Physics with *ep* and *pp* collisions

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(with input from many others)
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LHeC & FCC-eh Workshop @ CERN

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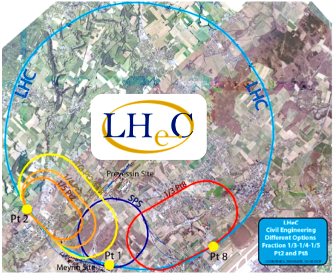
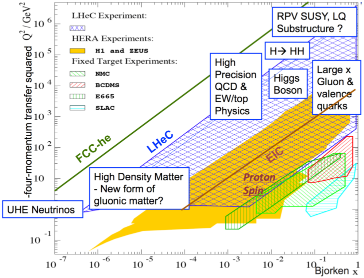
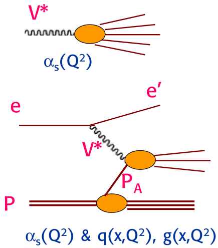
Introduction

- LHC expected to be upgraded to HL-LHC and deliver $\sim 3\,\mathrm{ab}^{-1}$ of pp collisions at $E_p = 7$ TeV, $\sqrt{s} = 14$ TeV: large potential to improve measurements and extend reach of searches
- LHeC proposed upgrade to run $e^{\pm}p$ collisions in parallel with HL-LHC with polarised $e^{\pm}$ beam $E_e \sim 60$ GeV, $\sqrt{s} = 1.3$ TeV and up to $1\,\mathrm{ab}^{-1}$
  - Which HL-LHC analyses and interpretation could be significantly improved by LHeC?
  - What unique measurements & searches are possible in ep that go beyond pp?
- Selected Topics (with some personal bias!):
  - LHC EWK precision m_W and $\sin^2\theta_W$
  - Heavy-flavour related issues in pp and ep
  - The gluon and α_S
  - Higgs in pp and ep
  - Searches in pp and ep
- Aiming to illustrate some points, many talks with more details following...
- Similarly, FCC-hh could run simultaneously with FCC-he using the same $e^{\pm}$ beam



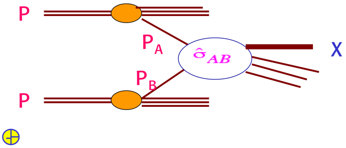


Proton structure in *ep* and *pp* Guido Altarelli, CERN 2015, see also arXiv:1211.5102



The basic experimental set ups for accelerator particle physics:

- no initial hadron (....LEP, ILC, CLIC)
- 1 hadron (....HERA, LHeC)
- 2 hadrons (Tevatron, LHC, FCC)



The pdf are defined in DIS

The theory of inclusive DIS is crystal clear

Thru the factorization "theorem" the pdf's and α_s determine the hadron collider rates

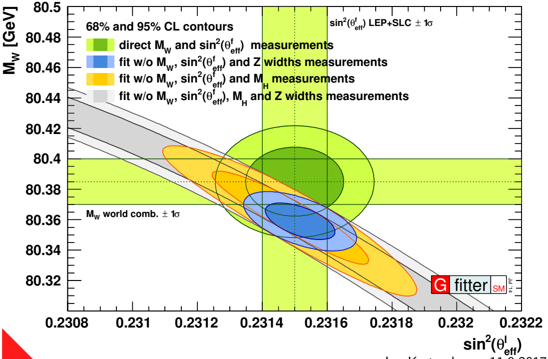
We often hear the statement that all the relevant info on pdf's can directly be obtained from the LHC without need of the LHeC

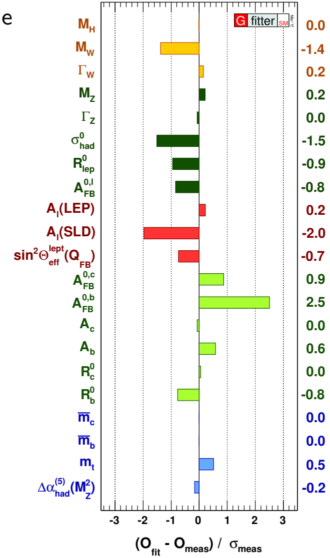
Not really true. Certainly not at the same level of precision

- Deep theoretical questions e.g. on non-perturbative effects and factorization breaking in *pp* – do not want to fold these into PDFs
- Illustrate limitations from limited PDF accuracy and issues we're facing in extracting PDFs from $pp/p\bar{p}$ data

Electroweak precision measurements

- Precise m_W, $\sin^2\theta_W$, m_t measurements test the overall consistency of the SM: m_W has the key-role in terms of precision currently, $\sin^2\theta_W$ (measured in Z/γ^* A_{FB}) – known LEP-SLD discrepancy
- *pp* collisions at LHC have the advantage of large numbers of W and Z/γ^* bosons produced (so far almost 10^9 W's), but the theoretical uncertainties are hard to control





Uncertainties on m_W, $\sin^2\theta_W$ [CMS-PAS-SMP-16-007, arXiv:1701.07240, ATL-PHYS-PUB-2014-015]

