Science & Technology Facilities Council

Durham University

Bad-Honnef, October 2016

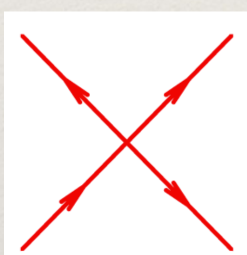
Status of the Standard Model and the Way Forward

Keith Ellis, IPPP, Durham

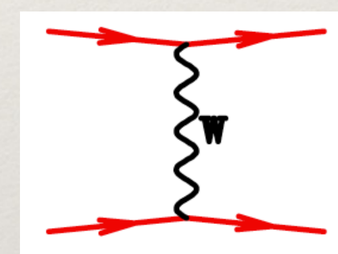
625. WE-Heraeus-Seminar: The High Energy LHC - Interplay between Precision Measurements and Searches for New Physics

No-lose completion of the standard model

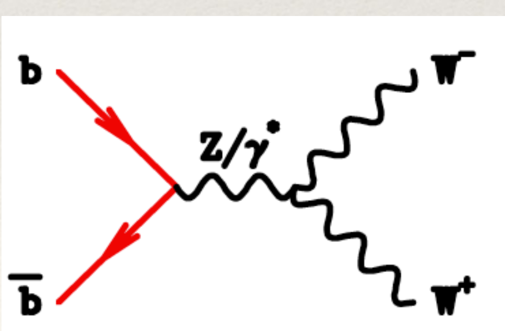
- In our quest to complete the standard model we have been aided by no-lose theorems.
- Motivation for the W



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



- Motivation for the top quark



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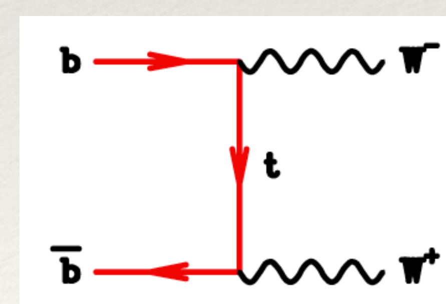
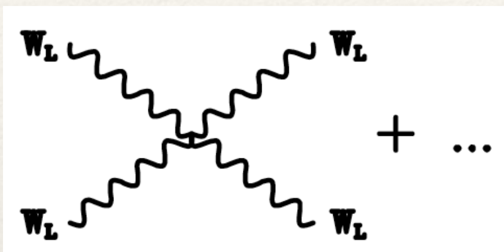


See e.g., Wulzer, 1510.05159

Completion of the SM –Higgs boson

Lee, Quigg & Thacker, 1977

- Shortcomings of theory of WW scattering



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

- before the critical energy Ec, new physics must enter,
- either a new particle, so that unitarity is preserved in the perturbation theory,

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

After the discovery of the Higgs boson, perturbative unitarity is restored, and 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

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

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

- Operators of d < 4 suffer from a naturalness problem; in the absence of a symmetry principle one would expect the value of μ,($M_{H)}$, 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,

$$\begin{aligned} M_H^2 &= 3.273, 459, 429, 634, 290, 543, 867, 496, 473, 159, 645 \\ &\quad -3.273, 459, 429, 634, 290, 543, 867, 496, 473, 159, 643 \end{aligned}$$

