framework of a single model

Review of “Multi-Messenger Astrophysics” (MMA)

- Relatively new field of research (I’d not heard of it!)
- Involves the coordinated observation and interpretation of disparate “messenger” signals from astronomical objects

Multi-Messenger Astrophysics (MMA) (MMA - P. Shawhan)



Astrophysical Messengers

Radio

IR / Visible / UV

X-ray

Gamma ray

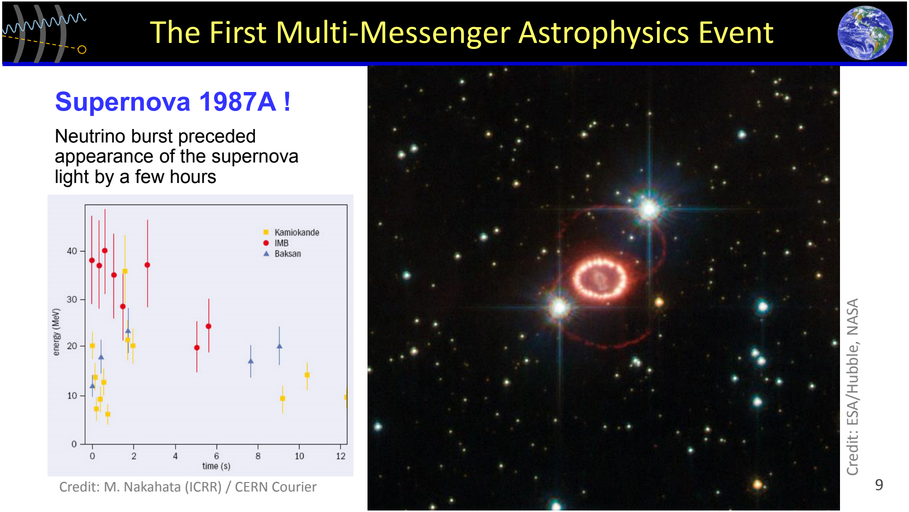
Electromagnetic waves / photons

Multi-Messenger Astronomy

Neutrinos

Gravitational Waves

Ultra-high-energy
Cosmic Rays



The First Multi-Messenger Astrophysics Event

Supernova 1987A !

Neutrino burst preceded appearance of the supernova light by a few hours

Credit: M. Nakahata (ICRR) / CERN Courier

Credit: ESA/Hubble, NASA

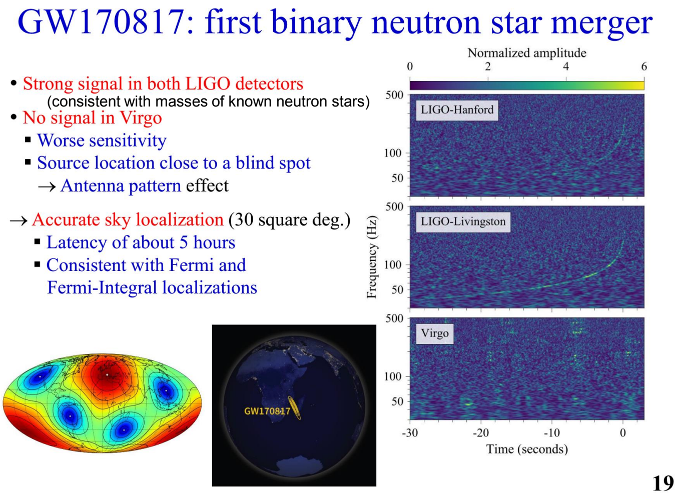
Multi-Messenger view of GW170817 I (MMA - P. Shawhan)

From Thursday:

N. Arnaud

"In between the Observation Runs 2 and 3, a status report on the Advanced LIGO and Advanced Virgo GW detectors"

Normally the sky localization would be available within minutes, but had to work around a glitch in the LIGO-Livingston data



GW170817: first binary neutron star merger

- Strong signal in both LIGO detectors
  (consistent with masses of known neutron stars)
- No signal in Virgo
  - Worse sensitivity
  - Source location close to a blind spot
    → Antenna pattern effect

→ Accurate sky localization (30 square deg.)
  - Latency of about 5 hours
  - Consistent with Fermi and Fermi-Integral localizations