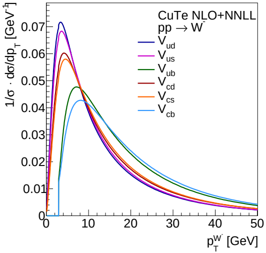
- PDF uncertainties are among the leading uncertainties in the first LHC precision measurements by CMS ($\sqrt{s} = 8$ TeV) and ATLAS ($\sqrt{s} = 7$ TeV)

$$\sin^2\theta_{\rm eff}^{\rm lept} = 0.23101 \pm 0.00036({\rm stat}) \pm 0.00018({\rm syst}) \pm 0.00016({\rm theory}) \pm 0.00030({\rm pdf}) \quad [\pm 0.00057({\rm unconstr. PDF})]$$

	Stat. Unc.	Muon Unc.	Elec. Unc.	Recoil Unc.	Bckg. Unc.	QCD Unc.	EW Unc.	PDF Unc.	Total Unc.
W^+	8.9	6.6	8.2	3.1	5.5	8.4	5.4	14.6	23.4
W^-	9.7	7.2	7.8	3.3	6.6	8.3	5.3	13.6	23.4
$W^\pm$	6.8	6.6	6.4	2.9	4.5	8.3	5.5	9.2	18.5

[MeV]

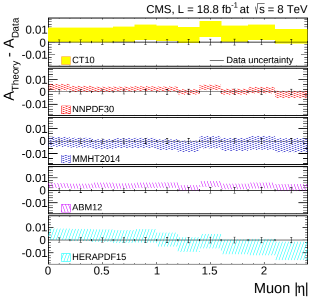
- Analyses made more challenging by limited PDF knowledge:
  - E.g. m_W measurement affected by modelling of $p_{T,W}$ spectrum and differences between light and heavy quarks – large uncertainty due to poorly known light-sea decomposition (u, d, s) and hence the $cs \to W$ fraction
  - Uncertainty on valence shape related to dilution and polarisation effects
- PDF uncertainties somewhat reduced using "in-situ" constraints in the analyses: W^+ vs. W^- consistency, A_{FB} vs. $m_{\ell\ell}$–$y_{\ell\ell}$

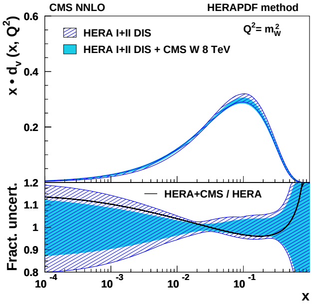


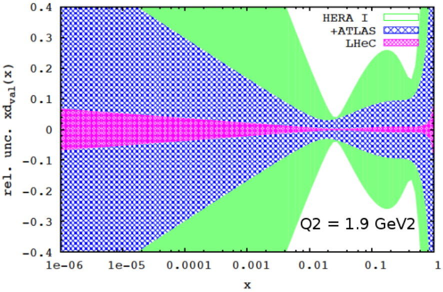
Valence quarks (at lower x)

[EPJC 76 (2016) 469, LHeC CDR]

- Valence quarks are prime example, where LHC pp (and TeVatron $p\bar{p}$) data add to the PDF knowledge, access especially through W^+/W^- production and their asymmetry
- Improvement over HERA DIS incremental: factor $1.2 \sim 2.0$ with (Run 1) measurements at $\sim 0.5 - 1.0\%$ level – same as uncertainty on DY theory at NNLO
- LHeC NC and CC measurements will improve knowledge by large factor

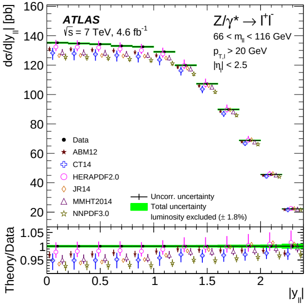


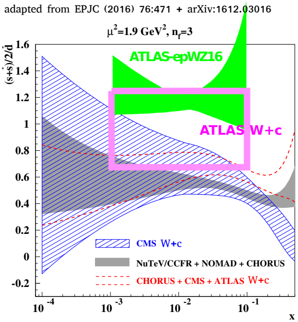


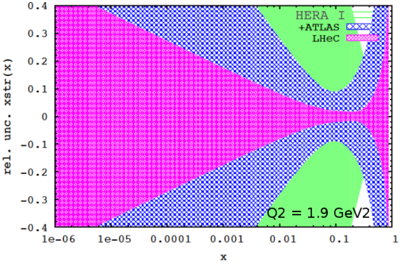


Low-x sea quarks

- Flavour composition of low-x sea quarks (u, d, s) not well constrained by HERA DIS
- Knowledge fro νN "di-muon", and more recently LHC W+charm and inclusive Z
  $\rightarrow$ large strangeness at lower x?
- Further improvements limited: nuclear effects, (N)NLO theory
- LHeC CC DIS with charm tag would provide good measurement of s and $\bar{s}$ quarks (and test $\bar{u}/\bar{d}$)







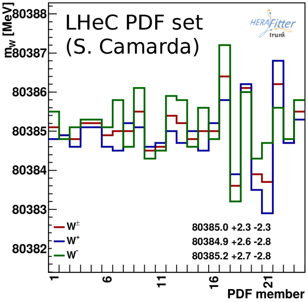
LHC m_W with LHeC PDFs

[Stefano Camarda, ATL-PHYS-PUB-2014-015, PRD 91 (2015) 113005]