Bare mass in Planck units

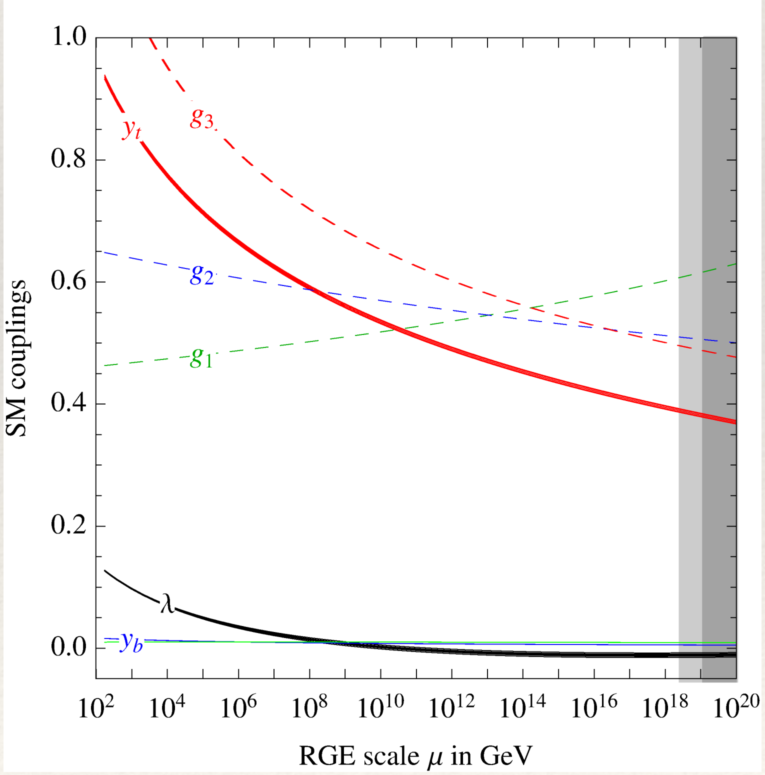
The standard model extrapolated

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

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

Numerical values at scale v

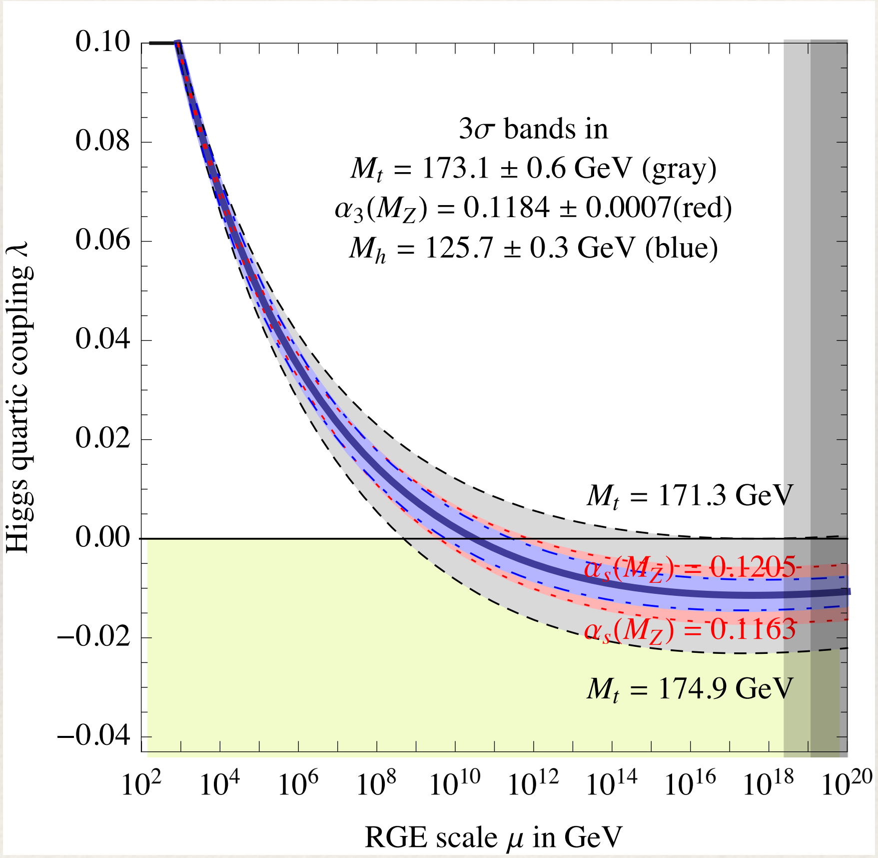
