Summary of the IPPP European Strategy Update Workshop

IPPP 16-18 April 2018

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Michael Spannowsky

2nd July 2018

IPPP European Strategy workshop

- Aimed to kick off thinking about the UK input
  - Ask ourselves what science we want to be doing in 20 years
- We were asked to organise the workshop to gather a broad spectrum of UK academics, with a focus on engaging “mid career” academics
  - Has been nucleated around a list of mid-career academics provided by group leaders, and in addition had an open registration call
- Is science-, not politics-, focused
- Emphasis on discussion sessions
- Was not aiming to be a town meeting - that will happen later in the year, led by PPAP, aiming at a large-scale community meeting
  - PPAP 16/17 July RAL; Town meeting 20 Sept Birmingham

Workshop

- Aimed to:
  - Identify consensus on the fundamental science questions
  - Engage minds across the community
    - Voices of experience and those driving future projects
    - But also encourage those who are focused on the "here and now" to look up!
  - Identify areas that will benefit from further studies and discussion
- Speakers were asked to:
  - Stimulate discussion by providing questions
  - Summarise broad areas of technology and physics analysis in an open-minded way
- Compiled a summary document to be released through HI-PHI this week, intended as a *briefing document*
  - *The UK final submission must take care to access the very latest projections, our write-up is just a snapshot and based on speakers' expertises and personal views*

This talk

- **Summarise the sessions (of course I cannot be exhaustive, so apologies for omissions)**
  - Theory
  - Technology
  - Leptons
  - Quark Flavour
  - Higgs
  - Exotics
  - Standard Model/Top
  - Dark Matter
  - Astroparticle/Gravitational waves

https://conference.ippp.dur.ac.uk/event/661

- **Summarise the workshop conclusions**
  - Consensus on some practical issues
  - Open questions/sticking points

Theory

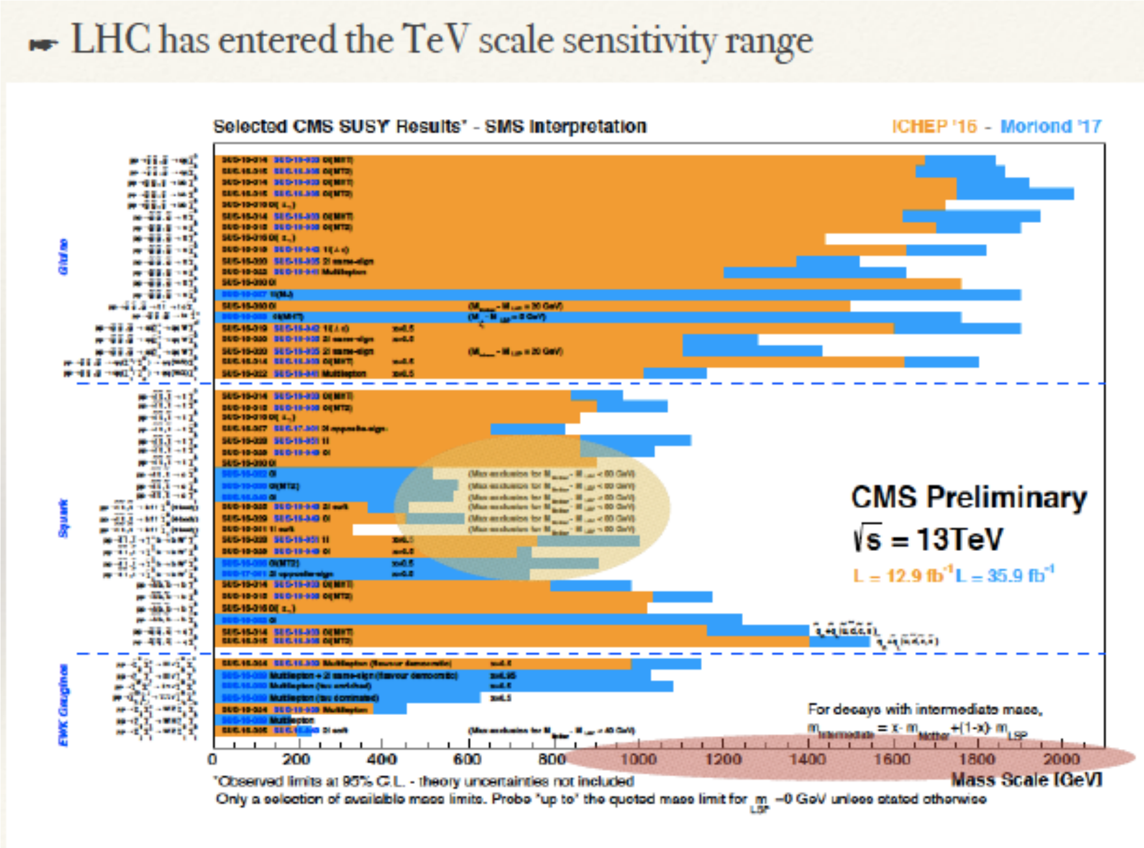
A Sense of Urgency: This theorist's perspective

- Extremely important and critical time for our field. For the first time no large scale ambitious experimental projects are being built. No time to waste now!
- Lessons from the LHC: there is the Higgs(!) but no BSM particles at sub-TeV scale -> plan future experiments to dial up energy rather than luminosity and precision.
- Plan general purpose experiments, not only single measurement experiments, something that has a multiple discovery potential.
- Theory prospects are very exciting intellectually! But uncertain predictive power: theory now has no dominant fashions, no consensus, no guarantees of a particular model framework to be realised -> dial up the energy and throw as wide net as possible.
- The time for action is now - if we are stuck for too long with the high-luminosity LHC or the cheapest ILC 250 option, and if there are no discoveries - there will be no money for future experiments. Also need to do better than the cancelled SSC equivalent.
- Without experimental data modern particle theory cannot progress on its own.

Valya Khoze

Theory

- **Report from future colliders working groups**



C. Englert

- But constraints can be avoided in non-minimal scenarios
- So "best bet" are Higgs precision measurements – must form part of any future program

Coupling projections FCChh/CLIC

C. Englert

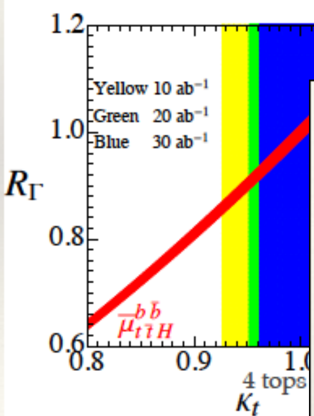
FCC-hh projections

	$\sigma(t\bar{t}H)$[pb]	$\sigma(t\bar{t}Z)$[pb]	$\frac{\sigma(t\bar{t}H)}{\sigma(t\bar{t}Z)}$
13 TeV	$0.475^{+5.79\%+3.33\%}_{-9.04\%-3.08\%}$	$0.785^{+9.81\%+3.27\%}_{-11.2\%-3.12\%}$	$0.606^{+2.45\%+0.525\%}_{-3.66\%-0.319\%}$
100 TeV	$33.9^{+7.06\%+2.17\%}_{-8.29\%-2.18\%}$	$57.9^{+8.93\%+2.24\%}_{-9.46\%-2.43\%}$	$0.585^{+1.29\%+0.314\%}_{-2.02\%-0.147\%}$

[Mangano, Plehn, Reimirz, Schell, Shao ` 15]

$$\mu^{bb}_{t\bar{t}H} = \frac{\kappa_t^2 \kappa_b^2}{R_\Gamma} \quad \text{with} \quad R_\Gamma \equiv \frac{\Gamma_H}{\Gamma_H^{SM}}$$

$$\sim 1.00 \pm 0.01 \ @\ 20/\text{ab}$$



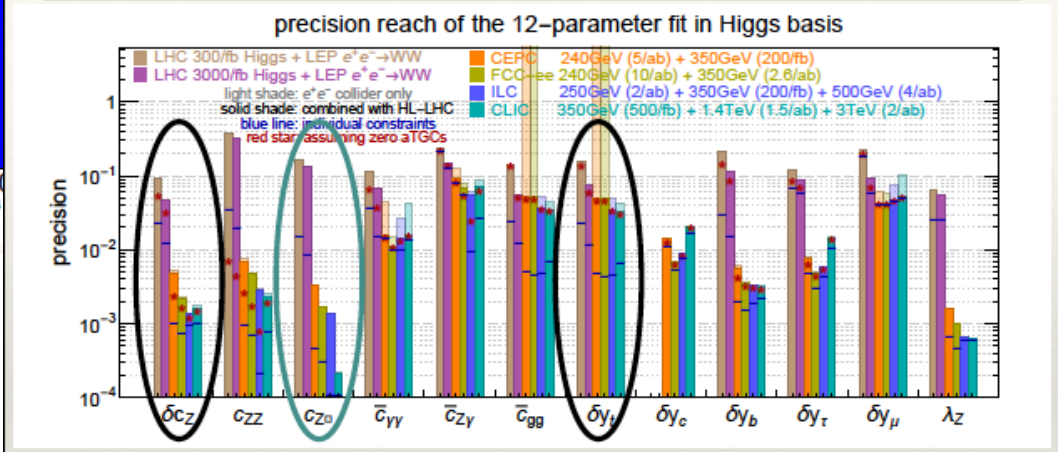
- Precise extraction of top/Higgs properties possible at 100 TeV including rare final states

[Cao, Chen, Liu ` 16]

[Contino et al. CERN YR ` 16]

Coupling projections: HL-LHC

[Durieux, Grojean, Gu, Wang ` 17]



see also [LCC working group ` 18], [CEPC working group ` 17]

- Precision environment of a lepton colliders allows to pin down gauge-Higgs sector at the per mille level in case of the Z
- CLIC energy coverage beneficial to pin down high energy behavior of electroweak sector e.g. $c_{Z\Box}\, g^2 Z_\mu \partial_\nu Z_{\mu\nu}$

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Non-collider theory summary

- **Physics Beyond Colliders is a CERN working group set up to identify possibilities in e.g. fixed target physics, Kaon physics**
- **Aimed at European Strategy Update – report ongoing**

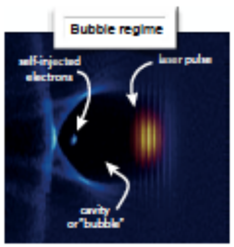
C. Burrage

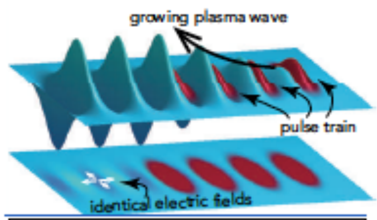
Technology: Accelerators

- **Accelerators: novel acceleration is needed whatever**

Laser & beam driven plasma wakefield: **100 GV/m**

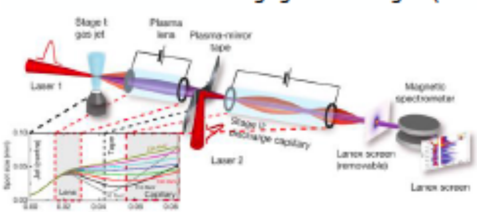
- ***Laser-plasma accelerators*** *(1 GeV demonstrated)*
  - Laser pulse in plasma filled capillary enables electrons to surf a plasma density wave.
  - Recent exciting developments in multi-pulse schemes and staging at low energies.





S.M. Hooker *et al. J. Phys. B* **47** 234003 (2013)

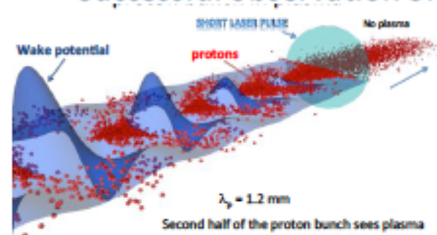
LBNL have demonstrated staging at low energies (~200 MeV increased to ~300 MeV).

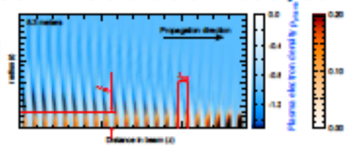


Steinke, S. et al. Multistage coupling of independent laser-plasma accelerators. Nature 530, 190–193 (2016).

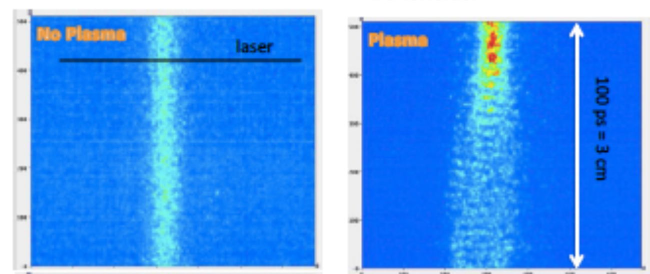
Van Tilborg, J. et al. Active Plasma Lensing for Relativistic Laser-Plasma-Accelerated Electron Beams. Phys. Rev. Lett. 115, 184802 (2015).

- ***Proton driven plasma wakefield***
  - 12cm, 3x10[11] proton bunch drives plasma wakefield in cell at SPS.
  - Acceleration of 15 MeV injected e- to >1GeV
  - Successful observation of self-modulation last year:





Self-modulated proton bunch resonantly driving plasma wakefields.