- Generator-level study of PDF uncertainty following methodology of ATL-PHYS-PUB-2014-015 (p_T^ℓ spectrum only, no categorisation or optimisation)
- Using PDFs as expected to be extracted from LHeC NC and CC cross-section data reduces uncertainty reduced from $10 \sim 20$ MeV level to ~ 2.5 MeV – factor $4 \sim 10$
- Precision PDFs will allow experimental categories to be used to constrain other effects than PDFs
- Similar improvement can be expected in PDF-related uncertainty on $\sin^2\theta_W$ extraction from *pp* data

	CT10nlo	MSTW2008CPdeutnlo	NNPDF30_nlo_as_118
W^+	+18 -22	+11 -10	+8 -10
W^-	+18 -23	+11 -10	+8 -9
$W^\pm$	+14 -18	+7 -7	+6 -5

ATL-PHYS-PUB-2014-015



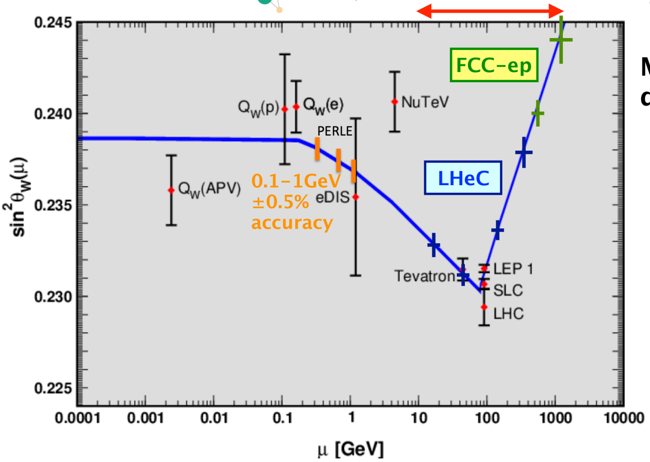
LHeC $\sin^2\theta_W$ and other EWK measurements

[D. Britzger et al]

- High luminosity *ep* data directly constrains electroweak observables like m_Z, m_W, $\sin^2\theta_W$ or the light-quark axial and vector couplings v_q, a_q $\rightarrow$ unique to *ep* data

PERLE CDR, Arduini et al, to be published
ICFA BeamNewsletter 68 (January 2016)

LHeC CDR, J.Phys. G39, 075001 (2012)



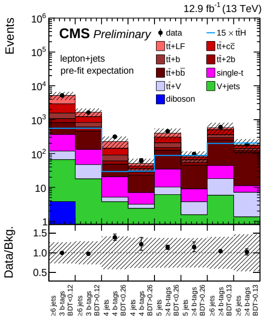
MSbar definition

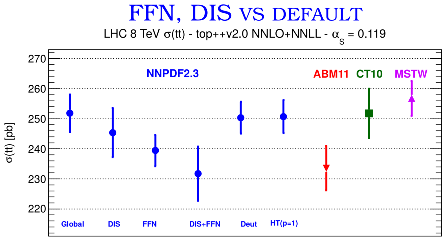
→ **probe large range of scale dependence**

Heavy flavour

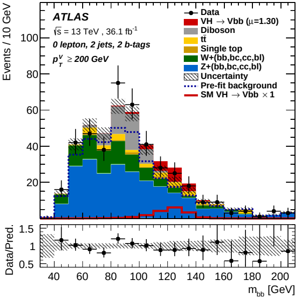
[arXiv:1708.03299, CMS-PAS-HIG-16-044, CMS-PAS-HIG-16-038]

- *pp*: strong production through or in association with heavy-flavour quarks important for many topics, e.g. as background to $VH(\to bb)$ and $t\bar{t}H(\to bb)$ (similarly for searches focusing on "3rd generation")
- *ep*: treatment of heavy flavour contribution to inclusive DIS (Fixed Flavour Number scheme FFN, General mass variable flavour number scheme GM-VFNS) has a significant impact on PDF fits





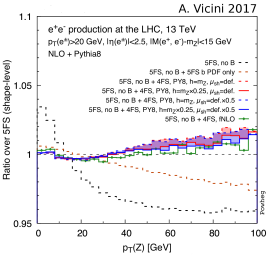
S. Forte, 2014

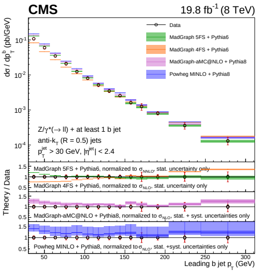


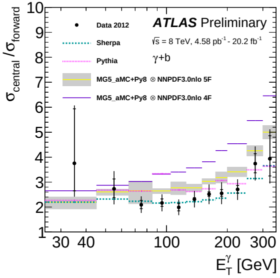
Heavy flavour

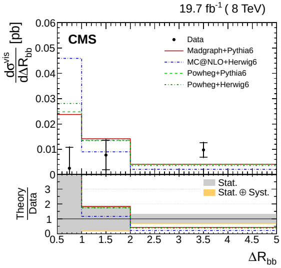
[arXiv:1611.06507, STDM-2017-02, EPJC 76 (2016) 379, A. Vicini]

- Inclusive pp calculations often not fully considering effect of heavy flavour contributions, e.g. recent efforts to improve the inclusive Z p_T calculation by matching 4 and 5 Flavour Schemes (4FS, 5FS) — relevant e.g. for W mass
- Data on heavy flavour production typically (but not always) better described by 5FS, additional complication from "gluon splitting" $g \to bb$