Degrassi et al, 1205.6497



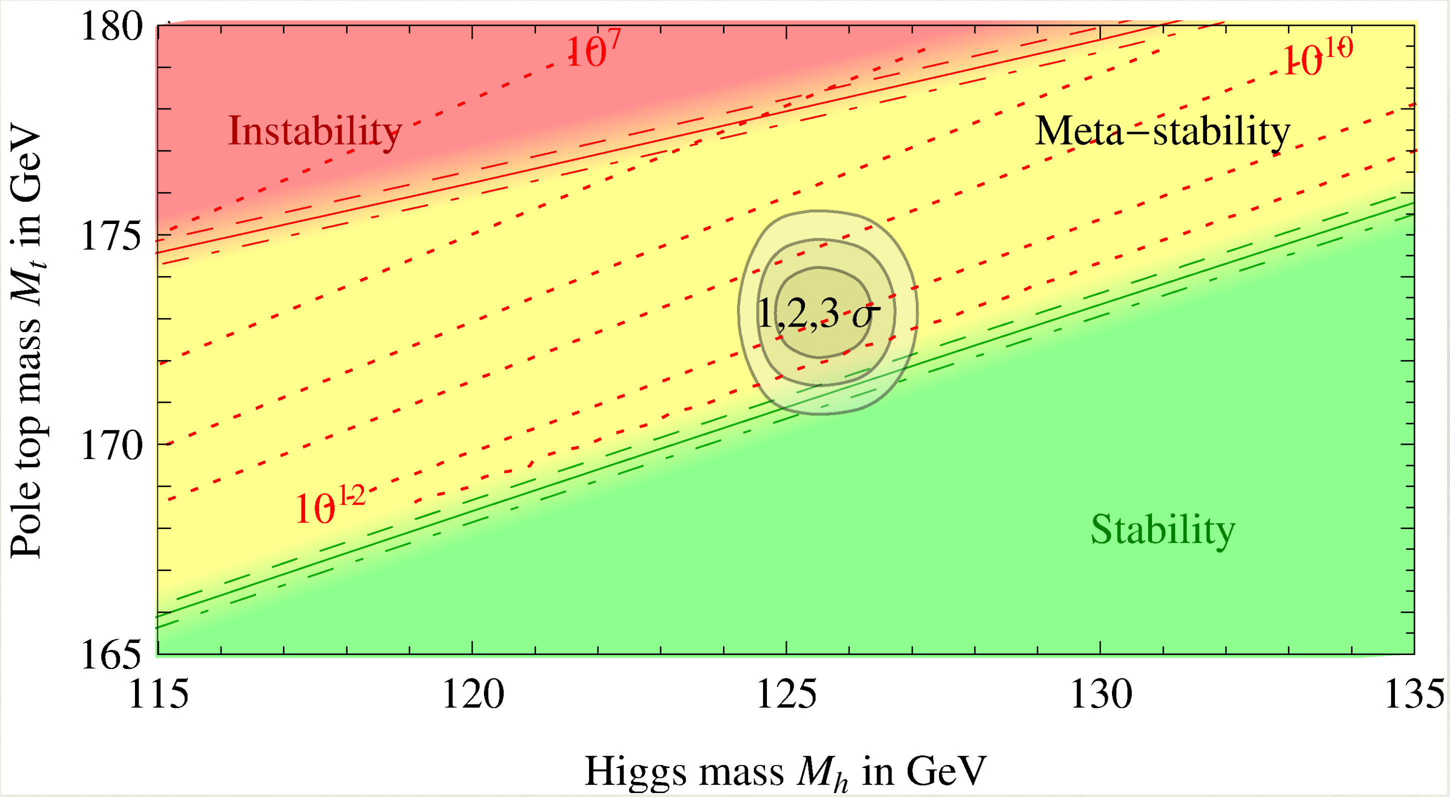
- The standard model can now be safely extrapolated to high energy.
- The quartic coupling, and all other couplings, run.
- Resultant behaviour is a complicated interplay of different couplings.

