Phenomenology

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UK Phenomenology

Approximately 48 academics in 12 institutions applying for consolidate grants (about 1/4 of total) + 15 academics at IPPP

Outside IPPP no enormous groups, but smaller groups have grown in the past 2-3 years. Including consortia, no phenomenology groups now with fewer than 3 members.

(Staff numbers rough as some only partially "phenomenology", and constant turn-over of people.)

Specific collaboration between

Southampton, RHUL, Sussex, RAL and QMUL in NEXT Institute
Kings, UCL, Imperial and CERN on ERC TERAUNIVERSE grant,
Lancaster, Manchester and RHUL and Sussex in consolidated grant consortia.

Research in the UK undoubtedly world-class, with about 1/3 of RA awards made to phenomenology scientific areas in latest round.

Research spread over a very wide range of areas. Main current emphasis on LHC physics and precision and searches here, but significant effort focused elsewhere.

About 50% working on precision Standard Model, i.e. QCD, PDFs, Generators, higher order calculations, Jets, ...

Significant number on BSM Physics at colliders (lots of SUSY) constrains, searches, model building, dark matter, impact on cosmology ...

Small, but highly visible number on neutrino physics.

Recent increase in Flavour physics.

Where both the last two involve both SM and BSM elements.

Major contributions to large scale collaborative efforts

General-purpose event generators for LHC physics**

The PDF4LHC Working Group Interim Report and Recommendations

The SM and NLO Multileg Working Group

HERA and the LHC workshop series on the implications of HERA for LHC physics

The Tools and Monte Carlo working group Summary Report

Jet Substructure at the Tevatron and LHC: New results, new tools, new benchmarks

A Large Hadron Electron Collider at CERN: Report on the Physics and Design Concepts for Machine and Detector

Handbook of LHC Higgs Cross Sections: 1, 2 and 3.

Boosted objects: A Probe of beyond the Standard Model physics

Simplified Models for LHC New Physics Searches (LHC New Physics Working Group)

Benchmark Models, Planes, Lines and Points for Future SUSY Searches at the LHC

Physics at a future Neutrino Factory and super-beam facility

Light Sterile Neutrinos: A White Paper

International Design Study for the Neutrino Factory, Interim Design Report

Flavor Physics in the Quark Sector

Implications of LHCb measurements and future prospects

SuperB Progress Reports – Physics

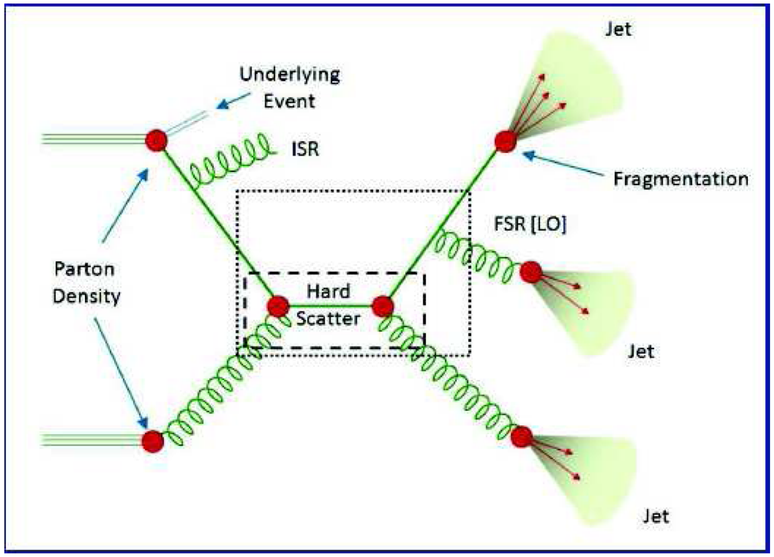
The International Large Detector: Letter of Intent

Gluons and the quark sea at high energies: Distributions, polarization, tomography

Design concepts for the Cherenkov Telescope Array CTA: An advanced facility for ground-based high-energy gamma-ray astronomy