John Adams Institute for Accelerator Science

Stephen Gibson – UK input to EU PP Strategy, Durham, 16 April 2018

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S. Gibson

Technology: Accelerators

- **Accelerators: novel acceleration is needed whatever the future decisions are**

Summary & points for discussion

- *Top priority: exploitation of LHC Run III & HL-LHC from 2026 – 2036…*
- *Which collider to build next? Depends on **IPPP**; **I**nnovation, **P**hysics, **P**rice & **P**olitics:*
  - Japan expected to decide whether to build ILC by end of 2018; if not, plenty of options:
  - e^+e^- Higgs factories: ILC, CLIC, CEPC, FCC-ee;
  - Hadron colliders: FCC-hh, HE-LHC.
- Novel acceleration: reaching >100 TeV in feasible size requires new technologies, priorities for development?
  - Laser-plasma, beam-driven plasma wakefield, THz, dielectrics, muon collider…
- Consider many non-collider PP experiments to exploit CERN accelerator infrastructure + UK engagement in high intensity accelerator driven neutrino programme.
- UK strategy for engagement in EU PP; scientific & economic return on investment.

John Adams Institute for Accelerator Science

Stephen Gibson – UK input to EU PP Strategy, Durham, 16 April 2018 38

S. Gibson

Technology: Silicon

- **Significant R&D in Monolithic Array Pixel Sensors (MAPS), for example pushing time resolution:**

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Timing resolution for 4D tracking and vertexing

In high occupancy experiments accurate timing information can help to reject hits or tracks from pile-up.

What is needed? At LHC need <100ps to discriminate between tracks from different vertices in a single bunch crossing.

- Track to vertex association with **a single timing layer** to reject tracks from pile-up vertices
- Timing measurement **in all layers** would also reduce the combinatorics in track finding. Need to keep small pixels for position resolution

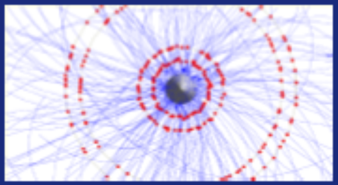
Current performance:

- 30-35 ps in sensors with gain (LGAD, SiPM), but sensing elements are typically a few mm^2
- In hybrid or depleted CMOS (small pixel) devices 10-20 ns is routinely achieved, O(1 ns) should be feasible

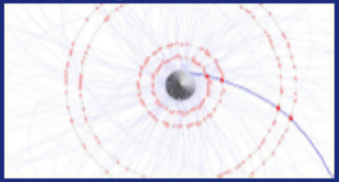
Future R&D:

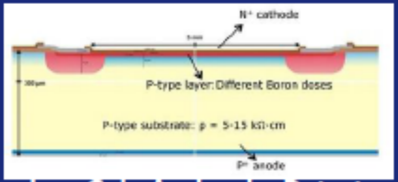
- difficult to go much below 30 ps in a single measurement (due to fluctuations in deposited charge). Use stacking to incorporate multiple measurements in a single wafer?
- push for sub ns timing in small CMOS pixels, very small feature sizes in HV-CMOS may achieve charge amplification.

Mu3e 10^9 μ/s with 50 ns frame



Mu3e 10^9 μ/s with 1 ns frame





Low Gain Avalanche Detector

G. Pellegrini et al., NIMA765 (2014) 12

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J. Vossebeld

Technology: Silicon

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Areas of European cooperation: Access to Industry

Silicon sensor development requires access to a range of commercial technologies:

1. **Software** for integrated circuit design and simulation and associated training
2. **Access to foundries**
3. Custom **wafer processing**: implantation, metallisation
4. Wafer **dicing and thinning**
5. **Interconnection techniques**: solder bump deposition, flip-chip bonding,

An important European project is **EuroPractice**: liaison industry and academia providing access to advanced software for academic users (sensor design and simulation, FPGA programming, ..) access to commercial technologies for R&D submissions and offering a broad training programmes

Currently no common provision for access to 3,4,5. (Challenging for small scale R&D)

J. Vossebeld

Technology: Trigger/DAQ

Questions from Input committee

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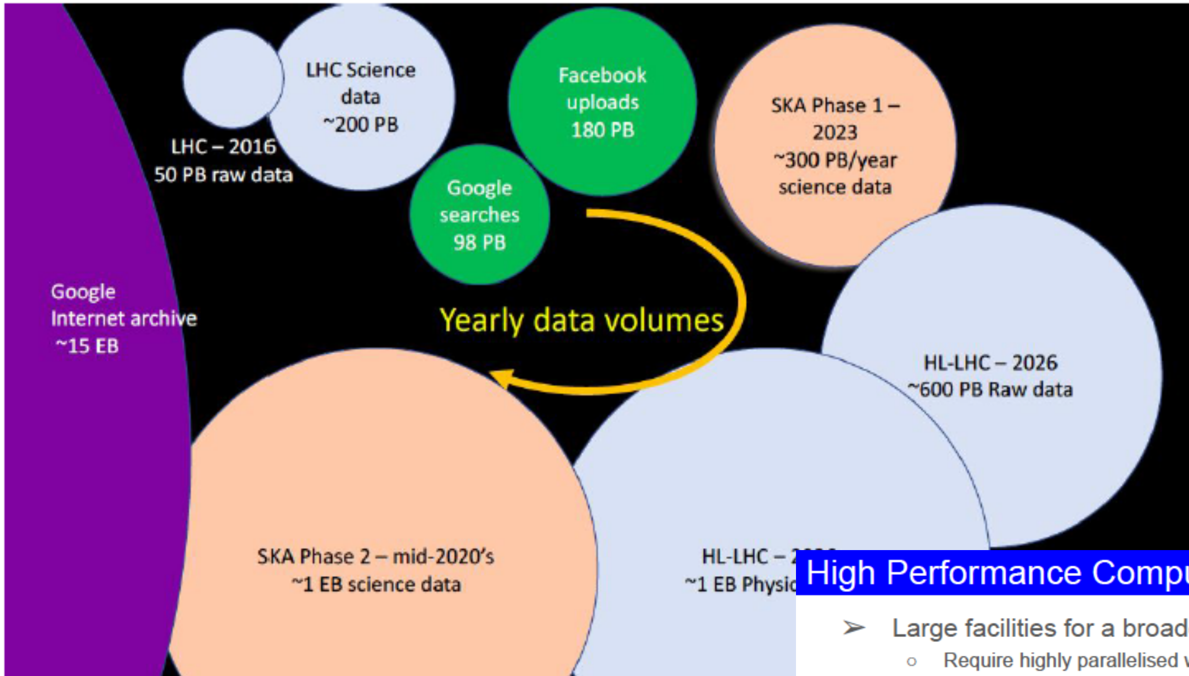
V. Boisvert

- 1. What are potential developments in this field?
  - see previous slides
  - reminder from A Tapper: Machine Learning in Trigger systems (NN in µs!)
  - reminder from M Wing: UK very active in DAQ for smaller experiments, developments and synergies happening there as well
- 2. What consensus / conflicts (on what should be done in longer term european particle physics) are there in this area?
  - Commercial vs custom components
  - Firmware done by engineers vs physicists/PhDs… (issues of design, maintenance, etc.)
  - 2 main future strategies:
    - Process data on-detector and move all of it without trigger to offline processing
    - Implement sophisticated multi-layer trigger algorithms using fast hardware components
- 3. What are experimental possibilities to do that? Are different scenarios already envisaged?
  - As shown in previous slides, some options currently being studied and looked into
  - Remember that detectors including TDAQ systems need a lot of R&D and long lead time

Technology: Computing

International data needs (2016+)

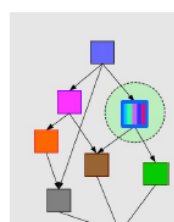


S&C week: The final talk

D. Costanzo

High Performance Computers - HPC

- Large facilities for a broader Science community
  - Require highly parallelised workflows
  - More recent ones use Intel Knightlanding CPUs
- Require dedicated attention to run HEP jobs
  - Software installation, I/O, memory usage, ...
  - ATLAS simulated ~9% of Geant4 events on HPC
- So far mostly US facilites
  - Some exist in Europe, collaborations with CSCS PizDaint
  - Bid under prep for time on Prace in EU (Knightlanding)



- Future challenge. Heterogeneous computing
  - Use GPU or FPGA part of HPCs
  - Ship threads to different facilites and reassemble events back together

alk

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Technology: Computing

Conclusions

- Computing and Software is an essential component of the future of HEP
  - Consolidation where possible for better economy of scale
- Computing infrastructure needs to evolve with technology
  - Investments in CPU, Storage (disk, tape, …), network, need to continue
  - Moore law helps, but it's not for granted!
  - Role of HPCs unclear, but likely to change our SW paradigm. We need our say in future facilities
- Development and improvement of Software is of critical importance
  - Training of new Software users. Large students' base in HEP experiments
  - Software professionals need to develop a career on par to detector builders
  - The days when we could patch a bit of code together and make a plot are long gone!
  - Personal opinion: US are ahead of Europe on this
- Data and analysis preservation, open access
  - Need to preserve our precious data for the future
  - And allow for public access. (most software stack is now public)

S&C week. The final talk

D. Costanzo

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Leptons

- **Neutrinoless beta decay**

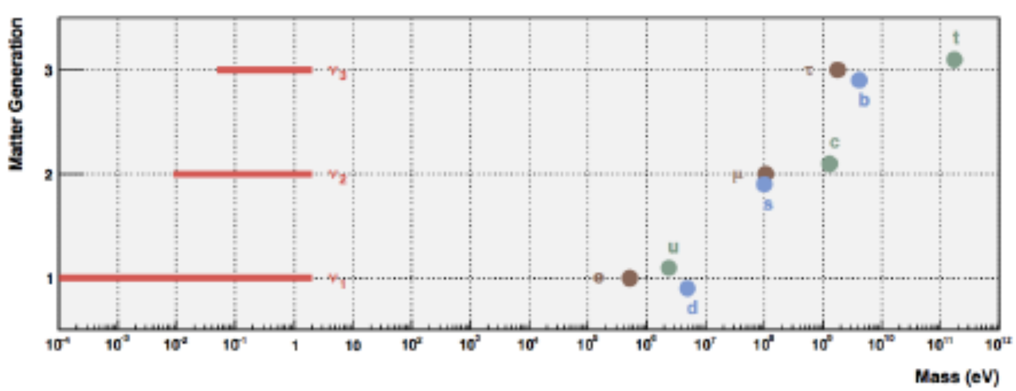
S. Peeters

0νββ is important on any current particle physics roadmap

Observation would imply:
- Violation of lepton number (by 2!)
- Neutrinos have Majorana masses (different than quarks and leptons, Schlechter and Valle, 1982)
- Neutrinos are their own anti-particles

It would inform us about:
- An explanation why neutrinos are so much lighter than other particles
- Leptogenesis, a possible origin of the baryon-antibaryon asymmetry *if neutrinos violate CP (DUNE/HK)*
- Neutrino absolute mass scale

(UK document on future strategy already exists)



SJM Peeters, UK Input to the European Particle Physics Strategy Update, Durham, 2018.04.14

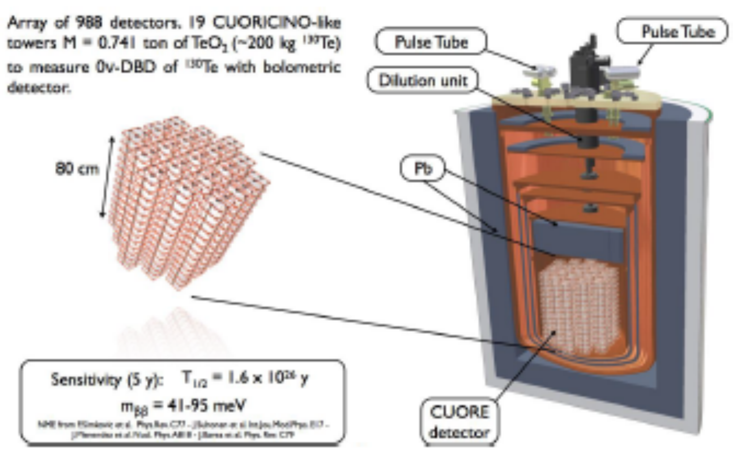
Leptons

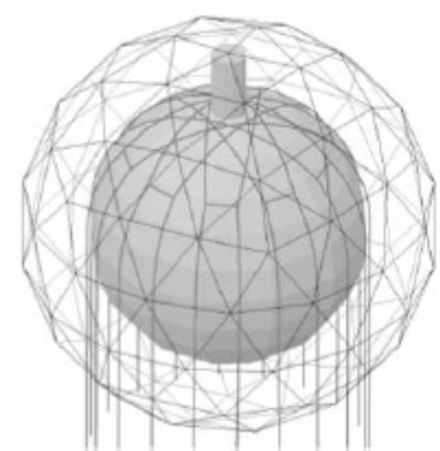
- **Neutrinoless beta decay**

S. Peeters

Approaches to the future

Modular (CUORE,LEGEND) **Monolithic (SNO+,LXe)**





NSAC review (US) Nov 2015:
"The modular and monolithic approaches both offer advantages and disadvantages. However, it is not possible to firmly conclude which approach will be optimal at this point"

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Tracking/PID will become important to suppress backgrounds and for interpretation, in case of an observation.

SJM Peeters, UK Input to the European Particle Physics Strategy Update, Durham, 2018.04.14

Neutrinos

A. Blake

Future Strategy

- Since 2015, the directive of the previous European Strategy Update has largely been implemented:
  - Formation of DUNE and Hyper-K collaborations with the aim of constructing new long-baseline experiments in USA and Japan.
  - Establishment of CERN Neutrino Platform to support these efforts.
- Much of the UK effort has also been focused along these lines.
  - Large UK collaborations within DUNE and Hyper-K projects.
  - Also, significant UK involvement in LAr-based SBN programme at Fermilab, and on Near Detector development for T2K-II / HK.
- If DUNE and Hyper-K remain on track, then the next few years will see their construction and the start of data-taking.
- One future strategy for European involvement in oscillation physics involves consolidating these existing efforts.

