Phenomenology

R. Keith Ellis
IPPP, Durham

PPAP Community meeting, 26-27 July 2016
University of Birmingham

Phenomenology

- Phenomenology is the part of Theoretical Physics concerned with the applications of theory to particle physics experiments.
- Two way street:-
  - Phenomenology informs and improves Experiment
  - Experiment informs and improves Phenomenology
- Part of the UK theory effort with an extraordinary tradition and record of scientific excellence.
- Strong UK activity in all areas QCD (non-perturbative and perturbative), Electroweak & Higgs physics, BSM, Neutrino and Astro-particle physics, hadronic flavour, Monte Carlo event generation, PDFs and computational tools.
- IPPP+ Cambridge, Edinburgh, Glasgow, KCL, Liverpool, Manchester, Oxford, RHUL, Southampton, Sussex, UCL,….

Review of Phenomenology

- Review of phenomenology in 2015 commissioned by the STFC. The report is available.

Science & Technology Facilities Council

Review of Phenomenology Report 2015 (Short Version)

Table of Contents

- Composition of panel
- Chris Sachrajda, chair (Southampton)
- Gavin Davies (Imperial)
- Herbi Dreiner (Bonn)
- Emilian Dudas (Ecole Polytechnique)
- Simon Hands (Swansea)
- Frank Krauss (Durham)
- Victoria Martin (Edinburgh)
- Michael Seymour (Manchester)

1. Executive Summary

1.1.1. The panel was asked to undertake a strategic review of UK phenomenology and to advise the STFC executive on future STFC support for UK phenomenology.

1.1.2. The panel found that there were a number of areas of phenomenology in which the UK is activity is world-leading, a number of other areas in which the UK has major strengths and some areas in which there are excellent individuals but a low critical mass.

- The current programme is broadly in line with the panel's view that the UK phenomenology community should not attempt to be leading or active in all areas of phenomenology, but should maintain a balance between world leadership and breadth of the programme.

Controversial

- The available limited resources are necessarily being devoted to supporting the current experimental programme, particularly at the LHC. As a consequence there is very little involvement in international exploratory studies in preparation for possible future facilities. This is of particular concern to the panel.

Lack of involvement in forward planning is a concern

1.1.3. The panel noted the impressive success of the IPPP, both in its support of the UK community and in its own research programme. The IPPP has strong interactions with the UK phenomenology and experimental communities and many groups utilise and benefit from the opportunities for interaction that the IPPP can provide in its role as a national centre.

Success of the IPPP

1.1.4. The panel strongly supports maintaining a national centre for phenomenology after the current grant to IPPP ends in 2018.

- Resources for core and support activities should be provided by a direct grant from the STFC.
- Current resources for remaining IPPP research activities should be transferred to the particle physics theory grants panel to which the national centre for phenomenology and university research groups would bid.

1.1.5. The Panel supported inviting the IPPP and other institutions to bid to run the national centre after 2018.

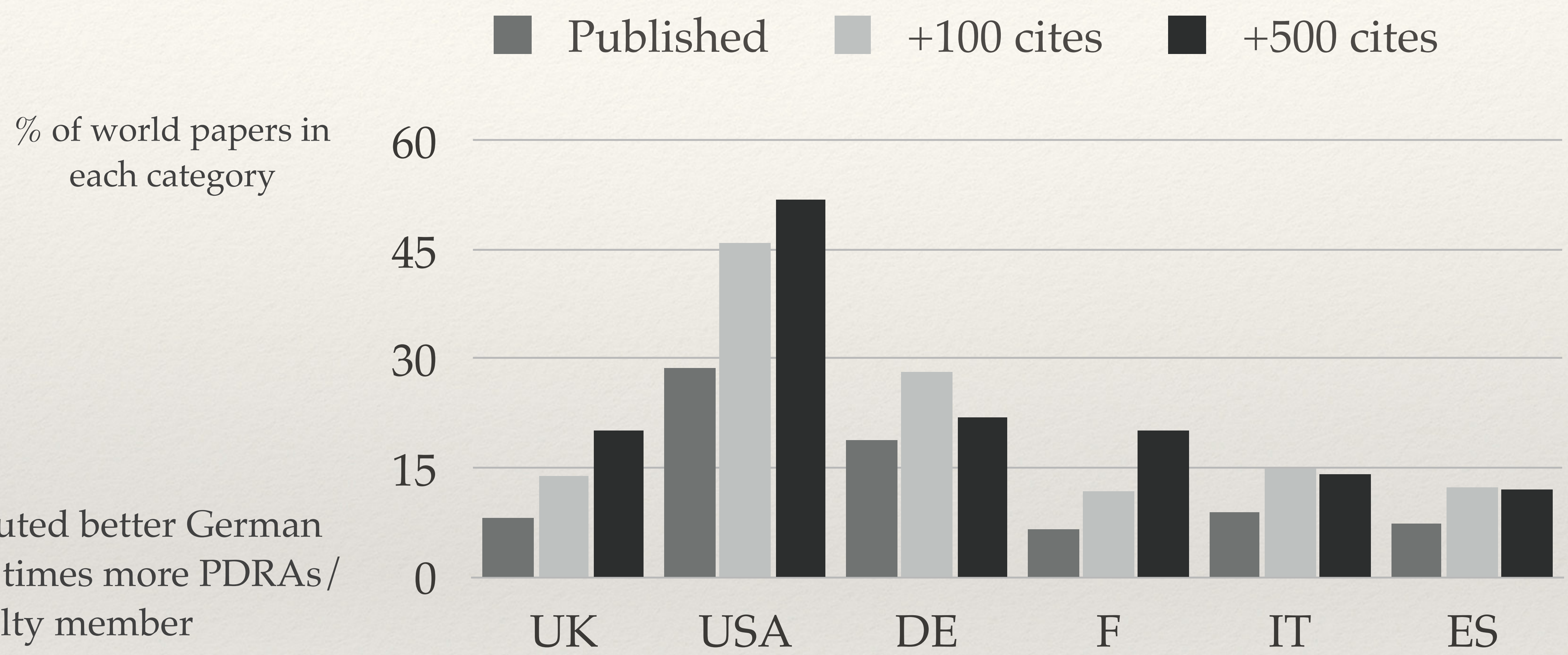
- STFC would have to be able to award a long-term grant (e.g. 4+4 years) to provide sufficient incentives for such bids.
- If such a long-term award is not possible, then the panel recommends that STFC negotiate with the IPPP to continue as the national centre after 2018.

1.1.6. The panel requests that STFC reviews the balance and level of funding for particle physics theory in general.

We have been informed that the IPPP will remain the National Phenomenology Centre until 2023.

