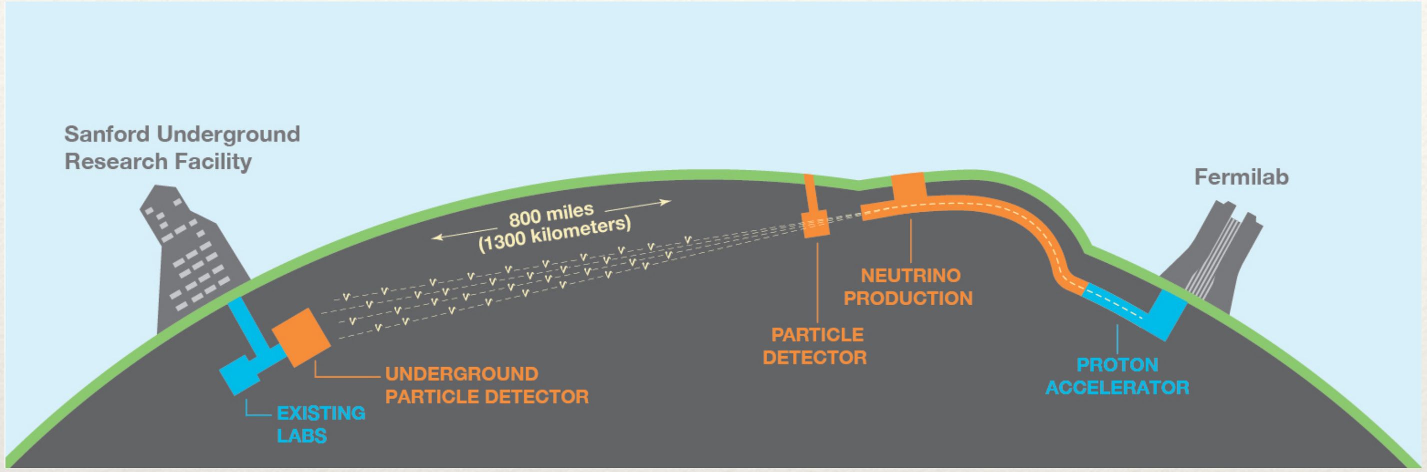
Vision for the future of strong interactions and DIS

Keith Ellis
IPPP, Durham

…25th in a series of International Workshops covering an eclectic mixture of material related to Quantum Chromodynamics and DIS as well as a survey of the hottest current topics in high energy physics.

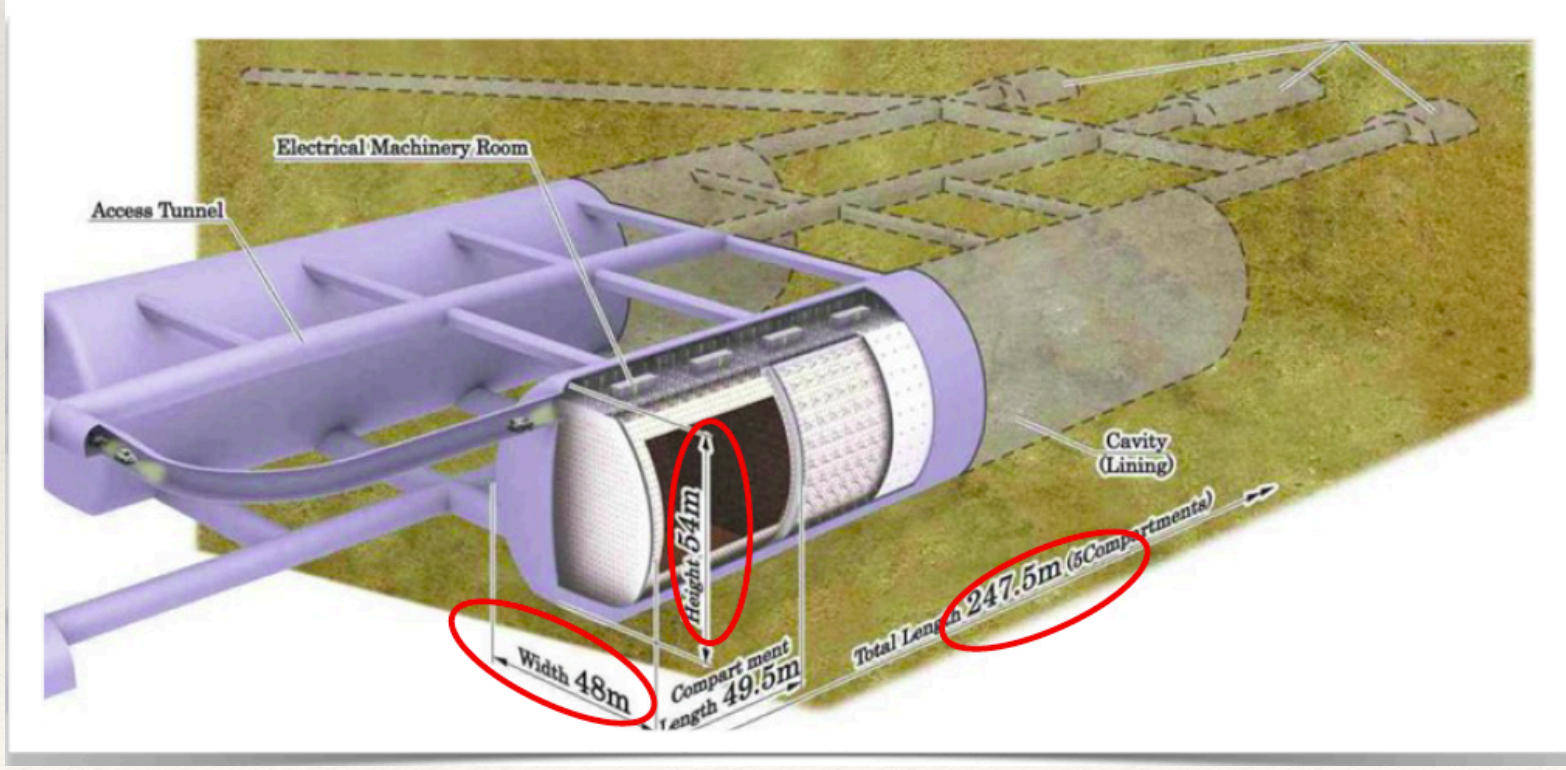
Shallow Inelastic Scattering (and Quasi Elastic Scattering).

A new generation of ν experiments



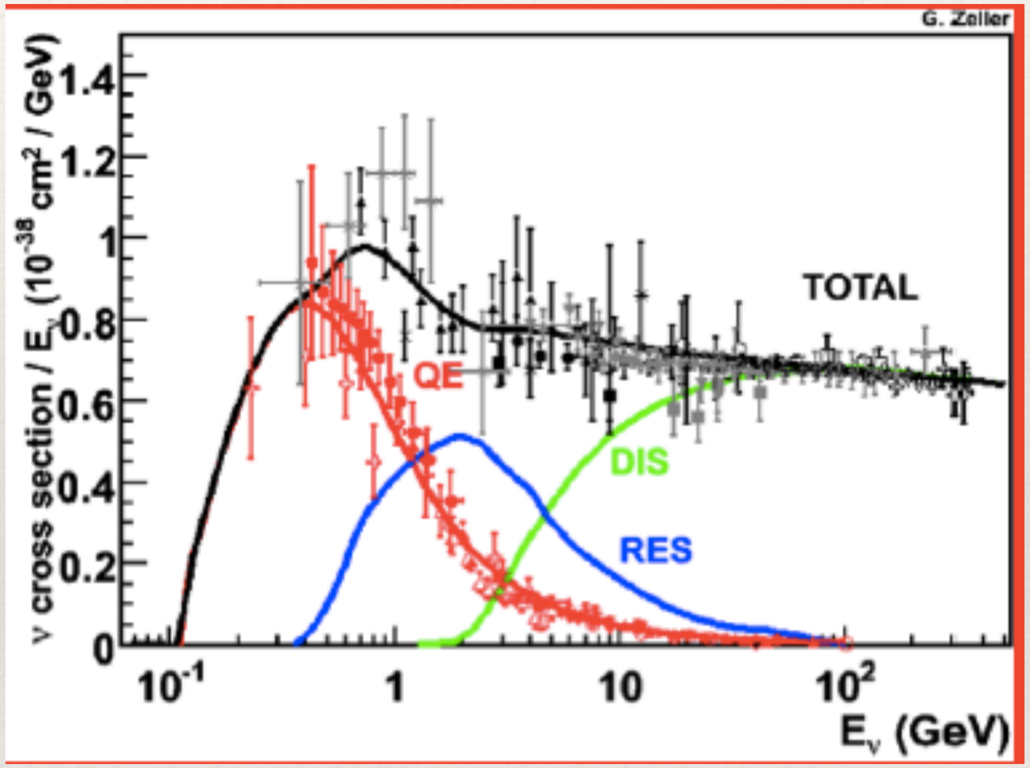
- DUNE: 2024 start of data-taking, 2026 beam and near detector available.

- HyperK experiment available ~2025

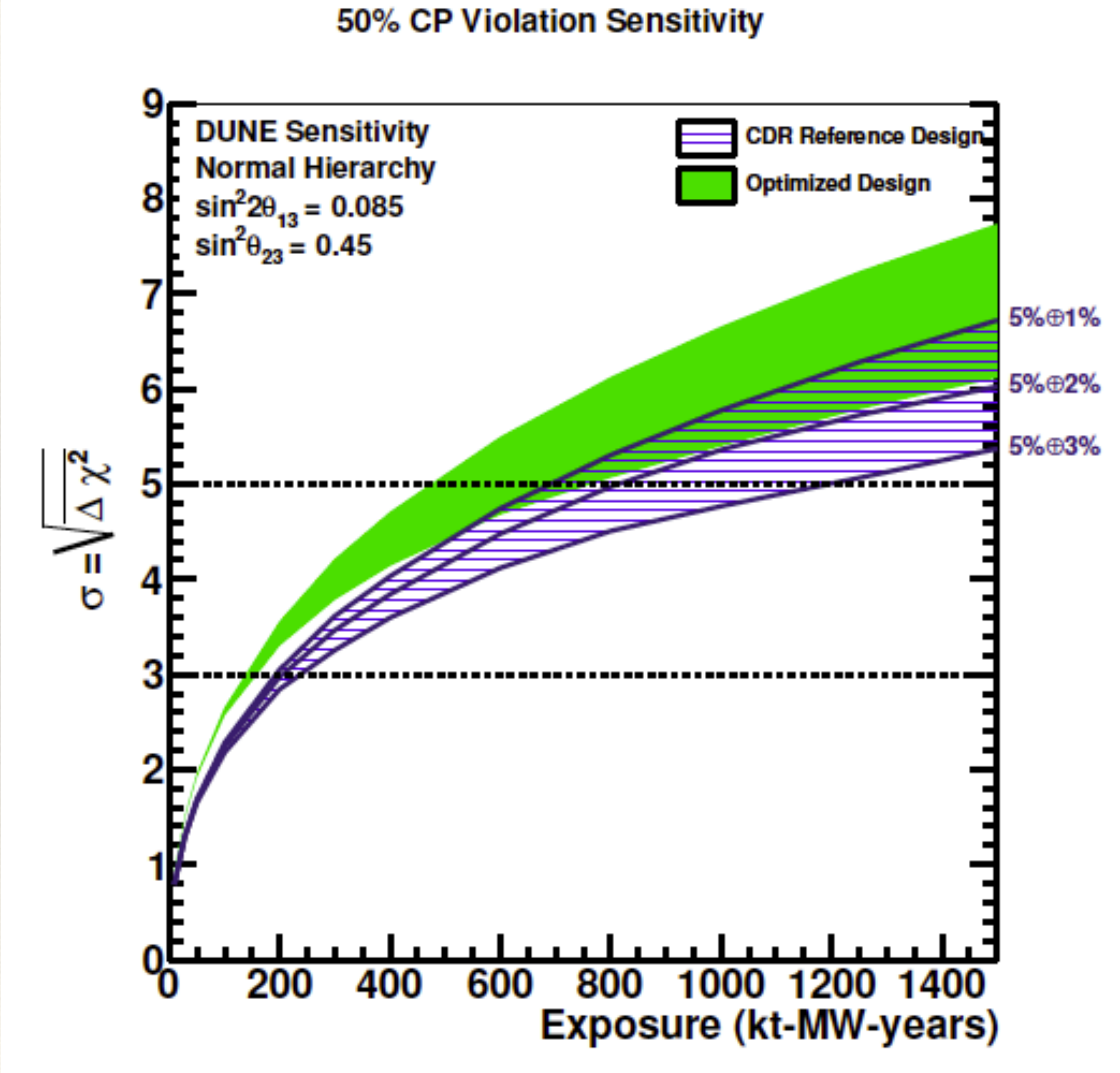


Extra challenges in this region

- Beam energy E_ν~0.5-1GeV (T2K) and E_ν~2-3GeV (DUNE).
- Beam energy is not known (event-by-event). In particular one is trying to reconstruct the beam energy by looking at the final state.
- Scattered products traverse the nucleus before appearing in the detector
- Exclusive description of the final state required, especially, neutron production, pion production, nuclear breakup.
- Unoscillated samples measure $\boldsymbol{\nu_\mu}$ not $\boldsymbol{\nu_e}$ scattering.



Effect of uncertainty on discovery potential



Dune CDR, arXiv 1512.06148

- Shows the effect of electron-neutrino cross section normalisation uncertainty on the discovery potential for CP violation for 50% of the values of the CP violating parameter.
- Theoretical work can save years!

Future developments

- Upcoming NuSTEC White Paper: defines and provides context for thinking about this problem.

NuSTEC White Paper: Status and Challenges of Neutrino-Nucleus Scattering

L. Alvarez-Ruso,[1] M. Sajjad Athar,[2] M. B. Barbaro,[3] D. Cherdack,[4] M. E. Christy,[5] P. Coloma,[6] T. W. Donnelly,[7] S. Dytman,[8] R. J. Hill,[9,10,6] P. Huber,[11] N. Jachowicz,[12] T. Katori,[13] A. S. Kronfeld,[6] K. Mahn,[14] M. Martini,[15] J. G. Morfín,[6] J. Nieves,[1] G. Perdue,[6] R. Petti,[16] D. G. Richards,[17] F. Sánchez,[18] T. Sato,[19,20] J. T. Sobczyk,[21] and G. P. Zeller[6]

- IPPP/NuSTEC Workshop 18-20 April in Durham.

IPPP/NuSTEC topical meeting on neutrino-nucleus scattering

http://conference.ippp.dur.ac.uk/event/583/

18-20 April 2017
Europe/London timezone

IPPP Durham

Search

- Obviously lots of scope for experimental, theoretical, and Monte Carlo work on Neutrino-Nucleus scattering.

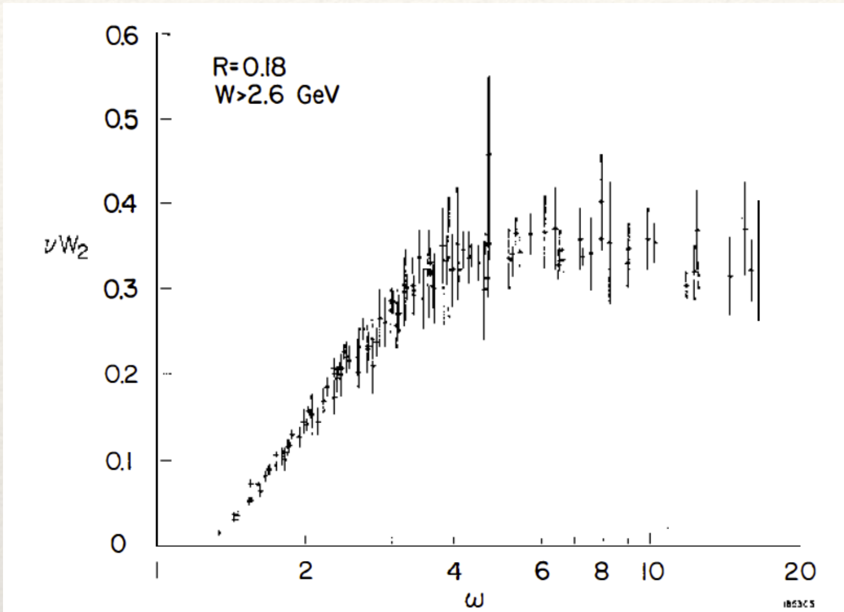
The goals of the workshop will be to:

- Take stock of the current status of , νA scattering data, the nuclear and particle theory through which it is understood and the phenomenological description of the cross sections and hadronic final states;
- Discuss the programme of measurement, theory and phenomenology required to develop an understanding commensurate with the future neutrino-physics programme; and to
- Evaluate the path towards "global fits" that can be used to make reliable predictions of neutrino-nucleus scattering.