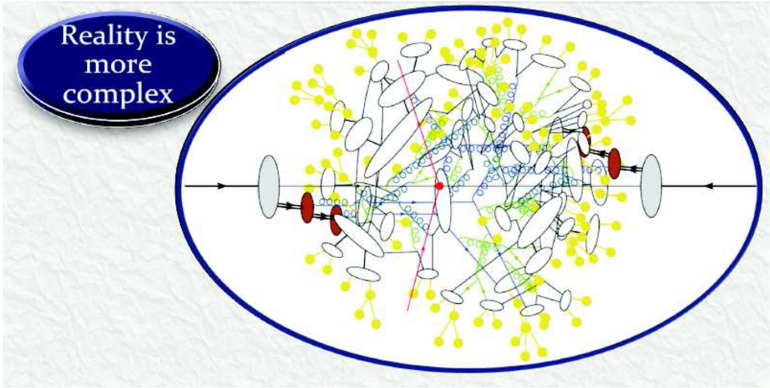
Collider Physics - very largely LHC

High energy scattering processes very complicated

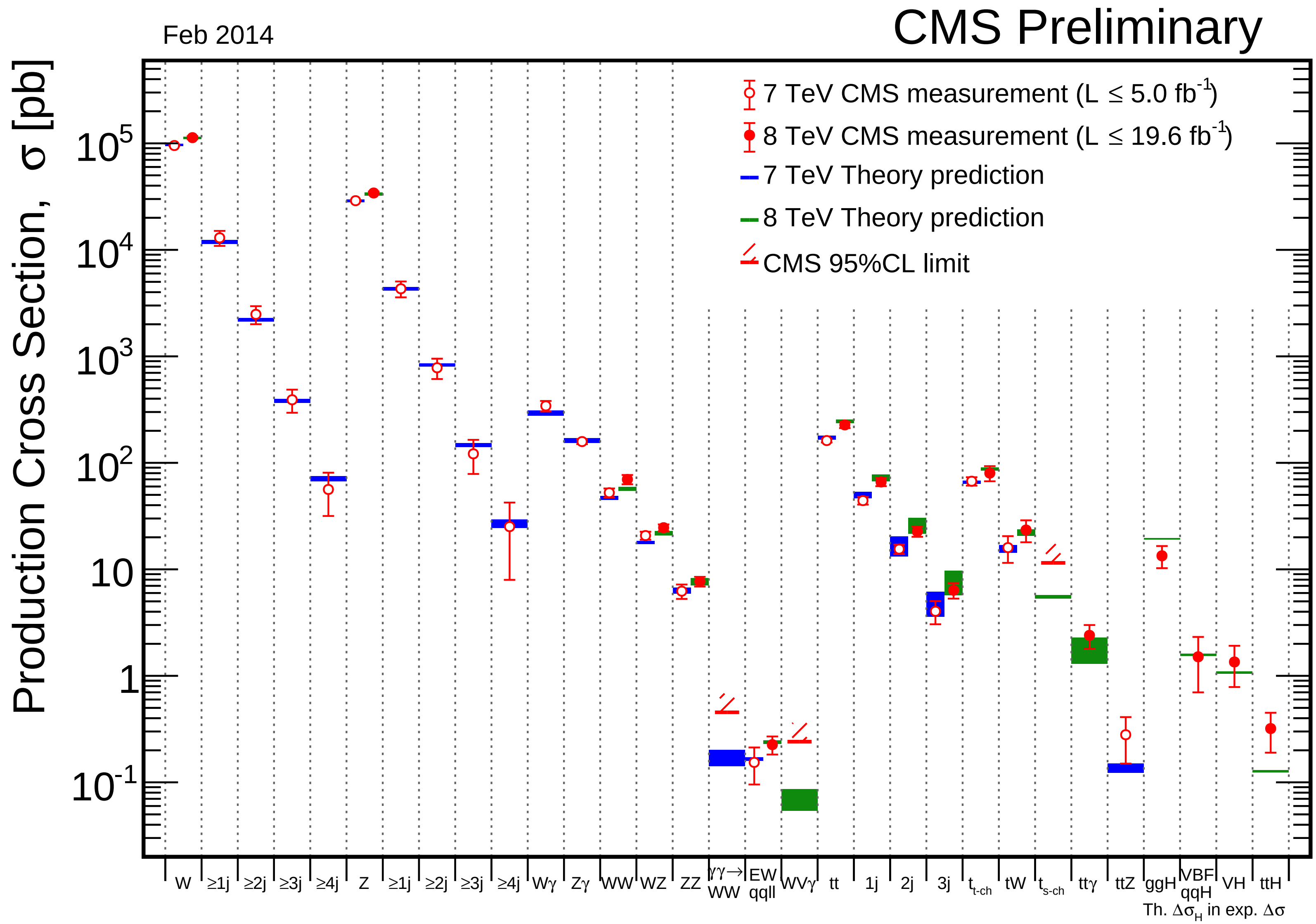


Particularly in reality

Varelas EPS-2011



Nevertheless a huge success with predictions so far

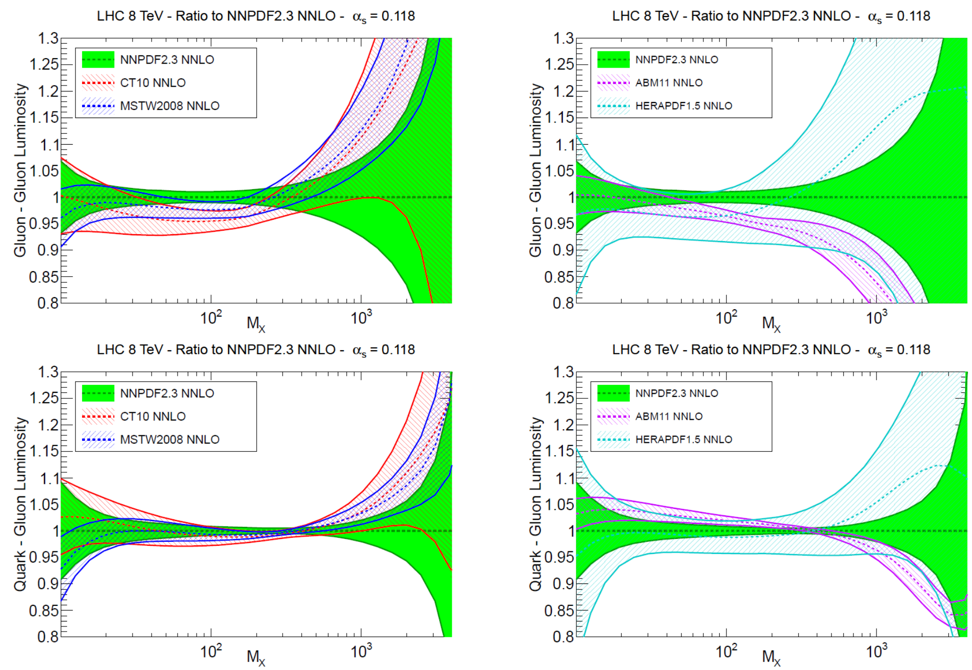


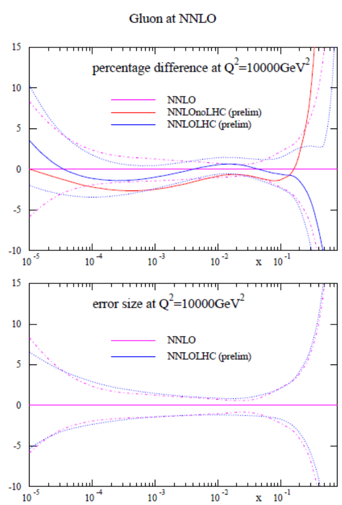
PDFs

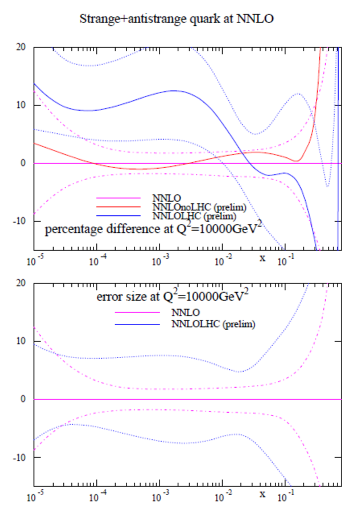
MSTW (MMHT?) based at UCL and IPPP.

NNPDF now 50% based in UK (Edinburgh, Oxford, Cambridge).

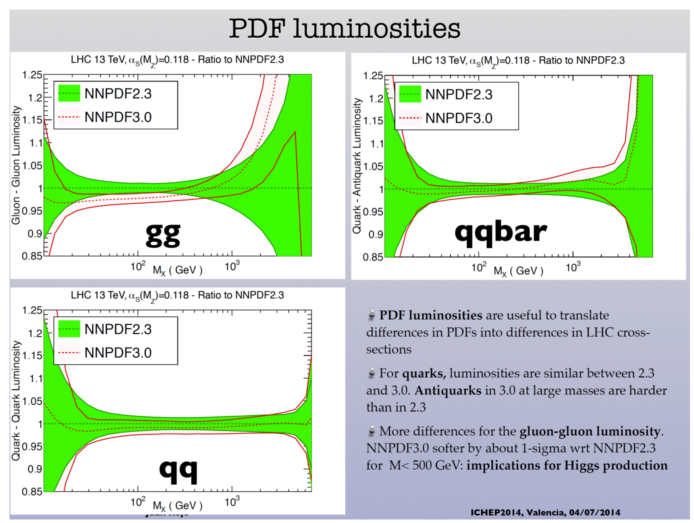
Also HERAPDF has strong UK involvement.







Harland-Lang, Motylinski, Martin and Thorne

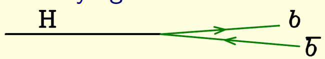


Jet Physics

UK leading contributor in developments in using details of jet physics to improve precision and search for new physics.

Resummation and Jet substructure

Boosted, massive objects decaying into hadrons look like jets:



How do we distinguish them from QCD jets? Pioneering work: Seymour 1993; Since 2008 (Butterworth,Davison,Rubin,Salam) very active research direction, with >100 papers and its own dedicated conference (Boost2014)

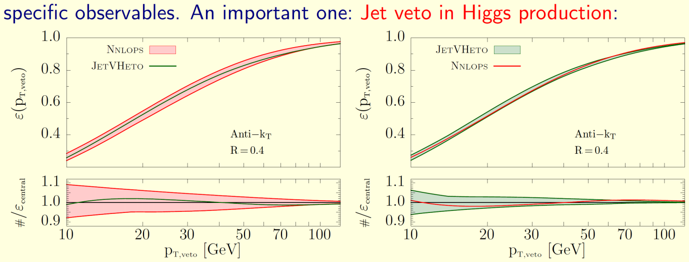
Main handles for QCD jets substructure

- They tend to be asymmetric (soft emission is favoured)
- They are surrounded by more activity with respect to neutral objects (colour coherence inhibits large angle soft radiation)

Several techniques have been put forward to select out QCD jets, using jet substructure: mass-drop, pruning and trimming techniques, N subjettiness, template overlap, energy correlation functions, shower deconstruction, planar flow and several others

Soft gluon resummation

Besides using PS generators, resummation can also be performed analytically for specific observables. An important one: Jet veto in Higgs production:



JetVHeto: dedicated NNLO+NNLL, Banfi,Salam,Monni,Zanderighi 2012

(modified) Mass drop tagger

- Break the jet j into two subjets j_1, j_2 with $m_1 > m_2$
- If there is a mass drop: $m_2 < \mu m$, and the splitting is not too asymmetric: $\min(p_{t,j_1}^2, p_{t,j_2}^2)\Delta R_{j_1 j_2}^2/m^2 > y_{\rm cut}$ the jet j is tagged; otherwise continue with the subjet with the largest $p_t^2 + m^2$.