Overall review of theory funding

Refereed publications since 2005 by country



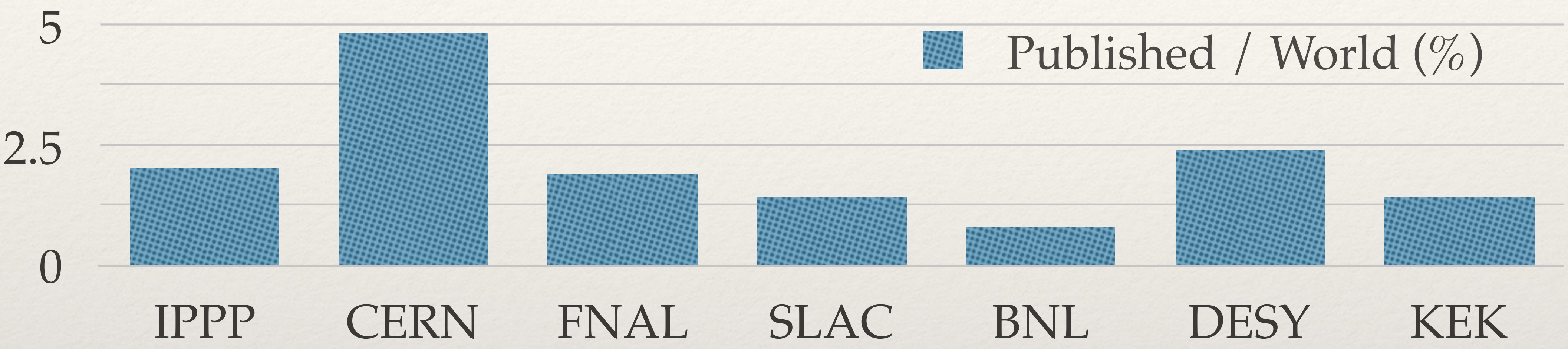
Panel attributed better German results to 3-4 times more PDRAs/ faculty member

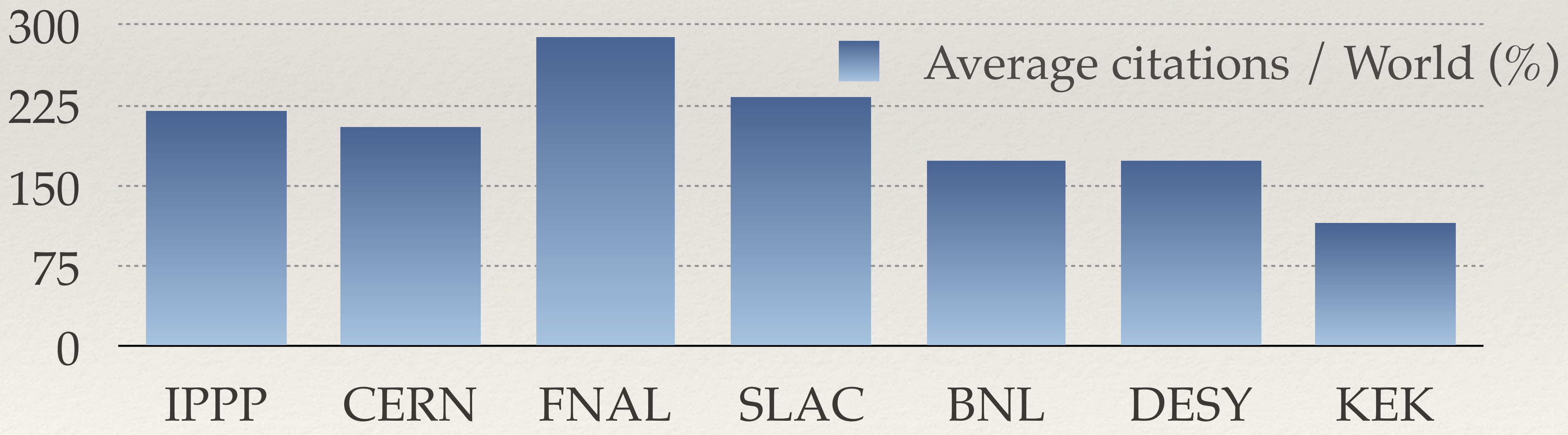
“However important to judge phenomenology not only by the output of papers,….but also by the value that it adds to the experimental program.”
eg, Rivet and HEPdata

One can also generate citations by chasing chimera

IPPP vs Peers(International Labs)

- IPPP is competitive internationally, at a fraction of the cost to the STFC, (cf Fermilab $10M/year)





- Importantly we also contribute to the training of students

Forthcoming IPPP events

- In Durham
- **Jet vetoes and multiplicity observables, 19-21/9/2016**
- **Future of VBF measurements, 22-23/9/2016**
- **Future Challenges for Precision QCD, 26-28/10/2016.**
- **Dark Matter from AeV to ZeV, 3rd IBS-IPPP-MultiDark Workshop, 21-25/11/2016**
- **Annual Theory Meeting, 19-21/12/2016**
- **YETI, (Young Experimentalist-Theorist Institute) 2017 8-11/01/2017**
- IPPP-supported workshops/conferences elsewhere
- Lattice 2016, 24-30/6/2016, (Southampton)
- Dark Matter Interpretations for Direct Detection 9/08/2016, (Lincoln College, Oxford)
- String Inflation after Planck, 7-9/09/2016 (Liverpool)
- UK Hep Forum, LHC Physics, 3-4/11/2016, (Cosener’s House,Abingdon)
- Kaon 2016 14-17/9/2016, (Birmingham)
- Higgs Maxwell meeting 8/2/2017 (Edinburgh).

Associateships 2012-2016

- Associateship program is designed to seed and sustain relationships between theorists and experimenters (and the IPPP).
- Associateship program currently funded by the University ~£25K/year

IPPP opportunities

IPPP is inviting applications for a new round of **IPPP Associateships**:

http://www.ippp.dur.ac.uk/ippp-associateships

Open for members of permanent academic staff UK PP

Duration 1 year, start date October 2016.

Application closing date: 31st August 2016

~£25K available

New round of **Senior Experimental Fellowships** at IPPP:

http://www.ippp.dur.ac.uk/senior-experimental-fellowships

To be awarded to small teams led by senior UK experimentalists.

Duration 1 year, start date 1 January 2017

Application closing date: 31st August 2016

~£20K available

We are looking for nominations for new members for **IPPP Steering Committee**

http://www.ippp.dur.ac.uk/steering-committee

The vacancies are for theorists and experimentalists. Nominations by 31st August 2016.

Associateships and Senior Experimental Fellowships decided by Steering committee.

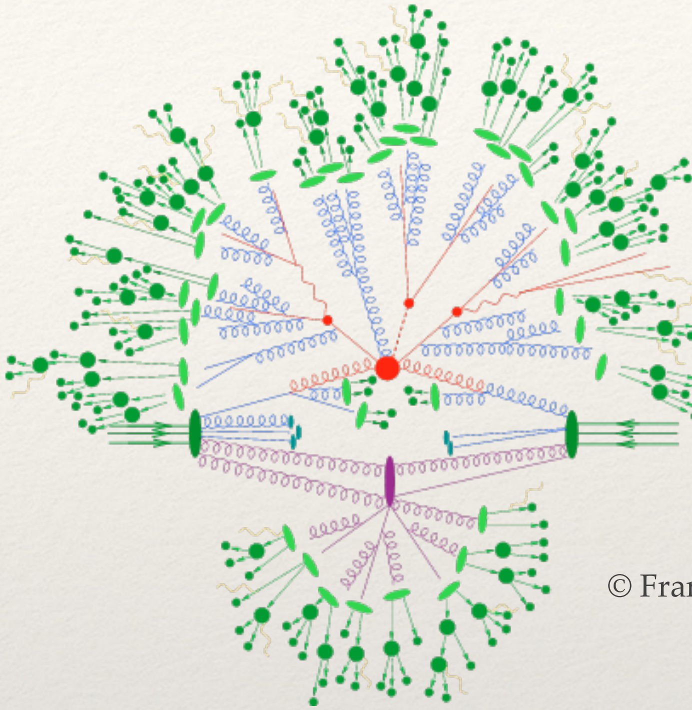
We need your input! (keith.ellis@durham.ac.uk)