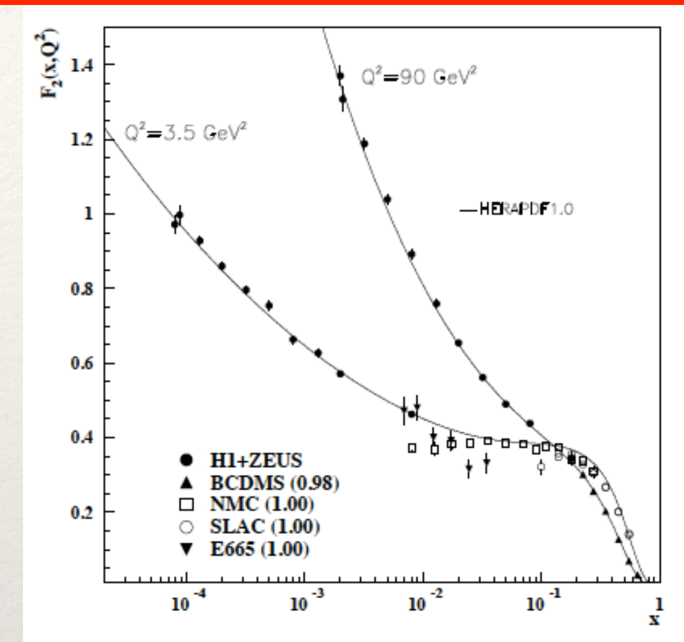
http://conference.ippp.dur.ac.uk/event/583/

50 years of parton dynamics

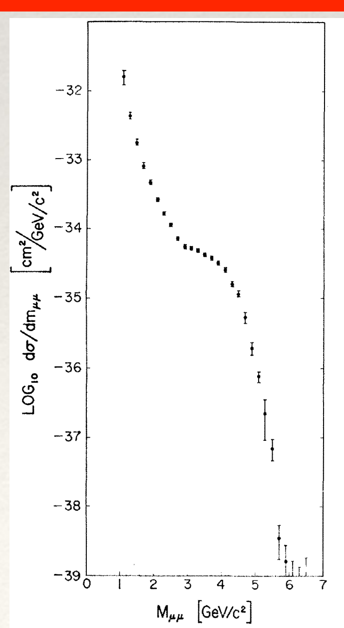
"Point-like" structures discovered within protons

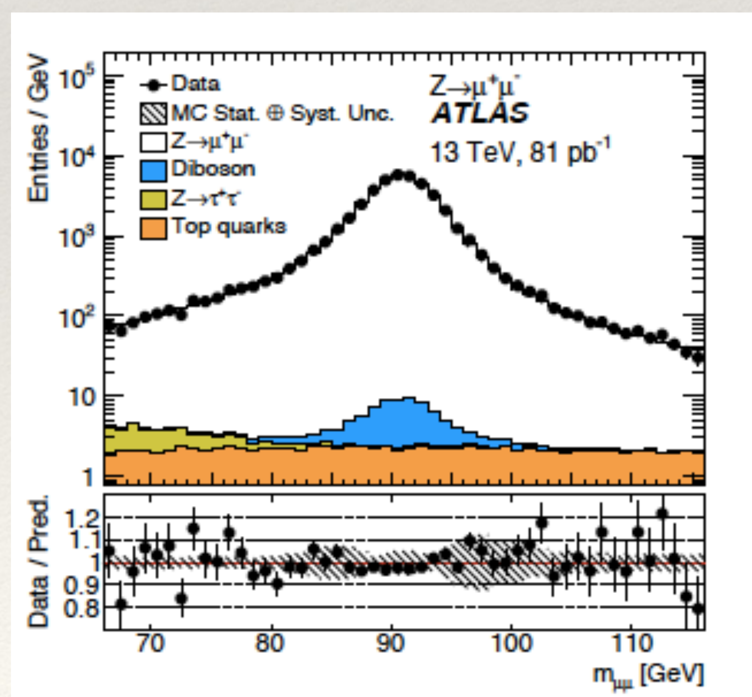


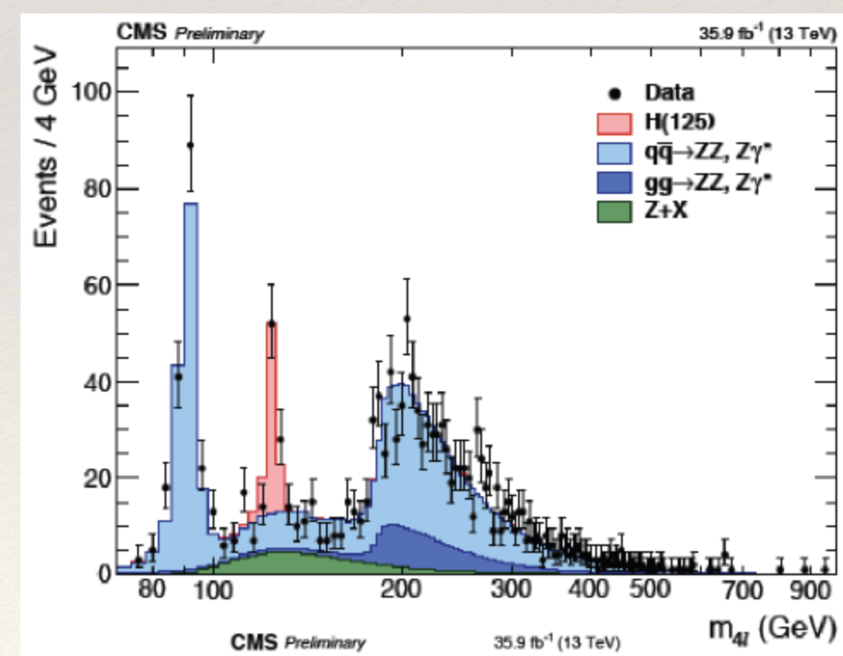
....which however change with the resolution



...partons can interact in hadron-hadron interactions







...to produce unknown bosons

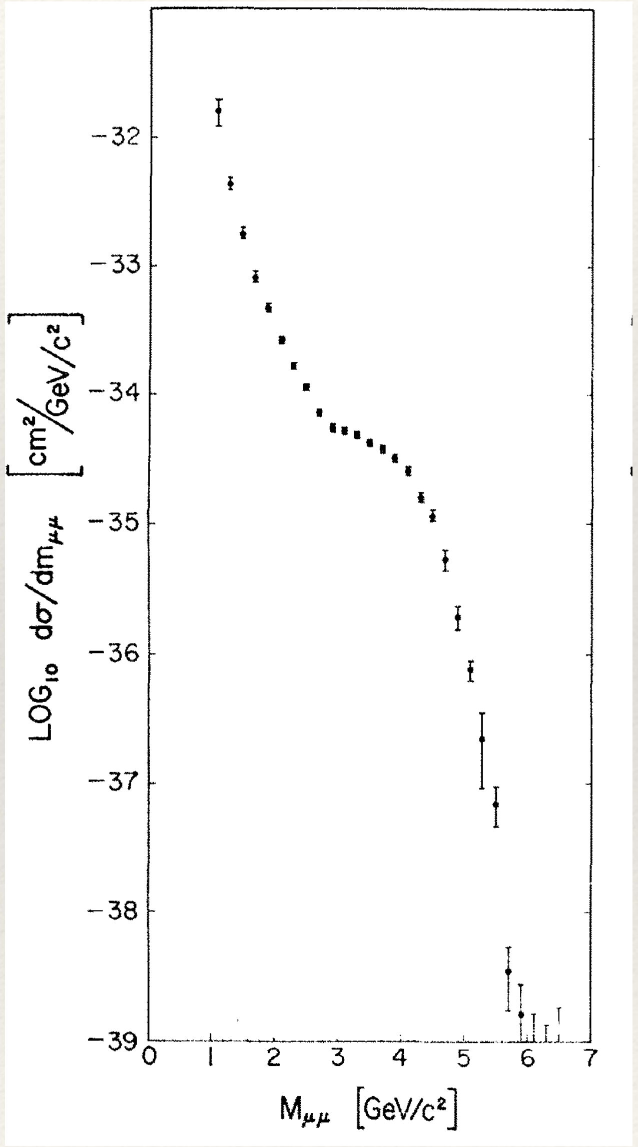
...as well as known ones

What are (my) motivations for this field?

- Observing a quantum field theory at work both in strong and weak interaction regimes. Detailed study of the parton structure of hadrons.
- The engineering importance: in order to use hadrons to probe the physics of the other interactions we must know them in exquisite detail.
- The field is more robust because of these two motivations.

Both motivations were present from the beginning

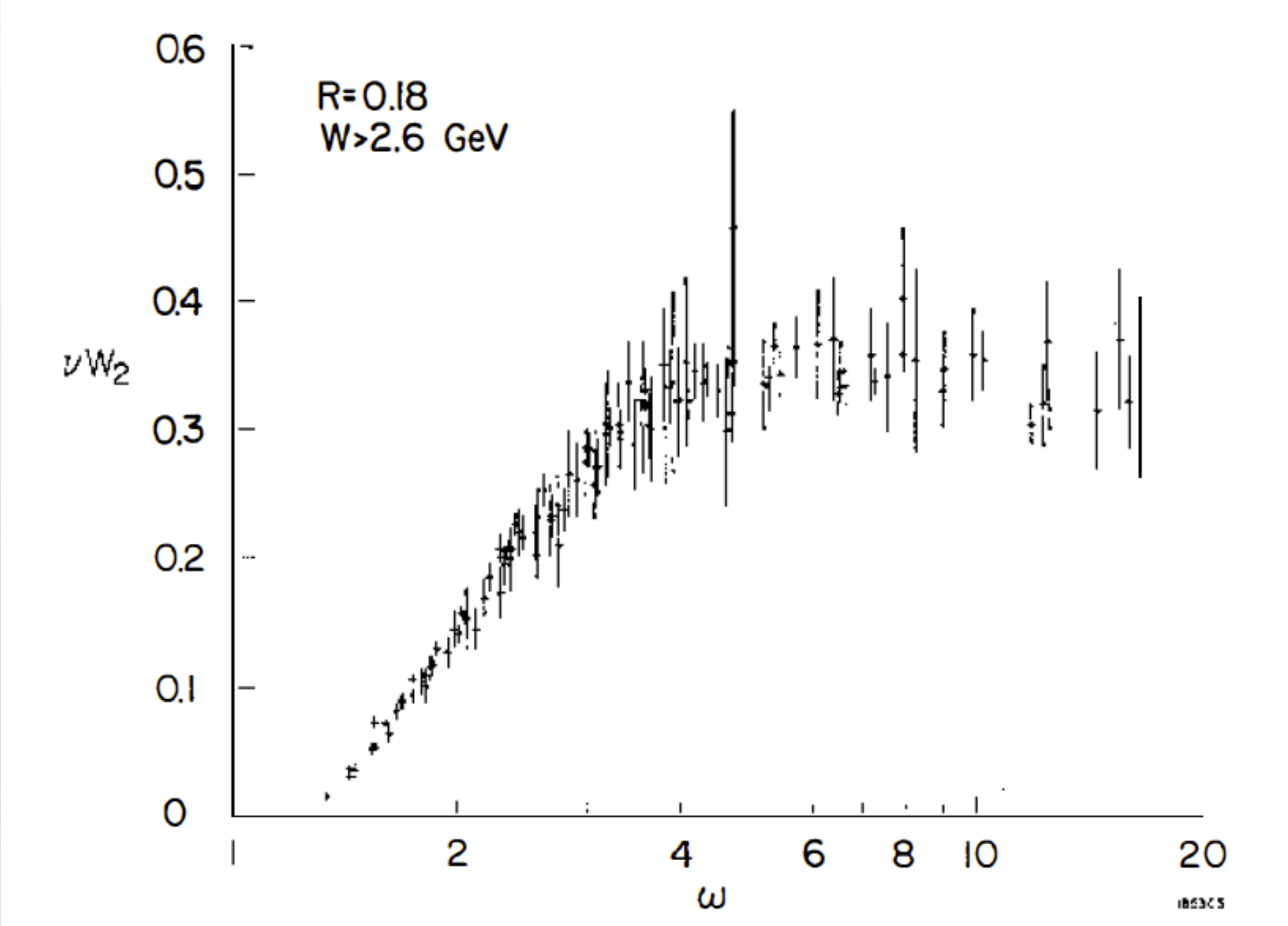
- "It has been noted that the production cross section for virtual photons is related to the probability of production of charged vector mesons $W^{\pm}$ of the same mass." J. Christenson et al., PRL25, (1970)1526.
- Part of the motivation to investigate Drell-Yan pairs was to experimentally bound the cross section for possible intermediate vector bosons.



Parton dynamics is front and centre.

- A direct and lasting connection between the first experiments on DIS and the most important topics at the LHC today.
- Discovery of approximate scaling behaviour, establishment of partonic degrees of freedom, discovery of gluons, discovery of asymptotic freedom, creation of a systematically improvable framework for calculation……all the way to the Higgs cross section.
- The LHC is a parton dynamics machine.

You've never had it so good!

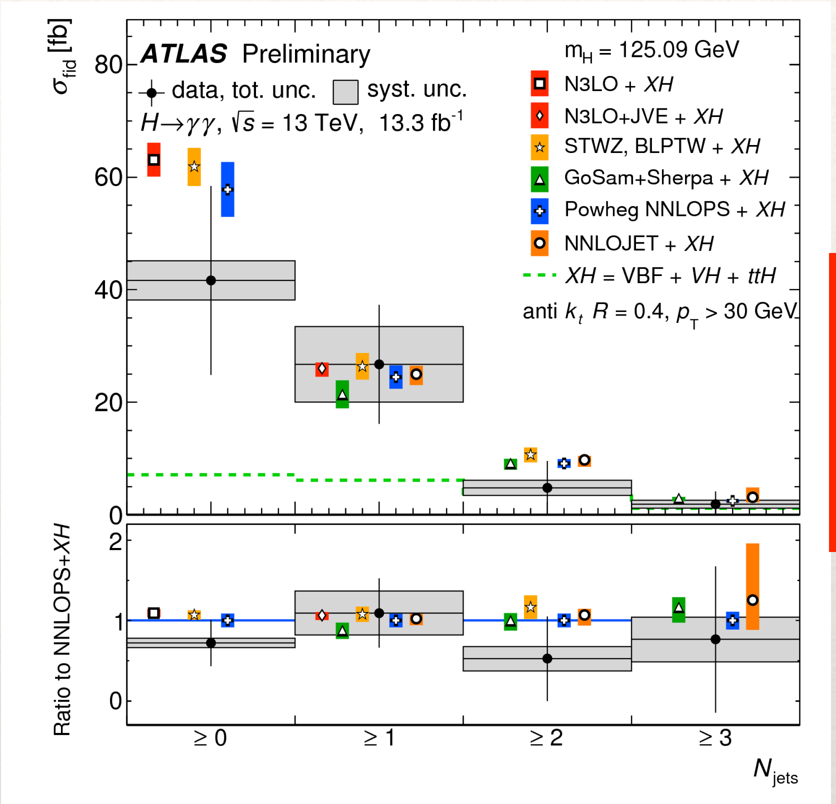


Kendall & Friedman, Annual Review of Nuclear Science

Vol. 22:203-254 (Volume publication date December 1972)

We now live in a QCD, parton-centric world

- The most significant result of Run I of the LHC is the discovery of the Higgs boson in 2012.
- Higgs bosons (produced predominantly by gluon fusion) radiate copiously, thus emphasising the importance of partonic degrees of freedom and radiative corrections.
- Our field (DIS, Parton dynamics, QCD) is front and centre in the physics program of the LHC.