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

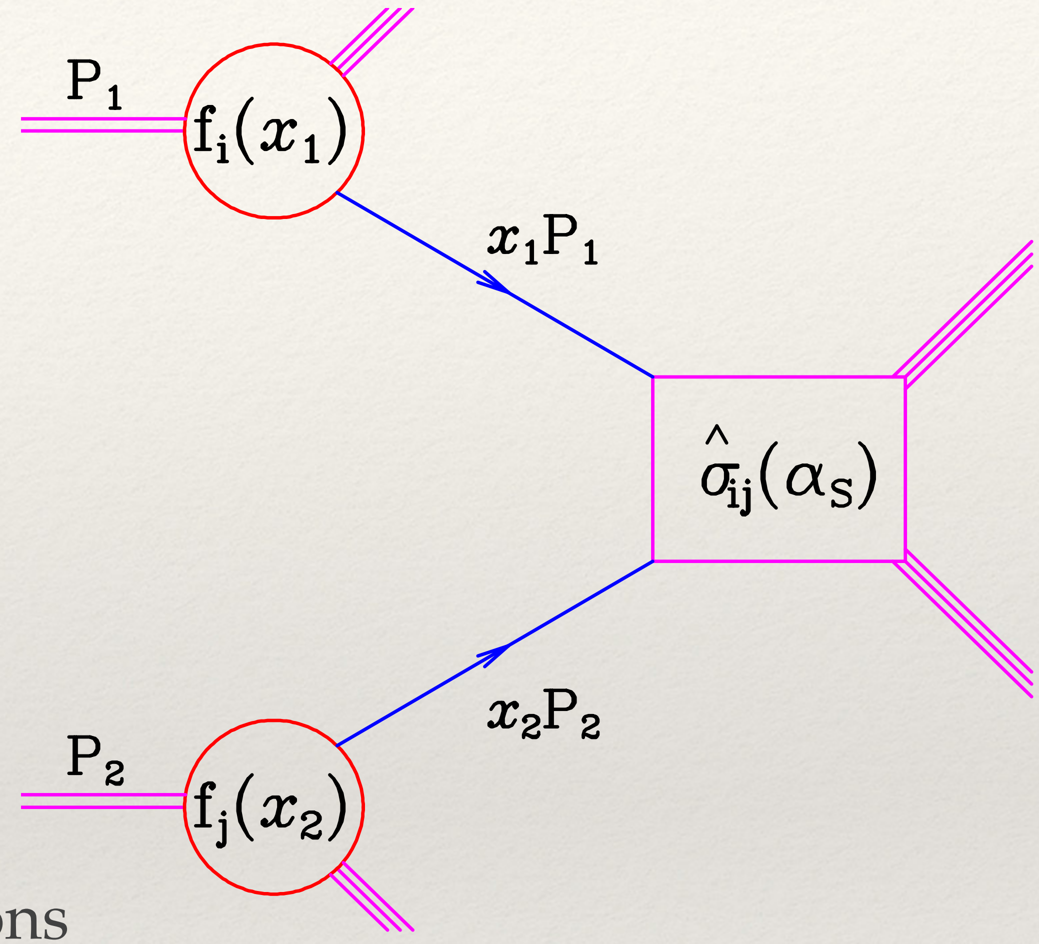


- The resultant picture depends sensitively on the top quark mass (and α_s)

The role of precision

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

$$d\sigma(P_1,P_2)=\sum_{i,k}\int dx_1dx_2\, f_i(x_1,\mu^2)f_k(x_2,\mu^2)\, d\hat{\sigma}_{ik}(p_1,p_2,p_J,\alpha_s(\mu^2),Q^2/\mu^2)F_J(p_J)+O(\Lambda/Q).$$