UK World-leading areas

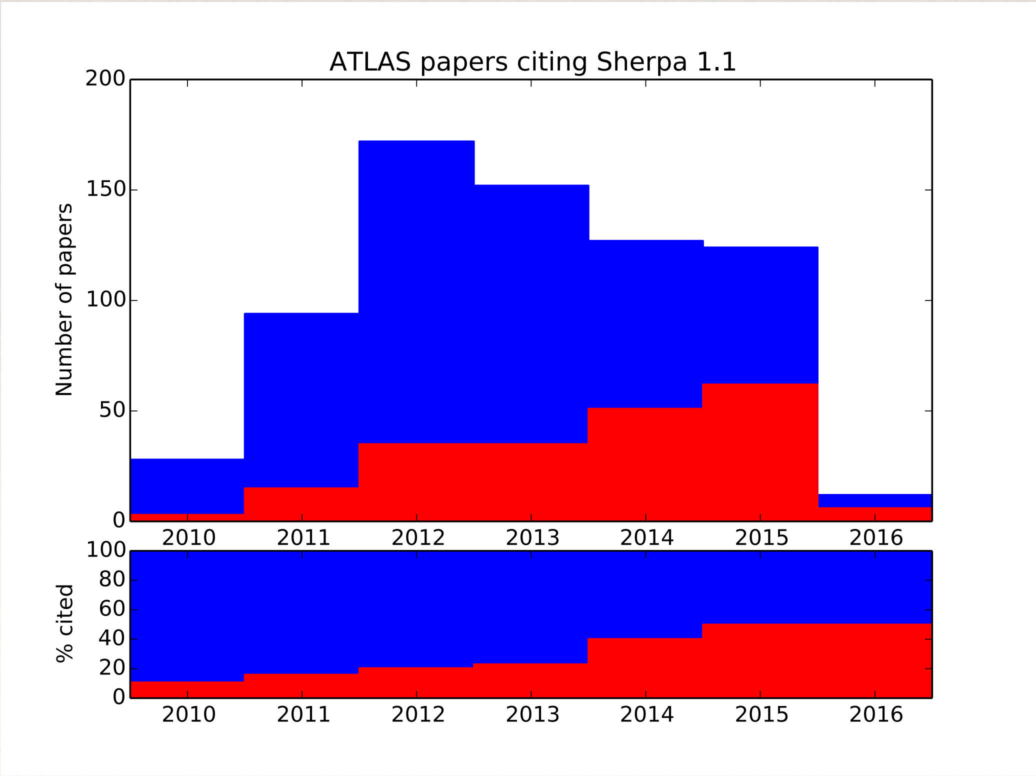
- From phenomenology report:-
- Parton distribution functions MMHT (UCL, DHM),NNPDF(EDI)
- Monte Carlo Event generators HERWIG (CAM,MAN,DHM), SHERPA (DHM)
- Precision QCD (CBG,OXF,DHM)
- Lattice QCD (CBG,EDI,GLA,LPL,OXF,PLH,SOU,SWS)
- (+7 other areas characterised as strong)

Event Simulation

- Proton collisions are messy complicated events, involving both prediction and modelling.
- Predictive part can be systematically improved —an IPPP speciality.
- Exploitation of the LHC requires understanding of these events.
- Two major IPPP (et al) general purpose programs to simulate proton collisions, HERWIG and SHERPA.
- Widely used, publicly distributed programs.
- e.g. an astonishing 50% of ATLAS papers now use and cite SHERPA



© Frank Krauss



Areas needing strengthening

- “There were several areas of phenomenology where it was felt that there were excellent individuals across UK institutes, but limited international impact due to low critical mass.
- These include:-
    - Neutrinoless double beta decay
    - Studies of Neutrino interactions with heavy nuclei
    - (non-lattice) heavy flavour physics
    - beyond the standard model (BSM) theory
    - precision electroweak calculations”

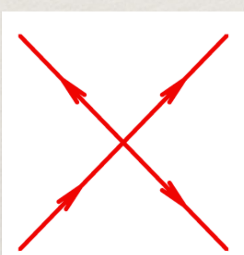
P5-Science Drivers

- Use the Higgs boson as a new tool for discovery
- Pursue the physics associated with neutrino mass
- Identify the new physics of Dark Matter
- Understand cosmic acceleration: dark energy and inflation
- Explore the unknown: new particles, interactions and physical principles

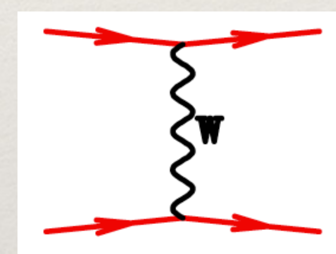
Talk about the science underlying the quest for the high energy frontier

No-lose completion of the standard model

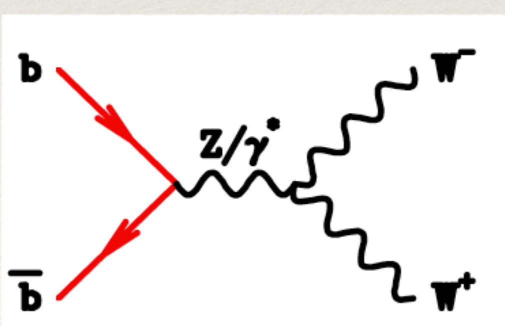
- In our quest to complete the standard model we have been aided by no-lose theorems.
- Motivation for the W



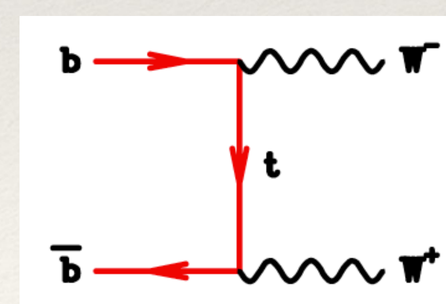
$$\sim \sqrt{2} G_F E^2 = \frac{E^2}{v^2} < 16\pi^2 \implies E_c < 4\pi v$$



- Motivation for the top quark



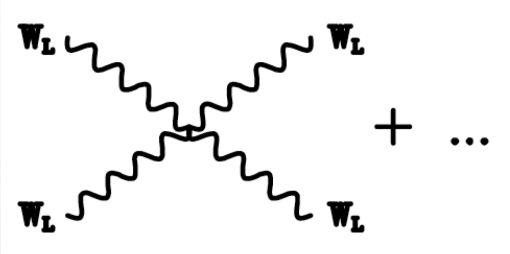
$$\sim \sqrt{2} G_F E^2 = \frac{E^2}{v^2} < 16\pi^2 \implies E_c < 4\pi v$$



see, 1510.05159

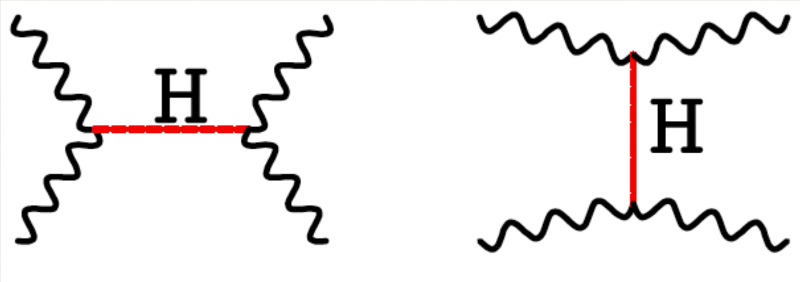
Completion of the SM –Higgs boson

- Shortcomings of theory of WW scattering



$$\sim g_W^2 E^2/m_W^2 < 16\pi^2 \implies E_c < 4\pi v$$

- before the critical energy Ec, new physics must enter,
- either a new particle which keeps the theory perturbative



- or, new physics to describe the non-perturbative regime.