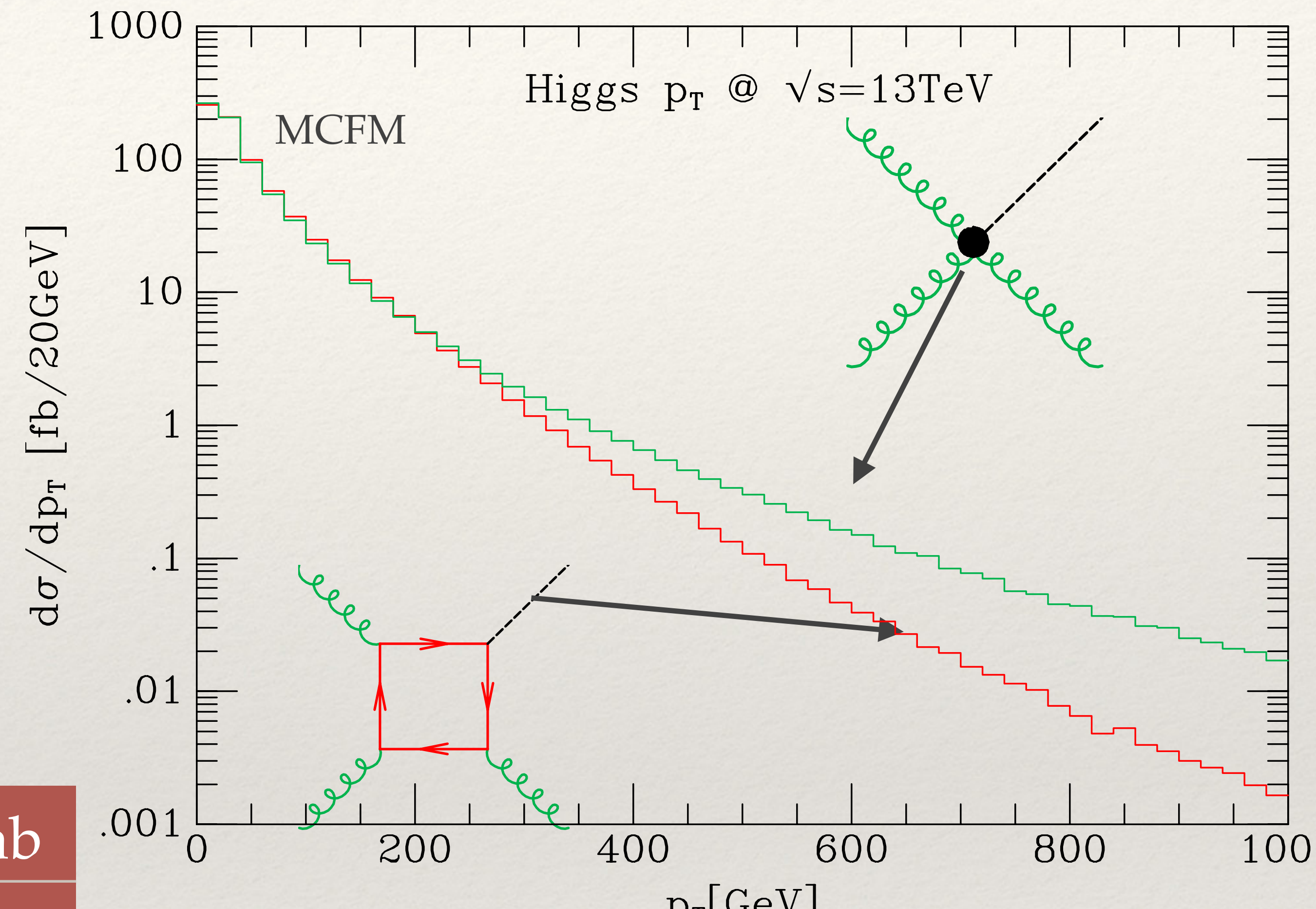
2/3 of Higgs bosons accompanied by jet activity

Corroborated by theory at √s=13 TeV

Process	α_s^2	α_s^3	α_s^4	α_s^5
$\sigma(pp \to H)$ pb [1]	13	30	40	43
$\sigma(pp \to H+$ jet) pb[2]		10	15	18
$\sigma(pp \to H+$ 2 jet) pb[3]			3.5	5.1
$\sigma(pp \to H+$ 3 jet) pb[3]				1.6

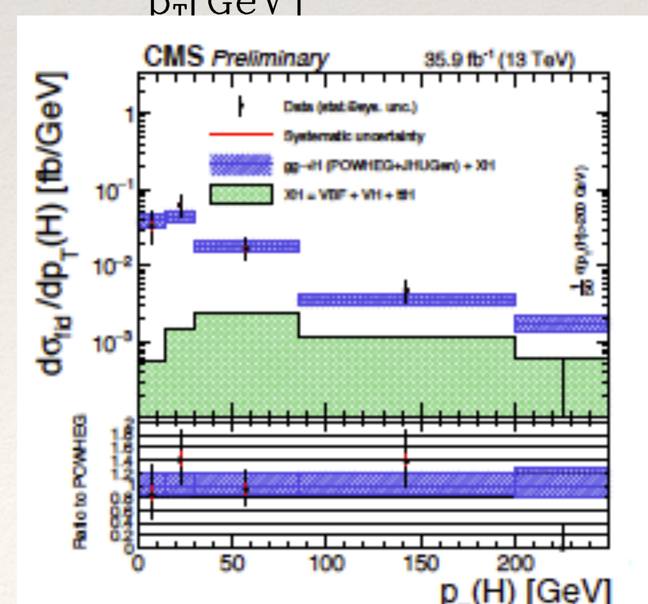
Higgs-pt

- High-pt Higgs gives us information about the particles flowing in the loop.
- p_T values for an observable cross section given below.
- Reach depends on which decay channels are useable.



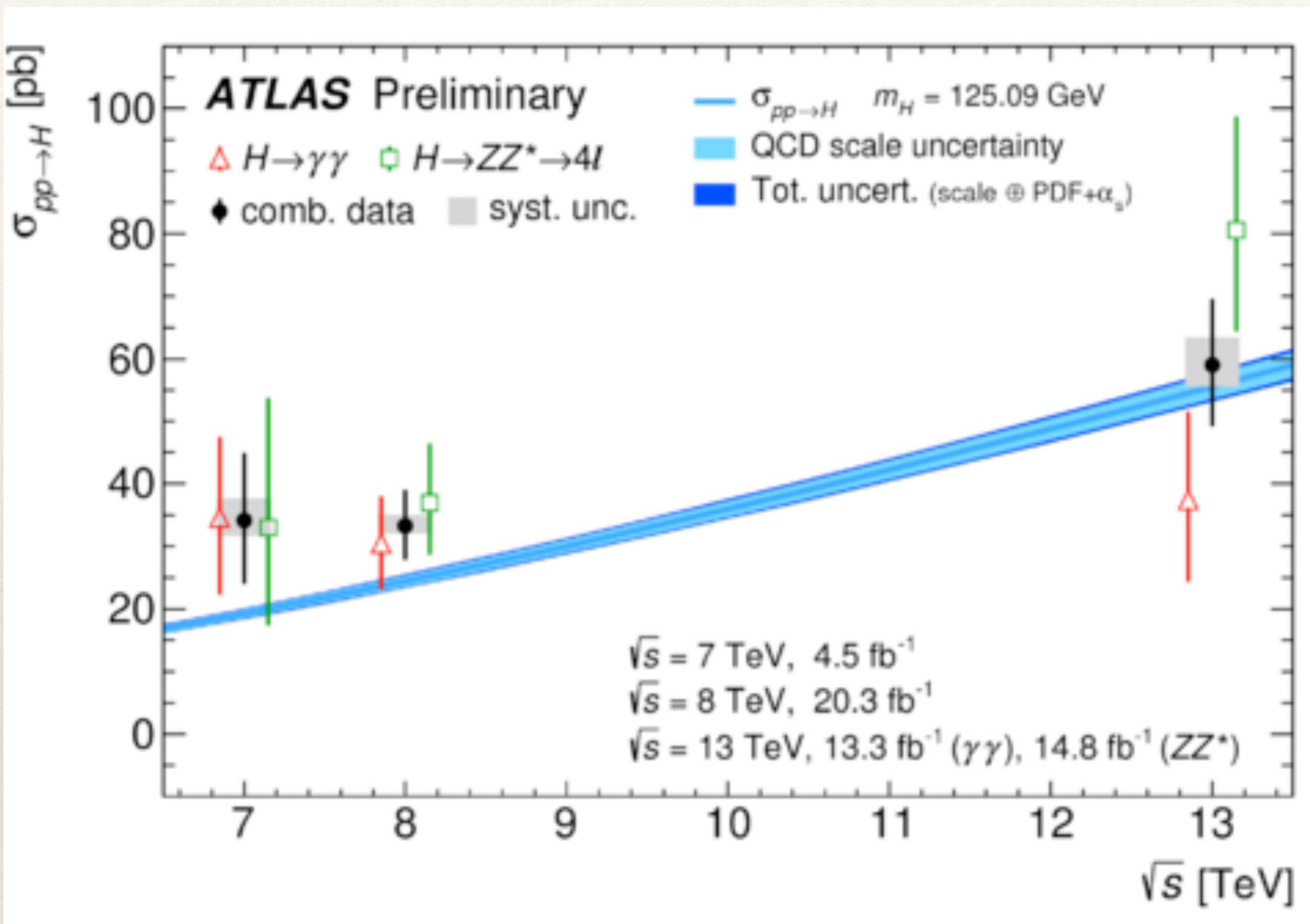
	$\sigma(p_T>p_{cut})$=1fb	$\sigma(p_T>p_{cut})$=1ab
	p_{cut}	p_{cut}
bb	~600GeV	~1.5TeV
$\tau\tau$	~400GeV	~1.2TeV
2l2v	~300GeV	~1TeV
$\gamma\gamma$	~200GeV	~750GeV
4l	~50GeV	~450GeV

Caola Higgs Hunting



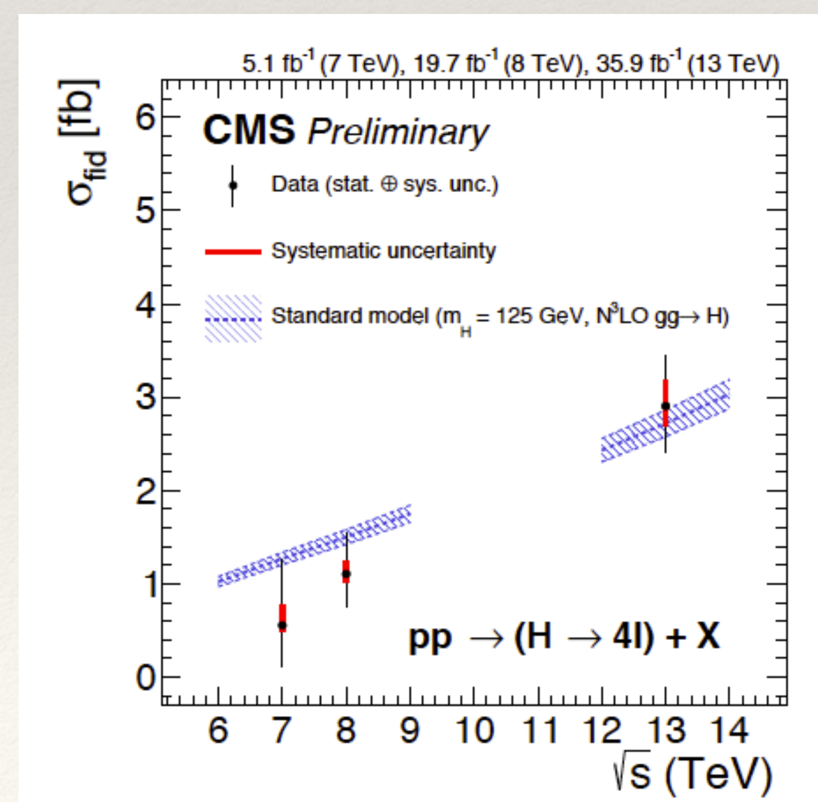
A precise calculus for partons

ATLAS-CONF-2016-081



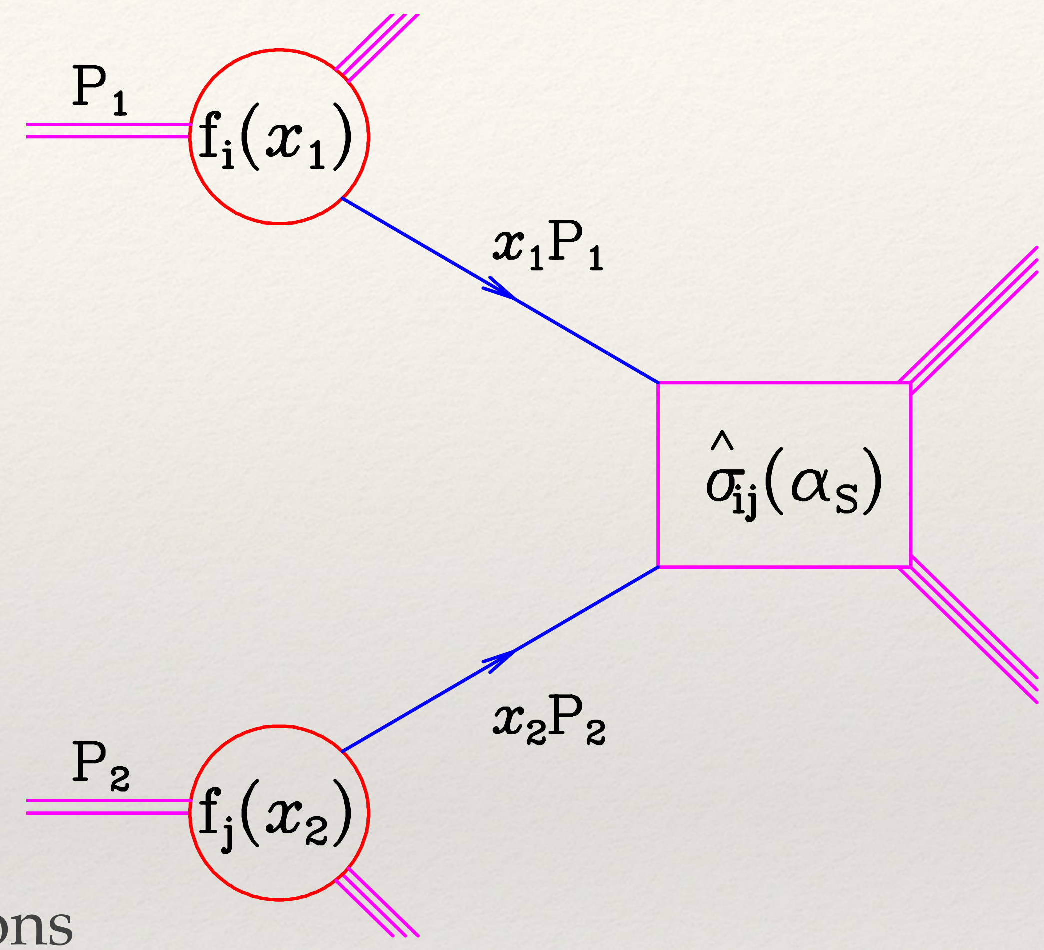
See the article by Giulia Zanderighi in the April edition.

- Use the Higgs boson as a tool for discovery
- Sophisticated QCD predictions to aid in measurement of Higgs boson properties.



How precise is precise?

- Hard cross section is represented as a convolution of a parton scattering cross section and non-perturbative parton distribution functions.
- Power corrections of order Λ/Q, for Q=100GeV, set a bound on the achievable precision of the factorisation formula of about 1%.
- The luminosity measurement at the LHC is in the range 2-5%, this also sets a scale for the precision to be aimed for.