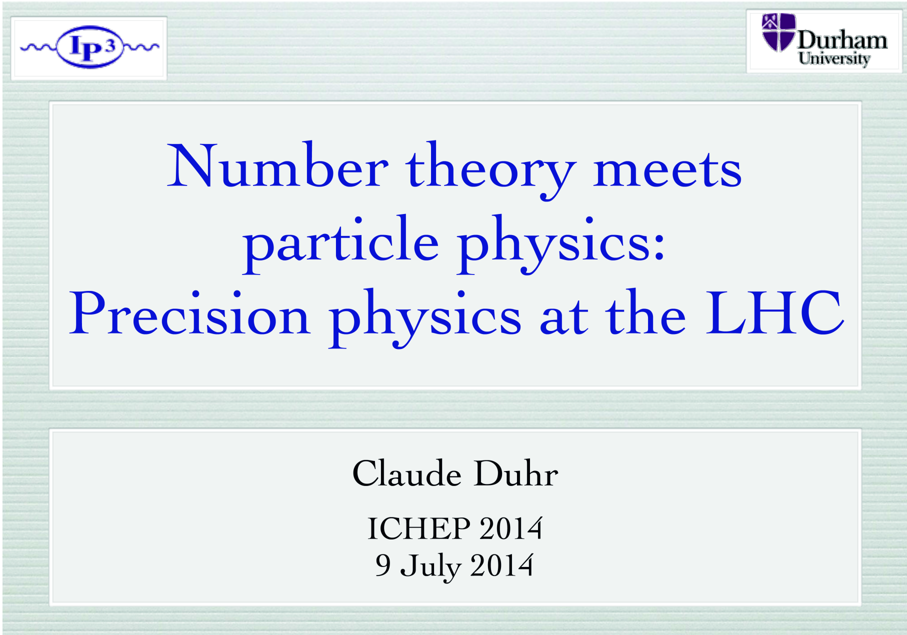
Pruning, Trimming

- Sets a radius R ($R = m/p_t$ for pruning, fixed $R = R_{\rm trim}$ for trimming)
- Recluster the jet; if any two objects have distance larger than R, and $\min(p_{t,a}, p_{t,b}) < z_{\rm cut}\, p_{t,(a+b)}$ discard softer object

Easiest way to assess performance of jet taggers is using Monte Carlo's;
Hard to do with all parameters combination and for the whole range of kinematics and jet definitions.

Analytic understanding needed: Dasgupta,Fregoso,Marzani,Salam,Powling 2013

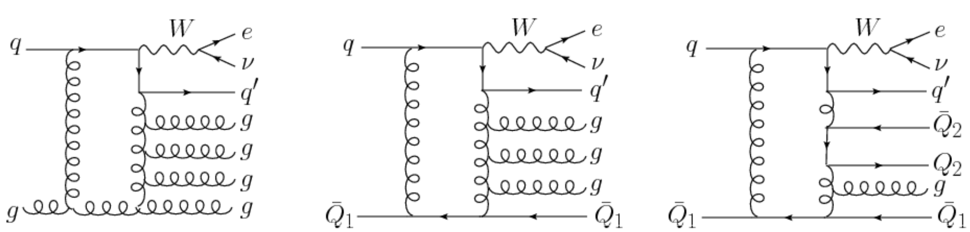
Higher order Corrections.

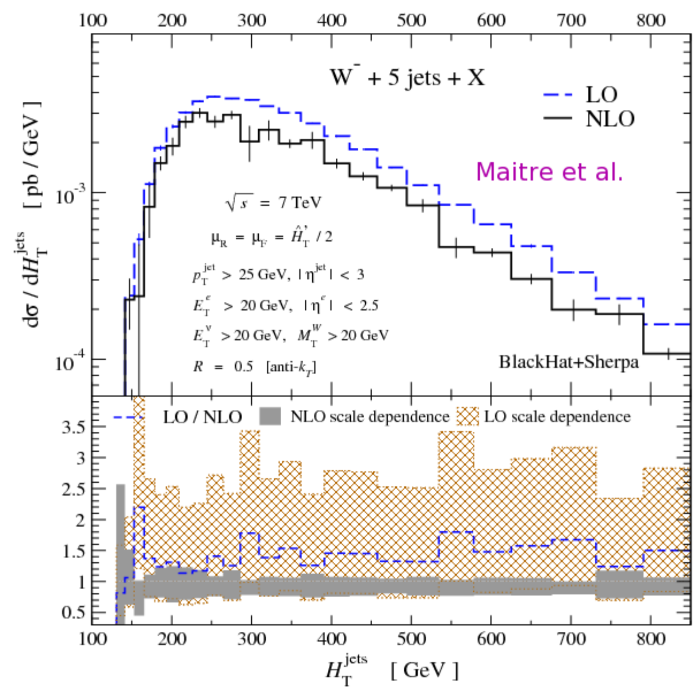


Real area of UK strength.

IUPAP young scientist prize winner on theoretical high energy physics at ICHEP 2014 – Duhr - IPPP.

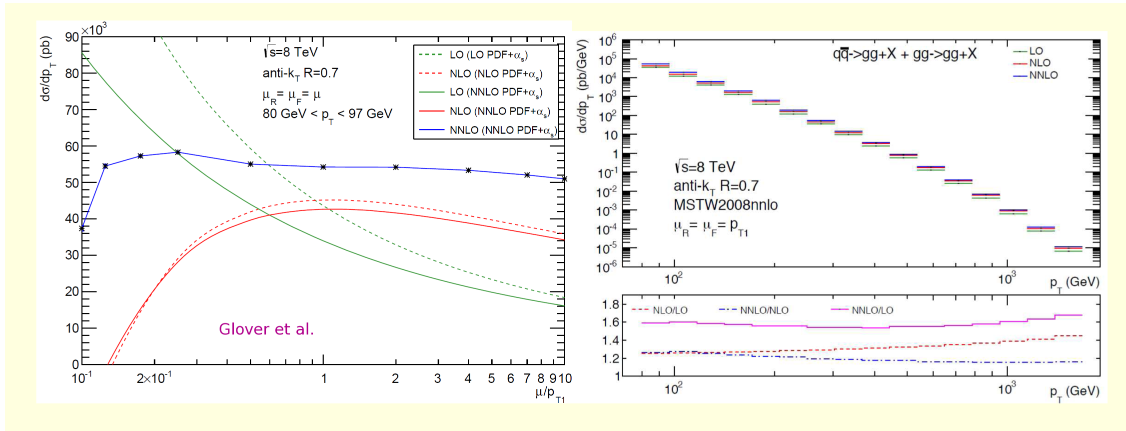
Important results in high multiplicity final states





NNLO Calculations

Major contribution towards completion of vital NNLO jet cross sections.