Now that the standard model is complete, there are no further no-lose theorems.
In principle, the standard model could be valid to the Planck scale

Naturalness

- The complete Lagrangian takes the form viewed as an effective theory

$$\mathcal{L} = o(\Lambda^4) + o(\Lambda^2)\mathcal{L}_2 + o(\Lambda)\mathcal{L}_3 + o(1)\mathcal{L}_4 + o(\frac{1}{\Lambda})\mathcal{L}_5 + o(\frac{1}{\Lambda^2})\mathcal{L}_6 + \ldots$$

$$\mathcal{L}_2 = \mu^2 H^\dagger H$$

- Operators of d < 4 suffer from a naturalness problem; in the absence of a symmetry principle one would expect the value of M_H to be of the order of the cut-off.
- Loop corrections to the Higgs mass are quadratic in the cut-off.
- So if the standard model is valid to the Planck mass,

$$M_H^2 = 3.273,459,429,634,290,543,867,496,473,159,645 - 3.273,459,429,634,290,543,867,496,473,159,643$$

Bare mass in Planck units

FCC-hh parameters and lum goals

Mangano, Annual Theory meeting,Durham 2015

Parameter	FCC-hh	LHC
Energy [TeV]	100 c.m.	14 c.m.
Dipole field [T]	16	8.33
# IP	2 main, +2	4
Luminosity/IP_{main} [$cm^{-2}s^{-1}$]	5 - 25 x 10^{34}	1 x 10^{34}
Stored energy/beam [GJ]	8.4	0.39
Synchrotron rad. [W/m/aperture]	28.4	0.17
Bunch spacing [ns]	25 (5)	25

- **Phase 1 (baseline): 5 x 10^{34} $cm^{-2}s^{-1}$ (peak),**
  250 fb^{-1}/year (averaged)
  2500 fb^{-1} within 10 years (~HL LHC total luminosity)

- **Phase 2 (ultimate): ~2.5 x 10^{35} $cm^{-2}s^{-1}$ (peak),**
  1000 fb^{-1}/year (averaged)
  ➔ 15,000 fb^{-1} within 15 years

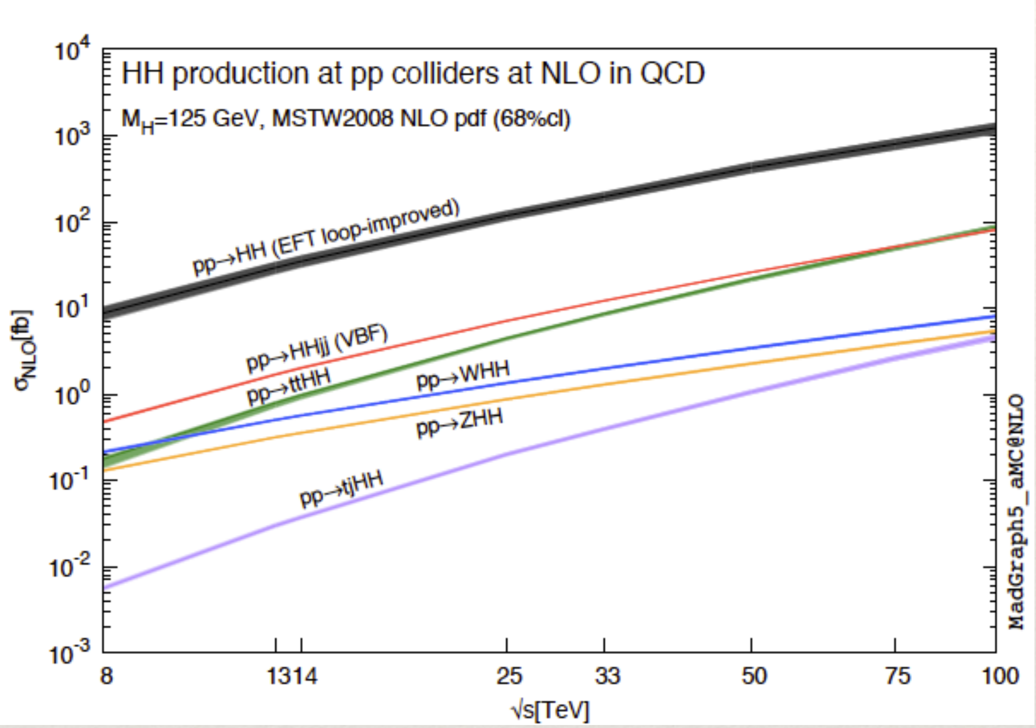
- **Yielding total luminosity O(20,000) fb^{-1} over ~25 years of operation**

Higgs pair production

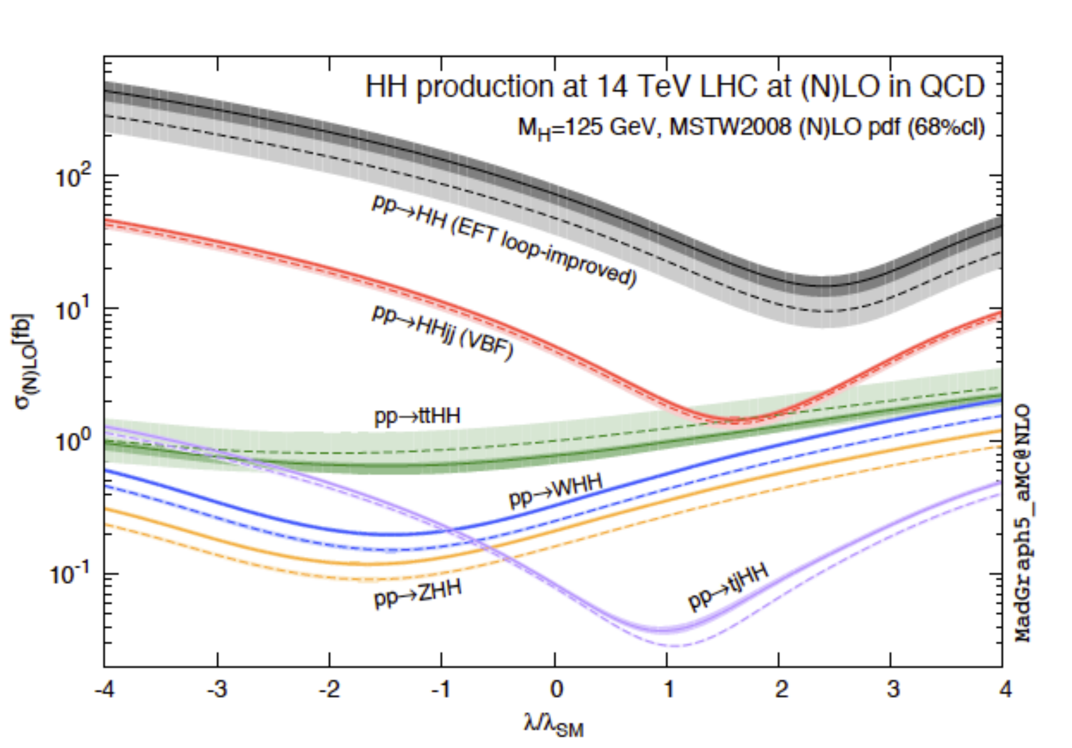
- Expected significance of observation at HL-LHC only about 2σ