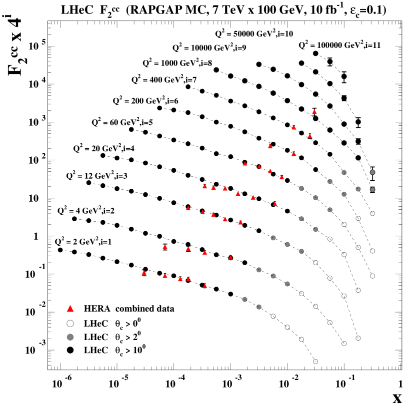


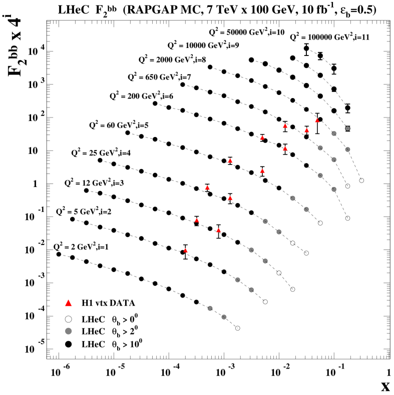




F_2^{cc} and F_2^{bb} at LHeC

- LHeC measurement of charm and beauty contribution to DIS covers large kinematic range from threshold to far above – can settle debates on DIS FNS with data
- Allows precision measurement of charm-quark mass to ± 3 MeV (PDG: ± 25 MeV, HERA: ± 60 MeV)
- *ep* will not settle *pp*-specific problems, but it will help to put treatment of heavy-flavour production on more solid footing
- LHeC will also be able to explore the top-quark PDF for first time

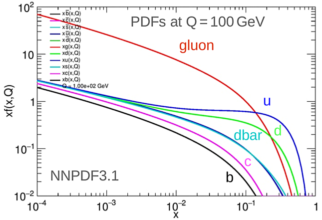




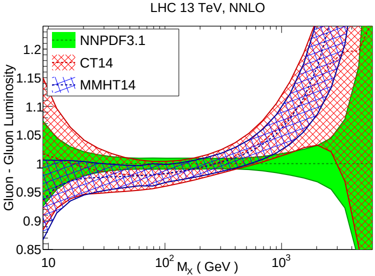
Gluon density

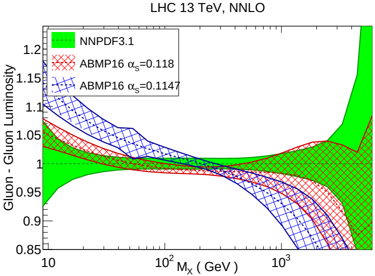
[arXiv:1706.00428, LHeC CDR]

- Half of the proton is gluon, many *pp* predictions affected: $t\bar{t}$, V+jets and (of course!) $gg \to H$
- Coupled to α_s – discussed later
- Uncertainty on gg luminosity:
  - large at low and high mass
  - At intermediate mass ($\sigma(gg \to H)$): 1.9% (PDF4LHC15) – or more?



- LHeC determines gluon just from DIS scaling violations with good precision
- Impact of LHC data on gluon currently significant – different data consistent and reliable?





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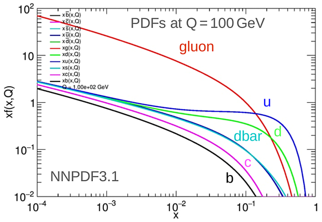

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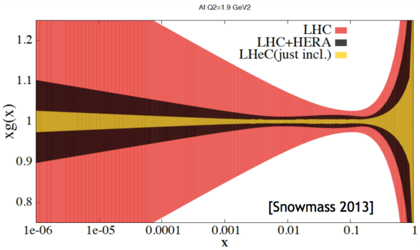
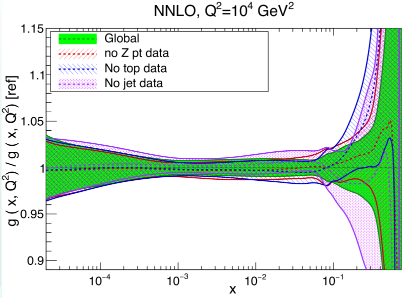