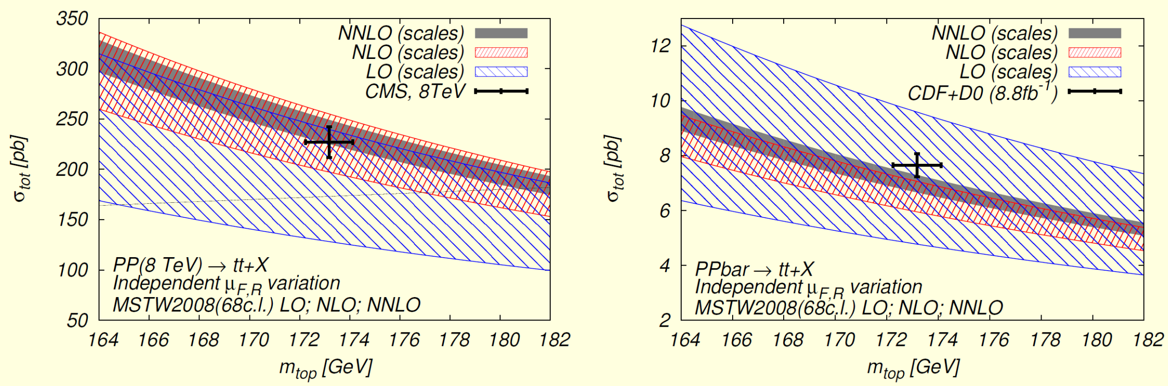


NNLO $t\bar{t}$ cross section one of the most important results of the past couple of years.

NNLO, $t\bar{t}$ and single top

Czakon, Fiedler, Mitov, 2013

Plot from Czakon, Fiedler, Mitov, Rojo 2013



Precision Physics

Progress on NNNLO Higgs production cross section, and estimates using known results.

Gluon fusion threshold Higgs production at NNNLO

Anastasiou,Duhr,Dulat,Furlan,Gehrmann,Herzog,Mistlberger, March 2014)

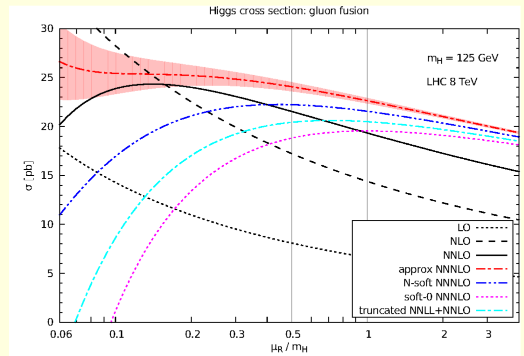
$$\hat{\sigma}_{ij}(m_{\rm H}^2,\hat{s}) = \frac{\pi C(\mu^2)^2}{8v^2}\sum_{k=0}^{\infty}\left(\frac{\alpha_s}{\pi}\right)^k \eta_{ij}^{(k)}(z)$$

where $C/4v$ is the effective ${\rm H}gg$ coupling, $z = m_{\rm H}^2/\hat{s}$. New result:

$$\begin{aligned}\eta^{(3)}(z) \;=\;& \delta(1-z)\,1124.308887\ldots + \left[\frac{1}{1-z}\right]_+ 1466.478272\ldots - \left[\frac{\log(1-z)}{1-z}\right]_+ 6062.08673\ldots \\ &+ \left[\frac{\log^2(1-z)}{1-z}\right]_+ 7116.015302\ldots - \left[\frac{\log^3(1-z)}{1-z}\right]_+ 1824.362531\ldots \\ &- \left[\frac{\log^4(1-z)}{1-z}\right]_+ 230 + \left[\frac{\log^5(1-z)}{1-z}\right]_+ 216 + \mathcal{O}(1-z)\end{aligned}$$

Offspins: soft contribution to $\delta(1-z)$ term is in fact universal; extended to Drell-Yan (Ahmed,Mahakhud,Rana,Ravindran, Apr. 2014) and to generic processes with colour-less final state (Catani,Cieri,de Florian,Ferrera,Grazzini, May 2014)

Not yet full NNNLO result; approximate results based upon it:



Plot: Bonvini,Ball,Forte, Marzani,Ridolfi,2014

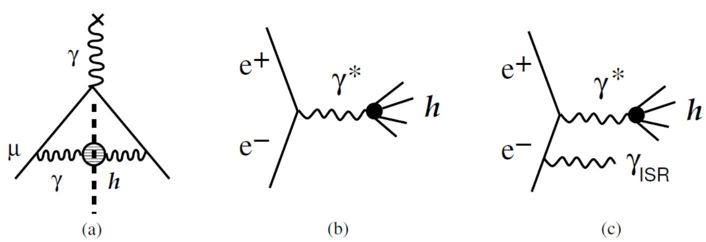
Soft-0 NNNLO, z space (Anastasiou,Duhr,...)

N-soft NNNLO N space (Moch,Vogt,2005; De Florian,Grazzini,2012)

approx NNNLO N space
N analyticity constraints
high energy limit
(Bonvini etal,2013)

Large spread in different approaches. Ongoing debate on whether N space or z space approaches is preferable (reaching a consensus on that may narrow the spread of predictions).

Contribution to real precision for $g-2$ calculation.



Teubner et al.

Figure 4: (a) The "cut" hadronic vacuum polarization diagram; (b) The e^+e^- annihilation into hadrons; (c) Initial state radiation accompanied by the production of hadrons.

Monte Carlo Issues

Long UK involvement in standard HERWIG and Sherpa generators.

Also at forefront of NLO matrix element generators, and now recent development of merged generators and NNLO accuracy.

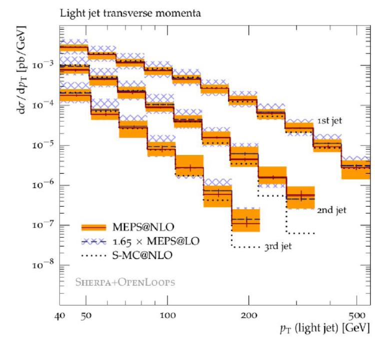
NLO matching (Sherpa-MC@NLO)

- Sherpa-MC@NLO [Hoeche,Krauss,Schoenherr,Siegert] (http://sherpa.hepforge.org)

- interfaced to 1 loop codes, typically with BLHA (BlackHat, OpenLoops, GoSam, MCFM)
- traditionally focussed on S + jets ($S = V, VV, H$)
- enormous progress over last 2 years; in particular:
  - NLO+PS multijet merging (MEPS@NLO)
  - thorough assessment of uncertainties

- $pp \to W+$ jets	[NLO merging]
- $e^+e^- \to$ jets	[NLO merging]
- $pp \to H+$ jets	[NLO merging]
- $pp \to t\bar{t}+$ jets	[NLO merging]
- $pp \to 4\ell+$ jets	[NLO merging]
- $pp \to VH/VV/VVV+$ jets	[NLO merging]
- $pp \to t\bar{t}b\bar{b}$ (4f)	[NLO+PS]

[Cascioli,Gehrmann,Hoeche,Huang,Krauss,Luisoni,Maierhöfer, Pozzorini,Schoenherr,Siegert,Thompson,Winter,Zapp '13-'14]