Andy Blake, Lancaster University

Slide 15

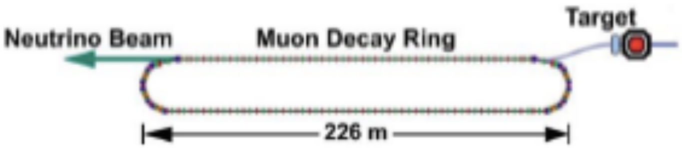
Neutrinos

A. Blake

Future Strategy

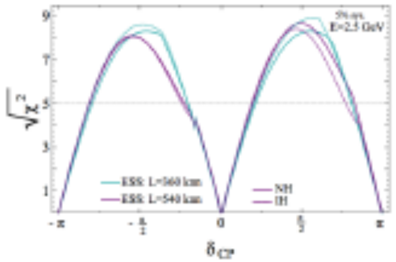
- But should Europe have its own accelerator neutrino programme? Here are two proposed projects that could be sited in Europe:

NuSTORM



- Long-standing UK involvement.
- One focus of the recent CERN-led Physics Beyond Colliders study.
- Would deliver an intense neutrino beam from a muon storage ring.
- Capable of precision measurements of neutrino interaction physics, plus searches for short-baseline neutrino oscillations.
- Could be cited at CERN or FNAL.

ESSνSB



- European Spallation Source has been under construction since 2014. (UK listed as a collaborating nation).
- Once complete, the facility could be extended to deliver a conventional neutrino beam (~300 MeV).
- Highly sensitive to CP violation as part of a long-baseline programme.

Andy Blake, Lancaster University — Slide 16

Muon Physics

New Physics in Loops

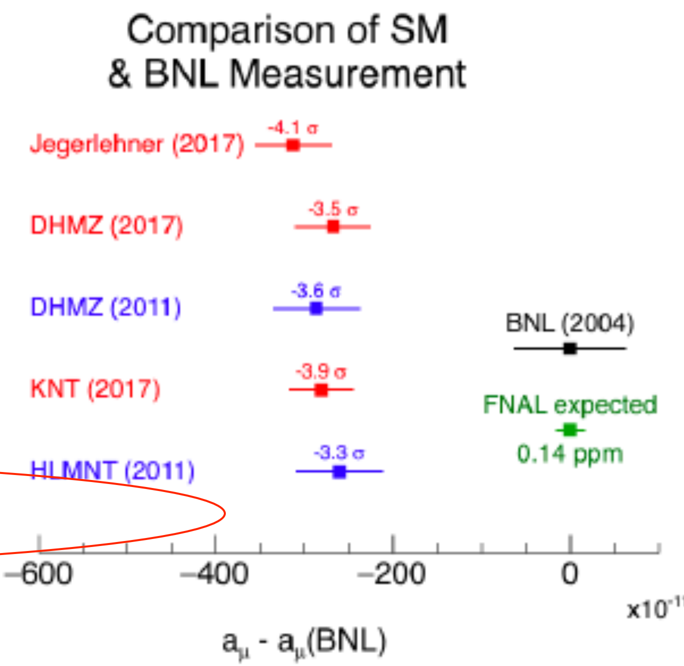
UCL

Anomalous contribution to magnetic moment:

$$a_\mu = \left(\frac{g-2}{2}\right)$$

Brookhaven measurement ~3.6σ from prediction

Muon g-2 experiment underway at Fermilab



G. Hesketh

Muon Physics

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G. Hesketh

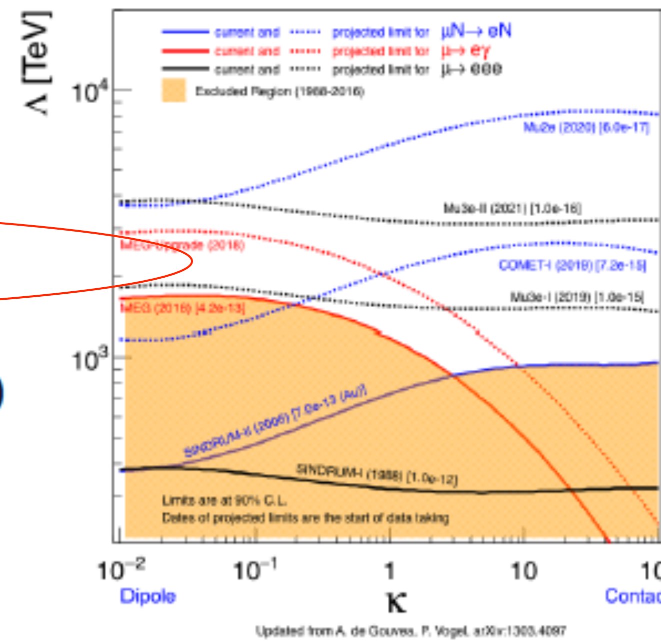
Talking Points

UCL

There is still a lot of phase space to explore: cLFV limits will reach 10^{-16}, SM ~ 10^{-50}!

Possible Mu2e upgrade (2020 HEPAP P5), give ~x10
- could make use of FNAL PIP-II beam
  - 100kW pulsed beam at 800 MeV

Discussions beginning between Mu3e/Mu2e/MEG/COMET
→ ***single experiment doing all 3 cLFV modes,***
→ push sensitivity by further x10.
- would happen after MEG-II and Mu3e Phase 2 (ie >2025?)
- possibly at FNAL, use PIP-II beams



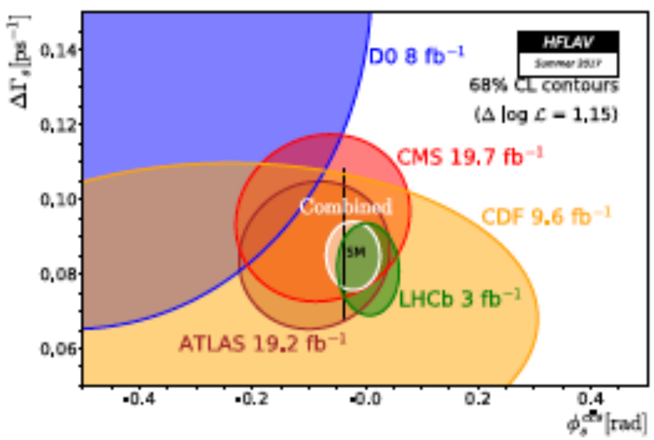
G. Hesketh

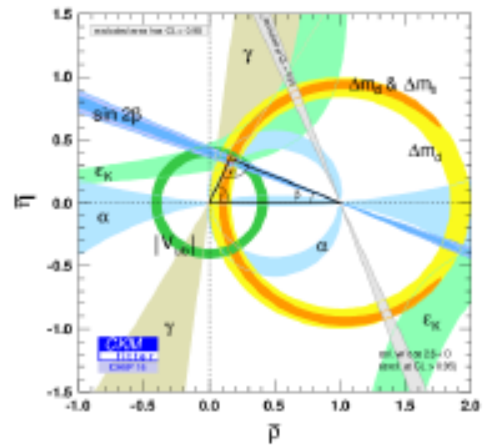
Quark Flavour

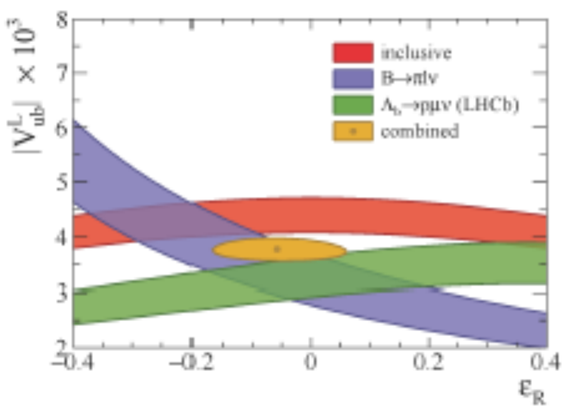
Slide 4

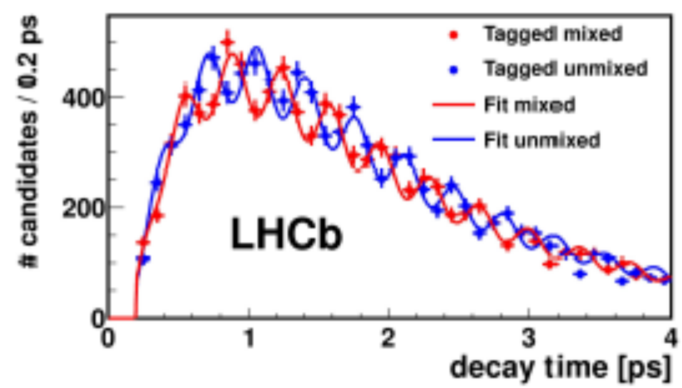
M. Vesterinen

Some of the LHCb highlights in these areas…









Amongst many notable results in rare B decays (Kostas' talk);
and charm, kaons, electroweak, QCD/spectroscopy, heavy ions, etc…

Quark Flavour

Slide 13

What will we know by 2030 then?

B2TiP report (in progress)

Observables	Expected th. accuracy	Expected exp. uncertainty	Facility (2025)
UT angles & sides			
ϕ_1 [°]	***	0.4	Belle II
ϕ_2 [°]	**	1.0	Belle II
ϕ_3 [°]	***	1.0	Belle II/LHCb
$S(B_s \to J/\psi\phi)$	***	0.01	LHCb
$\|V_{cb}\|$ incl.	***	1%	Belle II
$\|V_{cb}\|$ excl.	†††	1.5%	Belle II
$\|V_{ub}\|$ incl.	**	3%	Belle II
$\|V_{ub}\|$ excl.	**	2%	Belle II/LHCb
CPV			
$S(B \to \phi K^0)$	***	0.02	Belle II
$S(B \to \eta' K^0)$	***	0.01	Belle II
$\beta_s^{\rm eff}(B_s \to \phi\phi)$ [rad]	**	0.1	LHCb
$\beta_s^{\rm eff}(B_s \to K^{*0}\bar{K}^{*0})$ [rad]	**	0.1	LHCb
$\mathcal{A}(B \to K^0\pi^0)[10^{-2}]$	***	4	Belle II
$\mathcal{A}(B \to K^+\pi^-)$ $[10^{-2}]$	***	0.20	LHCb/Belle II
(Semi-)leptonic			
$\mathcal{B}(B \to \tau\nu)$ $[10^{-6}]$	**	3%	Belle II
$\mathcal{B}(B \to \mu\nu)$ $[10^{-6}]$	**	7%	Belle II
$R(B \to D\tau\nu)$	***	3%	Belle II
$R(B \to D^*\tau\nu)$	***	2%	Belle II/LHCb

1208.3355

Type	Observable	Current precision	LHCb 2018	Upgrade (50 fb^{-1})	Theory uncertainty
B_s^0 mixing	$2\beta_s\ (B_s^0 \to J/\psi\ \phi)$	0.10 [138]	0.025	0.008	~ 0.003
	$2\beta_s\ (B_s^0 \to J/\psi\ f_0(980))$	0.17 [214]	0.045	0.014	~ 0.01
	a_{sl}^s	6.4×10^{-3} [43]	0.6×10^{-3}	0.2×10^{-3}	0.03×10^{-3}
Gluonic penguins	$2\beta_s^{\rm eff}(B_s^0 \to \phi\phi)$	–	0.17	0.03	0.02
	$2\beta_s^{\rm eff}(B_s^0 \to K^{*0}\bar{K}^{*0})$	–	0.13	0.02	< 0.02
	$2\beta^{\rm eff}(B^0 \to \phi K_S^0)$	0.17 [43]	0.30	0.05	0.02
Right-handed currents	$2\beta_s^{\rm eff}(B_s^0 \to \phi\gamma)$	–	0.09	0.02	< 0.01
	$\tau^{\rm eff}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	–	5 %	1 %	0.2 %
Electroweak penguins	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,{\rm GeV}^2/c^4)$	0.08 [67]	0.025	0.008	0.02
	$s_0\,A_{\rm FB}(B^0 \to K^{*0}\mu^+\mu^-)$	25 % [67]	6 %	2 %	7 %
	$A_I(K\mu^+\mu^-; 1 < q^2 < 6\,{\rm GeV}^2/c^4)$	0.25 [76]	0.08	0.025	~ 0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	25 % [85]	8 %	2.5 %	~ 10 %
Higgs penguins	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	1.5×10^{-9} [13]	0.5×10^{-9}	0.15×10^{-9}	0.3×10^{-9}
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	–	~ 100 %	~ 35 %	~ 5 %
Unitarity triangle angles	$\gamma\ (B \to D^{(*)}K^{(*)})$	~ 10–$12°$ [244, 258]	4°	0.9°	negligible
	$\gamma\ (B_s^0 \to D_s K)$	–	11°	2.0°	negligible
	$\beta\ (B^0 \to J/\psi\ K_S^0)$	0.8° [43]	0.6°	0.2°	negligible
Charm CP violation	A_Γ	2.3×10^{-3} [43]	0.40×10^{-3}	0.07×10^{-3}	–
	ΔA_{CP}	2.1×10^{-3} [18]	0.65×10^{-3}	0.12×10^{-3}	–

In a nutshell:

- Belle-II / BaBar+Belle ~ 50
- LHCb Upgrade I / LHCb run 1 ~ 30-60

I.e. roughly an order of magnitude in precision.