Physical cross section

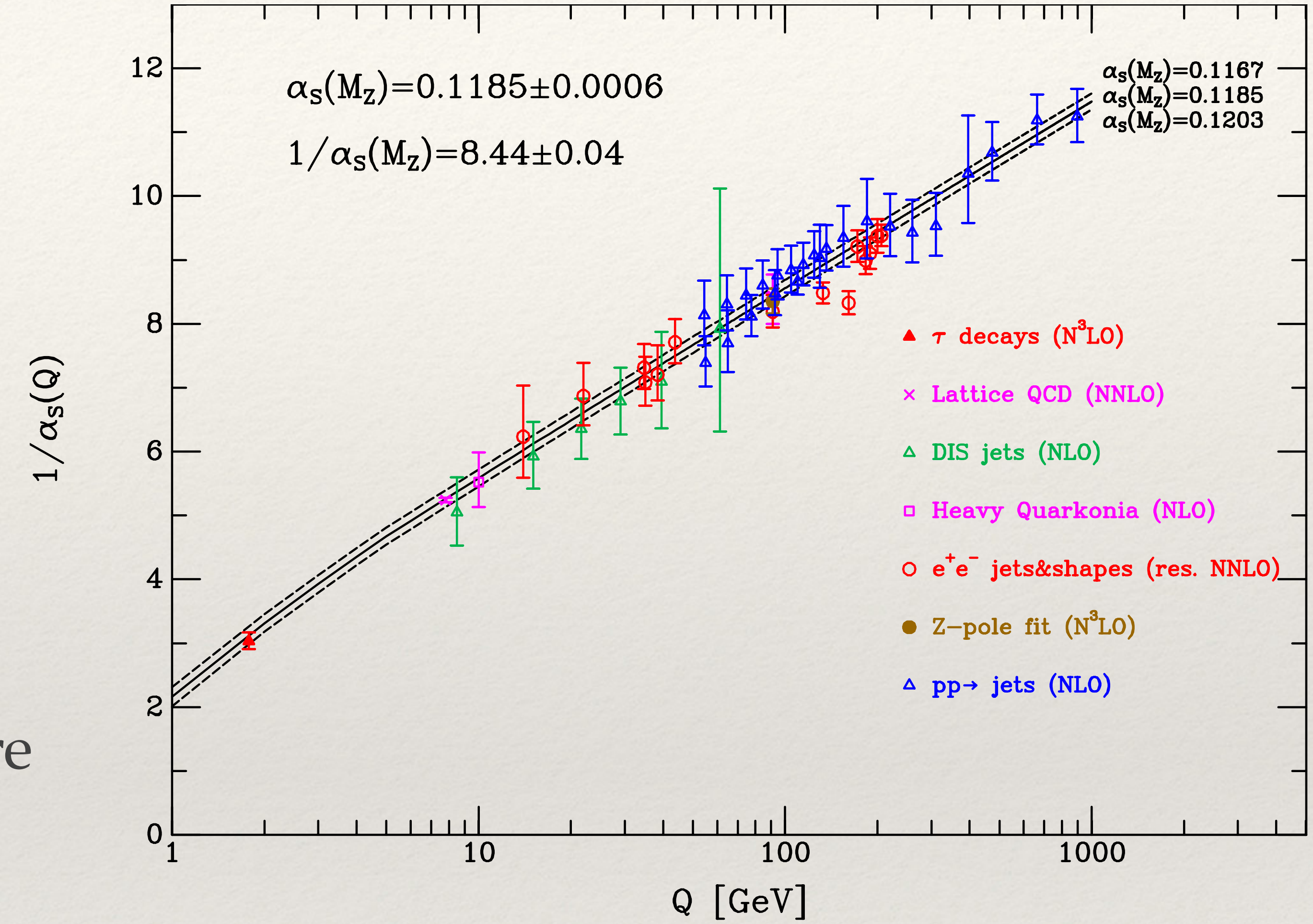
Factorization scale

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 1%