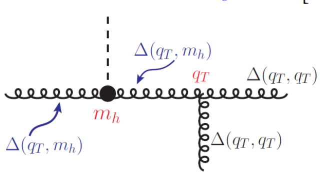
MiNLO

"Multiscale Improved NLO" [Hamilton,Nason,Oleari,Zanderighi '12]

- original goal: method to a-priori choose scales in multijet NLO computation
  (in a multiscale process, this is not straightforward, in regions with widely-separated scales)
- idea: correct weights of different NLO terms with CKKW-inspired approach
  (without spoiling formal NLO accuracy)

$$\bar{B}_{\mathrm{NLO}} = \alpha_S^3(\mu_R)\left[B + \alpha_S^{(\mathrm{NLO})} V(\mu_R) + \alpha_S^{(\mathrm{NLO})} \int d\Phi_{\mathrm{rad}} R\right]$$

$$\bar{B}_{\mathrm{MiNLO}} = \alpha_S^2(m_h)\alpha_S(q_T)\Delta_g^2(q_T, m_h)\left[B\left(1 - 2\Delta_g^{(1)}(q_T, m_h)\right) + \alpha_S^{(\mathrm{NLO})} V(\bar{\mu}_R) + \alpha_S^{(\mathrm{NLO})} \int d\Phi_{\mathrm{rad}}$$



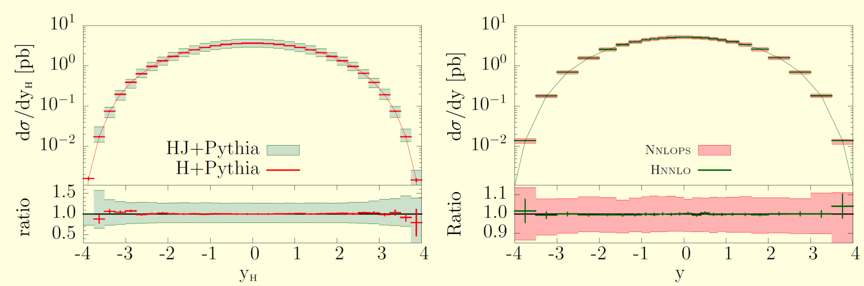
☞ Sudakov FF included on $H+j$ Born kinematics

☞ finite results if 1st jet unresolved

- $\bar{B}_{\mathrm{MiNLO}}$ ideal to extend validity of $H+j$ POWHEG
- including terms from NNLL resummation, NLO+PS merging for 0 and 1-jet, without a merging scale. However: for now not clear how to extend to higher multiplicity

First result on Higgs production at NNLO+PS:

Zanderighi,Hamilton,Re,P.N. Aug. 2013, reweighting MiNLO generator from Zanderighi,Hamilton,Oleari,P.N. 2012



Accuracy: (left) H-HJ MiNLO: ∼30%, (right) NNLO+PS:∼10%

Higgs Phenomenology

Many contributions to precision physics for Standard Model Higgs and implications for BSM physics.

Dolan, Englert Spannowsky

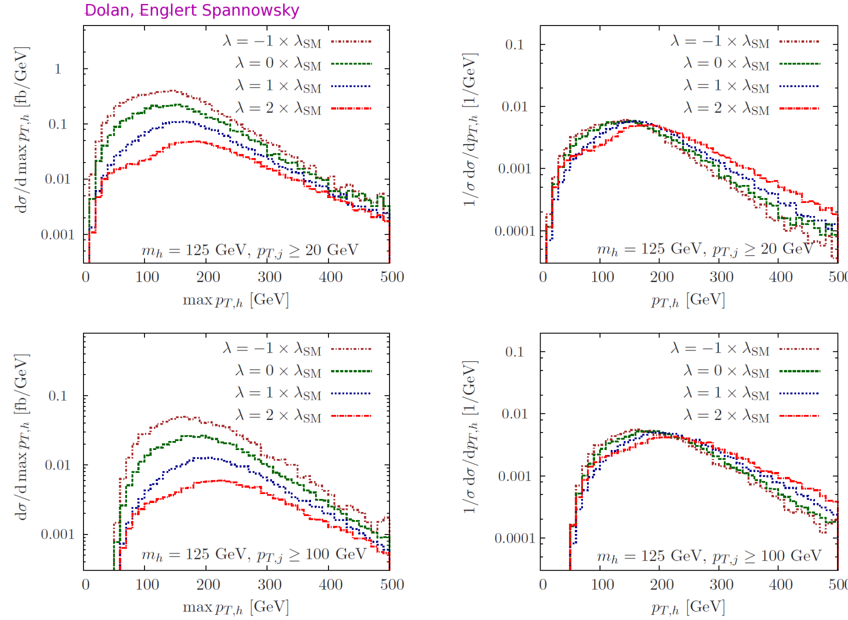
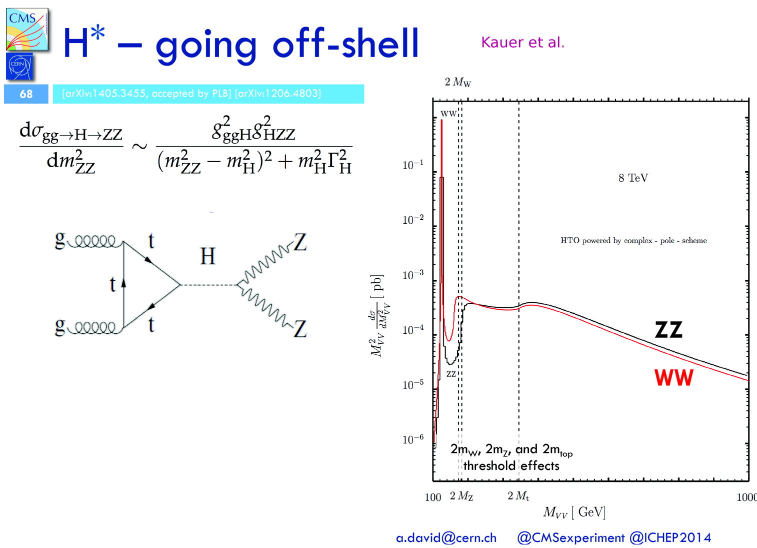


FIG. 6: Comparison of the (normalized) leading order max $p_{T,h}$ distributions in $pp \to hh + j + X$ for different multiples of the trilinear Higgs coupling λ ($m_t = 172.5$ GeV and $m_b = 4.5$ GeV using CTEQ6l1 parton densities), and $p_{T,j} \geq 20$ (100) GeV in pper (lower) row, respectively. Factorization and renormalization scales are chosen $\mu_F = \mu_R = p_{T,j} + 2m_h$.



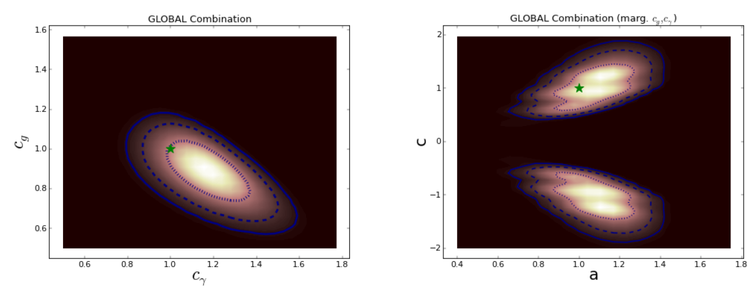
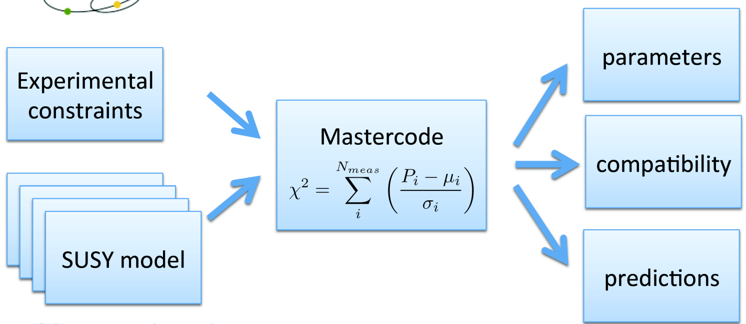


Figure 4: *Left: The constraints in the (c_γ, c_g) plane imposed by the measurements in Fig. 1, assuming the Standard Model values for the tree-level couplings to massive bosons and fermions, i.e., $a = c = 1$. Right: The constraints in the (a, c) plane when marginalizing over c_γ and c_g.* Ellis et al.