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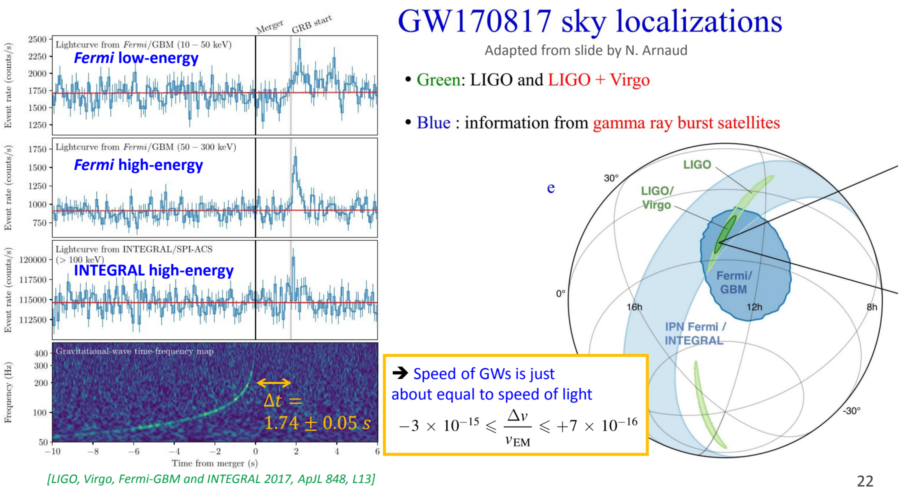
Multi-Messenger view of GW170817 II (MMA - P. Shawhan)



[LIGO, Virgo, Fermi-GBM and INTEGRAL 2017, ApJL 848, L13]

GW170817 sky localizations

Adapted from slide by N. Arnaud

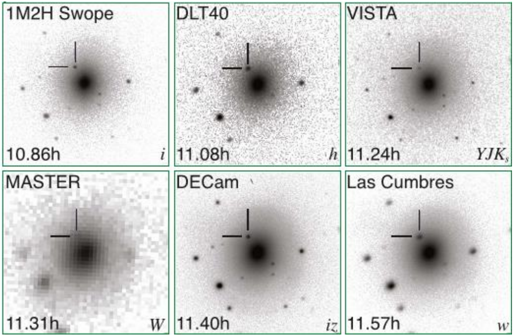
- Green: LIGO and LIGO + Virgo
- Blue : information from gamma ray burst satellites

➔ Speed of GWs is just about equal to speed of light

$$-3 \times 10^{-15} \leqslant \frac{\Delta v}{v_{\mathrm{EM}}} \leqslant +7 \times 10^{-16}$$

Astronomers found the optical counterpart!

Independently found by 6 teams within a span of 45 minutes, in the galaxy NGC 4993



GRB 170817A

GW170817

SSS17a

DLT17ck

MASTER J130948.10-232253.3

→ AT 2017gfo

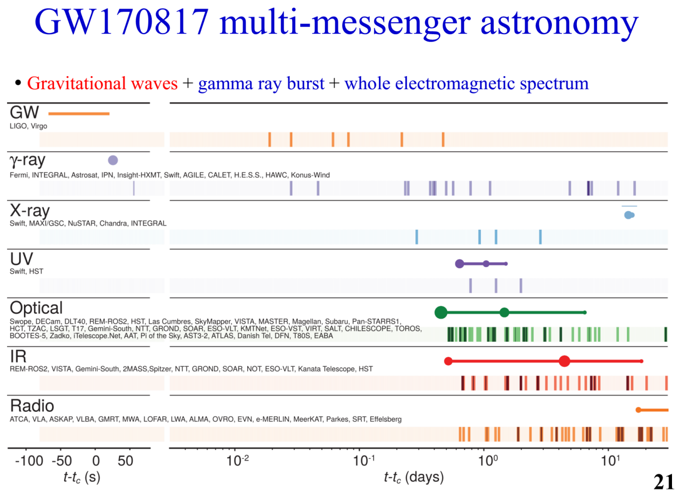
[Abbott and many others 2017, ApJL 848, L12]

Multi-Messenger view of GW170817 IV (MMA - P. Shawhan)

From Thursday:

N. Arnaud

“In between the Observation Runs 2 and 3, a status report on the Advanced LIGO and Advanced Virgo GW detectors”

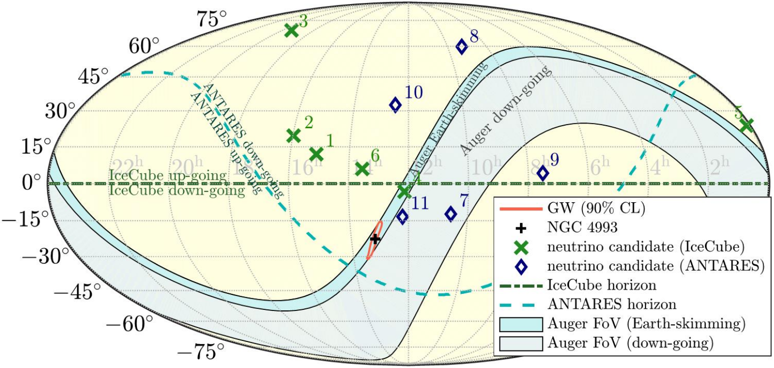


GW170817 multi-messenger astronomy

- Gravitational waves + gamma ray burst + whole electromagnetic spectrum

Multi-Messenger view of GW170817 V (MMA - P. Shawhan)