Data from PDG September, 2013

Also some other outliers mainly from e+e- data

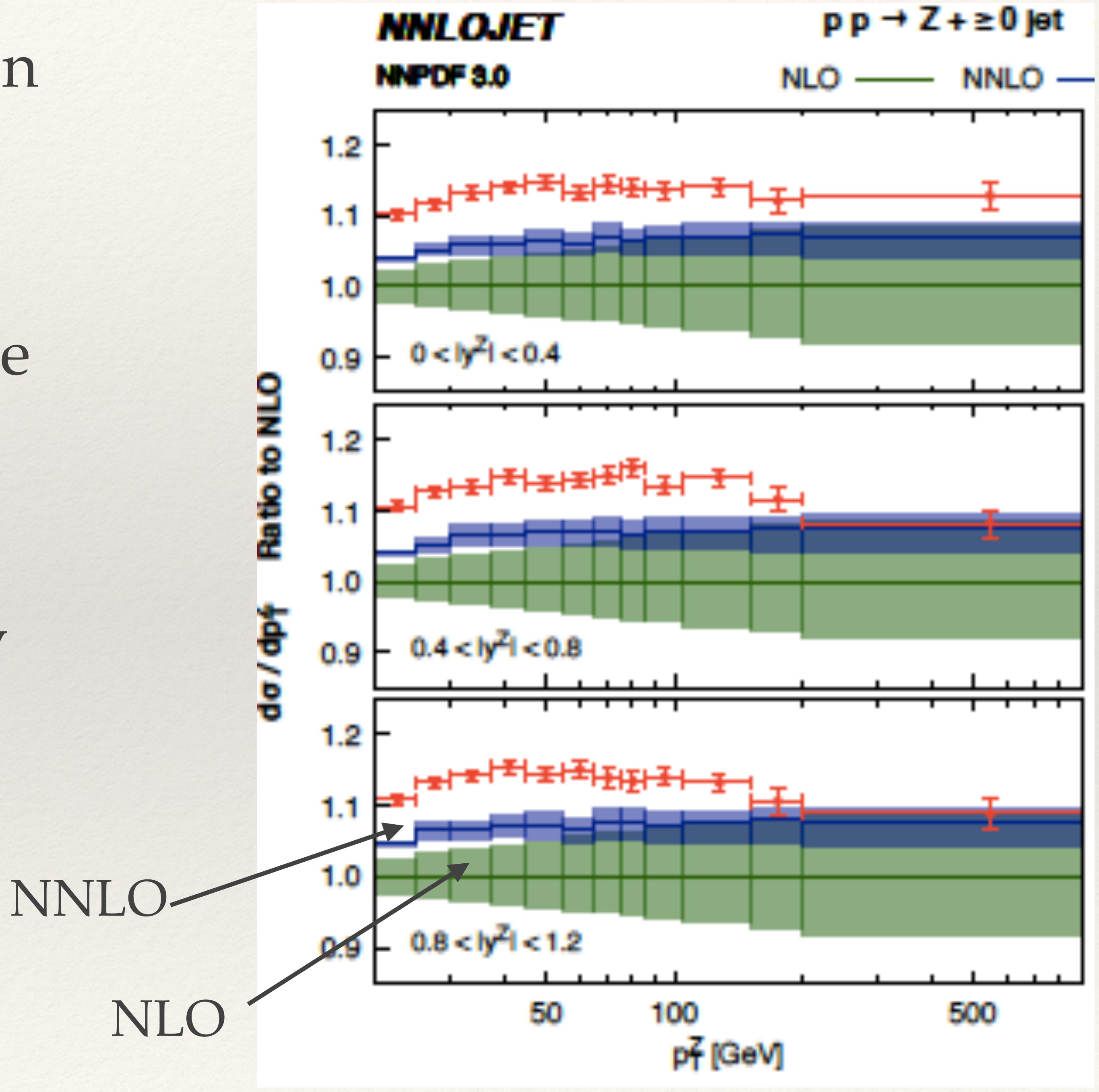
Abbate, 1006.3080, **α**s(MZ)=0.1135+0.0010