M. Vesterinen

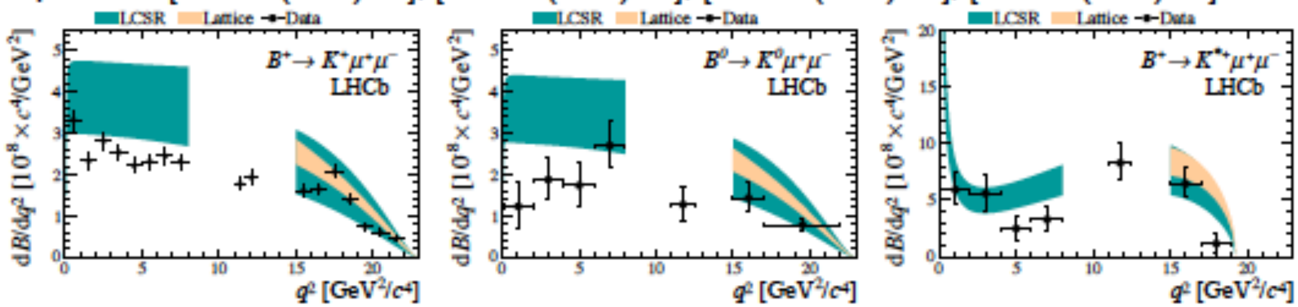
However, many key BSM-sensitive observables will still be far from the theory uncertainties.

Quark Flavour Anomalies

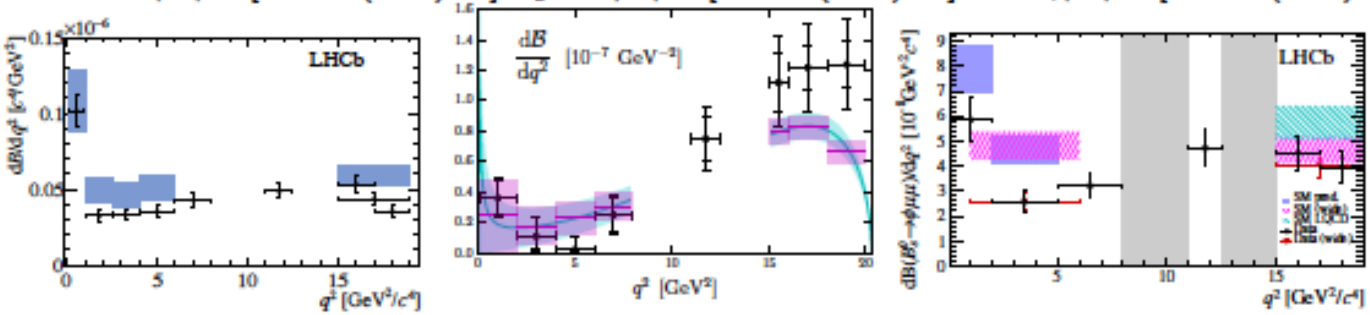
1. Differential branching fractions

- Measurements of $d\mathcal{B}/dq^2$ of $B \to K^{(*)}\mu^+\mu^-$, $\Lambda_b \to \Lambda\mu^+\mu^-$, $B_s \to \phi\mu^+\mu^-$

Experiment: [JHEP06(2014)133], [JHEP09(2015)179], [JHEP06(2015)115], [JHEP06(2015)115]



$B^0 \to K^{*0}\mu^+\mu^-$ [JHEP11(2016)047], $\Lambda_b \to \Lambda\mu^+\mu^-$ [JHEP06(2015)115] $B_s \to \phi\mu^+\mu^-$ [JHEP09(2015)179]



Theory: Bobeth et al [JHEP07(2011)067], Bharucha et al [JHEP08(2016)098], Detmold et al [PRD93,074501(2016)], Horgan et al [PRD89(2014)]

- Measurements below SM prediction ($2-3\sigma$ depending on final state)
- Measurements motivated higher precise in predictions

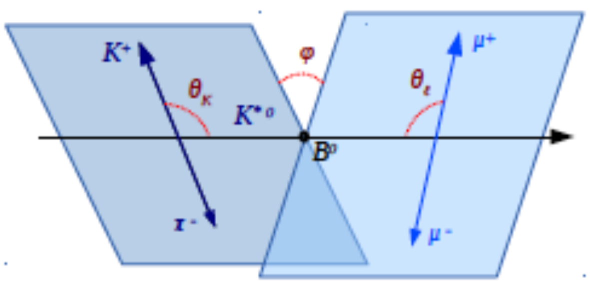
K. Pedtridis

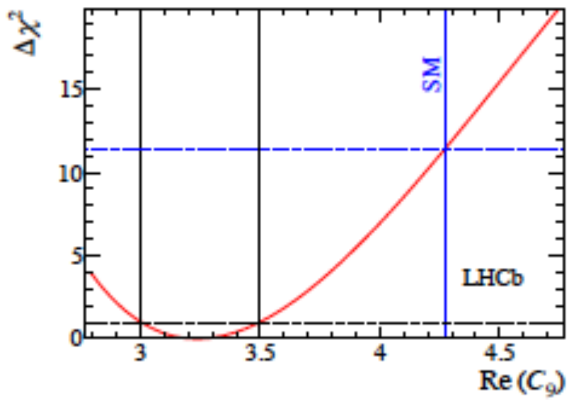
K.A. Petridis (UoB) | EU strategy April 2018 | EU strategy IPPP 7 / 21

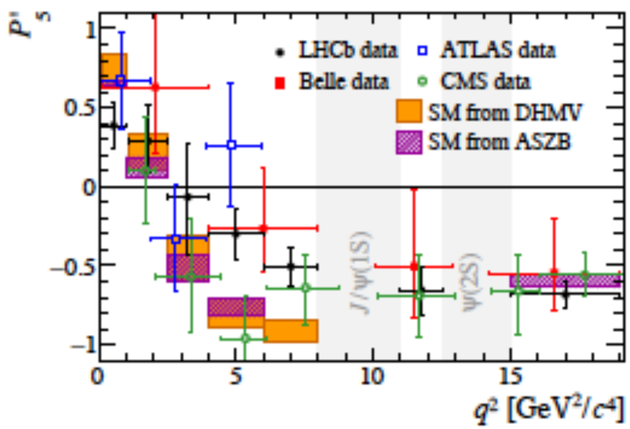
Quark Flavour Anomalies

2. $B^0 \to K^{*0}\mu^+\mu^-$ angular measurements

- Rich amplitude structure → 8 CP-even and 8 CP-odd observables







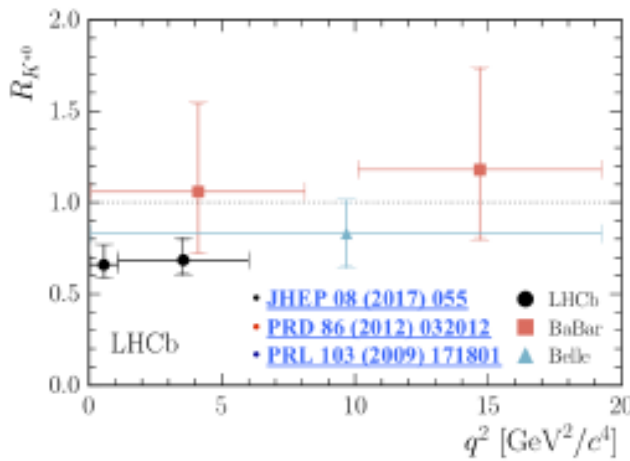
- Angular distribution at 3.4σ tension with SM
  → Anomalous vector-dilepton coupling

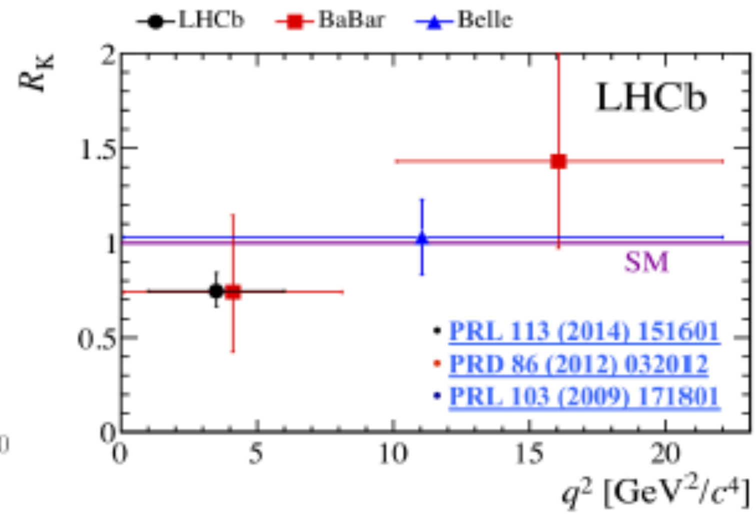
K. Pedtridis

Quark Flavour Anomalies

3. Lepton Flavour Universality tests

Measurement of: $R_{K^{(*)}} = \dfrac{d\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)/dq^2}{d\mathcal{B}(B \to K^{(*)}e^+e^-)/dq^2}$

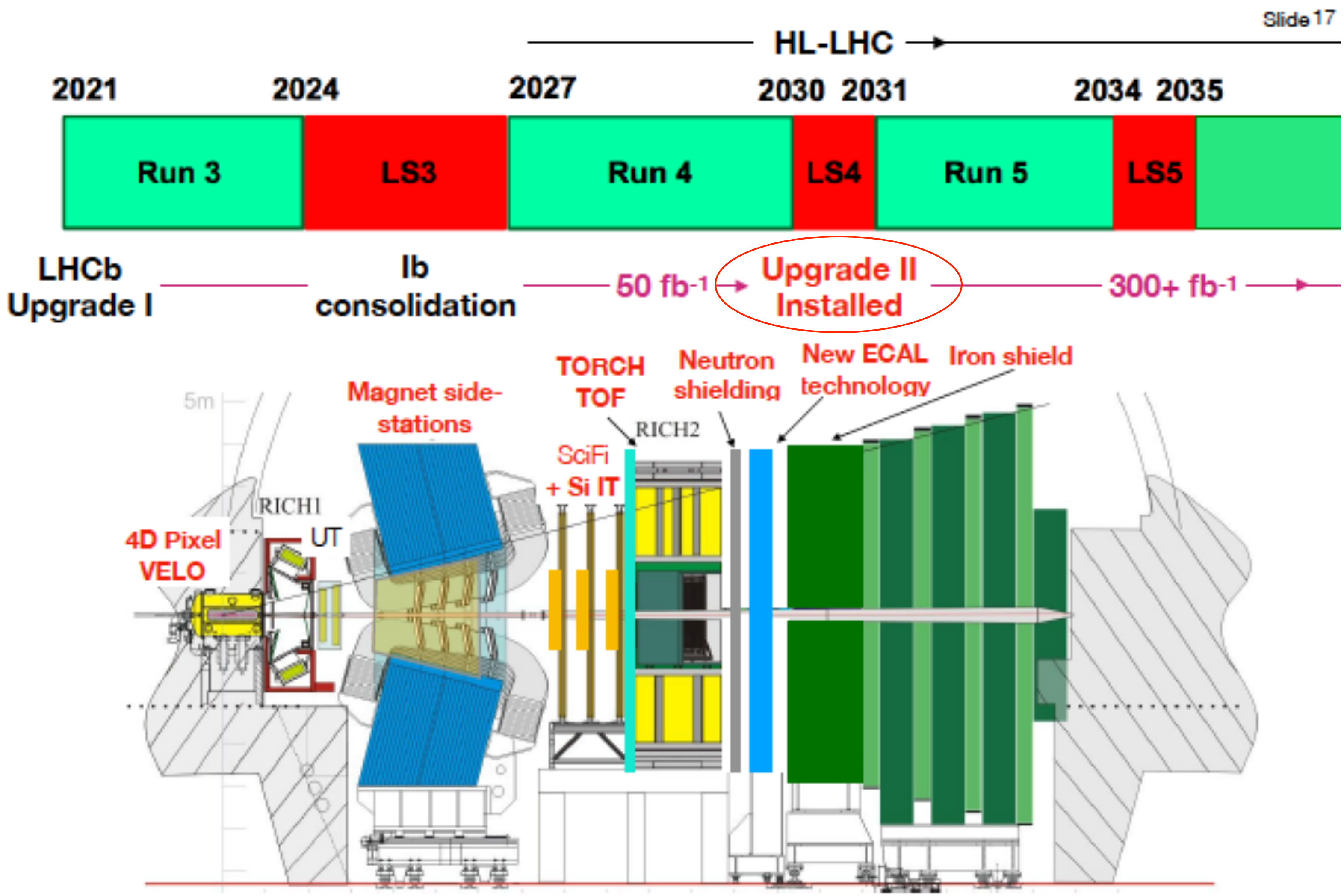




R_K: Central-q^2: 2.6σ from SM
R_{K^*}: Low-q^2: 2.1-2.3σ from SM
R_{K^*}: Central-q^2: 2.4-2.5σ from SM