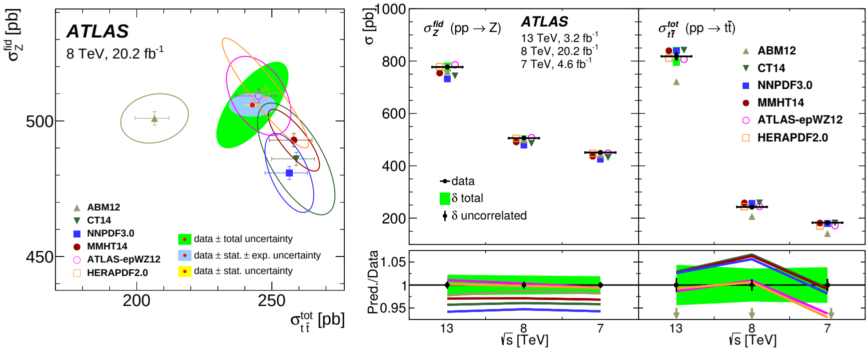
LHC = current LHC W, Z and jet data



Gluon density - $t\bar{t}$

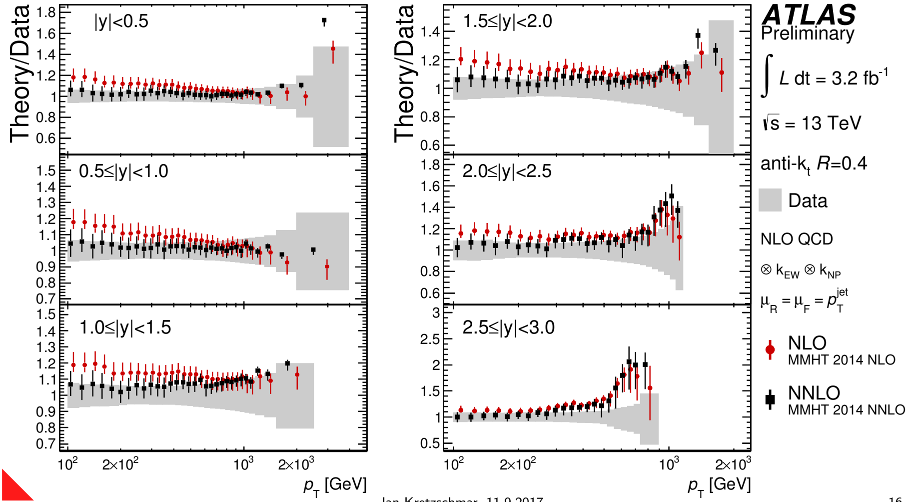
[JHEP 02 (2017) 117]

- top production now predicted at NNLO and routinely included in PDF fits
- Correlation between integrated Z and $t\bar{t}$ tests $q\bar{q}$ vs. gg luminosties
- CT14/NNPDF3.0/MMHT14 PDFs are systematically shifted, while HERAPDF and ATLAS-epWZ12 (HERA DIS + ATLAS W, Z) do better; ABM12 different for $t\bar{t}$



Gluon density - jets

- Jet production in hadron collision has been source of information on gluon (included by several groups with NLO predictions in NNLO PDF)
- Now NNLO corrections known: apparently good behaviour for $\mu = p_T^{\mathrm{jet}}$, however large change at $\mu = p_T^{\max}$; non-negligible uncertainty on non-perturbative corrections



Gluon density - jets

[ATLAS-CONF-2017-048, PRL 118 (2017) 072002]

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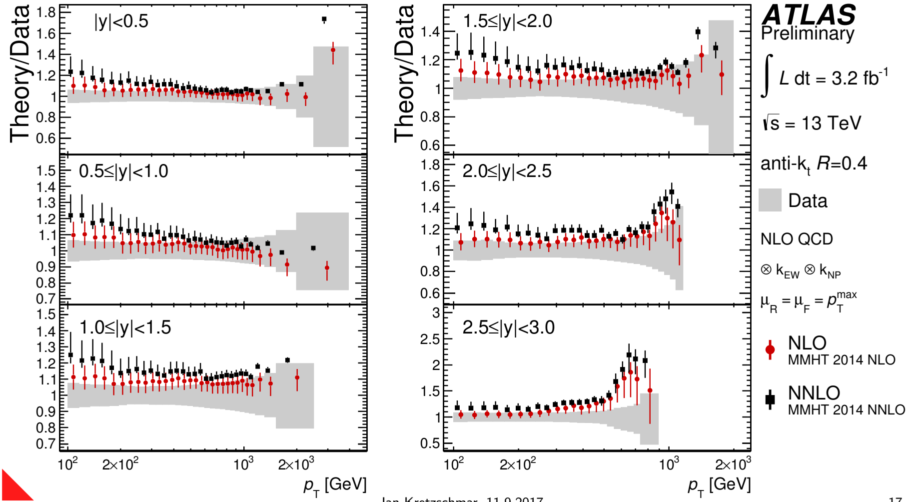
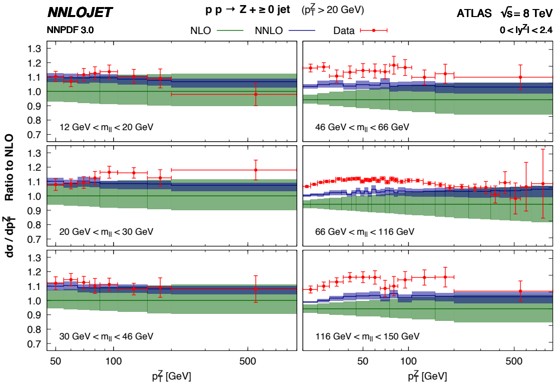
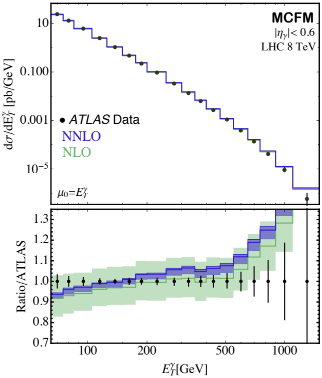


Gluon density - high p_T Z and γ

[JHEP 07 (2016) 133, PRL 118 (2017) 222001]