BSM/SUSY

Central to testing and devising searches for BSM particularly SUSY, and constructing models.

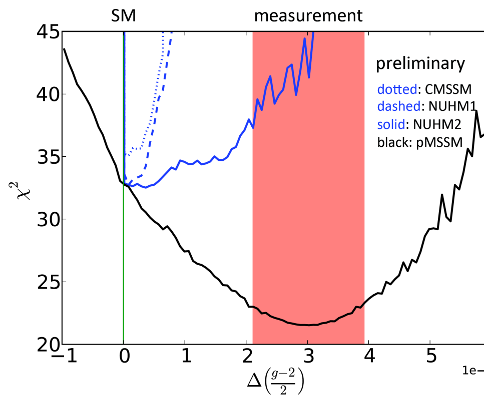
Global fit of SUSY



- Mastercode today
  - **supergravity:** CMSSM, NUHM1, NUHM2 NEW
    $m_0,\ m_{1/2},\ A_0,\ \tan\beta,\ (m^2_{H_u},\ m^2_{H_d})$
  - **phenomenological:** pMSSM10 NEW
    $m_{\tilde{q}_{12}},\ m_{\tilde{q}_3},\ m_{\tilde{l}},\ M_1,\ M_2,\ M_3,\ A,\ M_A,\ \tan\beta,\ \mu$

03/07/2014 Kees Jan de Vries; Mastercode; ICHEP 2014 Imperial College London

Resolving tension (g-2) and LHC



	X^2/n_{dof}	p-value
CMSSM	35.1/23	5.1 %
NUHM1	32.7/22	6.6 %
NUHM2	32.5/21	5.2 %
pMSSM10	21.1/17	22 %

pMSSM10 resolves the **tension** between (g-2) and LHC constraints. This **significantly improves** the **fit**.

03/07/2014 Kees Jan de Vries; Mastercode; ICHEP 2014 Imperial College London 11

Allanach, Gripaios

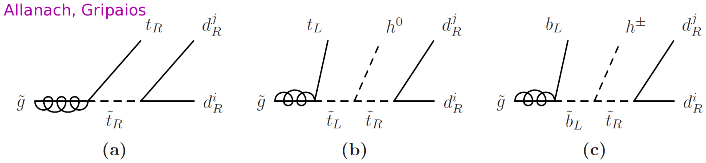


Figure 1. Gluino decays without right-handed bottom squarks in the presence of $W \supset U_3 D_i D_j$, via (a) right-handed top, (b) left-handed top, and (c) left-handed bottom. Same sign leptons are obtained in (c) only if the charged Higgs subsequently decays to $t\bar{b}$ or to leptons.

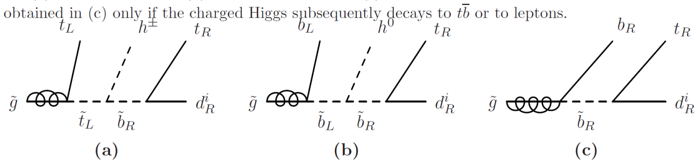


Figure 2. Gluino decays with right-handed bottom squarks in the presence of $W \supset U_3 D_i D_3$, via (a) left-handed top squark, (b) left-handed bottom squark, and (c) right-handed bottom squark.

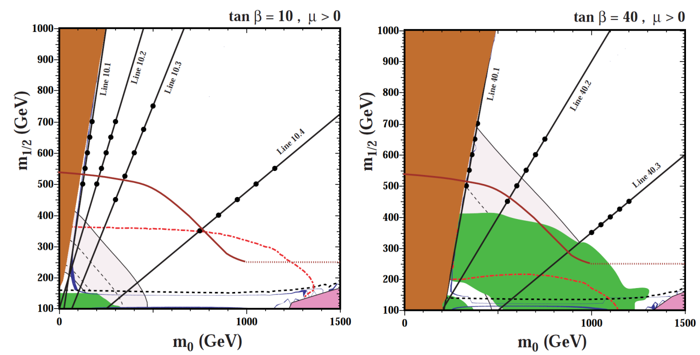


Fig. 2: The CMSSM $(m_0, m_{1/2})$ planes for (left) $\tan\beta = 10, \mu > 0$ and $A_0 = 0$, and (right) $\tan\beta = 40, \mu > 0$ and $A_0 = -500$ GeV. In the brown shaded regions at small m_0 the LSP is charged, in the pink shaded regions at large m_0 there is no consistent electroweak vacuum, the green shaded regions are excluded by $b \to s\gamma$, and the grey shaded regions are favoured by $(g-2)_\mu$ at the 1- (2-)σ level indicated by dashed (solid) lines. LEP searches for charginos exclude the regions below the near-horizontal black dashed lines, LEP searches for the Higgs boson exclude the regions below the near-horizontal red dot-dashed lines, and LHC searches exclude the regions below the purple lines. The benchmark lines are solid black, and the dots denote the benchmark points spaced regularly along these lines. The dark blue strips yield the correct cold dark matter density in the CMSSM. All experimental numbers and the corresponding references can be found in [68].

BSM

Also in investigating novel non-SUSY approaches, e.g. Higgs portal, 4 generations, Higgs triplet models

Englert, Khoze, Spannowsky et al.

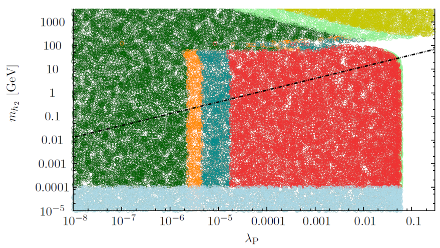


Figure 2: Scatter plot of the model described in Sec. 4 for 10^5 randomly generated parameter choices in the (λ_P, m_{h_2}) plane. Points below the black dash-dotted line require some fine-tuning according to Eqs. (4.12), (4.13). The region excluded by current LHC measurements is shown in red. The cyan region can be probed by LHC with high luminosity and the orange region shows a projection for a combination of a high luminosity LHC with a linear collider. Light blue indicates constraints from stellar evolution. The constraints on the parameter space for a Landau pole separation of 4, and 16 orders of magnitude are included in yellow and light green, respectively. The remaining allowed parameter points are depicted in green.