$$\mathcal{L} = -\frac{1}{2}m_h^2 h^2 - \lambda_3 \frac{m_h^2}{2v} h^3 - \lambda_4 \frac{m_h^2}{8v^2} h^4$$

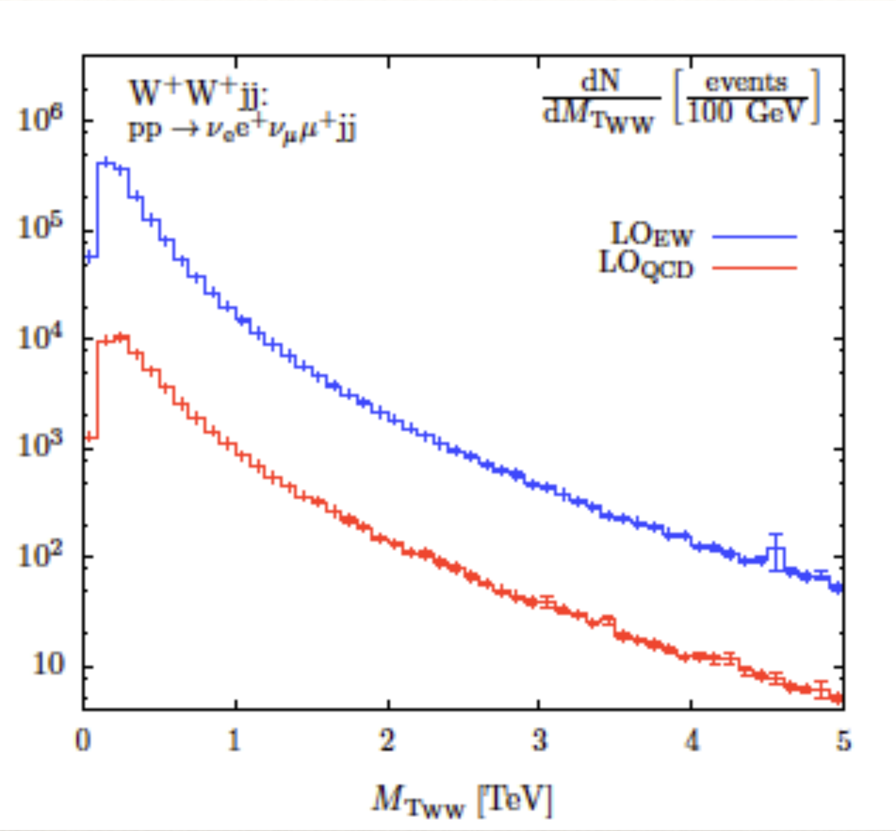
- In SM $\lambda_3 = \lambda_4 = 1$
- Figure similar in shape at $\sqrt{S}$=100TeV
- Golden channel $bb\gamma\gamma$
- Higgs trilinear coupling determined to 3-4% at 100 TeV