Parton distributions

$$d\sigma(P_1,P_2) = \sum_{i,k} \int dx_1 dx_2\, f_i(x_1,\mu^2) f_k(x_2,\mu^2)\, d\hat{\sigma}_{ik}(p_1,p_2,p_J,\alpha_s(\mu^2),Q^2/\mu^2) F_J(p_J) + O(\Lambda/Q).$$

Physical cross section

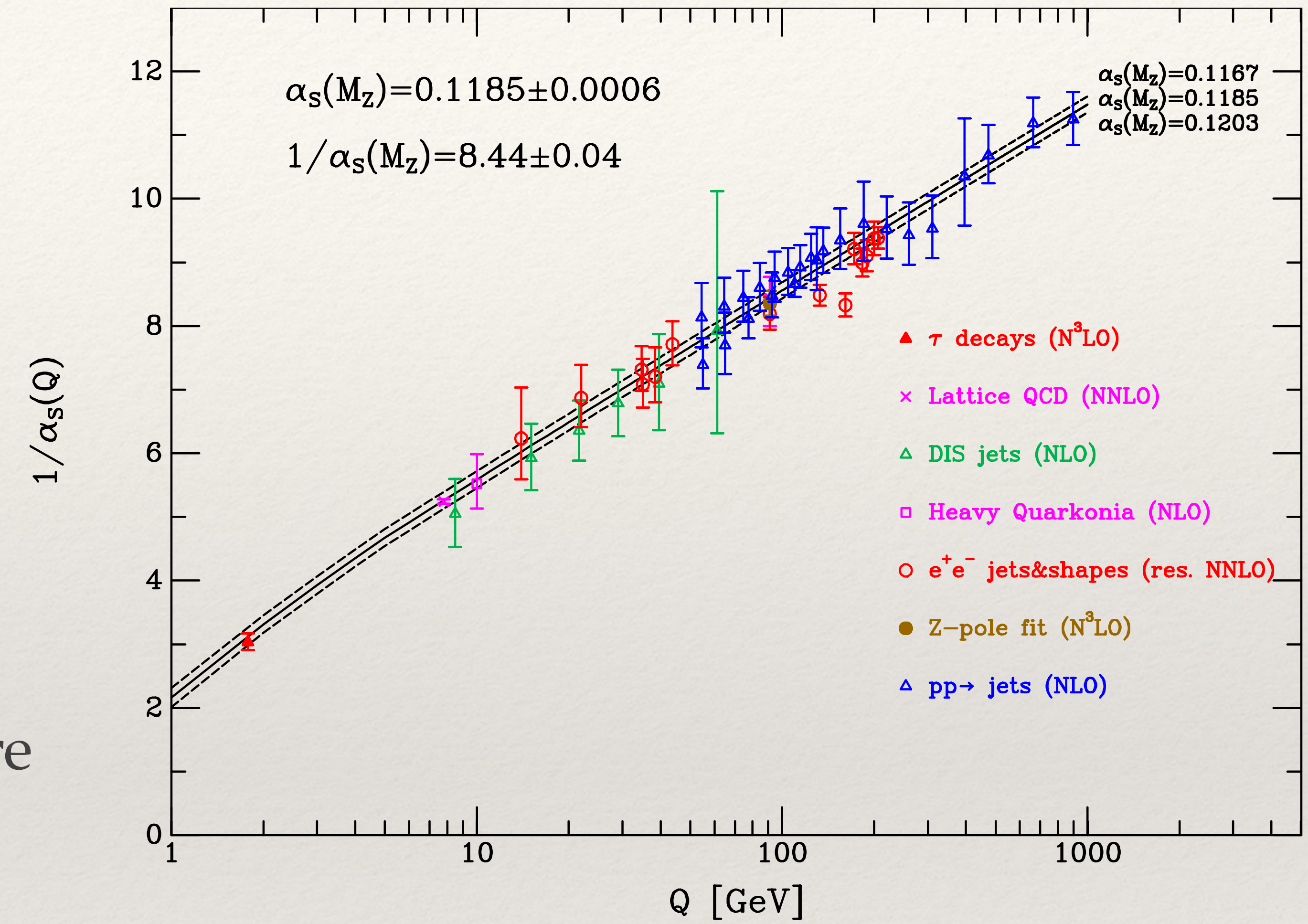
Factorization scale

Renormalization scale

Power corrections

Measurements of α_s

- Incontrovertible fact that α_s is smallish at energies accessible with current machines.
- $1/\alpha_s$ as grows as ~log (Q).
- $1/\alpha_s(Mz)=8.44\pm0.04$
- c.f QED: $1/\alpha=128....137$
- Radiative corrections ~15 times more important in QCD than QED.
- The standard view is that $\alpha_s(Mz)$ is known to about 1%.



Data from PDG September, 2013

Also some other outliers mainly from e+e- data

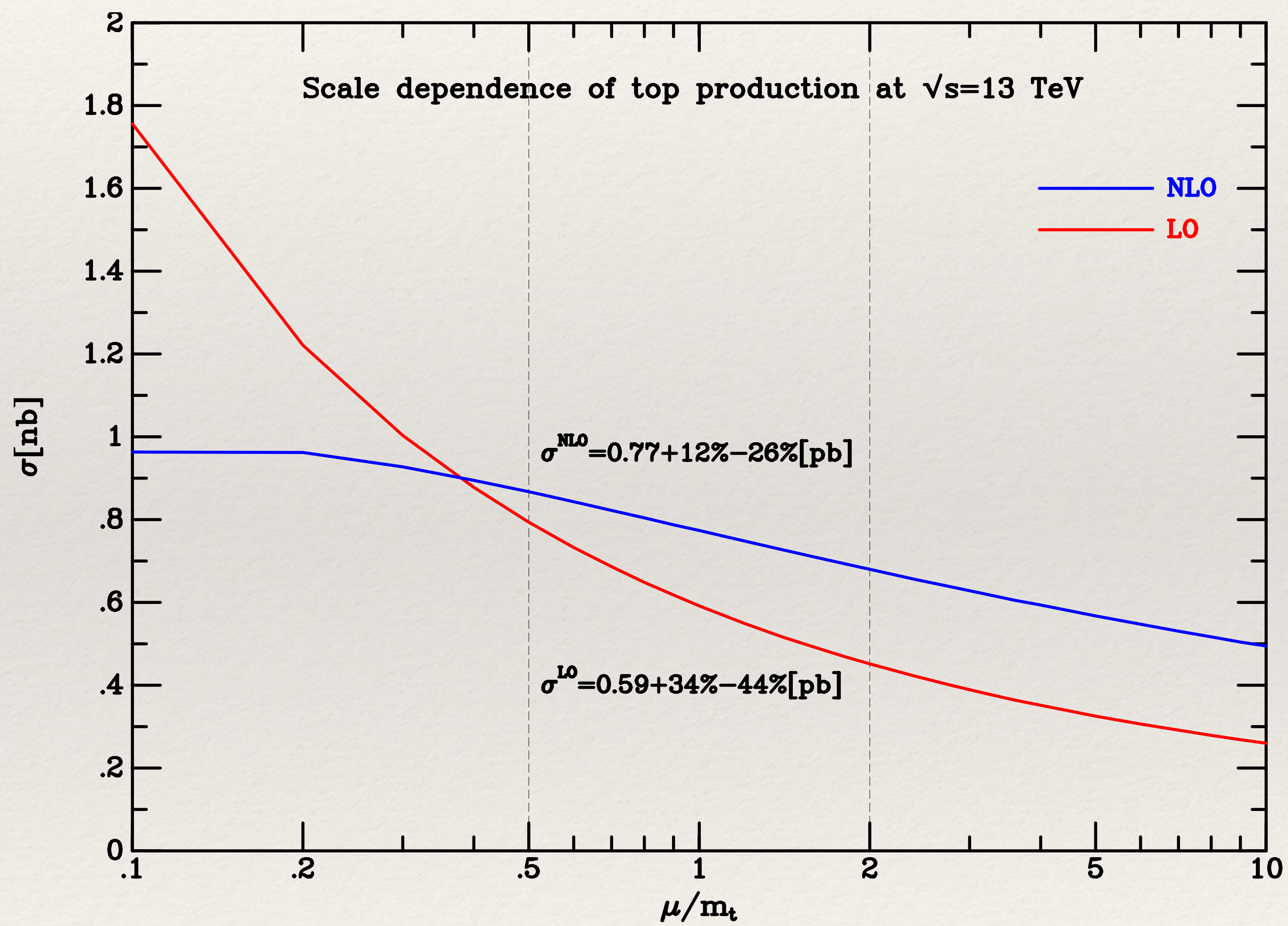
Abbate, 1006.3080, $\alpha s(M_Z)=0.1135+0.0010$

Hoang, 1501.04753, $\alpha s(M_Z)=0.1123+0.0002$

Renormalisation group improved perturbation theory

$$\sigma_{NLO} = c_1 \alpha_s^2 (1 + c_2 \alpha_s + O(\alpha_s^2))$$

- Take top pair production at 13 TeV.
- Estimate of error at NLO is not the $(12\%)^2$ suggested by the size of **α**s, because of the special nature of renormalisation group improved perturbation theory.
- Given that e.g. the luminosity measurement at the LHC is in the range 2-5%, this set an estimate for the precision we need to achieve.



$\mu R = \mu F = \mu$

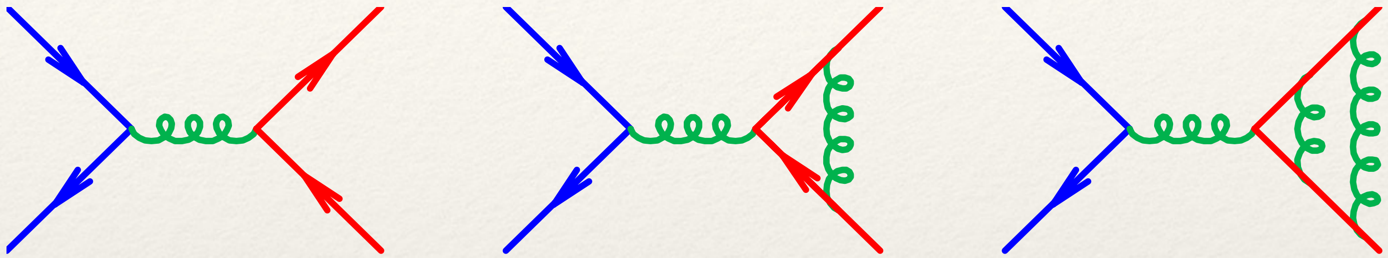
NNLO

- NLO declared solved in ~2010 with the establishment of numerical methods
- NNLO calculations roughly at the level of NLO in 1990.
  - NLO 2 to 2 virtual matrix elements known
  - NLO top cross section (total and differential) known
  - NLO 2 to 3 calculations just beginning to be tackled?
- Will we make faster progress on NNLO?

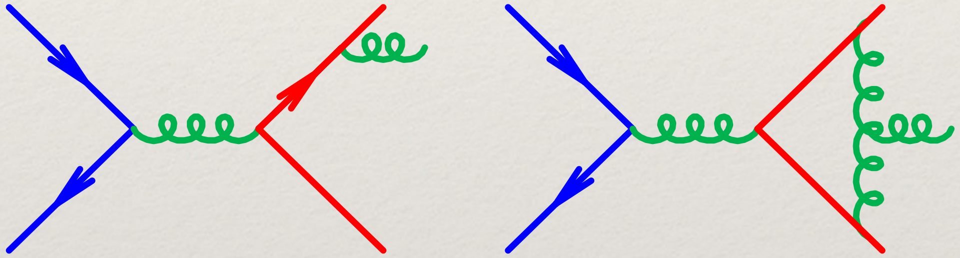
NNLO diagrams

- Challenge is not the calculation of the individual diagrams, but rather the assembly of pieces that individually contain infrared divergences.

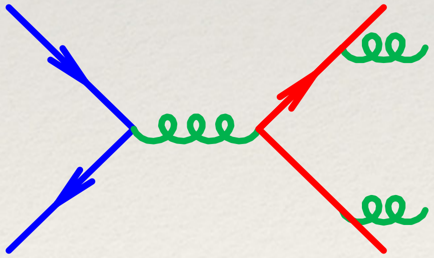
examples of 2➝2
diagrams:VV



examples of 2➝3
diagrams:RV



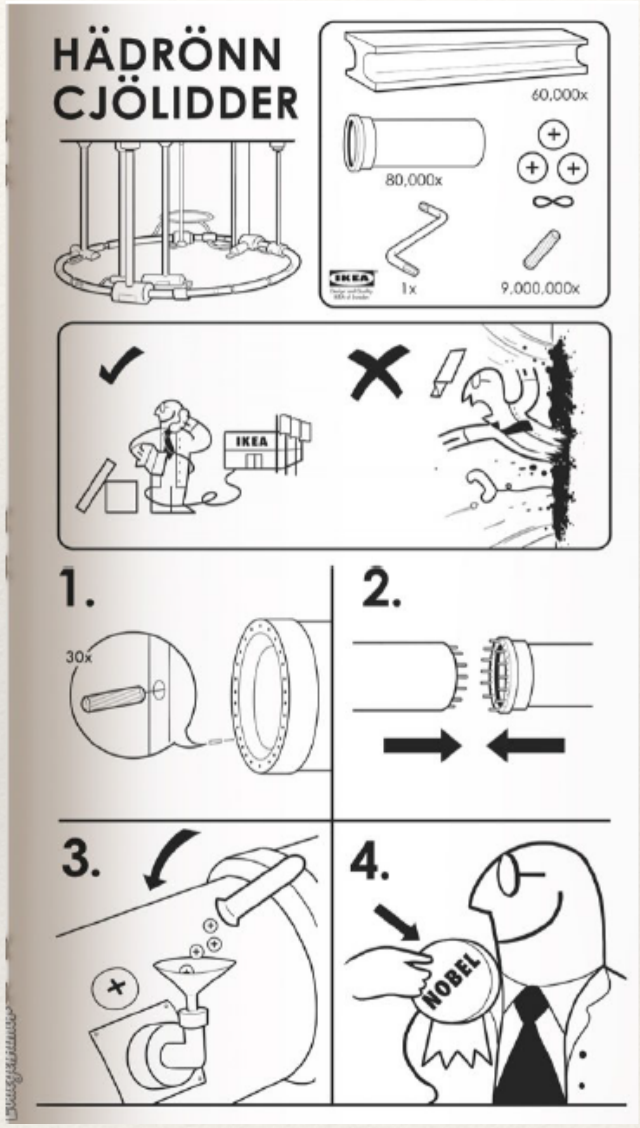
examples of 2➝4
diagram:RR



- Cancellation of singularities between phase spaces of different dimensionality.

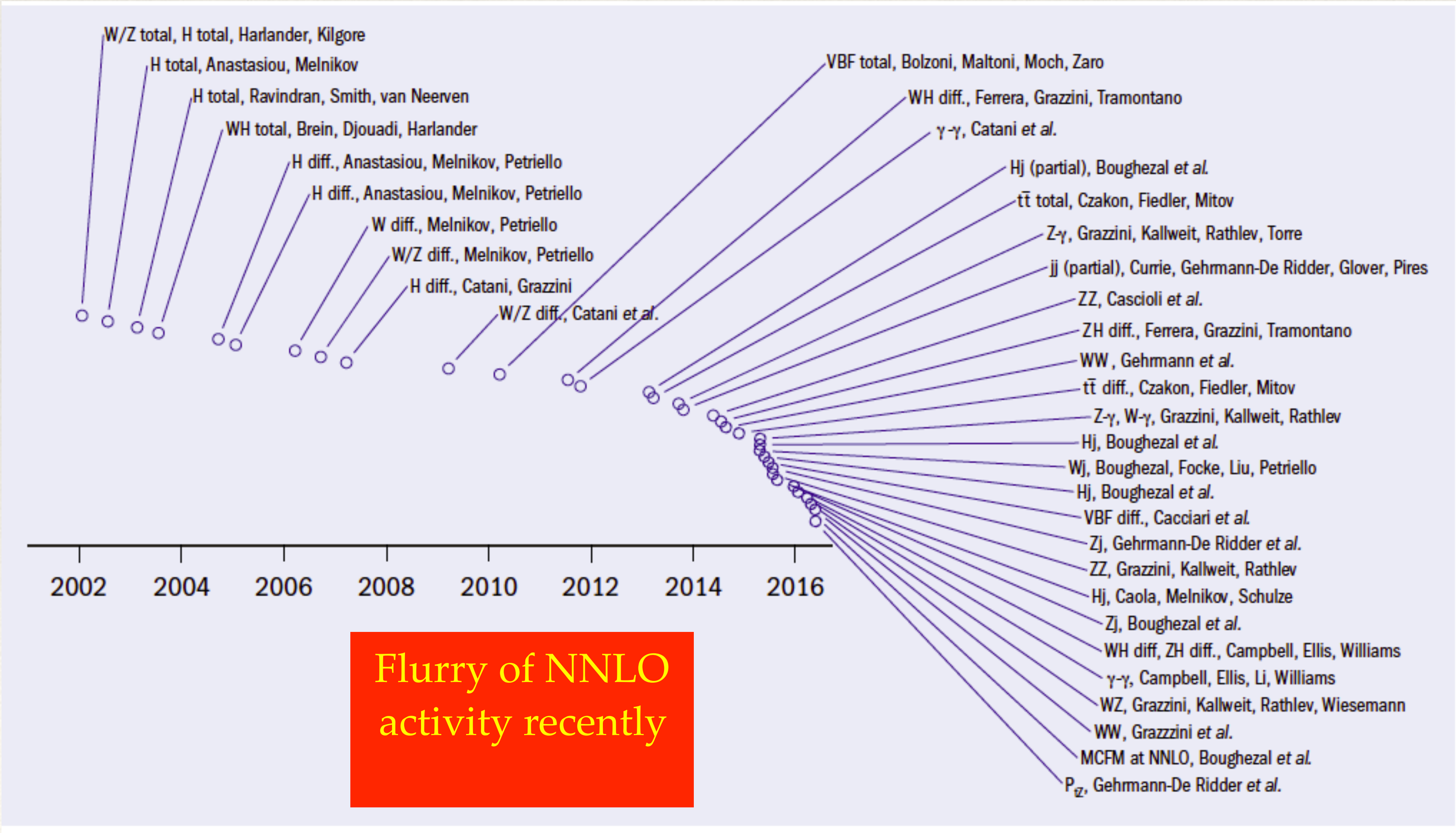
NNLO-some assembly required

- Contributions from VV, RV and RR.
- For the lower multiplicities the poles are explicit, whereas as for higher multiplicities, they appear after integration.
- Thus the requirement to cancel the poles appears to be in contradiction with the desire for a differential cross section.