Hoang, 1501.04753,**α**s(MZ)=0.1123+0.0002

Parton distribution functions

Gehrmann-De Ridder et al, 1605.04295

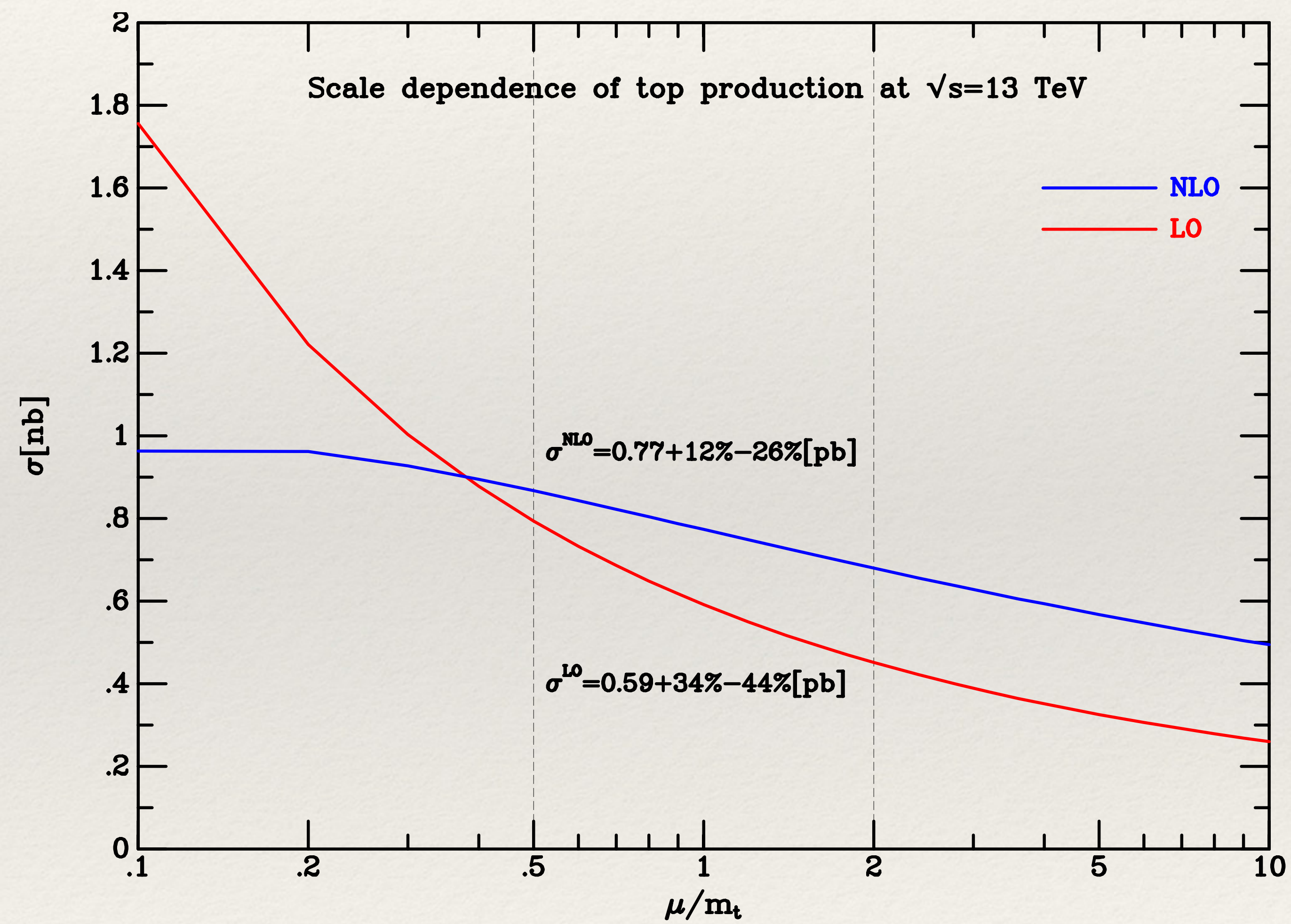
- Errors on Parton distribution functions are at the 2-3% level
- LHC can be used to improve measurements of partons
- e.g. Z pT distributions, accurate data, robust theory
- Important to include ttbar, Z-p_T, 2-jet data into fits at NNLO.



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 renormalization 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.