- $Z \to \ell\ell$ and isolated γ measurable to $0.5 \sim 2\%$ precision at high p_T – information on qg luminosity
- NNLO corrections recently completed: large improvement on scale uncertainty, but also large correction, NNLO needed to fit the data with good χ^2

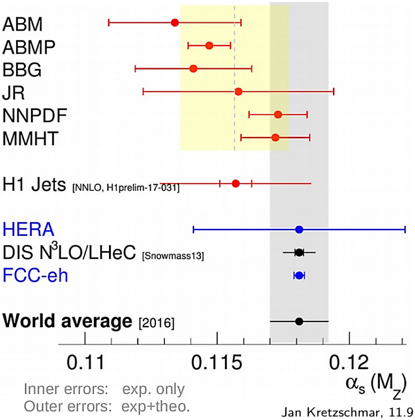


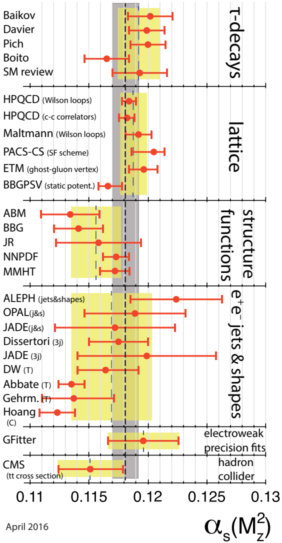


Strong coupling α_s

[LHeC CDR, PDG, D. Britzger]

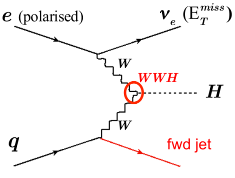
- The least well measured fundamental coupling constant of the SM at $1 \sim 2\%$ precision – beyond the fundamental interest, a significant uncertainty e.g. on $\sigma(gg \to H)$, pp can measure scale dependence only
- LHeC measurement with N^{3}LO theory can reach $\pm 0.1\,(\text{exp.}) \pm 0.5\,(\text{theo.})[\%]$



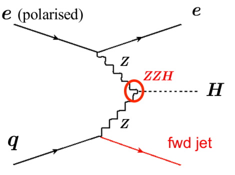


Measurement of Higgs properties in *ep* [LHeC CDR, U. Klein, M. Tanaka et. al]

- Precision measurements of H coupling to fermion and bosons to percent level (e.g. to test level of deviations predicted by SUSY models)
- Higgs is produced in *ep*: pure Vector Boson Fusion (VBF) – CC or NC
- With $\sqrt{s} = 1.3$ TeV and $1\,\mathrm{ab}^{-1}$ sizeable cross section (200 fb), Event counts:



Charged Current



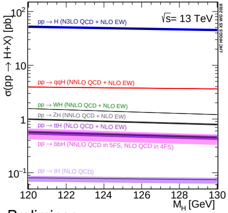
Neutral Current

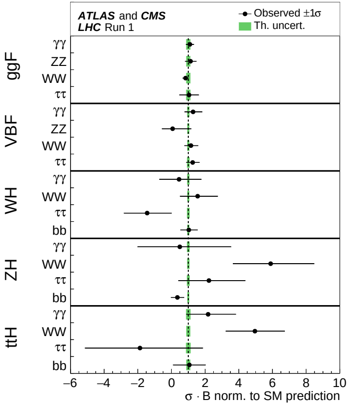
LHeC Higgs		CC (e^-p)	NC (e^-p)	CC (e^+p)
Polarisation		-0.8	-0.8	0
Luminosity [ab^{-1}]		1	1	0.1
Cross Section [fb]		196	25	58
Decay	BrFraction	$N^H_{CC}\ e^-p$	$N^H_{NC}\ e^-p$	$N^H_{CC}\ e^+p$
$H \to b\bar{b}$	0.577	113 100	13 900	3 350
$H \to c\bar{c}$	0.029	5 700	700	170
$H \to \tau^+\tau^-$	0.063	12 350	1 600	370
$H \to \mu\mu$	0.00022	50	5	–
$H \to 4l$	0.00013	30	3	–
$H \to 2l2\nu$	0.0106	2 080	250	60
$H \to gg$	0.086	16 850	2 050	500
$H \to WW$	0.215	42 100	5 150	1 250
$H \to ZZ$	0.0264	5 200	600	150
$H \to \gamma\gamma$	0.00228	450	60	15
$H \to Z\gamma$	0.00154	300	40	10

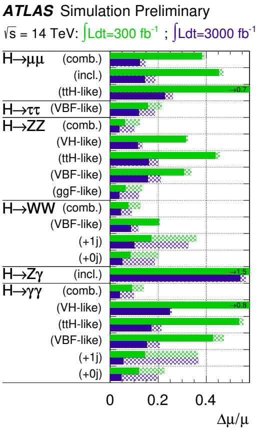
- How does this compare to *pp*?