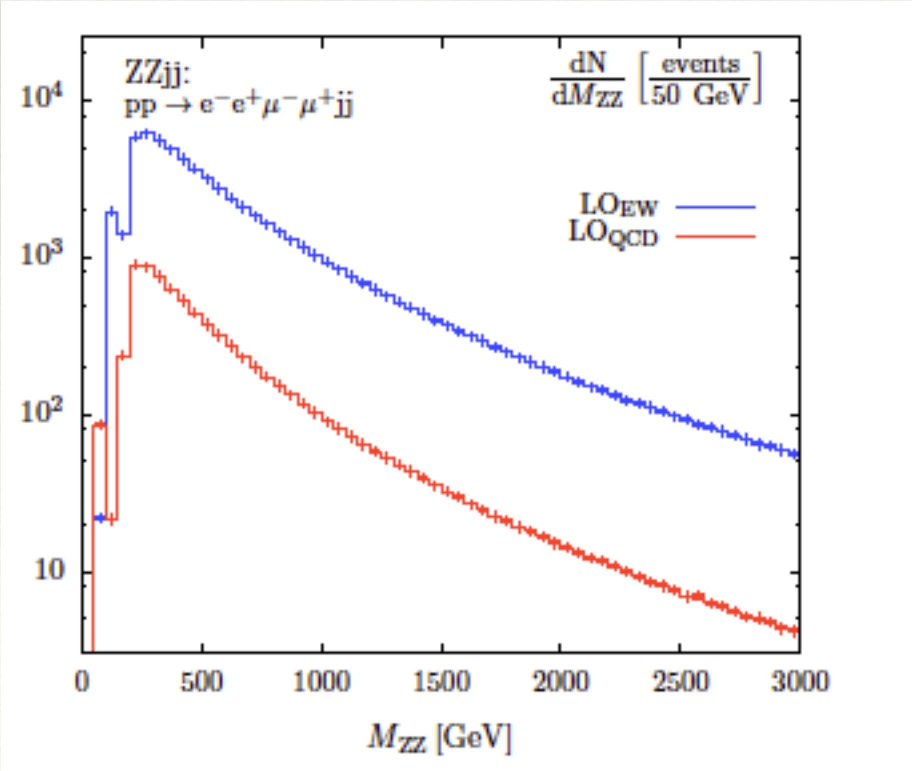


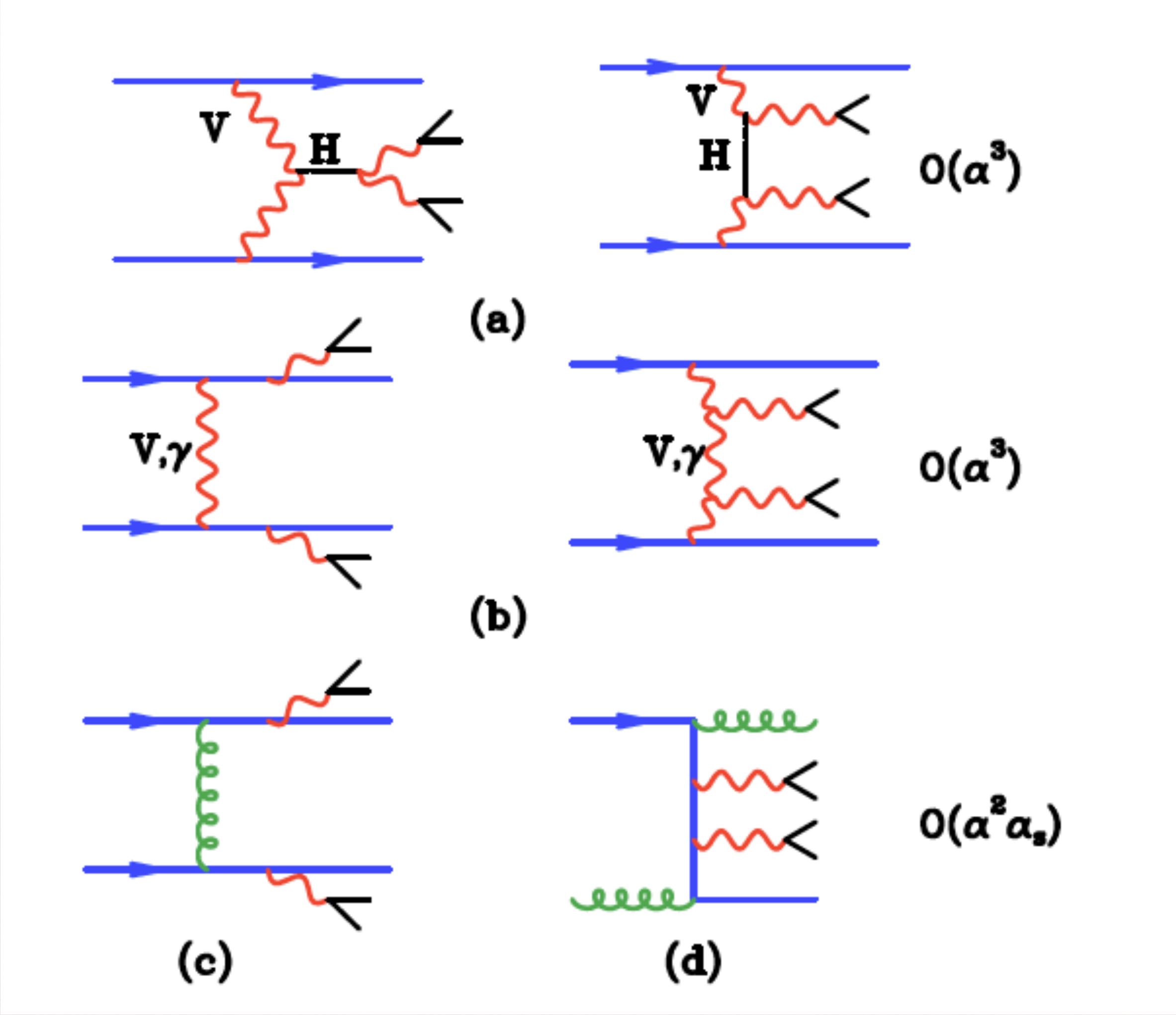
x100



Vector boson fusion and scattering



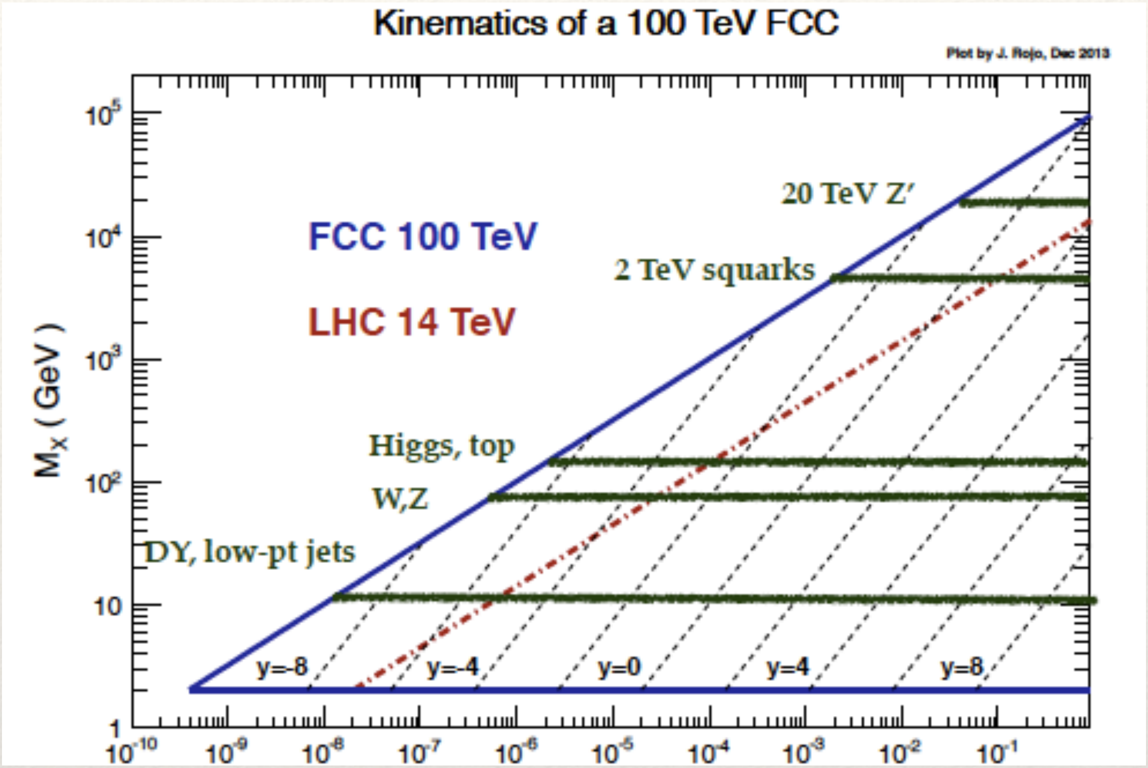


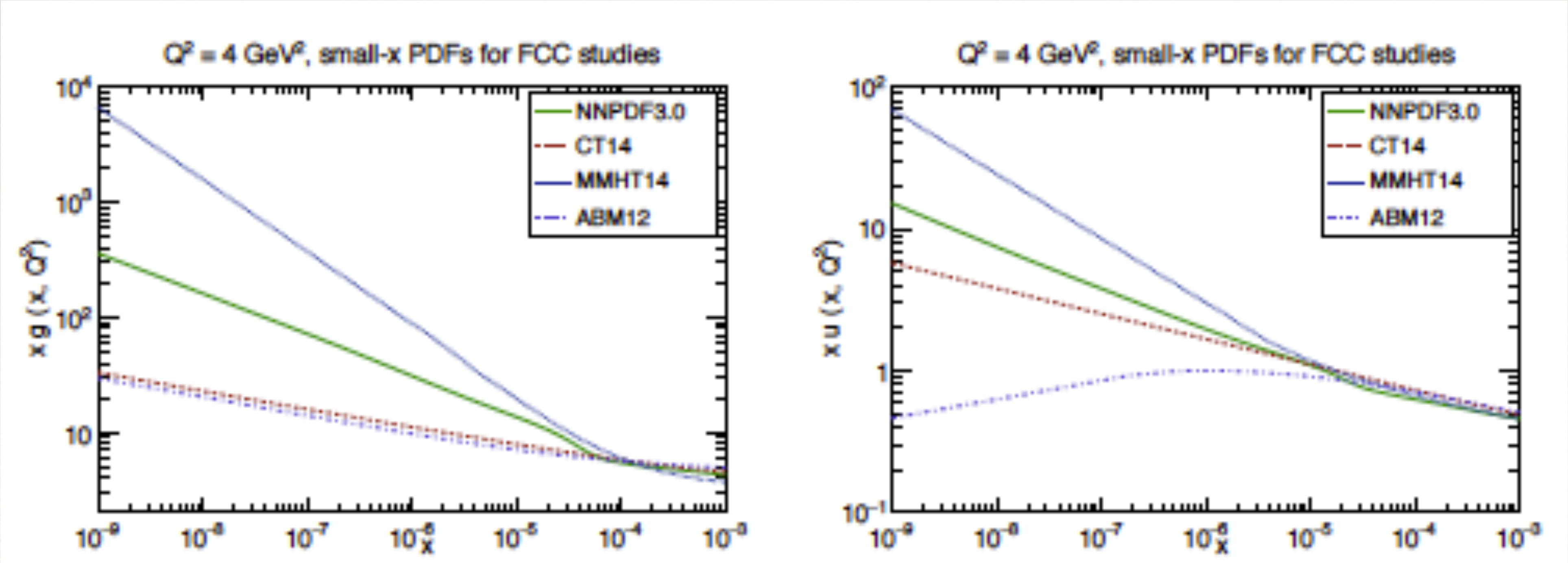


Rates for 3 inverse attobarns 1607.0183

Parton distribution functions

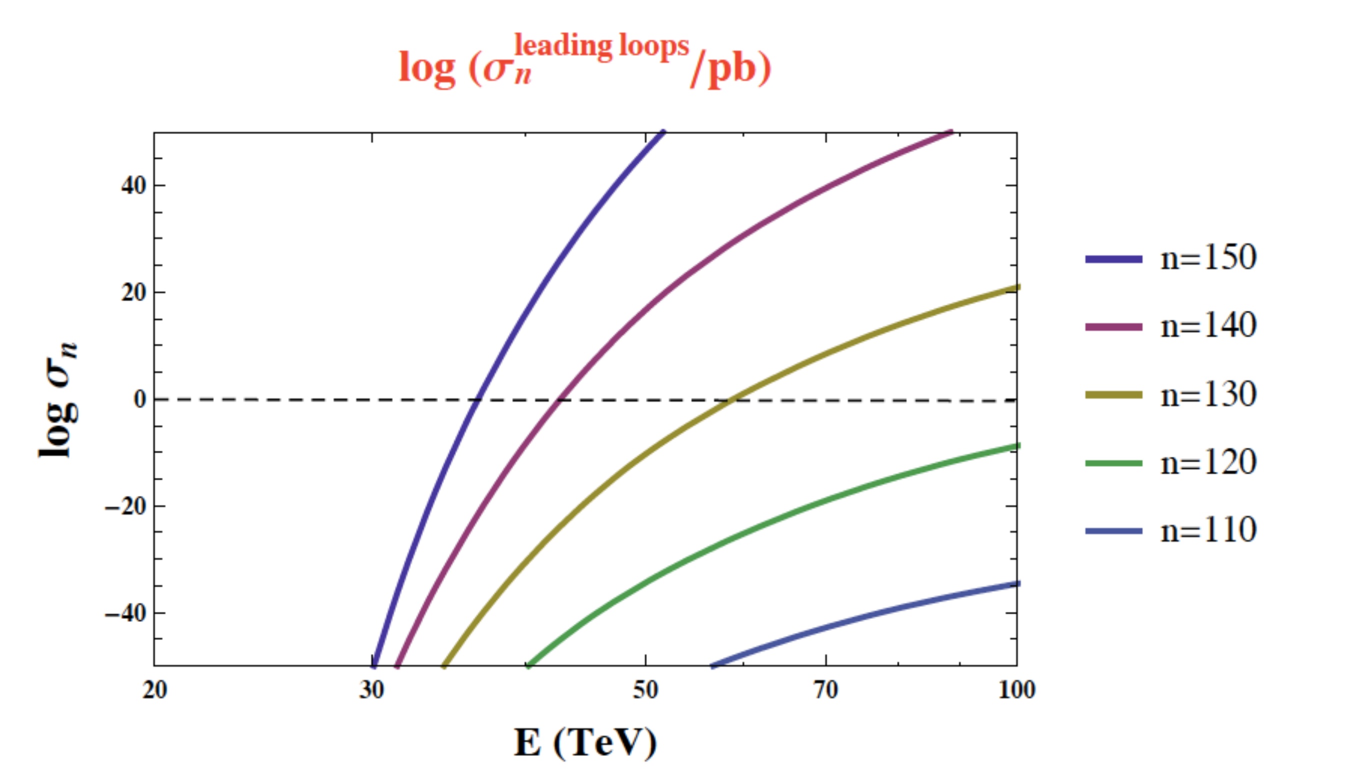
- Extension of range of PDFs to $x<5x10^{-5}$ where unconstrained by data.
- small x important for tuning of soft and semi-hard physics





Multiple Higgs boson production

- Perturbation theory is subject to n! growth
- Applied to multiple Higgs boson production.
- Indicates failure of our ability to calculate.



Degrande et al, 1605.06372

FCC-hh collider

Physics at a 100 TeV *pp* collider: beyond the Standard Model phenomena arXiv:1606.00947v1 [hep-ph] 3 Jun 2016

197 pages

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- Topics
  - Supersymmetry
  - Dark Matter
  - Other BSM signatures

FCC-hh

Physics at a 100 TeV *pp* collider: Higgs and EW symmetry breaking studies

arXiv:1606.09408v1 [hep-ph] 30 Jun 2016

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- SM Higgs production
- Prospects for measurements of SM Higgs properties
- Multi-Higgs production
- BSM aspects of Higgs physics and EWSB

FCC-hh

Physics at a 100 TeV *pp* collider: Standard Model processes arXiv:1607.01831v1 [hep-ph] 6 Jul 2016

257 pages

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UK authors

- Parton distribution functions
- Global event properties
- Inclusive Vector boson production
- V+jets
- Vector bosons and heavy flavours
- Gauge boson pair production
- Electroweak production of gauge bosons in VBF and VBS processes
- Jets
- Multijets
- Heavy Flavour production
- Top properties
- Production of multiple heavy objects.
- Loop-induced processes
- Electroweak corrections
- Sources of missing transverse energy

IPPP investment in the future

5.5.2 Post-Doctoral Researchers in Strategic Areas

The University recognises need for long range planning for future particle physics experiments. In particular, there are no UK-funded RA post dedicated to theory and phenomenology support for the future circular colliders programme. Our aim is to create such a research stream and to use it strategically to build a UK-led research arena in the area of very high energy phenomenology at up to 100 TeV. Therefore, Durham University will invest in making the physics case for future experiments and facilities through feasibility studies for new discoveries and the development of precision tools and calculations. It will support this important core function for the overall UK particle physics community with up to two PDRA positions targeted at:

- Making the Science Case for Facilities at Ultra High Energy
- Predictions and Simulations for Frontier Capabilities