The role of various approximations

- LO: estimate
- NLO: information about normalisation
- NNLO: information about reliability of error
- N^3LO: verification of reliability of error

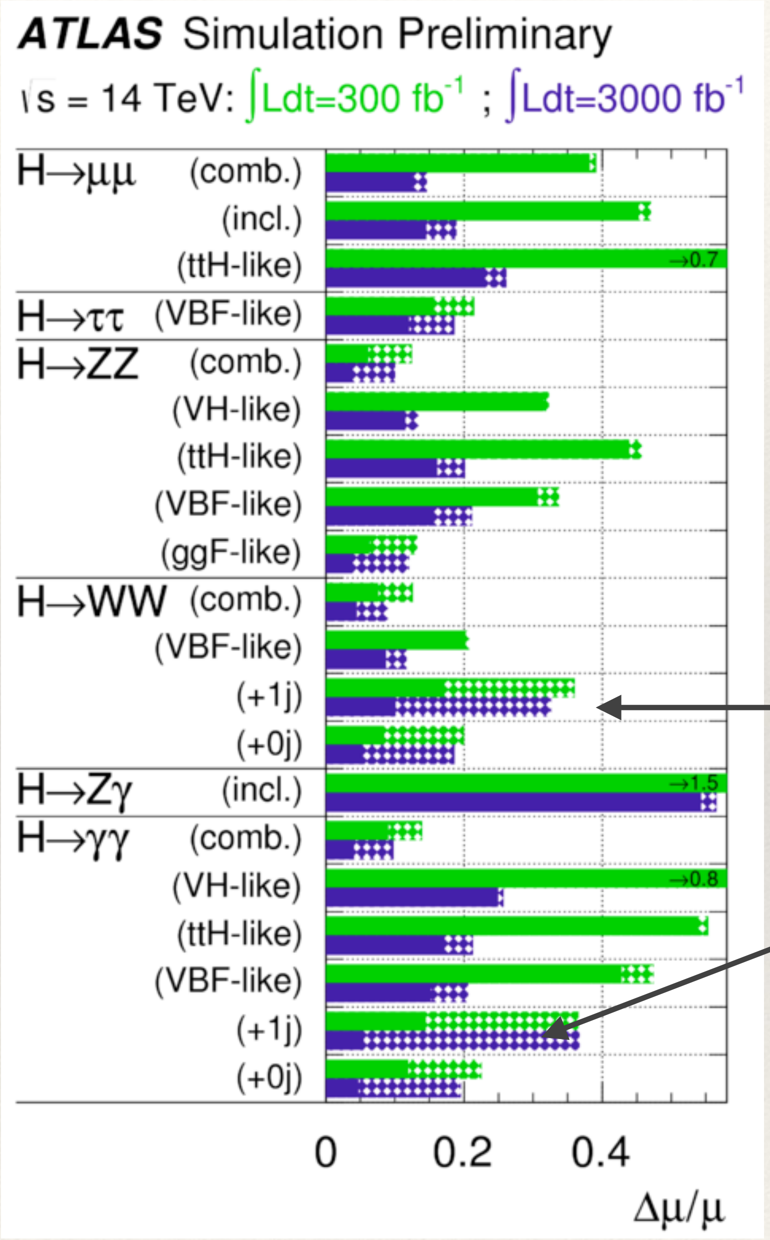


From the talk given by G P Salam at the 2016 LHCP conference.

Influence of theory on signal strengths

ATL-PHYS-PUB-2013-014

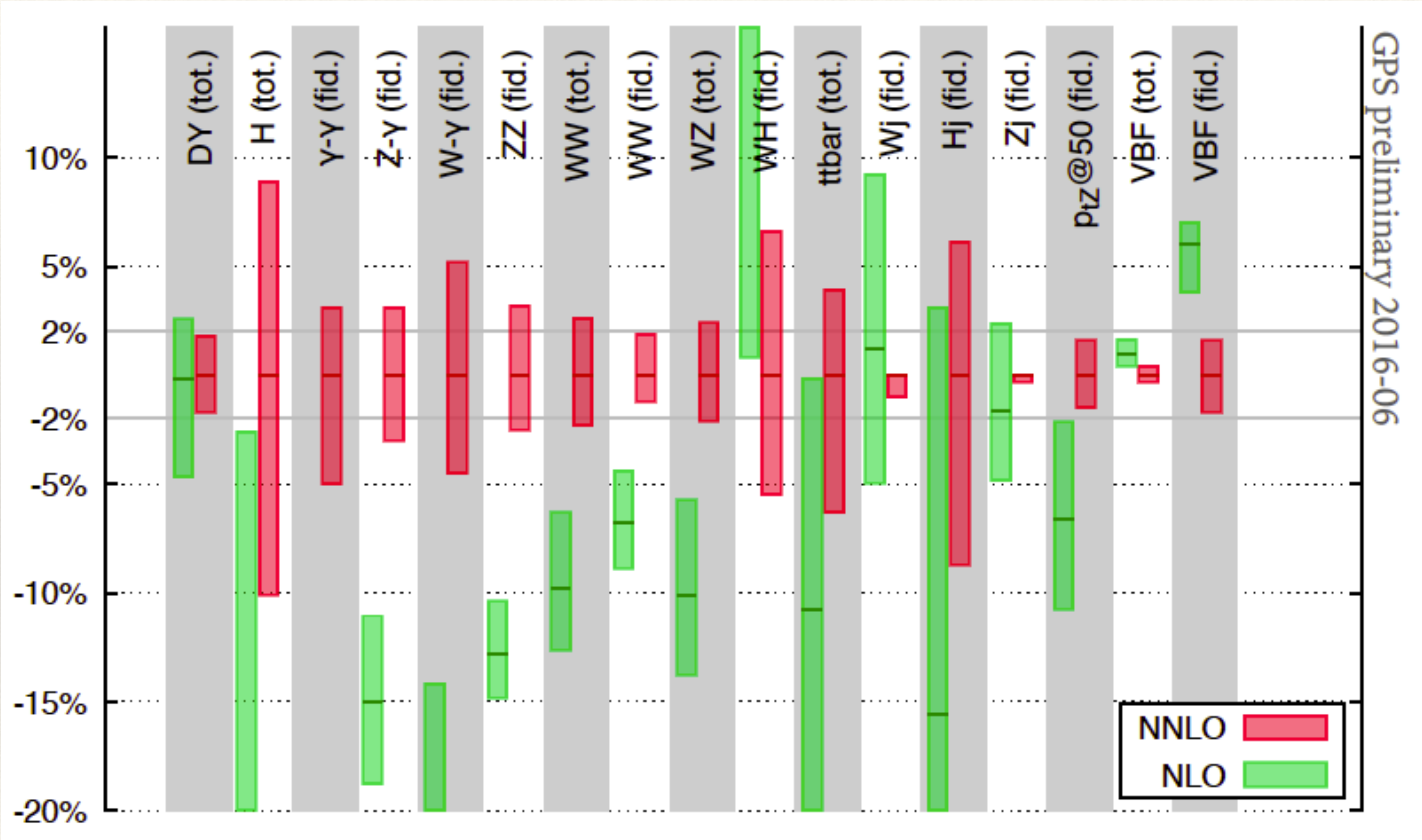
- It is important to measure Higgs coupling strengths as well as possible
- Theoretical improvements already since 2013.



Already impact here

ATLAS: Syst. errors as run 1, with (without) theory errors

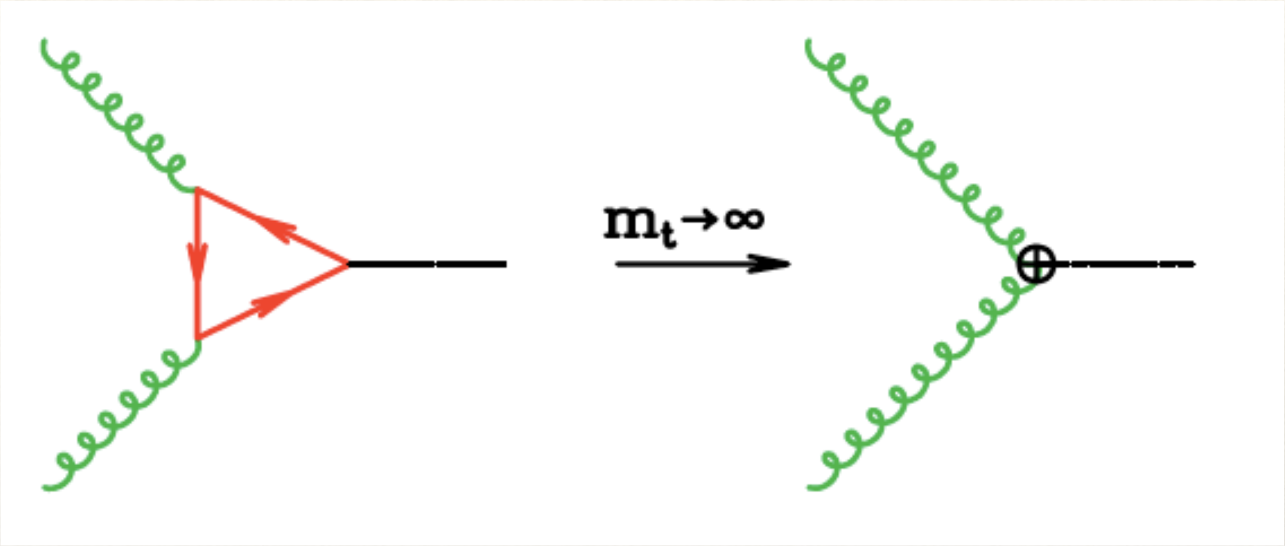
The necessity of NNLO

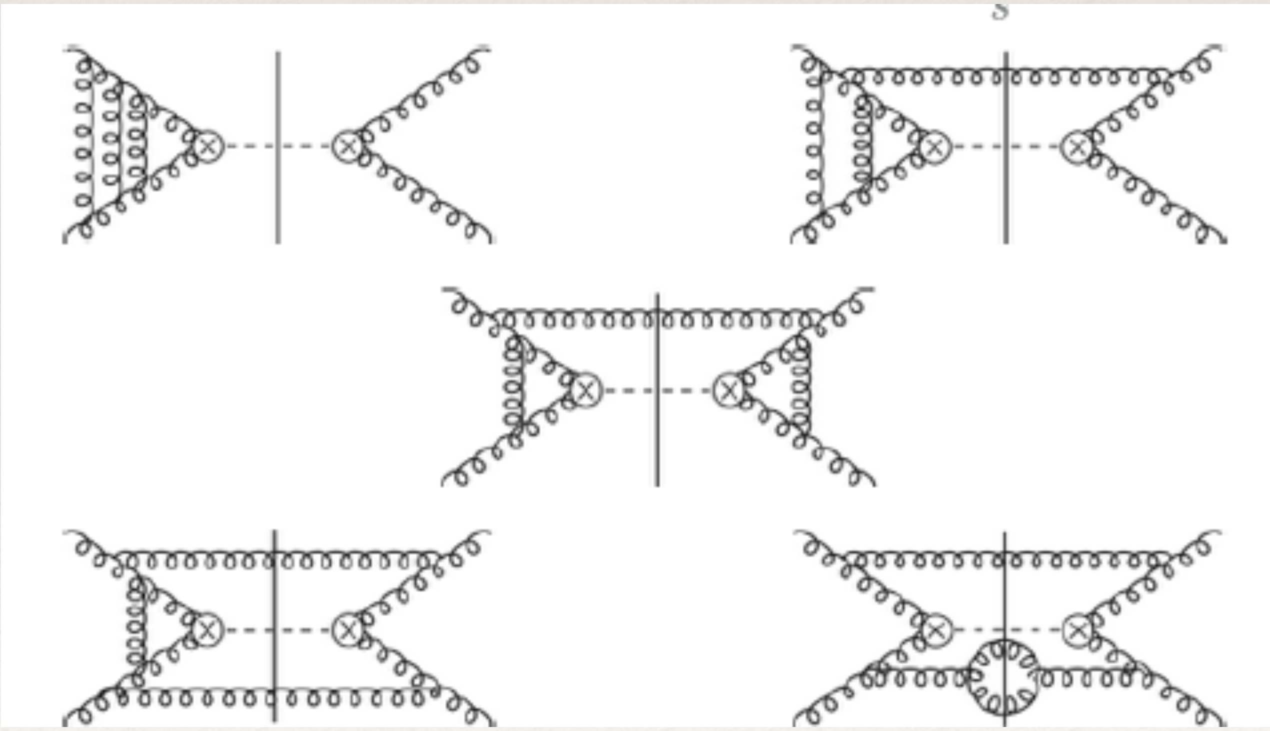


- This plot (by Salam) indicates that NNLO (central value) lies within the NLO error band (based on scale variation) in only 3 cases out of 17.

The new frontier N^3LO

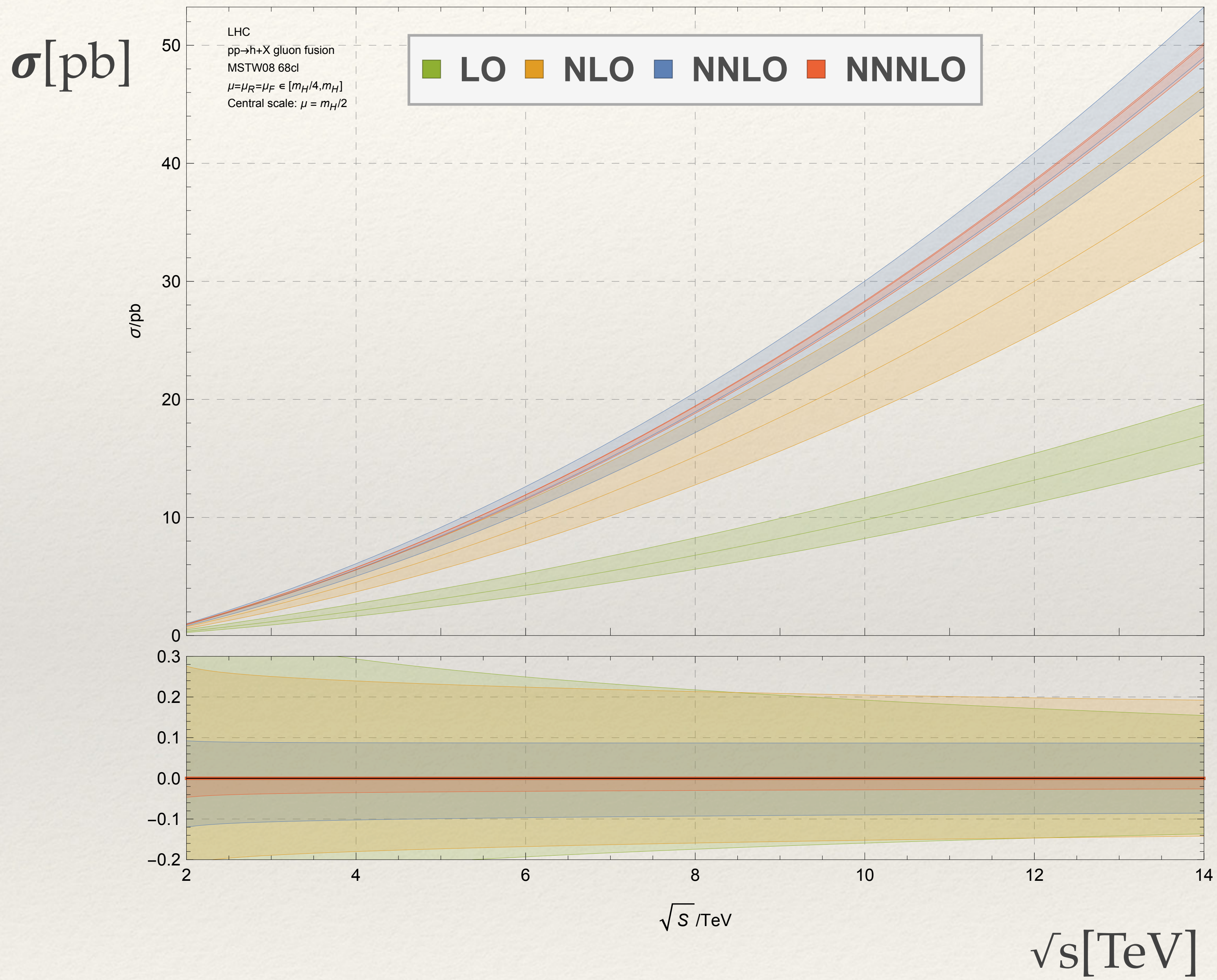
- A simple "Drell-Yan" process
- Great practical importance for the determination of Higgs couplings.
- Performed in effective theory
  - Requires H at 3-loop
  - H+parton at 2-loop
  - (H+1-partons at 1-loop)^2
  - H+2-partons at 1-loop
  - H+3 partons at tree graph-level





Behaviour of perturbation series

- Perturbation series for Higgs is well-tempered at all energies
- Assume effective expansion parameter is as Ca = 0.3
- Therefore size of N^{4}LO correction would notionally be of order (0.3)^4=1%
- Instead scale uncertainty gives an error of 3%



arXiv:1602.00695

Higgs boson is new physics

- Totally new, the first apparently fundamental scalar particle.
- Potential discovery of a theory valid to the Planck scale.
- Unique property of self-interaction.
- Self interaction dictated by the shape of the potential which has consequences for the meta-stability of the vacuum.
- Discovery of the self-interaction of the Higgs boson would give us a fourth force beyond strong, electroweak and gravitational.