K. Pedtridis

Quark Flavour

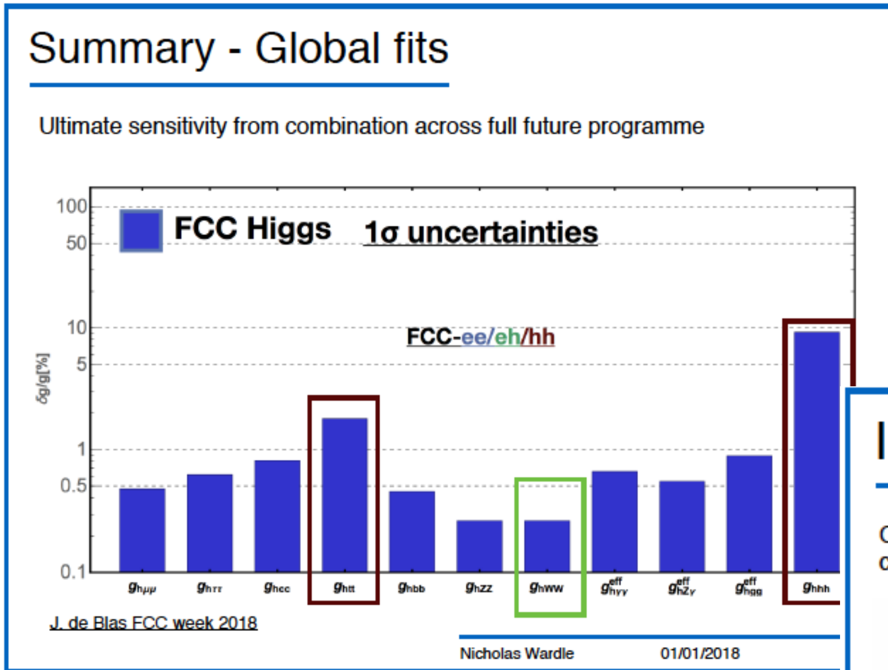


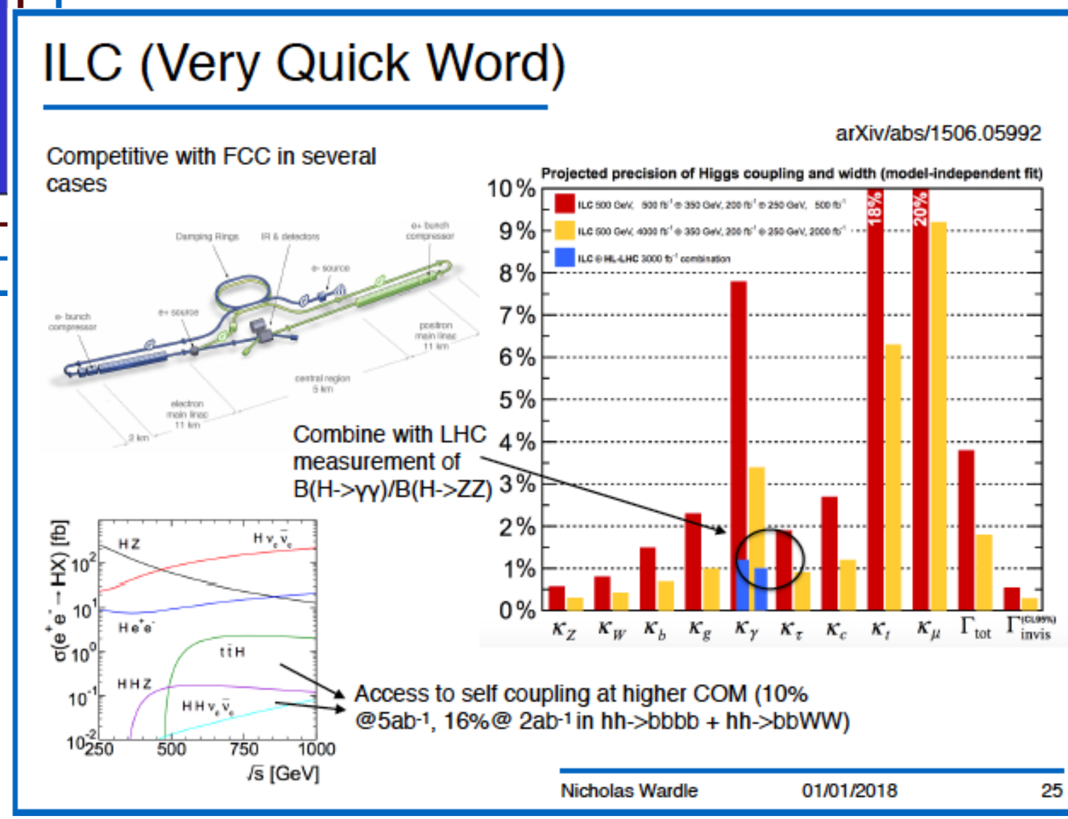
Challenging environment, but common themes of fast-timing, granularity++, rad-hardness.
Clear synergies with ATLAS and CMS, and unique challenges.

K. Pedtridis

Higgs

N. Wardle,
V. Martin

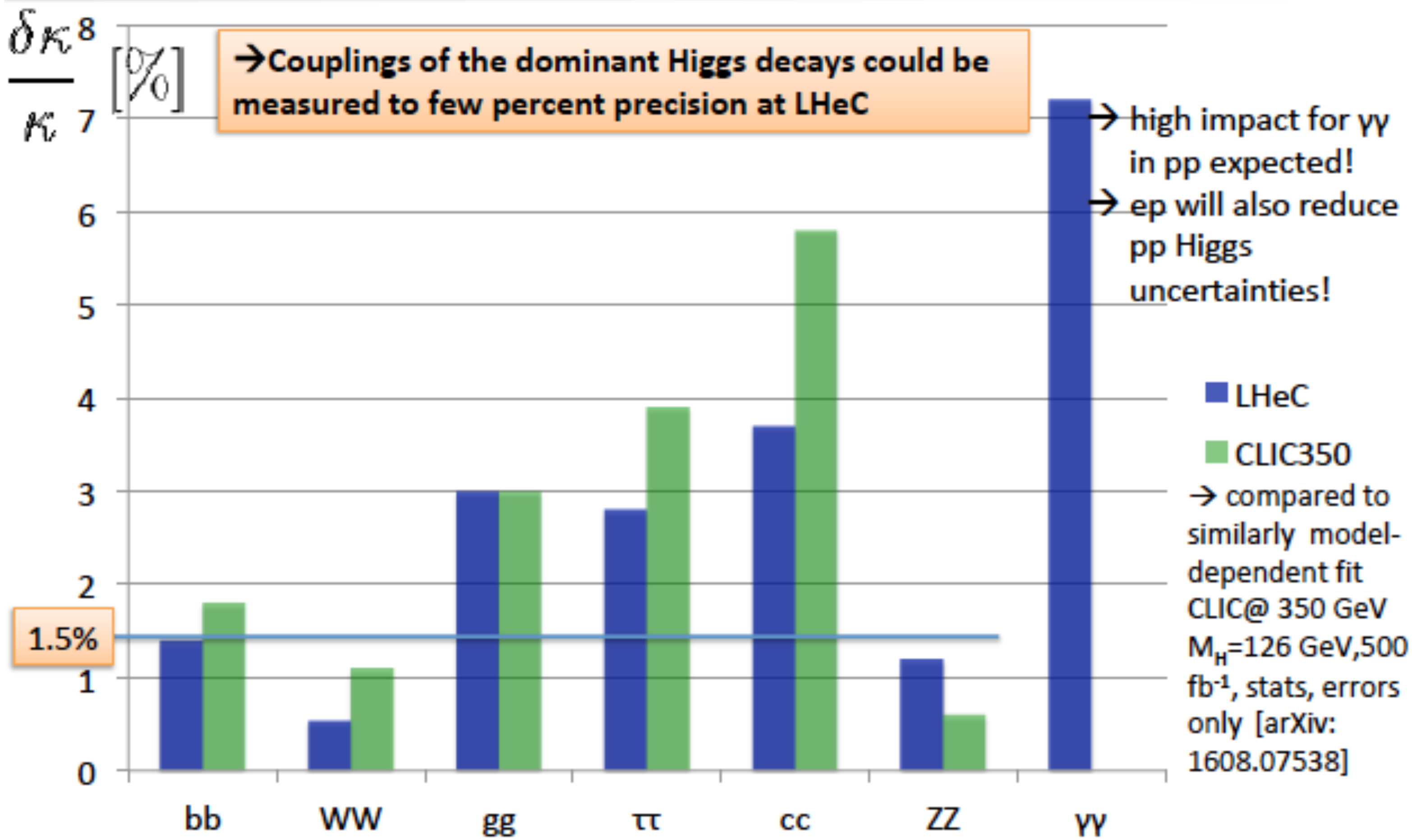




LHeC

Uta & Max Klein, Contribution to HL/HE Workshop, 4.4.2018, preliminary

Model-dependent Coupling Fit



Uta Klein, Higgs@LHeC

→ Very nice prospects of combining further Higgs from pp@HL-LHC and ep@HL-LHC

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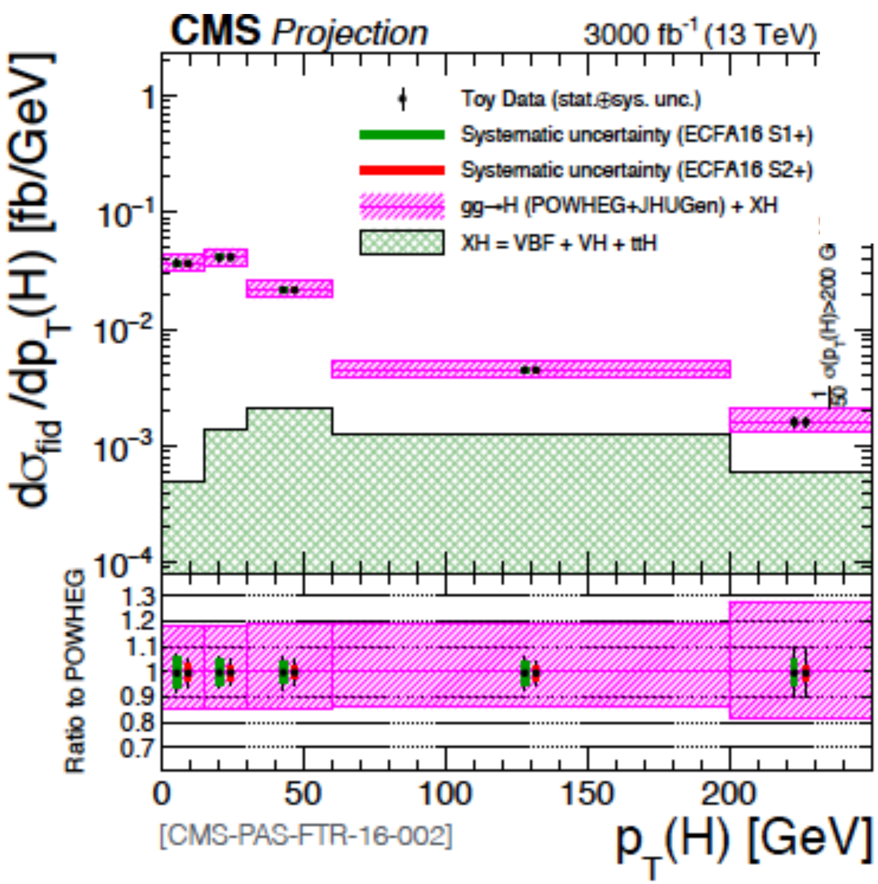
Higgs

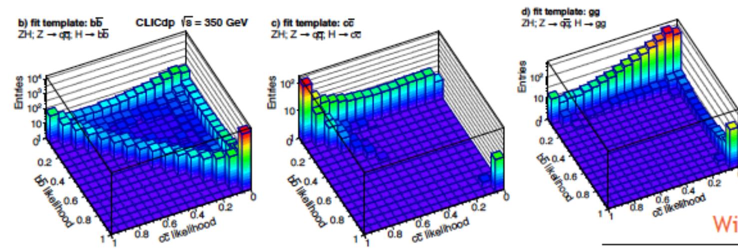


[CMS-PAS-FTR-16-002]

Higgs Hadronic BRs at CLIC

arXiv:1608.07538

- Aim: resolve $H\to2$ jets signal into $H\to b\bar{b}$, $H\to c\bar{c}$ and $H\to gg$
- Fit to multivariate-derived templates using flavour tagging info *e.g.* at 350 GeV, $HZ\to4$ jets



Also with:
- ➡ $HZ\to2$ jets + 2 ℓ,
- ➡ $\nu\nu H\to$ E̸ + 2 jets

With 500/fb at 350 GeV

Decay	Statistical uncertainty Higgsstrahlung	WW-fusion
$H\to b\bar{b}$	0.86 %	1.9 %
$H\to c\bar{c}$	14 %	26 %
$H\to gg$	6.1 %	10 %