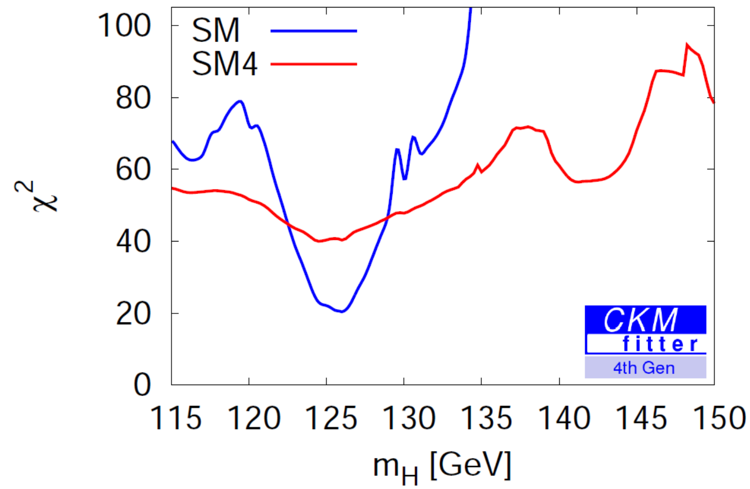


FIG. 4. Higgs mass scan for the SM (blue line) and the SM4 (red line) based on the input set in the second column of Table I.

Lenz et al.

Akeroyd, Moretti

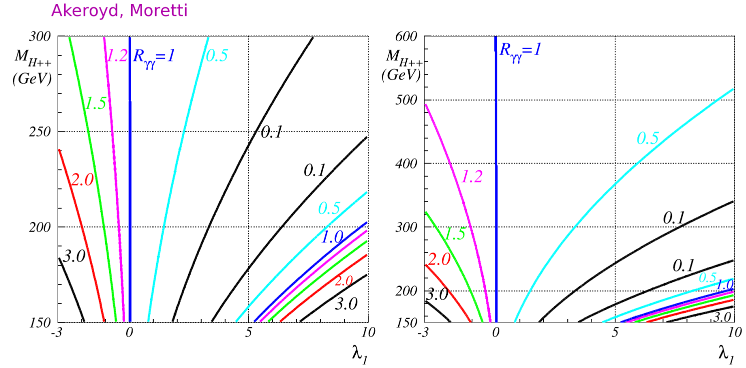


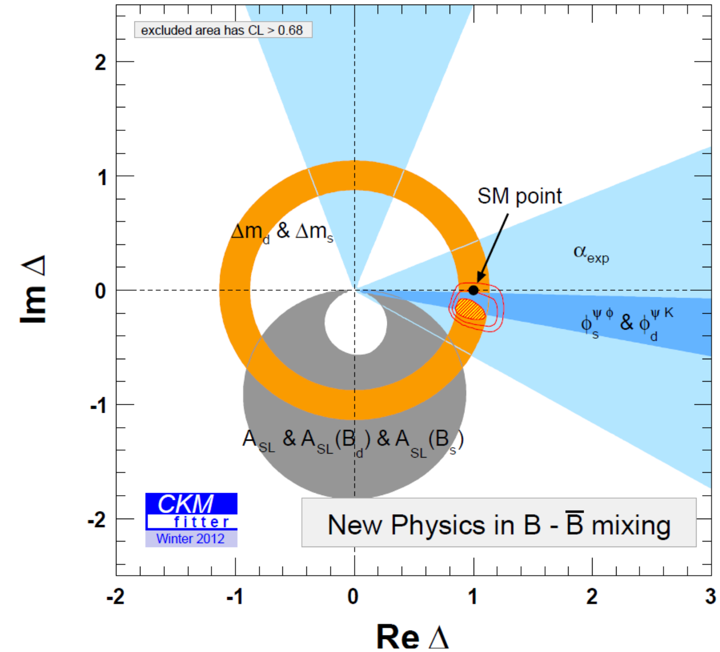
FIG. 2: The ratio $R_{\gamma\gamma}$ in the plane of $[\lambda_1, m_{H^{\pm\pm}}]$ for 150 GeV $< m_{H^{\pm\pm}} <$ 300 GeV (left panel) and 150 GeV $< m_{H^{\pm\pm}} <$ 600 GeV (right panel), for $m_{H_1} \sim 125$ GeV and $m_{H^{\pm\pm}} = m_{H^\pm}$.

Flavour Physics

Work in flavour physics both precise predictions using the standard model.

And in modelling and constraining BSM physics.

Lenz et al



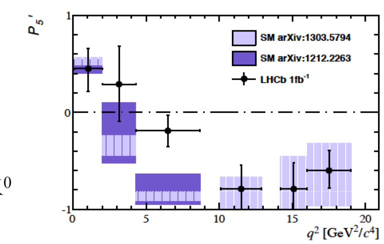
G. Isidori – Looking for New Physics via the Flavor Window ICHEP 2014 - Valencia

The anomalies:

I. The P_5' anomaly in $B \to K^{*0}\mu\mu$

3.7σ local discrepancy vs. SM [Descotes-Genon et al. '13]

II. Overall smallness of the four $BR(B \to H\mu\mu)$, $H=K^{*0}, K^{*+}, K^+, K^0$



Pro NP:

- Reduced tension with data in both cases with a unique fit of modified Wilson coefficients (mainly C_9)
- The corresponding effective NP scale is high (~10 TeV), not in contradiction with other data

Against NP:

- Main effect in P_5' not far from cc threshold
- Significance reduced with conservative estimates of non-factorizable corrections

Jaeger *et al.* '12
Hambrock *et al.* '13
Hiller & Zwicky '13

Example II: $B_{s,d} \to \mu\mu$ & SUSY

Recent developments both on the theory and on the experimental side:

$\boxed{\overline{BR}_{s,SM} = (3.65 \pm 0.23)\times 10^{-9}}$

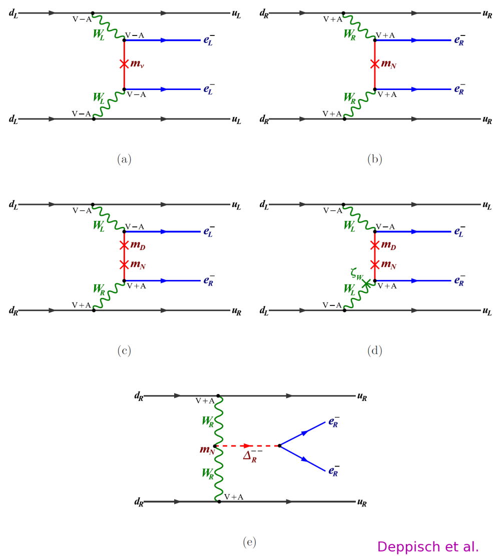
(time-integrated average)

Bobeth, Gorbahn, Hermann, Misiak, Stamou, Steinhauser '13
+
progress from Lattice QCD

$\boxed{\overline{BR}_s^{(exp)} = (2.9 \pm 0.7)\times 10^{-9}}$

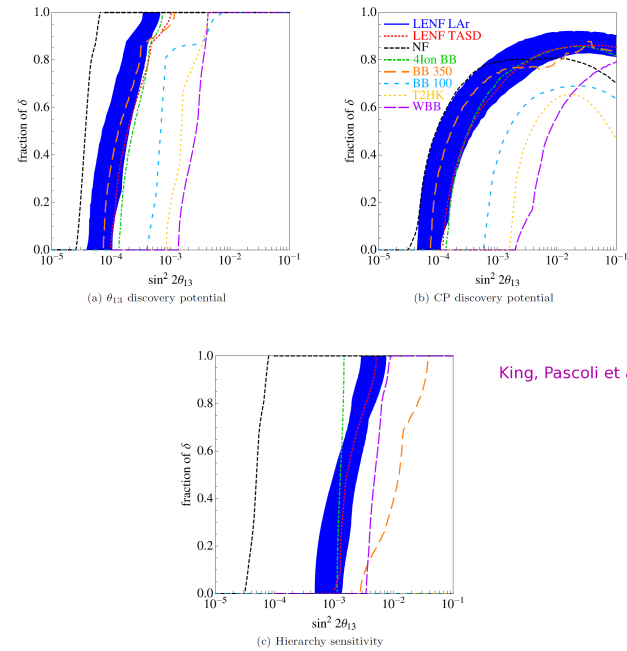
LHCb + CMS '13

Neutrino Physics



Deppisch et al.