Summary

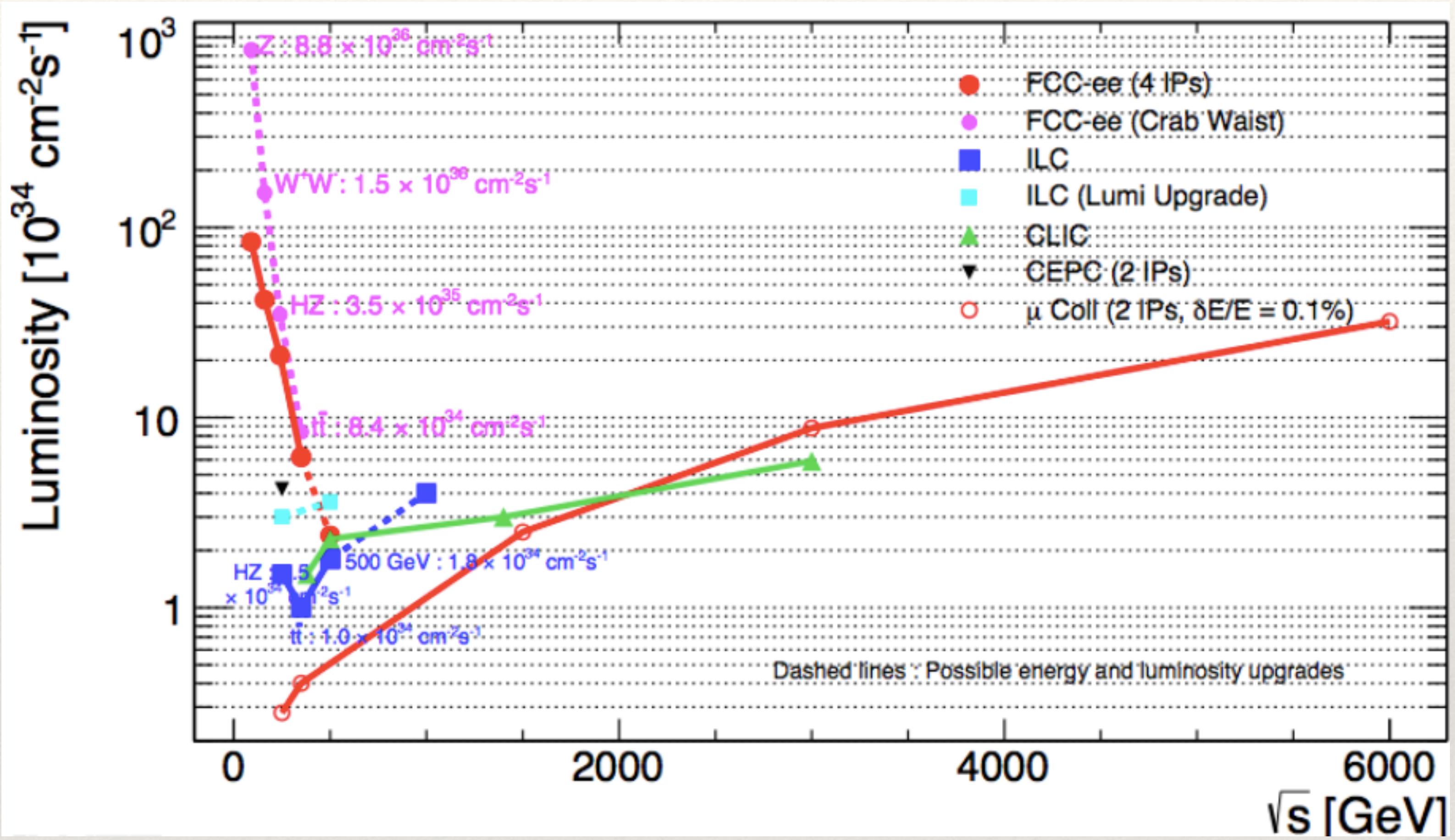
- UK phenomenology effort is world-class, with areas in which it is world leading.
- IPPP is very good value for money; we aim to continue good record of involvement with experiment.
- We should strive in all areas; in theoretical physics, just one person can make a difference.
- New areas for investment identified in the phenomenology review.

Examples of lepton-collider Higgs factories

Factory	Example	Circumference	√s	Prospect	Needs
e+e- Linear	ILC	∞	Phase 1 up to 500GeV	1TeV, GigaZ	New physics below 1 TeV?
e+e- Circular	FCC(ee)	100km	Up to 350GeV	FCC(pp)	New tunnel
μ+μ- Circular	muon collider	50m	125 GeV	ν factory √s -> 5 TeV	Cooling, Extensive R&D

Luminosity comparison

- Luminosity 32x bigger for FCC-ee at ZH peak, (for 4 interaction regions/detectors).
- Cross section fall like 1/s, so luminosity growth needed at high-energy.



http://tlep.web.cern.ch/content/machine-parameters
and Klute (Higgs Couplings Durham October 2015)

Expected Precision Higgs parameters

Uncertainties	μ-Collider	CLIC	ILC	CEPC	FCC-ee
m_H [MeV]	0.06		30	5.5	8
Γ_H [MeV]	0.17	8.5	0.16	0.12	0.04
g_{HZZ} [%]	-	2.1	0.6	0.25	0.15
g_{HWW} [%]	2.2	2.1	0.8	1.2	0.2
g_{Hbb} [%]	2.3	2.2	1.5	1.3	0.4
$g_{H\tau\tau}$ [%]	5	2.5	1.9	1.4	0.5
$g_{H\gamma\gamma}$ [%]	10	5.9	7.8	4.7	1.5
g_{Hcc} [%]	-	2.4	2.7	1.7	0.7
g_{Hgg} [%]	-	2.3	2.3	1.5	0.8
g_{Htt} [%]	-	4.5	18	-	-
$g_{H\mu\mu}$ [%]	2.1	11	20	8.6	6.2
g_{HHH} [%]	-	24	-	-	-

for ~10y operation
lots of "!,*,?" in this table

Marcus Klute (Higgs couplings 2015)

Yifang Wang (24/7/2016) at http://indico.ihep.ac.cn/event/5301/

Science of CEPC-SPPC

- **Electron-positron collider(90, 250 GeV)**
  - Higgs Factory（10^6 Higgs）:
    - Precision study of Higgs(m_H, J^{PC}, couplings), Similar & complementary to ILC
    - Looking for hints of new physics
  - Z & W factory（10^{10} Z^0）:
    - precision test of SM
    - Rare decays ?
  - Flavor factory: b, c, τ and QCD studies
- **Proton-proton collider(~100 TeV)**
  - Directly search for new physics beyond SM
  - Precision test of SM
    - e.g., h^3 & h^4 couplings

Precision measurement + searches: Complementary with each other !

2016-7-24

- pre-CDR available http://cepc.ihep.ac.cn/preCDR/volume.html
- Current plan calls for 54 km circumference ring and Ecm=240 GeV (e+e-), Ecm(pp)=70GeV

Muon collider Higgs Factory

- Compact, fits on CERN/Fermilab site
- Advantages associated with circular geometry
- Multipass acceleration, multipass collisions, more than one detector
- Narrow energy spread, negligible synchrotron radiation. Higgs signal depends on resolution.
- Enhanced cross section for s-channel Higgs production, direct measurement scan of Higgs width.
- A separate ring for every energy (Z,H,ttbar)?
- No obvious constraints limiting scaling to Multi-TeV energy.