N. Wardle
V. Martin

Exotics

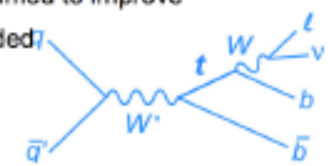
Reach with HL-LHC: W'→tb

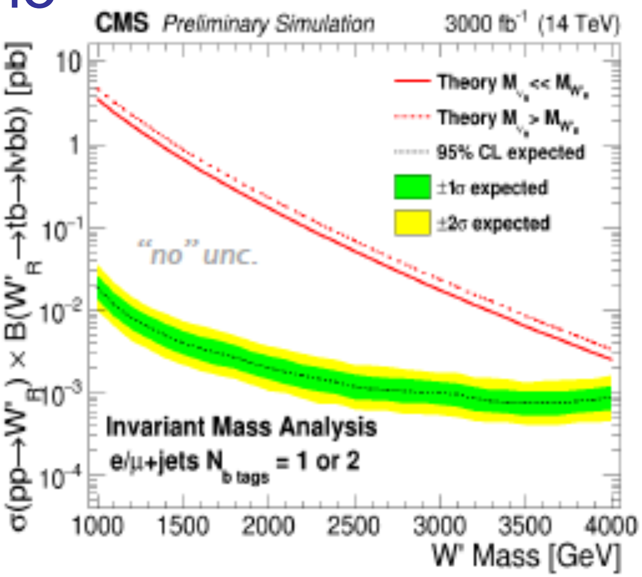
- Projections performed - assuming NWA using 2015 and 2016 analyses

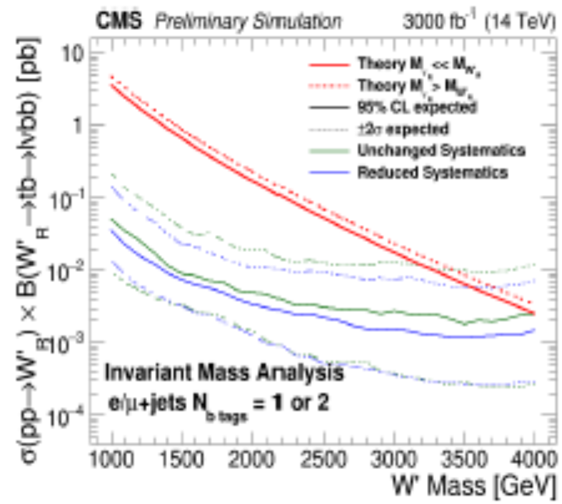
M. D'Onofrio

Three possibilities for the evolution of systematic uncertainties with integrated luminosity are considered

- (Flat) All systematic uncertainties are assumed to remain unchanged
- (Scaled) All systematic uncertainties are assumed to improve
- (None) No systematic uncertainties are included







Again, dependence on assumptions on uncertainties

CMS DP016_064

Reach: beyond 4 TeV

For W' in eν and μν → reach up to 7 TeV

15 Monica D'Onofrio, HL/HE-LHC Workshop 30/10/2017

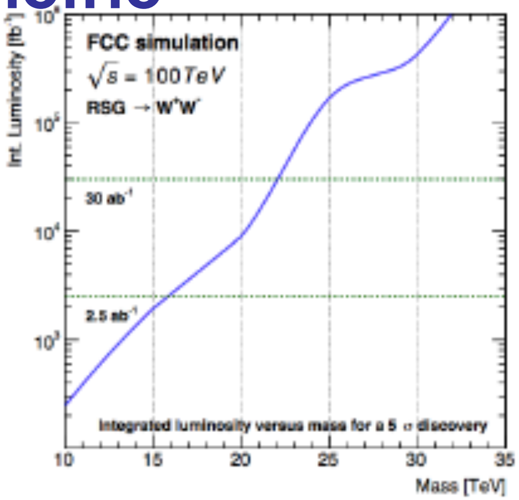
Exotics

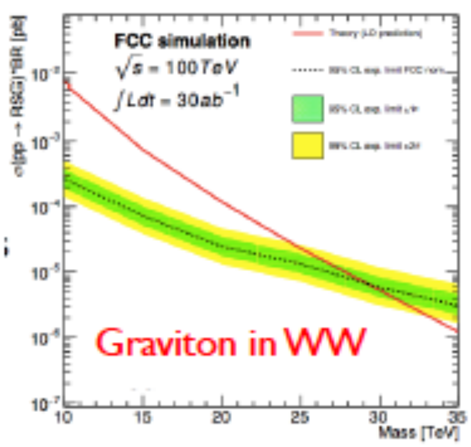
The (far) future

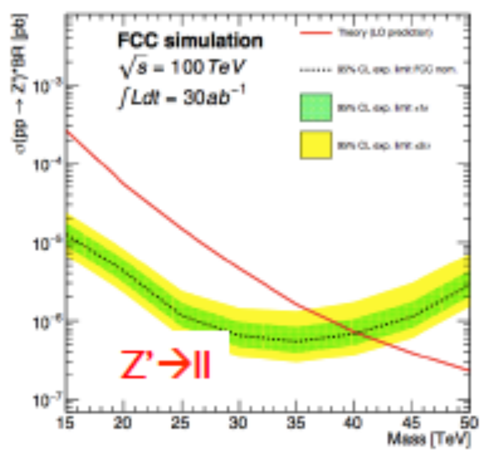
On the optimistic side: if deviations are observed in Run 3, HL-LHC will allow to study new physics properties with high statistics in characteristic distributions, e.g. A_{FB}. On LQ, depending on mixture and mass, studies could be also possible at e-p (limited by com energy)

- Clearly, the higher c.o.m. energy, the better
  - If nothing is found by HL-LHC, only option for direct observation
  - @100 TeV collider would increase the reach of **a factor 10** with full dataset (30/ab) [question: to discover an m=6-10 TeV new particle produced via gluon-fusion, do we wait for FCC-hh or is HE-LHC enough? What do we need?]

M. D'Onofrio







16 Monica D'Onofrio, UK Inputs, IPPP 17/04/2018

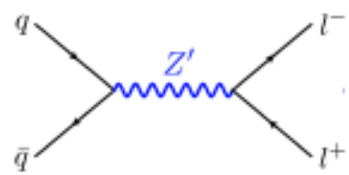
Exotics

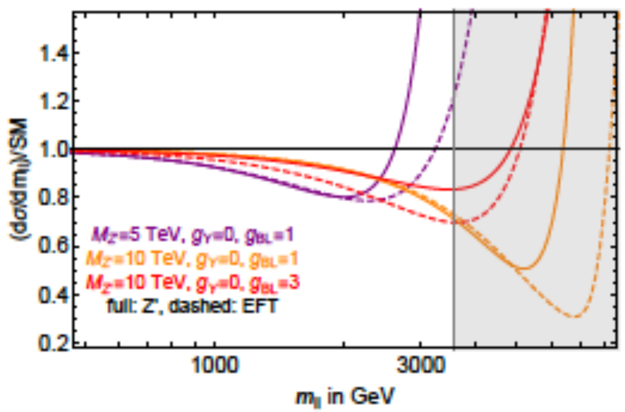
M. D'Onofrio

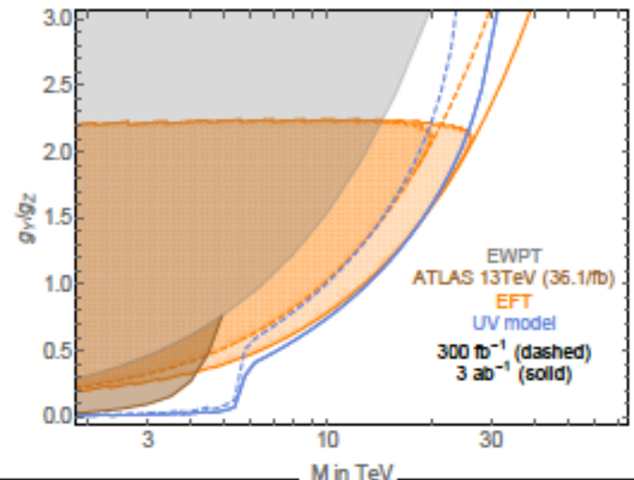
Indirect constraints on Z'

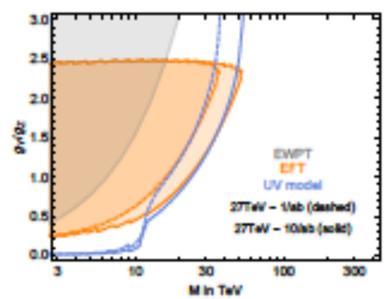
- If mZ'>>5 TeV, main contributions from interference effects modifying DY
- The precision of e^+e^- colliders help but LHC (and HL-LHC) can do a lot

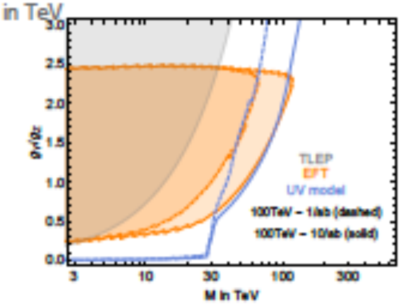
Alioli, Farina, Pappadopulo, JTR, Phys. Rev. Lett. **120**, no. 10, 101801 (2018)











17 Monica D'Onofrio, UK Inputs, IPPP 17/04/2018

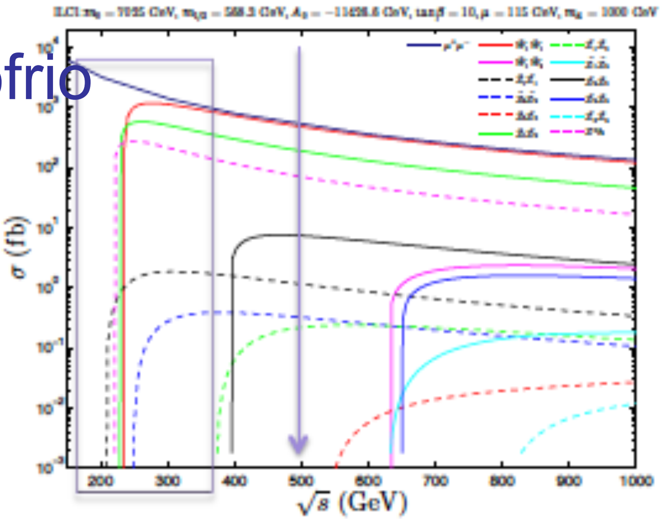
Exotics

M. D'Onofrio

potential @ electron-positron machines

- Sensitive to EWK processes and useful to target compressed scenarios
- Caveat: depends on the center of of mass energy

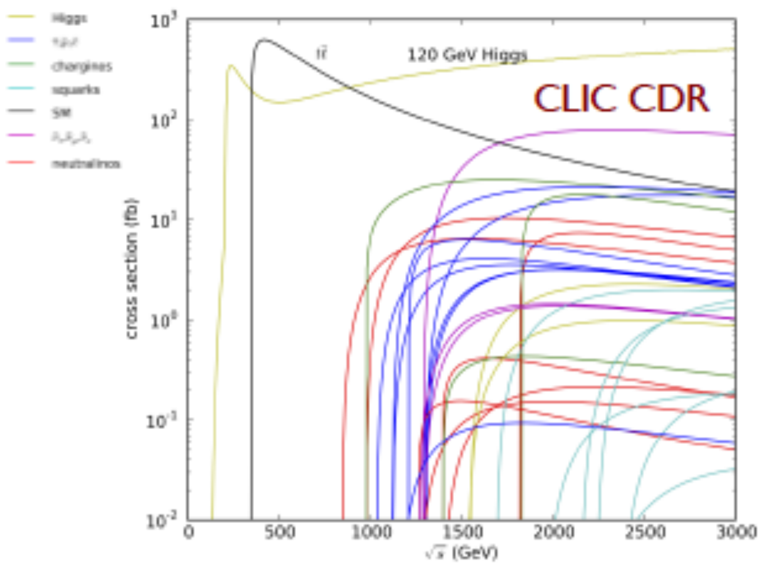
Sparticle σ for unpolarized beams at e+e- for ILC benchmark but also for FCC-ee



arXiV:1404.7510

High cross section for $\chi^{\pm}_1$ and χ_0 production and sleptons: clean environment to access very compressed scenarios

Sparticle σ at e+e- for one CLIC benchmark point



Cross-section for higgsinos too low also for CLIC?

arXiV:1801.05192

Sensitivity for sleptons and charg/neut up to ~√s/2

24 Monica D'Onofrio, UK Inputs, IPPP 17/04/2018

Exotics

Some points for discussion

- At the moment, it is not possible to define a preferred direction
  - Direct searches limited by kinematic reach, indirect searches limited (e.g.) by precisions → not a unique recipe
- Directions: HARD until we see some deviations from SM predictions!
  - Not necessarily at LHC, could be on any other related field (cosmo, neutrino…)
    - Correlations LHC/non-LHC signals could be pursued, hints of DM candidates and more could indicate the scale
- A proton-proton machine provides a wide range for exploration of NP
  - **My take:** the potential of HE-LHC is huge for new particles up to ~10+ TeV with large datasets. FCC-hh is great, but far away in time (after FCC-ee)
    - We should ask ourselves how long should we wait to reach (ie) 40 TeV in Z'?
    - Help in improving SM predictions could come from additional e-p option (also for HL-LHC)
    - Unfortunately, won't be able to constrain higgsinos up to 1 TeV without FCC-hh (?)
  - HE-LHC pp (+ep) running at the same time of a e+e- machine in 25-30 yrs from now?
    - Lot of advantages also for retaining expertise, develop detector technology, FCC-hh later ?

M. D'Onofrio

PAST

Tevatron/HERA/LEP → LHC → HL-LHC *(ep?)* → HE-LHC/(ep)/ee(CepC?,ILC)

(fermiscale) (Terascale) (multi-Terascale)

PRESENT

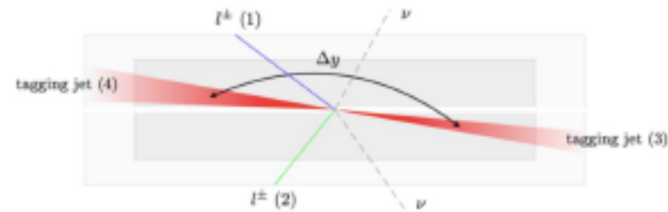
FUTURE ?