FIG. 2: Diagrams contributing to $0\nu\beta\beta$ decay in left-right symmetry: (a) Light neutrino exchange (standard mass mechanism), (b) Heavy neutrino exchange, (c) Neutrino and heavy W exchange with Dirac mass helicity flip (λ mechanism), (d) Neutrino and light W exchange with Dirac mass and W mixing suppression (η mechanism), (e) Doubly charged Higgs Triplet exchange.

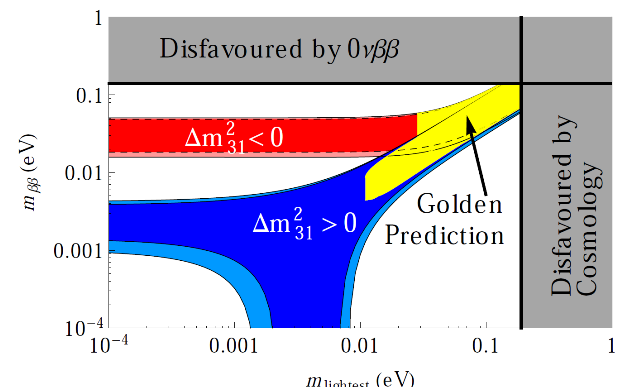


King, Pascoli et al.

FIG. 8: Comparison of 3σ allowed contours for the low energy neutrino factory with a 20 kton TASD (red line) and 100 kton LAr detector (blue band), the high energy neutrino factory (black line), the wide-band beam (purple line), T2HK (yellow line) and three β-beams (green, orange, light blue lines) for a) θ_{13} discovery potential, b) CP discovery potential, c) hierarchy sensitivity.

Very strong interaction with experimental community.

planning and exploitation of decay experiments and neutrino factory.



King, Luhn

Figure 2: $m_{\beta\beta}$ vs. m_{lightest}: The red and light red regions represent the model independent values that the inverted neutrino mass ordering can take based on the central value and 1σ deviation of a recent global fit of neutrino parameters. The blue and light blue regions are the analogue of this for the normal neutrino mass ordering. The gold regions correspond to the golden ratio prediction for $m_{\beta\beta}$ in both the normal and inverted orderings, resulting from the A_5 inverse mass sum rule.

Dark Matter

Work on both constraints on dark matter from astrophysical cross section uncertainties.

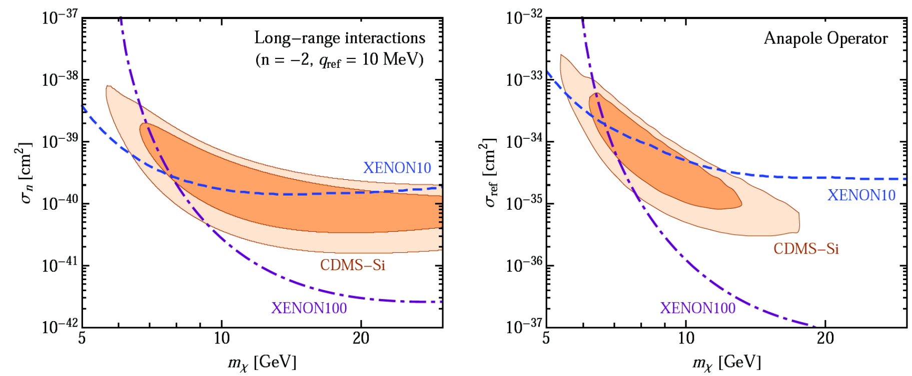


Figure 4. Two examples for modifications of the momentum- and velocity-dependence of the differential cross-section. Left: Long-range interactions, which enhance the cross-section for small momentum transfer. Right: Anapole interactions, which suppress the cross-section for small momentum transfer and small velocity (note the change of vertical scale).

Sarkar, et al.

Also the relation to parameters in SUSY models taking into account Higgs constraints.

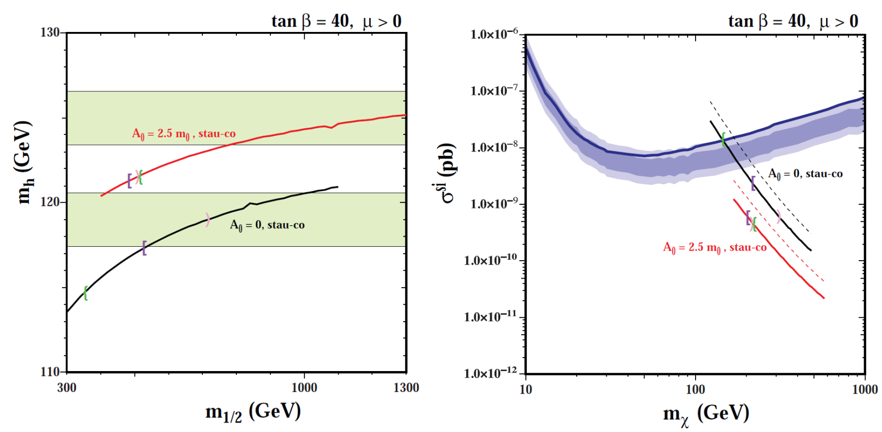


Figure 8: *Left panel: m_h as calculated using* FeynHiggs *(showing the bands $m_h = 119 \pm 1.5$ GeV and 125 ± 1.5 GeV) and right panel: spin-independent elastic $\chi - p$ scattering cross section (showing the XENON100 exclusion [30] as in Fig. 7), along WMAP strips for* $\tan\beta = 40$ *- the $\tilde{\tau}_1 - \chi$ coannihilation strips for $A_0 = 0$ (5) (black) and $A_0/m_0 = 2.5$ (red) (6). The lower bounds on $m_{1/2}$ along these strips due to $b \to s\gamma$ are indicated by green brackets* $\{$.

Ellis et al.

IPPP **connections**

Large degree of collaboration with other phenomenology groups in the UK, and the experimental community.

Recently underwent mid-term review successfully.

Have established a **Phenomenology Network**

Senior Experimental Fellowships – to support participation of UK experimentalists in the IPPP UK Phenomenology Network.

IPPP Associateships – to enhance interactions and enable new collaborations between the Associate, the Associates Institution and the IPPP. Change in focus from previous Associateships and fewer in number.

Annual Research Focus Programme – topical IPPP Research Programme for 2014 is dedicated to New Physics/Beyond the Standard Model phenomenology and searches at the LHC.

As well as continuing with generally more than 15 Workshops each year.

Summary

UK phenomenology is undoubtedly world leading in a number of subject areas and of at least internationally competitive standard across the full range of particle physics. Very good interaction with global experimental community.

There has been a significant growth in staff numbers (using number of 40 + IPPP from Khoze of 2012) - expansion of some smaller groups, but no commensurate increase in funding. PDRA numbers are very similar.

The UK phenomenology community is very well placed to contribute to the planning and exploitation of future high energy/luminosity colliders and smaller scale precision experiments across the board, provided sufficient time and resources can be contributed.

Back-up