No Neutrino Counterpart to GW170817



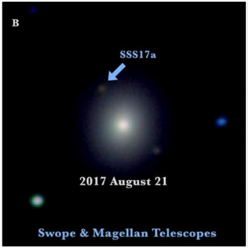
[Albert et al. (ANTARES, IceCube, Pierre Auger, LIGO and Virgo) 2017, ApJL 850, L35]

Multi-Messenger view of GW170817 VI (MMA - P. Shawhan)

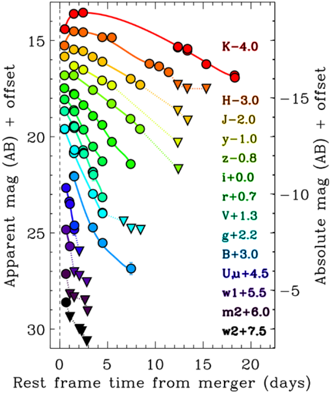
Saw the GW170817 counterpart fade – and change color

Initially visible in ultraviolet and blue – but those faded quickly

Infrared peaked after 2-3 days, then remained visible for weeks

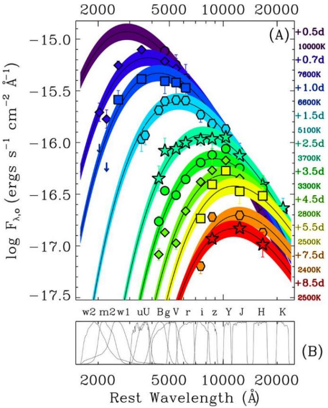


[Drout et al. 2017, Science 10.1126/science.aaq0049]



Multi-Messenger view of GW170817 VII (MMA - P. Shawhan)

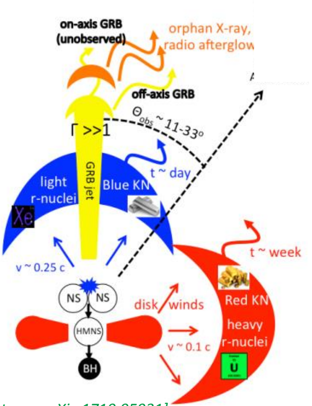
… as it cooled



[Drout et al. 2017, Science 10.1126/science.aaq0049]

Multi-Messenger view of GW170817 VII (MMA - P. Shawhan)

Optical emission matches “kilonova” model



[Metzger, arXiv:1710.05931]

r-process nucleosynthesis takes place in ejected material

Then radioactive decays drive thermal emission

Evidence for two components:
“blue” (lanthanide-poor) and
“red” (lanthanide-rich)

Different r-process elements produced ➔ different opacities

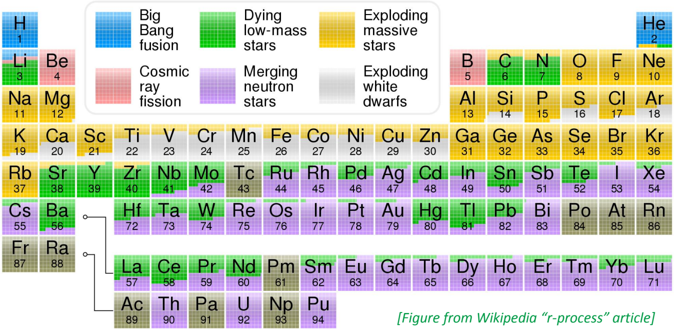
Hypermassive neutron star may irradiate central ejecta with neutrinos, converting some neutrons to protons

e.g., Cowperthwaite et al. estimate
$0.01\ M_\odot$ of “blue” ejecta moving at $\sim 0.3\ c$ plus
$0.04\ M_\odot$ of “red” ejecta moving at $\sim 0.1\ c$

Also late-time X-ray and radio afterglows

Implication for heavy elements

Strengthens the picture that neutron star mergers produce most of the heaviest elements



[Figure from Wikipedia "r-process" article]

Conclusion

Summary

- Difficult enough to summarise in one seminar, will not attempt to draw a concise conclusion here!
- Overall a very intense and diverse week of contributions, reflecting the breadth of the modern field!
- I'd encrourage you to browse the slides! (https://indico.cern.ch/event/686555/)

ICHEP 2020 will be held in Prague, Czech Republic

Additional Slides