38 Monica D'Onofrio, UK Inputs, IPPP 17/04/2018

Standard Model/Top

A. Buckley

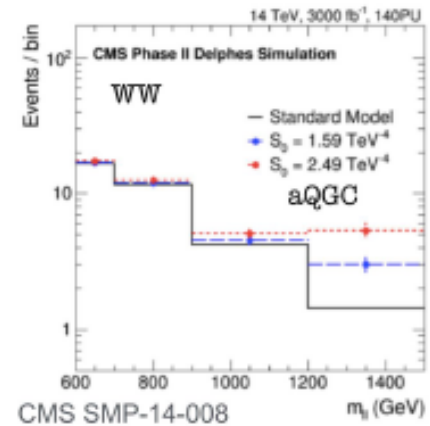
Vector boson fusion/scattering (VBF/VBS)



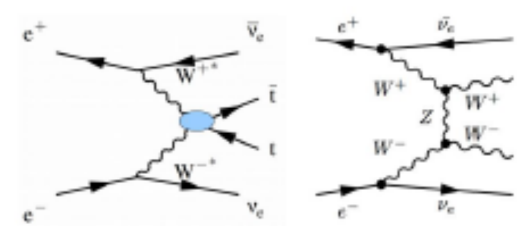
Single and pair particle production via EW t-channel
⇒ distinct event topology with hadronic rapidity gap

Linked to SM unitarisation: cancellations of EW couplings & Higgs exchange make it sensitive to BSM. Important dimension-8 SM EFT operators

ATLAS: forward jets at 50 GeV difficult with μ ~ 200: forward tracking/timing would help. Fine dσ measurements at high m_{jj} ⇒ strong constraints on aT/QGCs [Manchester]



CMS estimate 3 /ab VBS discovery significance at 2.75 σ
Main HL-LHC gains from (again) forward lepton reco



CLIC can study VBF tt production, and e+e- WW VBS: in fully hadronic qqqqνν mode unlike LHC: extra aGCs

8

Dark Matter

D. Cerdeno

The European Strategy for Particle Physics
Update 2013

j) A range of important non-accelerator experiments take place at the overlap of particle and astroparticle physics, such as searches for proton decay, neutrinoless double beta decay and dark matter, and the study of high-energy cosmic-rays. These experiments address fundamental questions beyond the Standard Model of particle physics. The exchange of information between CERN and ApPEC has progressed since 2006. *In the coming years, CERN should seek a closer collaboration with ApPEC on detector R&D with a view to maintaining the community's capability for unique projects in this field.*

Dark Matter only mentioned once (once more in the abstract)

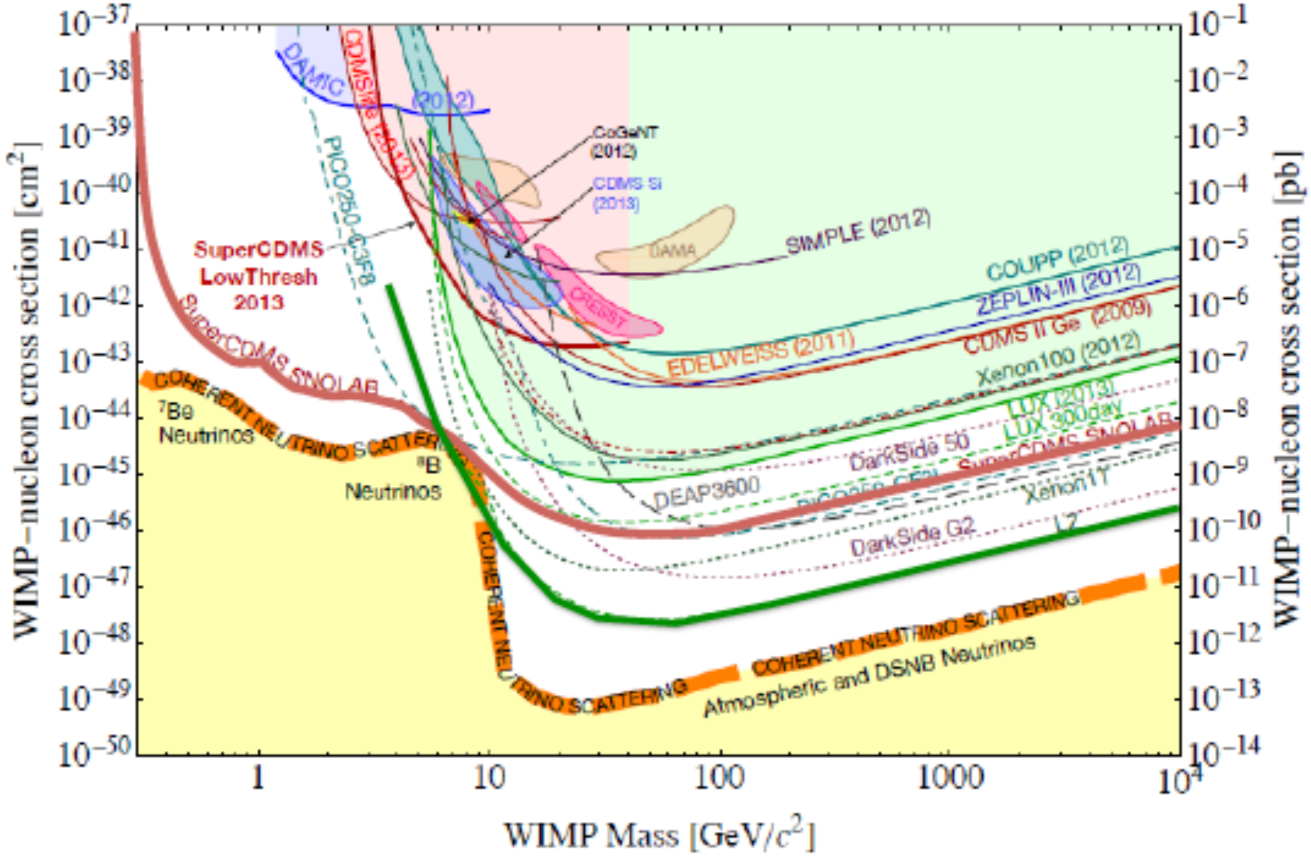
Can we get a more concrete statement?

3

Dark Matter

D. Cerdeno

Future prospects



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Dark Matter

Points for debate

D. Cerdeno

- Direct Detection experiments are becoming **extremely sensitive** and **increasingly versatile**, probing DM models beyond the vanilla WIMP

- Probing the WIMP paradigm for masses from ~TeV to keV scale (and below), but **also looking for:**

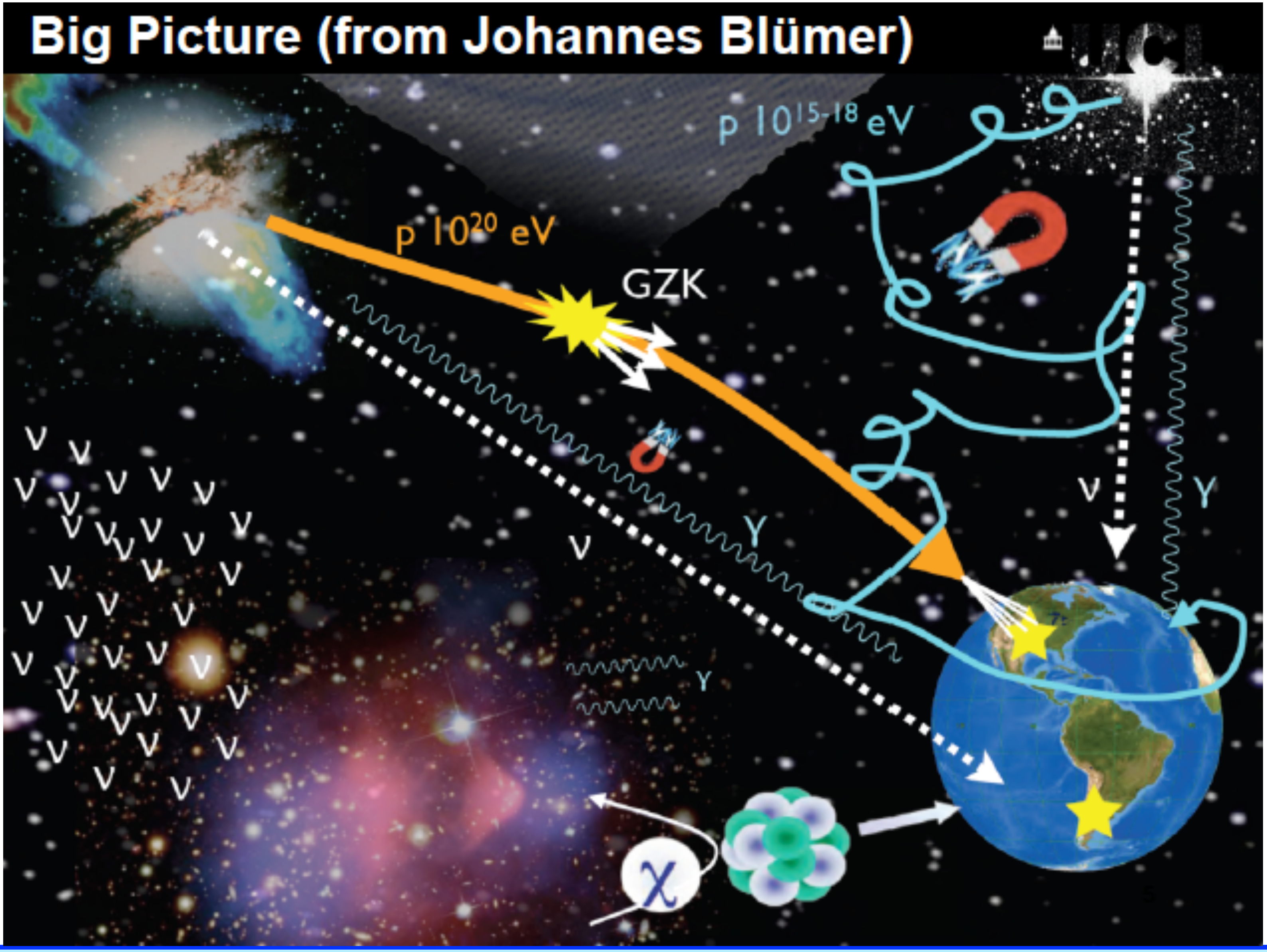
  - SIDM, Inelastic DM, dark photons
  - Axions
  - New physics in the neutrino sector

- **Bigger + Better** experiments are needed

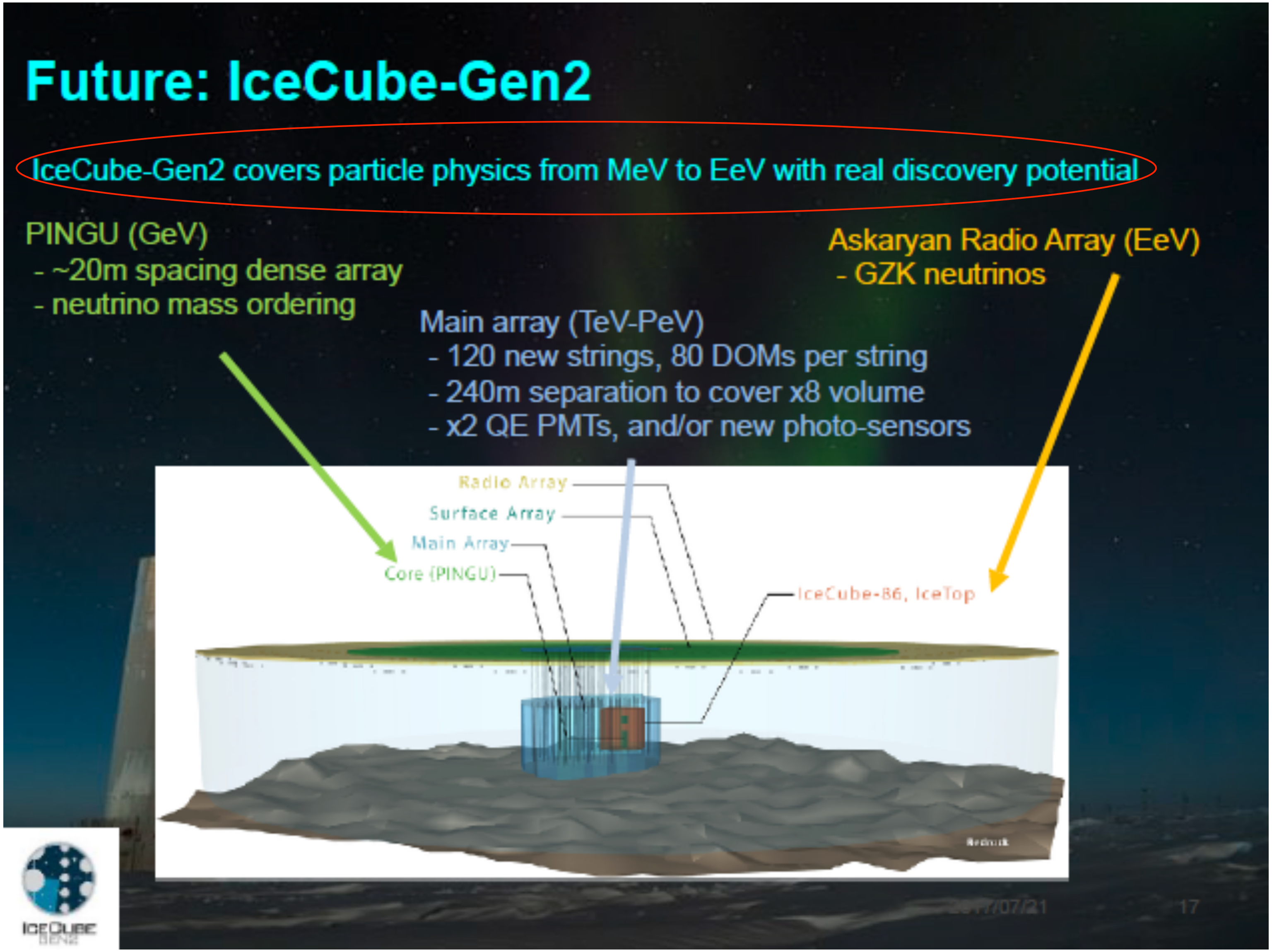
- **Variety of targets and techniques** not only probe different DM candidates, but also crucial for DM parameter reconstruction