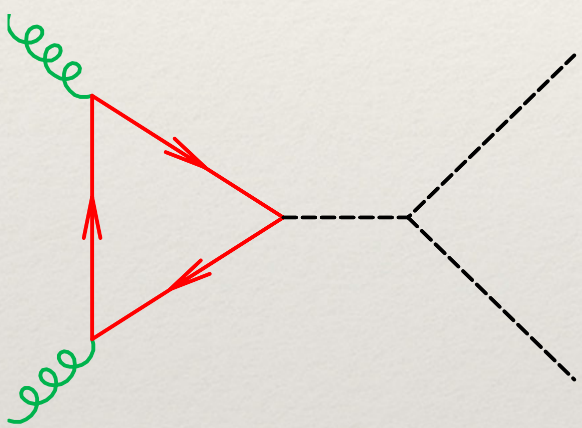
Arkani-Hamed et al, 1511.06495

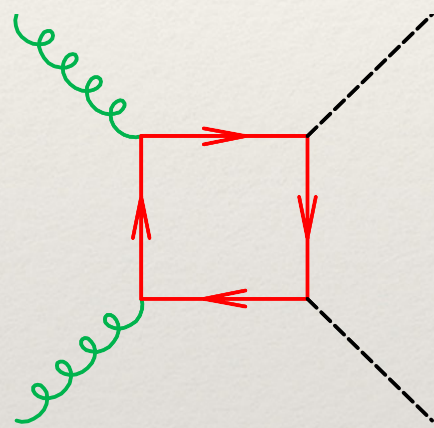
Discovery of fundamental forces

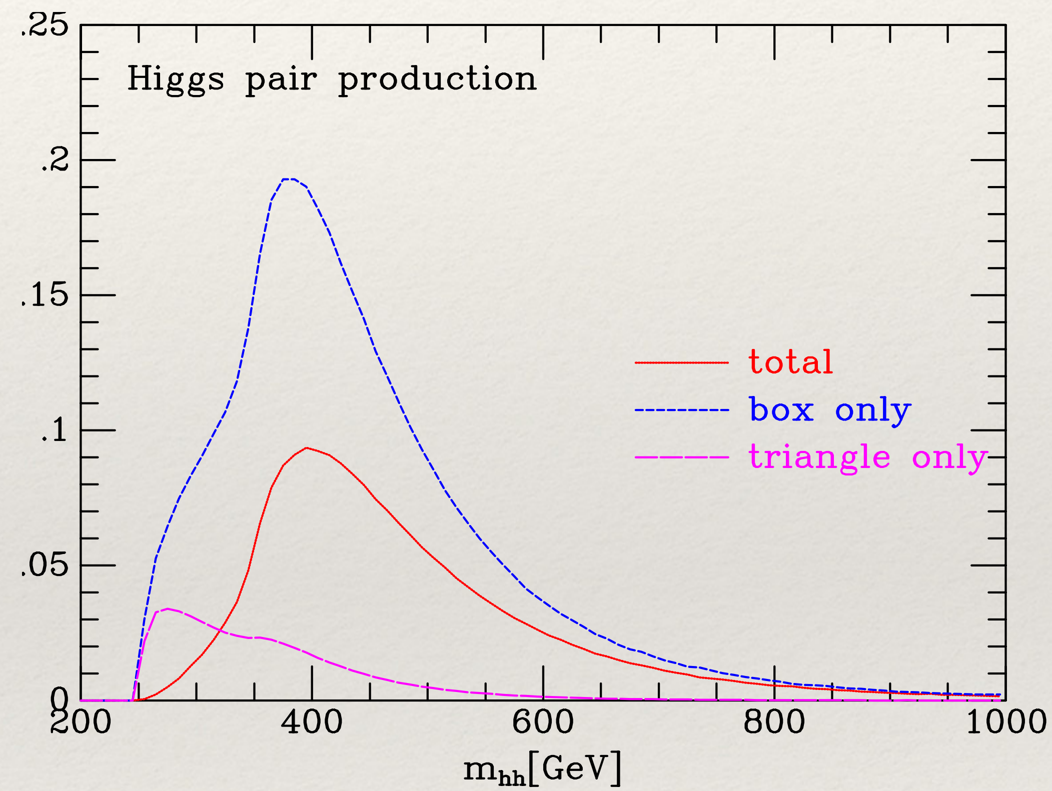
Newton	Maxwell+Rutherford
Yukawa	Your name here

LO Higgs pair production - full theory

- ~1000 times smaller than single Higgs production.
- Sensitivity to triple Higgs coupling comes from threshold region





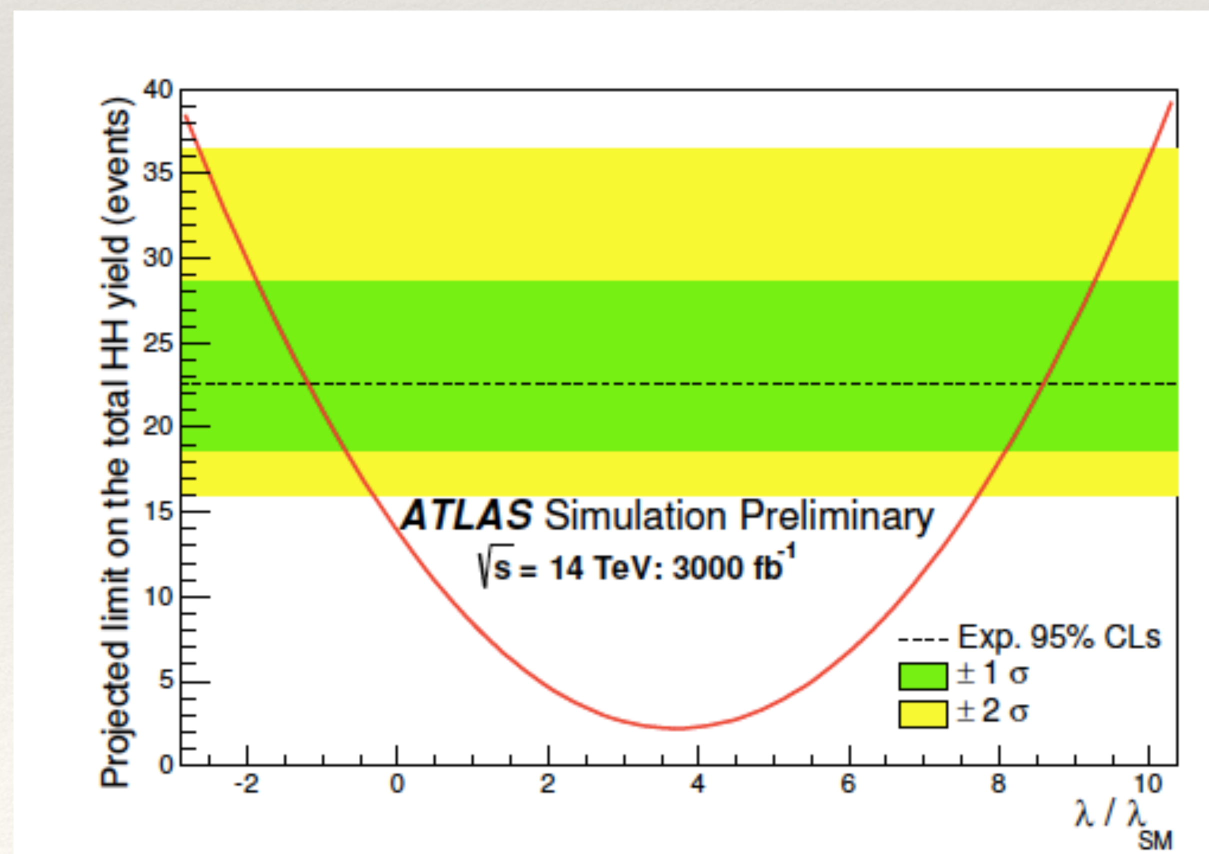


- As m_{hh} becomes large s-channel propagator suppresses first diagram.
- In the effective theory, double Higgs production amplitude vanishes in soft Higgs approximation (i.e. at threshold).

At high luminosity LHC

- Constraints on the triple coupling will require combination of results from a number of channels.
- Shown is the predicted (modest) constraint from bb$\gamma\gamma$

Decay Channel	Branching Ratio	Total Yield (3000 fb^{-1})
$b\bar{b} + b\bar{b}$	33%	40,000
$b\bar{b} + W^+W^-$	25%	31,000
$b\bar{b} + \tau^+\tau^-$	7.3%	8,900
$ZZ + b\bar{b}$	3.1%	3,800
$W^+W^- + \tau^+\tau^-$	2.7%	3,300
$ZZ + W^+W^-$	1.1%	1,300
$\gamma\gamma + b\bar{b}$	0.26%	320
$\gamma\gamma + \gamma\gamma$	0.0010%	1.2



ATL-PHYS-PUB-2014-019

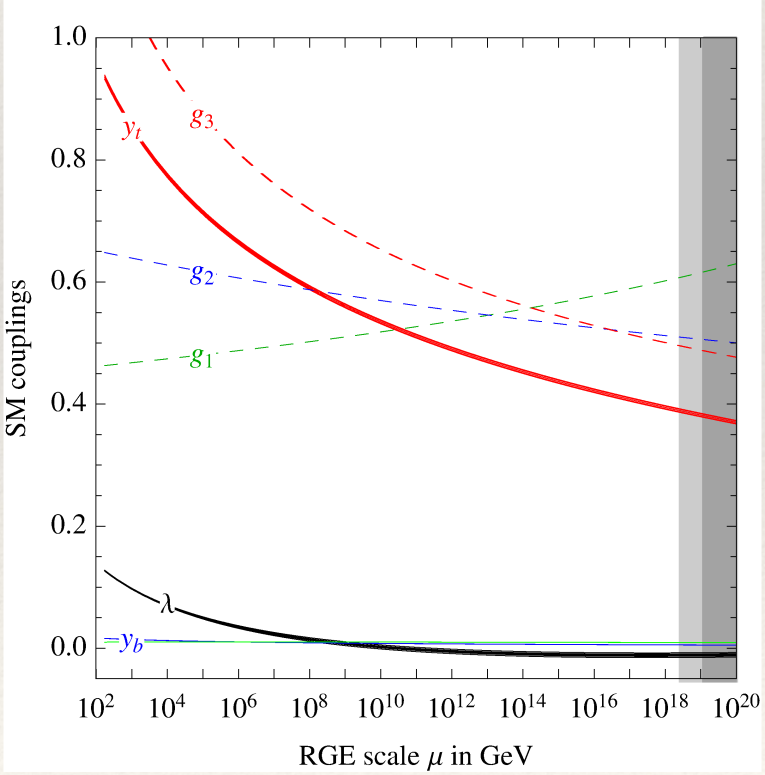
The standard model extrapolated

$$\frac{d\lambda}{d\ln Q^2} = \frac{1}{16\pi^2}\left[12\lambda^2 + 6y_t^2\lambda - 3y_t^4 - \frac{3}{2}(\frac{3}{5}g_1^2 + 3g_2^2)\lambda + \frac{3}{16}((\frac{3}{5}g_1^2 + g_2^2)^2 + 2g_2^4)\right]$$
$$= \frac{1}{16\pi^2}\left[0.20 + 0.78 - 2.9 - 0.28 \qquad\qquad + 0.13\right]$$

$g_2^2 = g_w^2, g_1^2 = \frac{5}{3}g_w'^2$

Numerical values at scale v

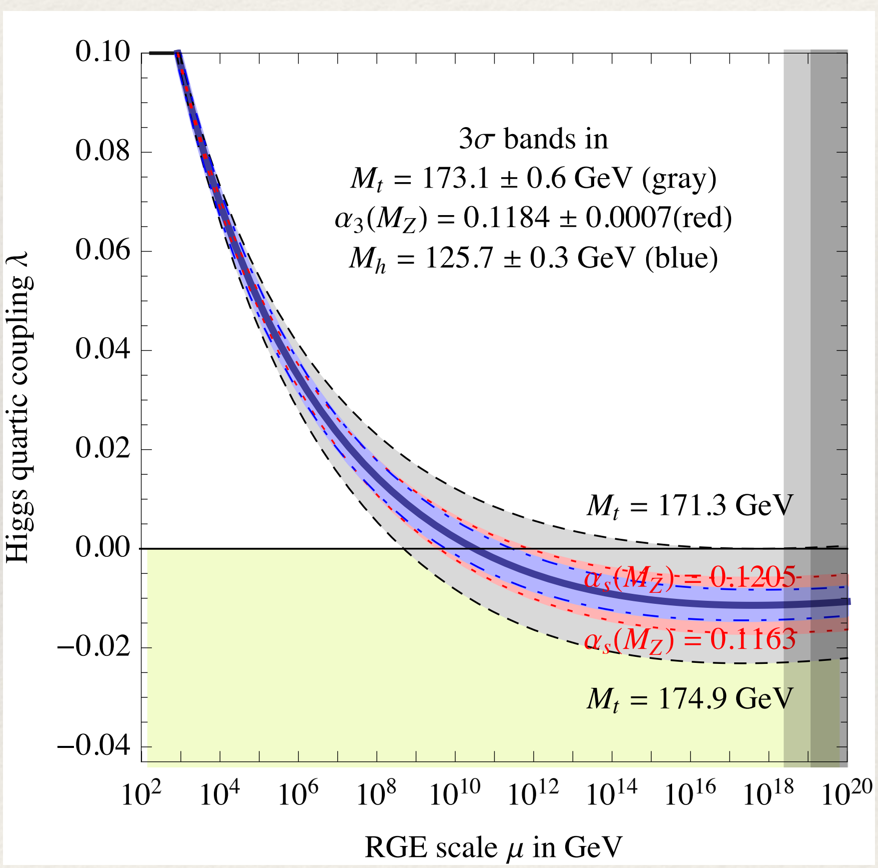
Degrassi et al, 1205.6497



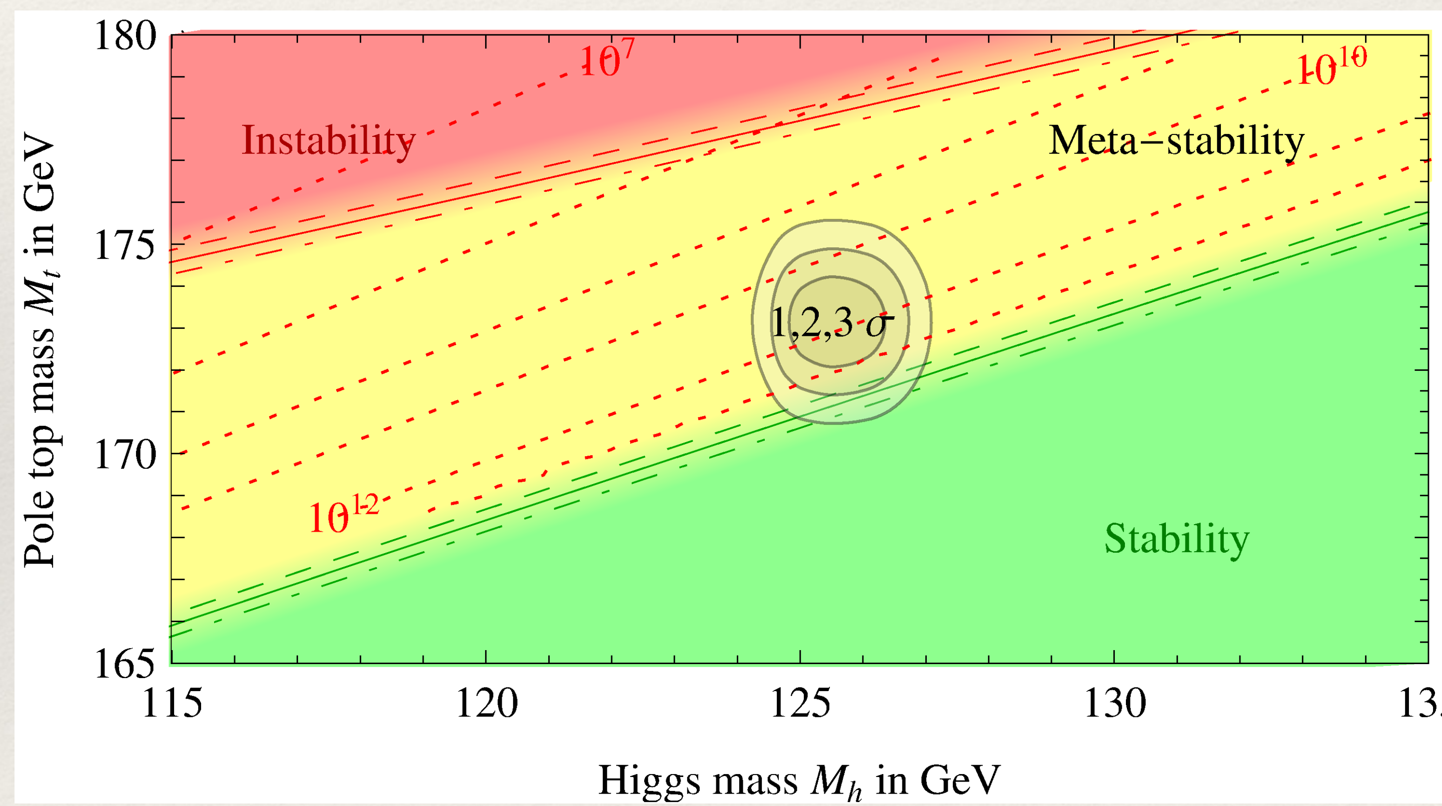
- After the Higgs discovery the standard model can now be safely extrapolated to high energy.
- The quartic coupling, and all other couplings, run.
- Resultant behaviour is a complicated interplay of different couplings.