H in pp

- Access to production modes ggH, VBF, WH, ZH, $t\bar{t}H$
- ggH dominates with large cross section – often small S/B and significant theory uncertainty ($\sim 6\%$ on total ggH @ N^{3}LO from theory, PDF, α_s)
- Disentangling H production and decay not trivial, many combinations are not directly accessible

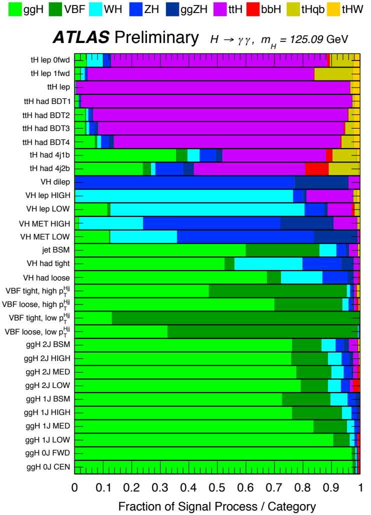


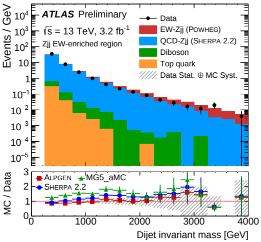


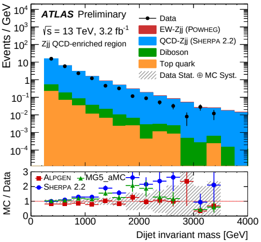


Disentangling H production modes in pp [ATLAS-CONF-2017-045, STDM-2016-09]

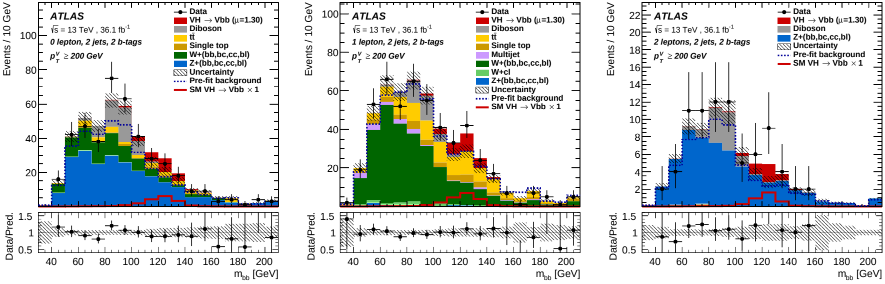
- Example $H \to \gamma\gamma$ categorisation: only some production modes are easily separated
- Separation of VBF from $gg \to H$ is non-trivial – need to "tag" with high m_{jj} dijet system:
  - Best S/B in extreme phase space
  - Experimental issues with forward jets (pileup)
  - $gg \to Hjj$ "contamination" in VBF categories
  - Cannot disentangle $WW \to H$ and $ZZ \to H$
- What can go wrong in modelling $gg \to Hjj$ in VBF-like phase space? Measurement of VBF Z observes indeed large mismodelling of strong Zjj background – correction via "control region"







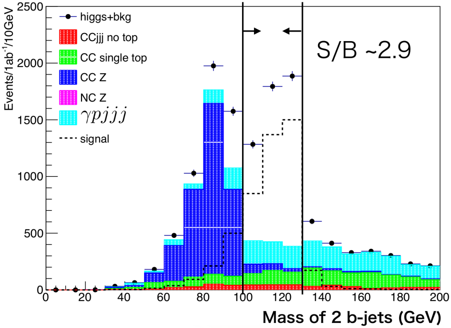
- Recently ATLAS and CMS presented evidence for $H \to bb$ in VH: $3.5/3.8\sigma$
- Sensitivity best at large p_T^V: theory uncertainty on prediction currently quoted as 17% by ATLAS
- Similar effect present on ggH measurements at high p_T^H: S/B improved – theory uncertainty increased

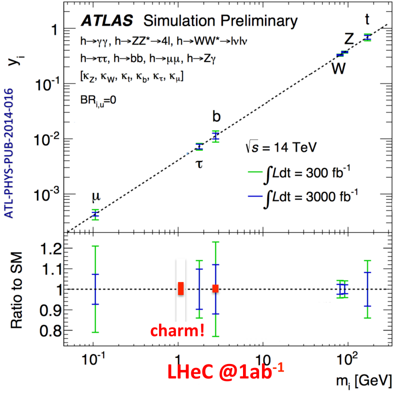


$H \to bb$ in ep

[U. Klein, M. Tanaka et. al]

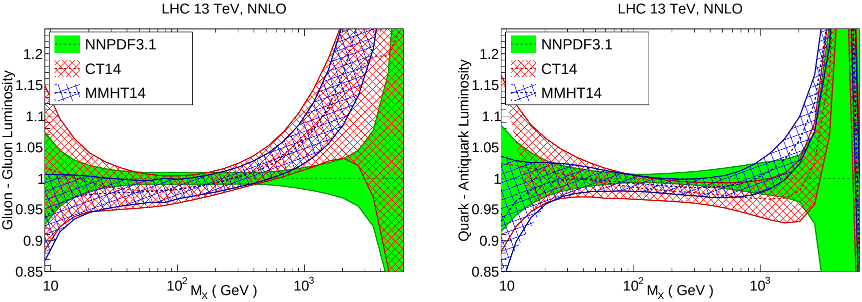
- $ep \to WW \to H \to bb$ simulation study with MadGraph+Pythia + Delphes (ATLAS/CMS-like detector): high $S/B \sim 2.9$ with moderate cuts; unambiguous production process (VBF – lowest theoretical uncertainty)
  $\Rightarrow \sim 1\%$ on $H \to bb$ coupling can be reached
- Simulation study on $WW \to H \to cc$ gives 4% on $H \to cc$ coupling
- High luminosity opens possibilities also for rarer channels, e.g. NC production ($ZZ \to H$) and other decays