- **Annual Modulation and Directionality?**

Astroparticle/Gravitational Waves

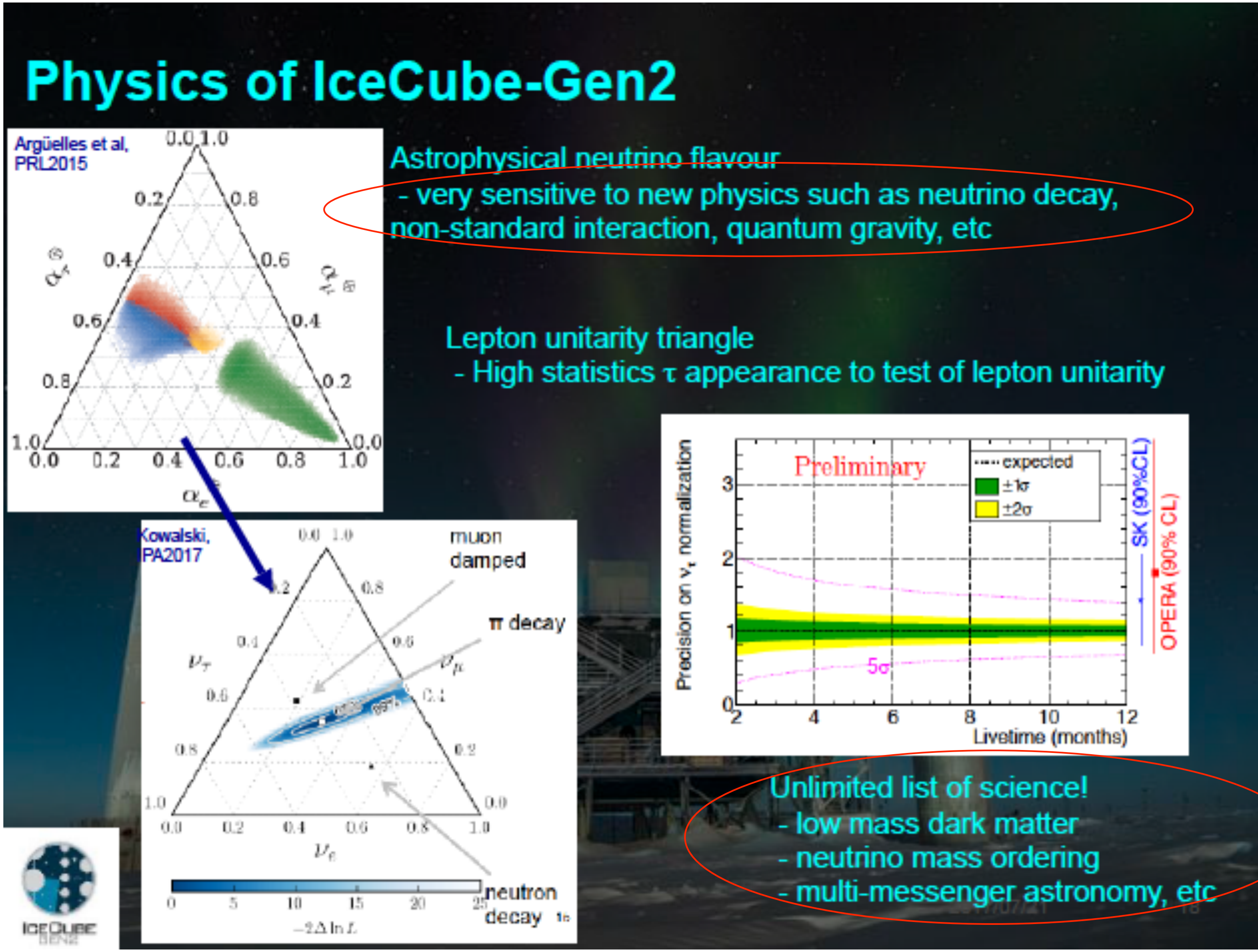


Astroparticle/Gravitational waves



R. McNicol

Astroparticle/Gravitational Waves



Astroparticle/Gravitational Waves

Questions?

UCL

- What consensus / conflicts (on what should be done in longer term European HEP) are there in this area?
- What are the experimental possibilities? Are different scenarios already envisaged?
  - IceCube is a tremendous success, the science case for IceCube-Gen2 (both the high and low energy extensions) are clear
  - Some version of KM3NeT will exist
  - Small experiments (i.e. ANITA) have discovery potential
  - Hard to disentangle politics
- What are the choices for the strategy? What can the UK agree to input?
  - Astroparticle physics should be mentioned
- What are the potential developments in this field? How do they relate to fundamental physics questions?

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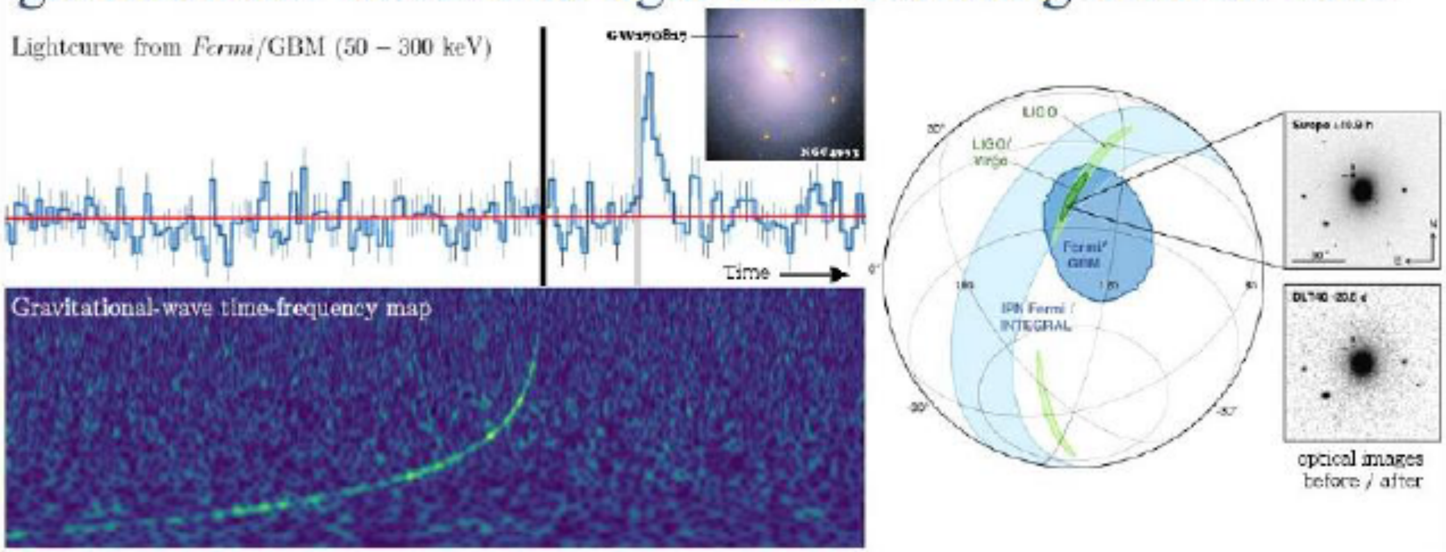
R. McNicol

Gravitational Waves

T. Sumner

LIGO, Virgo, and partners make first detection of gravitational waves and light from colliding neutron stars



- Multi-messenger astronomy!
- Observed GW from matter
- Evidence for link between BNS and some sGRB
- Tight constraint of speed of GW
- Setting constraint on EOS of neutron stars
- Good sky localisation allowed finding optical counter part and identification of host galaxy.
- Many telescopes around the globe and in space joined observation campaign.
- Enabled observation of kilonova.

8

European Particle Physics Strategy Input, Durham 18/04/2018 10

Gravitational Waves

Future Plans – Other Opportunities

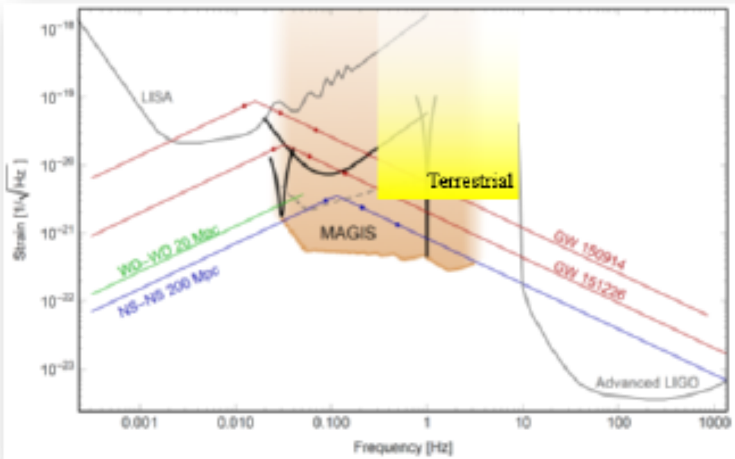
http://www.fnal.gov/pub/science/particle-physics/quantum/#magis

T. Sumner

Mid-band Gravitational Wave Detection with Quantum Sensors: MAGIS-100

- 100m quantum sensor at Fermilab using atom-interferometry
- Based in the vertical NUMI access shaft
- Test-bed for **1km** device (in yellow), at Homestake
- Also sensitive to tests of **axion dark matter**
- and Macroscopic tests of Quantum Mechanics

Atom Interferometry



- Stanford U.
- FNAL
- U.C. Berkeley
- NIU
- U. Liverpool

European Particle Physics Strategy Input, Durham 18/04/2018 28

Open Questions

1. The physics cases for FCC and CLIC are clearly both strong. Can CERN reaffirm the strategy of funding R&D programs towards both CLIC and FCC throughout the 2020s? Is the progress achieved by R&D for each accelerator held back by the investment that could be released by reducing the other? It was recognised that this is obviously a difficult question, and one in which the UK has strong interests

1a) What is the possible scale of new physics - to what extent could insights be delivered by flavour physics anomalies on the timescale of the ES update? While some hints will be available it is not clear if an energy scale could be identified, such that it could inform a choice of future collider.

1b) Is there a consensus among theorists on a CoM energy at which null observations would definitively tell us something about the way in which the SM is broken ("no-lose theorems")?

Open Questions

2) Which program(s) can best engage a generation of physicists over the next decades such that expertise is retained in operating experiments/accelerators and analysing data, rather than witnessing a brain drain while waiting for a large next project?

3) In relation to (2) the importance of usually smaller, non-collider experiments was agreed both for their own science objectives and as training grounds for the field in general.

4) It was a clear outcome from the talks that the extensions to current sensitivities provided by HL-LHC provide important constraints to many SM parameters and search capability for BSM physics. The commissioning and exploitation of the HL-LHC should therefore be one of the highest priorities for European Particle Physics in the 2020s.

Omissions

Some topics were raised in addition to the program of the meeting, and these could be addressed at the UK community meetings:

- Should a deep-underground-facility be part of a future ES?
- Axion experiments, in the context of dark matter, were not discussed but this was noted as an omission. There is no UK involvement in these experiments but the UK could take a view on this for ES submission.
- Availability of satellite data for astroparticle physics - it has been so far fortuitous that this is public, can we rely on this in future?
- Contact should be increased between collider experiment efforts to search for dark matter and direct detection experiments
- The SHIP experiment was not discussed and should be addressed in future discussions.

Practical Suggestions

— Technical:

1) The positive benefits of RD collaborations were discussed and it was suggested that these could be extended to cover more areas and to have a more open structure, for example envisaging RD's on Trigger and DAQ; silicon work across Europe on producing wafers/ dicing.

2) It was noted that the role of physicist programmer underpins experimental particle physics and should be supported appropriately with a better defined career path across European institutes and labs.

Practical Suggestions

Theory:

1) A concerted approach to theory combinations may be of use e.g. to combine EDM's;

2) global fits with neutrinos were suggested;

3) greater engagement of nuclear theorists with neutrino research would be of benefit. This could be developed by the CERN theory division as part of the CERN Neutrino Platform, the existence of which was strongly appreciated by the workshop attendees.

Summary

- Workshop a success in engaging broad range of interested physicists, discussing the science
- Write-up intended to be of use as a briefing document giving snapshots of the science and project status (and noting omissions in the program – important for UK document to be comprehensive)
- Useful practical suggestions were made

- PPAP meeting and town meeting are the places to try to work out a UK consensus view