High stakes measurements

- The change of sign of the coupling can be taken as a proxy for the stability of the standard model.



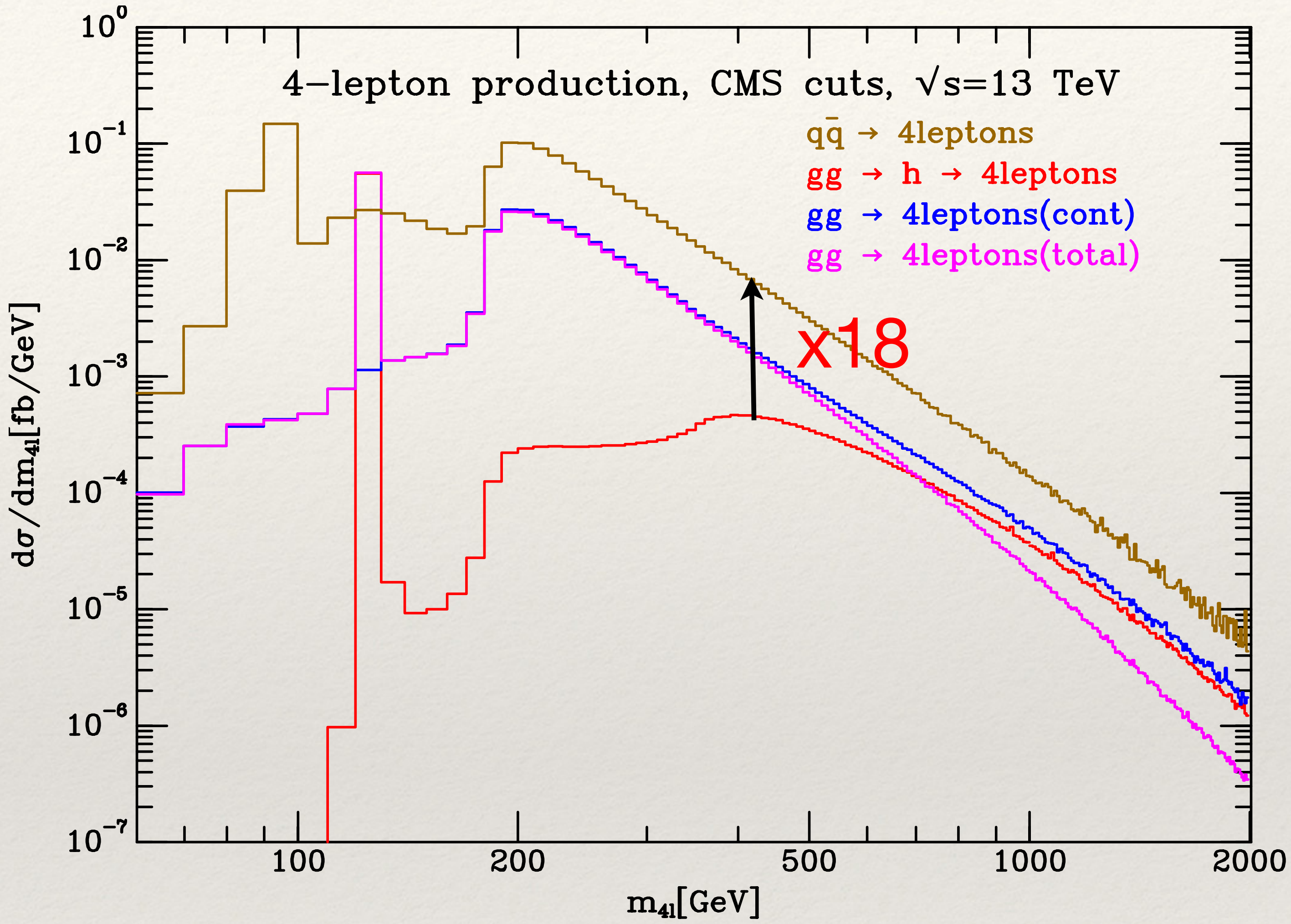
Degrassi et al, 1205.6497



- The resultant picture depends sensitively on the top quark mass (and $\boldsymbol{\alpha}_s$)

Higgs tail

- At least 15% of the cross section comes from $m_{4l} > 130$GeV. (Kauer&Passarino)
- Interference is an important effect off-resonance.
- Destructive at large mass, as expected.
- Sensitivity to the Higgs production method.



"Mine is a long and a sad tale!" said the Mouse, turning to Alice, and sighing.
"It *is* a long tail, certainly," said Alice, looking down with wonder at the Mouse's tail; "but why do you call it sad?"

The discovery of the Upsilon

Observation of a Dimuon Resonance at 9.5 GeV in 400-GeV Proton-Nucleus Collisions

S. W. Herb, D. C. Hom, L. M. Lederman, J. C. Sens,[a] H. D. Snyder, and J. K. Yoh
Columbia University, New York, New York 10027

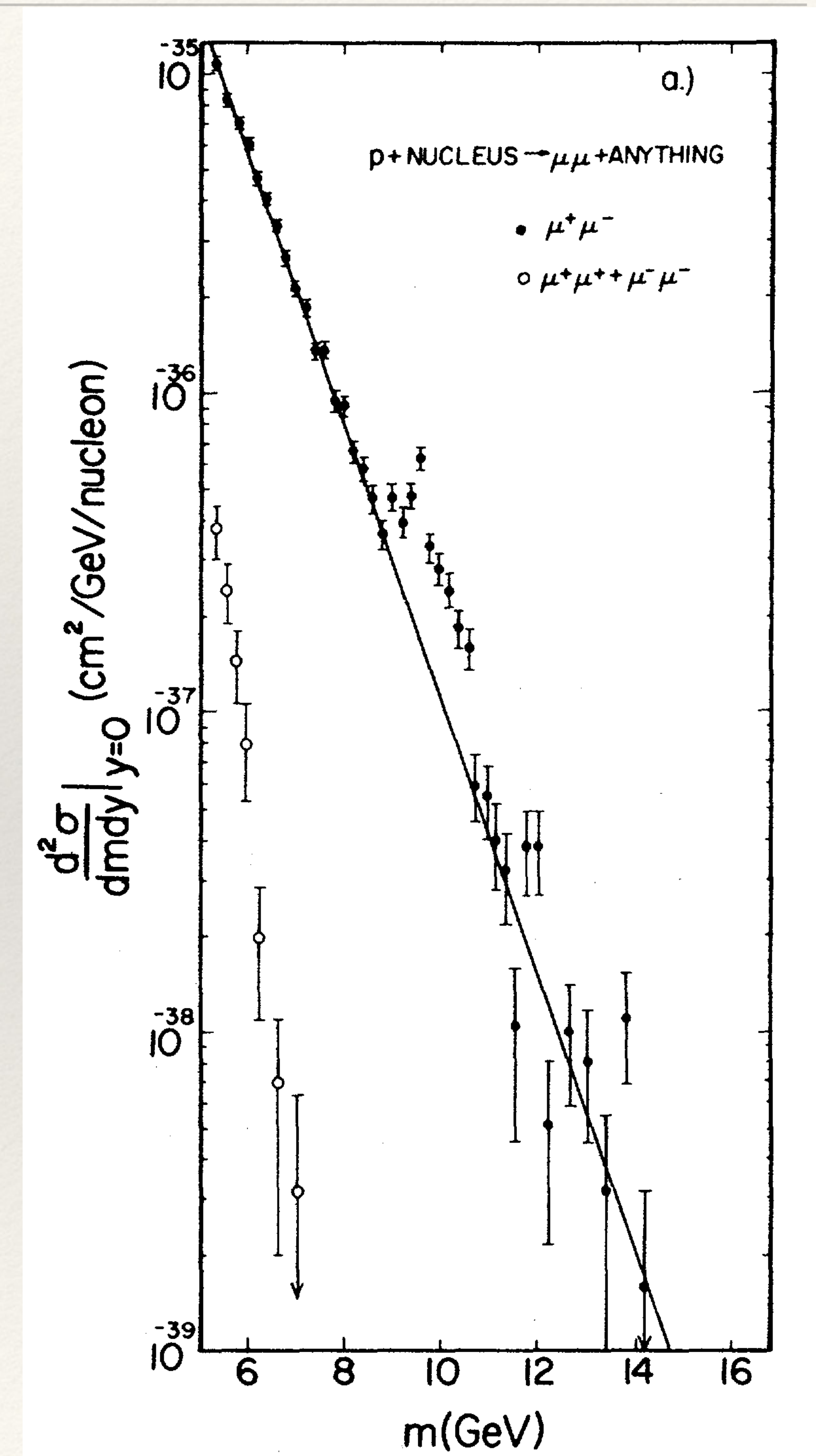
and

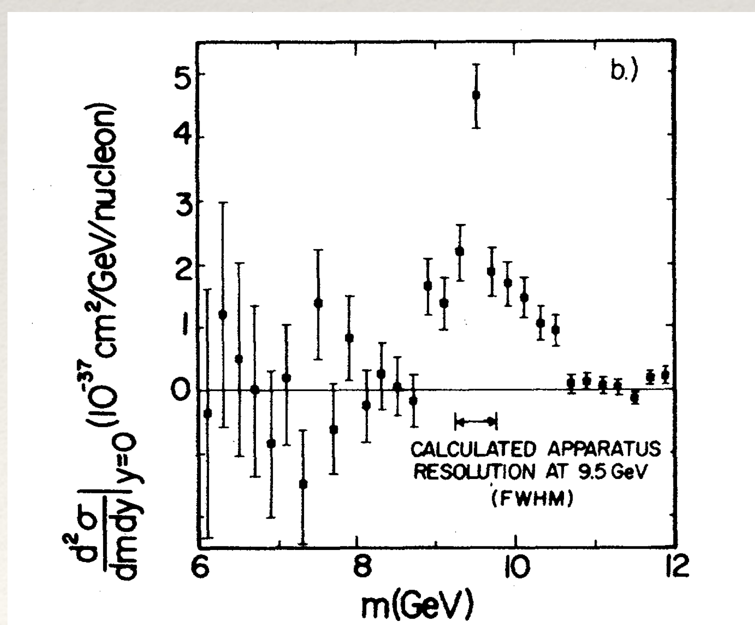
J. A. Appel, B. C. Brown, C. N. Brown, W. R. Innes, K. Ueno, and T. Yamanouchi
Fermi National Accelerator Laboratory, Batavia, Illinois 60510

and

A. S. Ito, H. Jöstlein, D. M. Kaplan, and R. D. Kephart
State University of New York at Stony Brook, Stony Brook, New York 11974
(Received 1 July 1977)

- Subsequently in 1977 the true Upsilon was discovered at 9.5 GeV.





40 year history b-quark

- The subsequent discovery of b-hadrons held other surprises for the field, notably the long-lifetime of the b-hadrons, allowing successful tagging of b-hadrons using vertex-detectors.
- What is remarkable is that 40 years later we are initiating a new program to study the b-quark in even greater detail at BelleII, as well as the continuing program of LHCb.
- We can anticipate that in 2052, we will be still involved in the detailed investigation of the Higgs boson….

Outlook

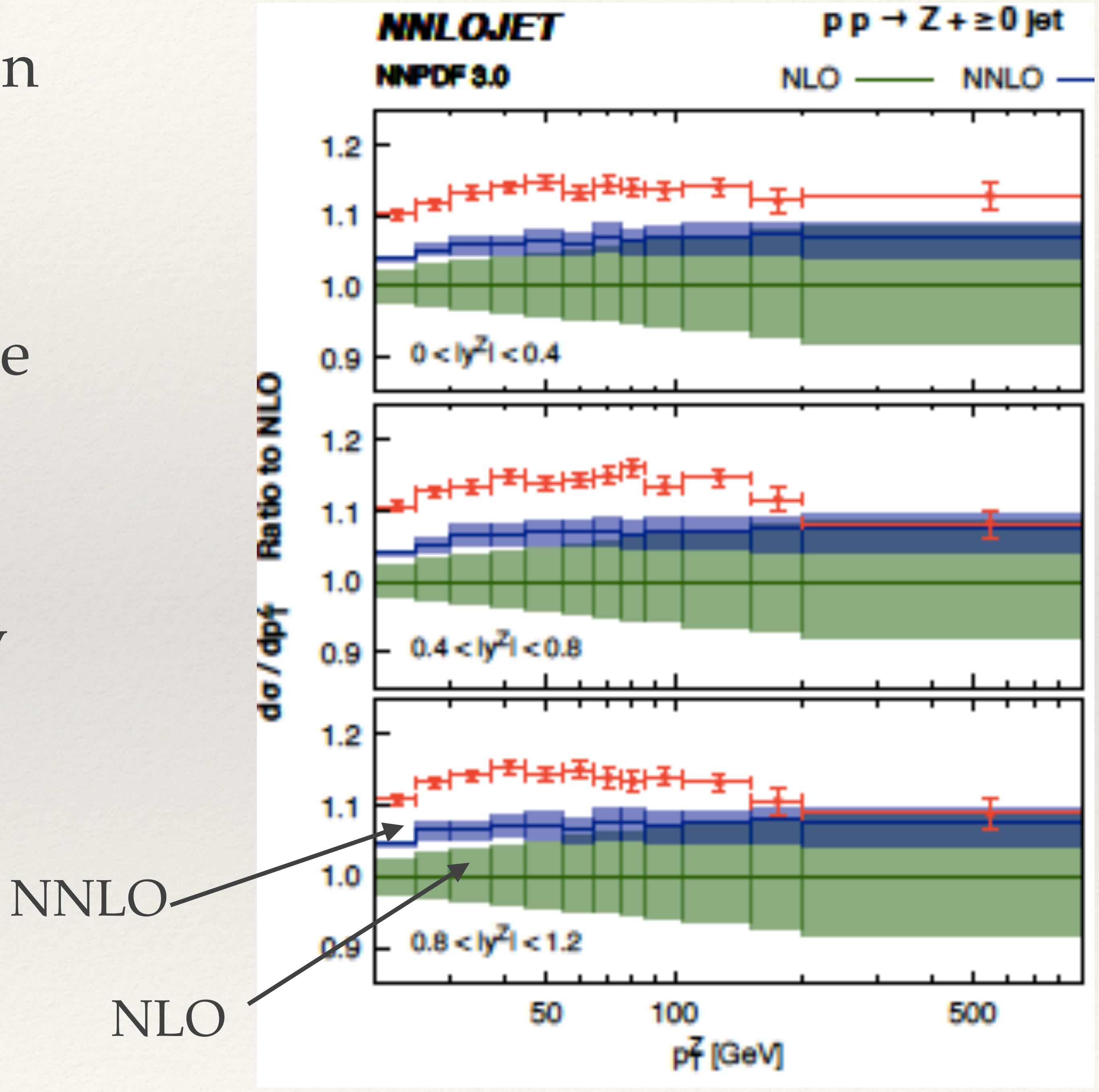
- We have about ~20 years more of an energy frontier machine exploring parton dynamics. You have never had it so good!
- Do not underestimate the power of human ingenuity to invent the future.
- It might seem that precision QCD is a game of diminishing returns; higher orders terms are harder to calculate and, if the perturbative series is well-tempered, less important.
- On the contrary it is a great time to work on radiative corrections. The Higgs boson is a central theme of run II at the LHC; it radiates copiously.
- To achieve ~2% level accuracy one needs at least NNLO, plus improvements in the PDF's, and in some cases to α_S.