High-mass searches in *pp*

- High parton luminosity uncertainties grow rapidly starting from $1 \sim 3$ TeV
- Mitigated by use of data-driven procedures, control regions, sidebands: dijet search able to "fit" m_{jj} spectrum close to kinematic limit; in contrast $Z' \to \ell\ell$ relies on predictions to interpret data in tails – higher PDF uncertainty means less discovery potential



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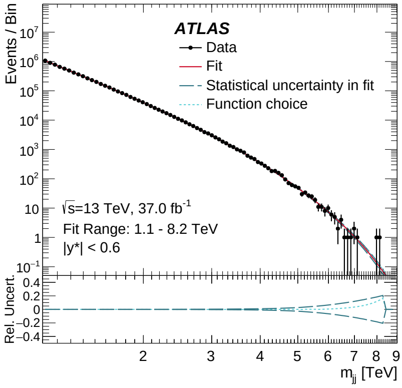
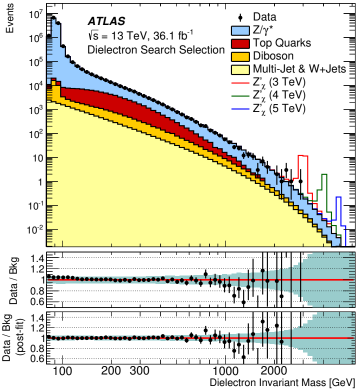
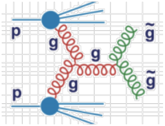
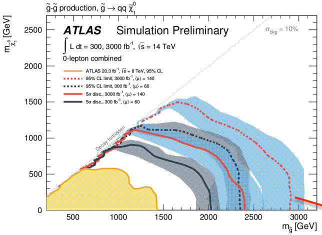


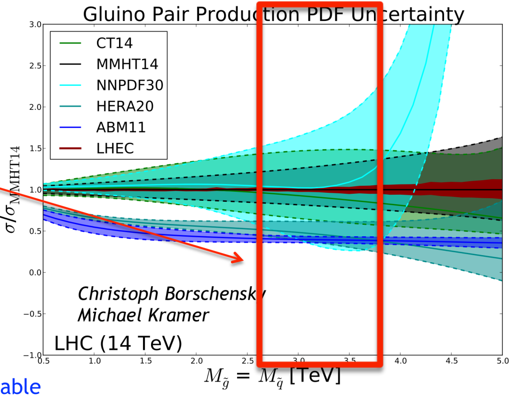


Gluino pair-production *pp*

- Gluino pair-production is gluon-induced: very large uncertainties in interesting region 2 $\sim$ 3 TeV; effect similar in size to gain $300 \rightarrow 3000\,\mathrm{fb}^{-1}$
- Improved LHeC gluon PDF makes uncertainty negligible





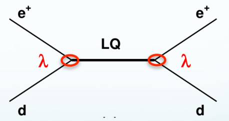


- Studies updated with modern PDF sets!
  - M(squark)=M(gluino)=μ_R=μ_F
  - LHeC PDF uncertainties unchanged
  - Normalized to MMHT14

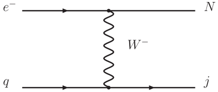
Use prescription from J. Rojo to avoid negative x-section at at high masses for NNPDF30nlo → x-section calculation unstable

Direct searches in *ep*

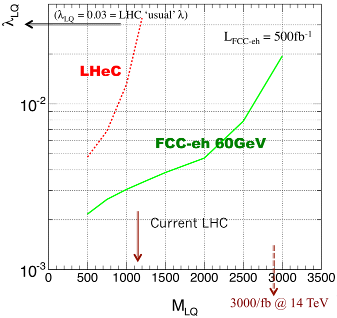
[M. D'Onofrio, G. Azuelos for the BSM group]

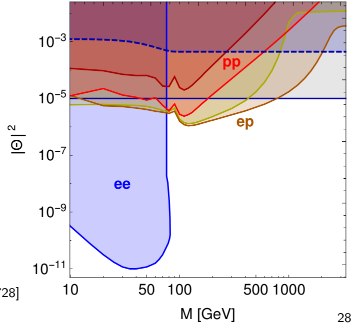


- Ideal to search and study properties of new particles with couplings to electron-quark like leptoquarks, *eeqq* contact interactions, R-parity violating SUSY
- Anomalous top-quark couplings and EWK SUSY being studied
- Sterile neutrino neutrino search with complementary in *ee*, *ep* and *pp* – *ep* (LHeC and FCC-eh) adds unique discovery potential
- More discussion in the BSM session this afternoon



[arXiv:1612.02728]





Conclusion

- Almost all LHC *pp* analyses are affected by limited knowledge on proton PDFs:
  - Improvement possible using LHC data, but mostly "incremental" or data already as precise as theory
  - Next generation *ep* data from LHeC guarantees a qualitative jump and will thus solve one (of the many) issues of complex *pp* analyses and their interpretation
- Several unique ep analyses, showed only a few:
  - Higgs: $< 1\%$ precision on $WW \to H \to bb$ and several other possible %-level opportunities like $H \to cc$
  - Electroweak precision $\sin^2 \theta_W$ vs. scale and others
  - Unique reach in searches like sterile neutrinos