Backup

Parton distribution functions

Gehrmann-De Ridder et al, 1605.04295

- Errors on Parton distribution functions are at the 2-3% level
- LHC can be used to improve measurements of partons
- e.g. Z pT distributions, accurate data, robust theory
- Important to include ttbar, Z-p_T, 2-jet data into fits at NNLO.



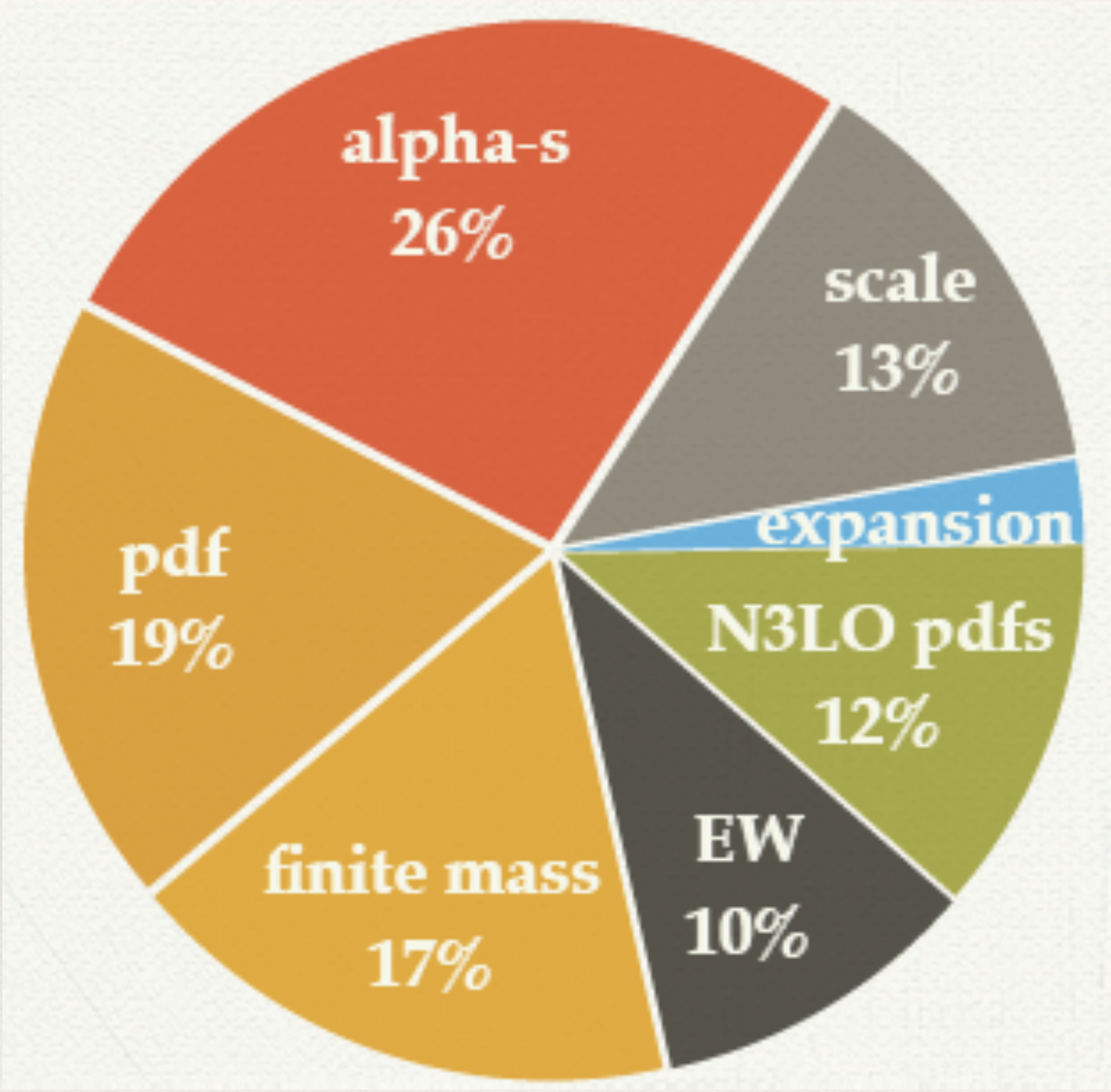
Best prediction at 13 TeV

F. Dulat, CERN, December 2015, https://indico.cern.ch/event/462111/

- The best prediction at 13 TeV, combining all sources of uncertainty

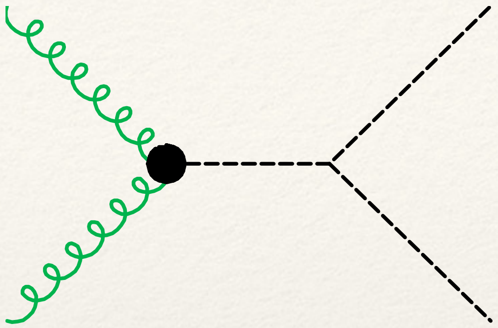
$$\sigma = 48.48^{+2.60}_{-3.47} \text{ pb} = 48.48 \text{ pb}^{+5.36\%}_{-7.15\%}$$

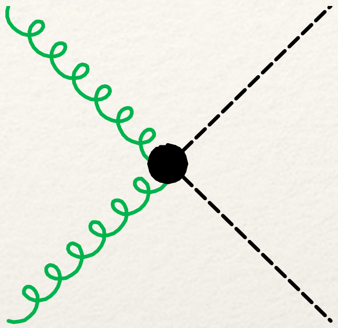
- Uncertainty budget indicates the areas for future improvement.
- Important to extend to more differential distributions.



Higgs-pair production EFT

- Effective field theory for single and double Higgs production





$$\mathcal{L}_1 = g_{ggH}\frac{1}{v}HG^{\mu\nu}G_{\mu\nu}$$

$$\mathcal{L}_2 = g_{ggHH}\frac{1}{2v^2}HHG^{\mu\nu}G_{\mu\nu}$$

- soft Higgs insertion theorem

$$m_t^2\frac{d}{dm_t}\frac{g_{ggH}}{m_t} = g_{ggHH} \Rightarrow g_{ggHH} = -g_{ggH}$$

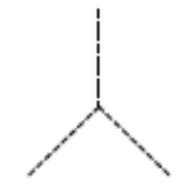
- Effective field theory for soft multi-Higgs production

$$\mathcal{L} \sim G^{\mu\nu}G_{\mu\nu}\ln\left(1+\frac{H}{v}\right)$$

- Double Higgs production amplitude vanishes in soft Higgs approximation (i.e. at threshold).

$$\mathcal{M} = \left[\frac{g_{ggH}}{v}\frac{i}{[s-m_h^2]}(-i)6\lambda v + \frac{g_{ggHH}}{v^2}\right]$$

$$= \left[\frac{g_{ggH}}{v}\frac{3m_h^2}{[s-m_h^2]}\frac{1}{v} + \frac{g_{ggHH}}{v^2}\right]$$

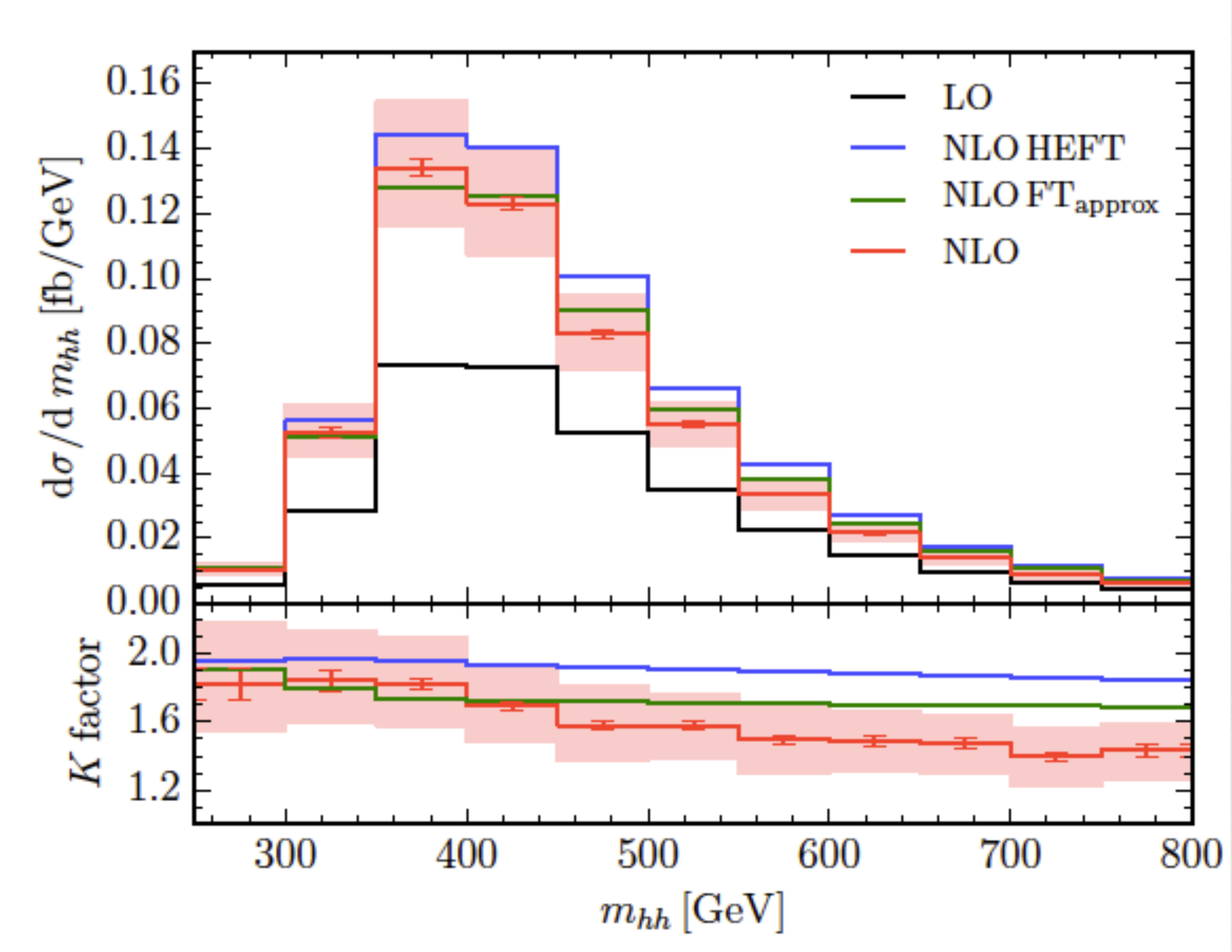


$-6i\lambda v = -3im_H^2/v$

Higgs pair NLO effects

Borowka et al, 1604.06447, 1608.04798

- Complete numerical NLO calculation in full theory shows that Born-improved NLO EFT calculation is reliable for small m_{hh}.
- Deviations observed for large m_{hh}, (this the region not directly sensitive to triple Higgs coupling).



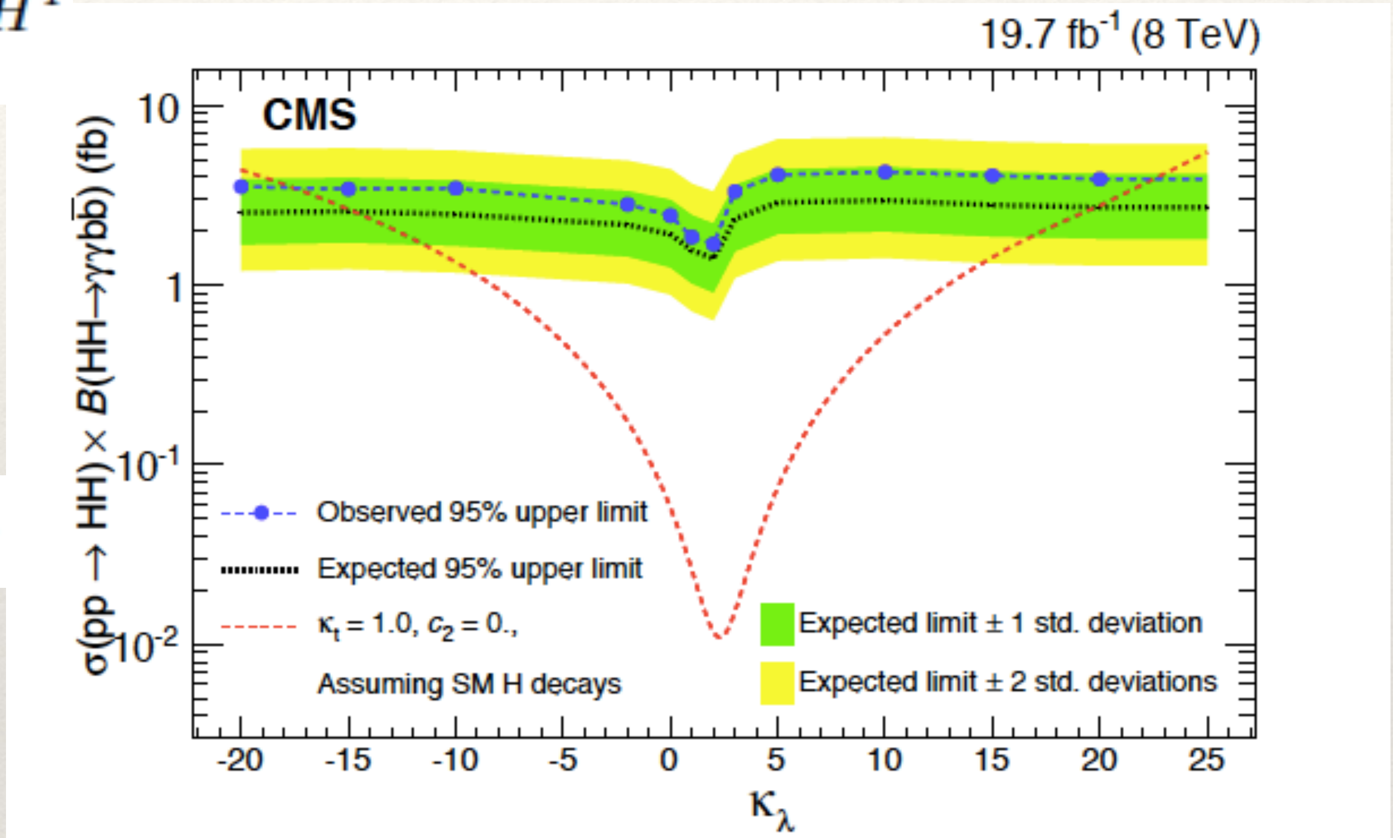
$\sqrt{s} = 13\,\mathrm{TeV}$ $\qquad \sigma^{\mathrm{NLO}} = 27.80^{+13.8\%}_{-12.8\%}\,\mathrm{fb} \pm 0.3\%\,(\mathrm{stat.}) \pm 0.1\%\,(\mathrm{int.})\,.$

Tiny cross section after Higgs branching ratios applied.

Current bounds on the effective Higgs self-coupling

$$\mathcal{L}_{\text{Higgs}} = \frac{1}{2}\partial_\mu H \partial^\mu H - \mu^2 H^2 - \kappa_3 \lambda v H^3 - \frac{1}{4}\kappa_4 \lambda H^4$$

arXiv:1603.06896



- Using the final state $\gamma\gamma b\bar{b}$
- bound on effective couplings are $\kappa_3 \leq -17.5$ and $\kappa_3 \geq 22.5$
- Most promising channels for the future $b\bar{b}b\bar{b},\ \tau\tau b\bar{b},\ \gamma\gamma b\bar{b},\ WWb\bar{b}$