μR = μF =μ

The historical role of precision in QCD

- Precision matters!
- Three examples spanning 30 years,
    - Monojets at UA1 (SppS),
    - Discovery of the top quark at the Tevatron, indirect and direct limits,
    - WW production at LHC.

Missing E_T events (Bern, 1984)

EXPERIMENTAL OBSERVATION OF EVENTS WITH LARGE MISSING TRANSVERSE ENERGY ACCOMPANIED BY A JET OR A PHOTON(S) IN $p\bar{p}$ COLLISIONS AT $\sqrt{s}$ = 540 GeV

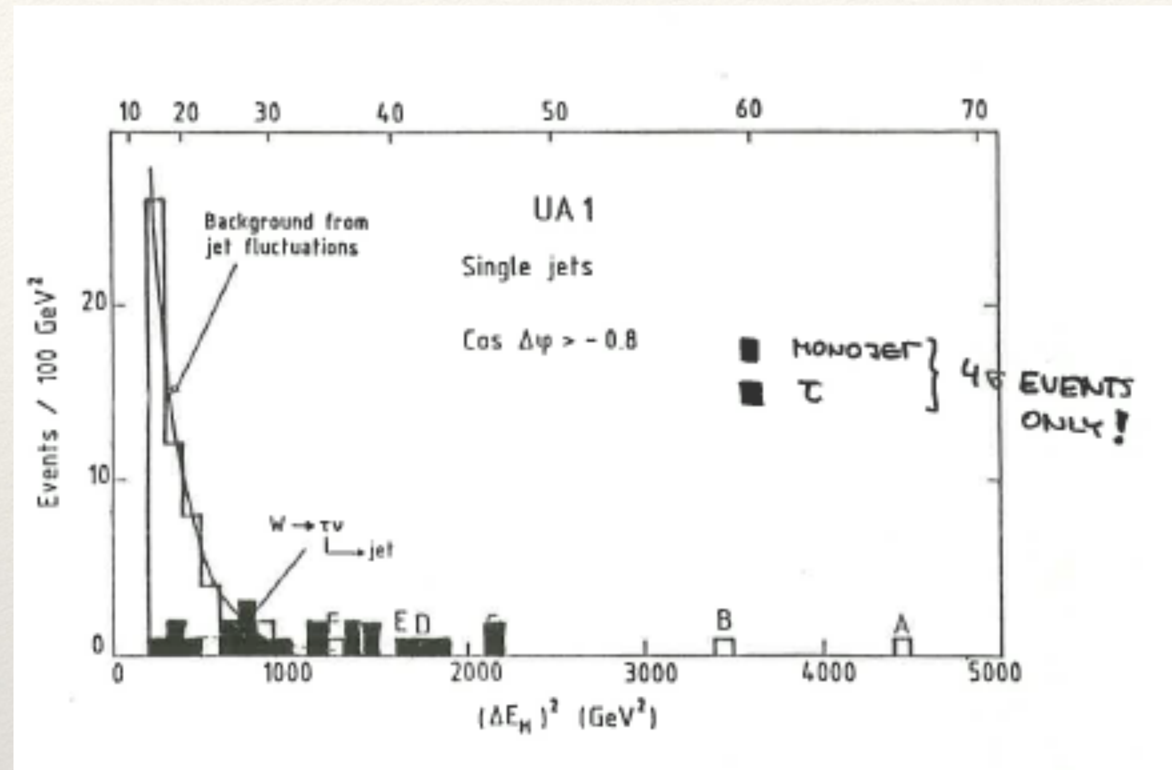
UA1 Collaboration, CERN, Geneva, Switzerland

Presented by C. Rubbia, CERN

No written contribution received

Abstract from Physics Letters, 139B, 115 (1984)

We report the observation of five events in which a missing transverse energy larger than 40 GeV is associated with a narrow hadronic jet and of two similar events with a neutral electromagnetic cluster (either one or more closely spaced photons). We cannot find an explanation for such events in terms of backgrounds or within the expectations of the Standard Model.



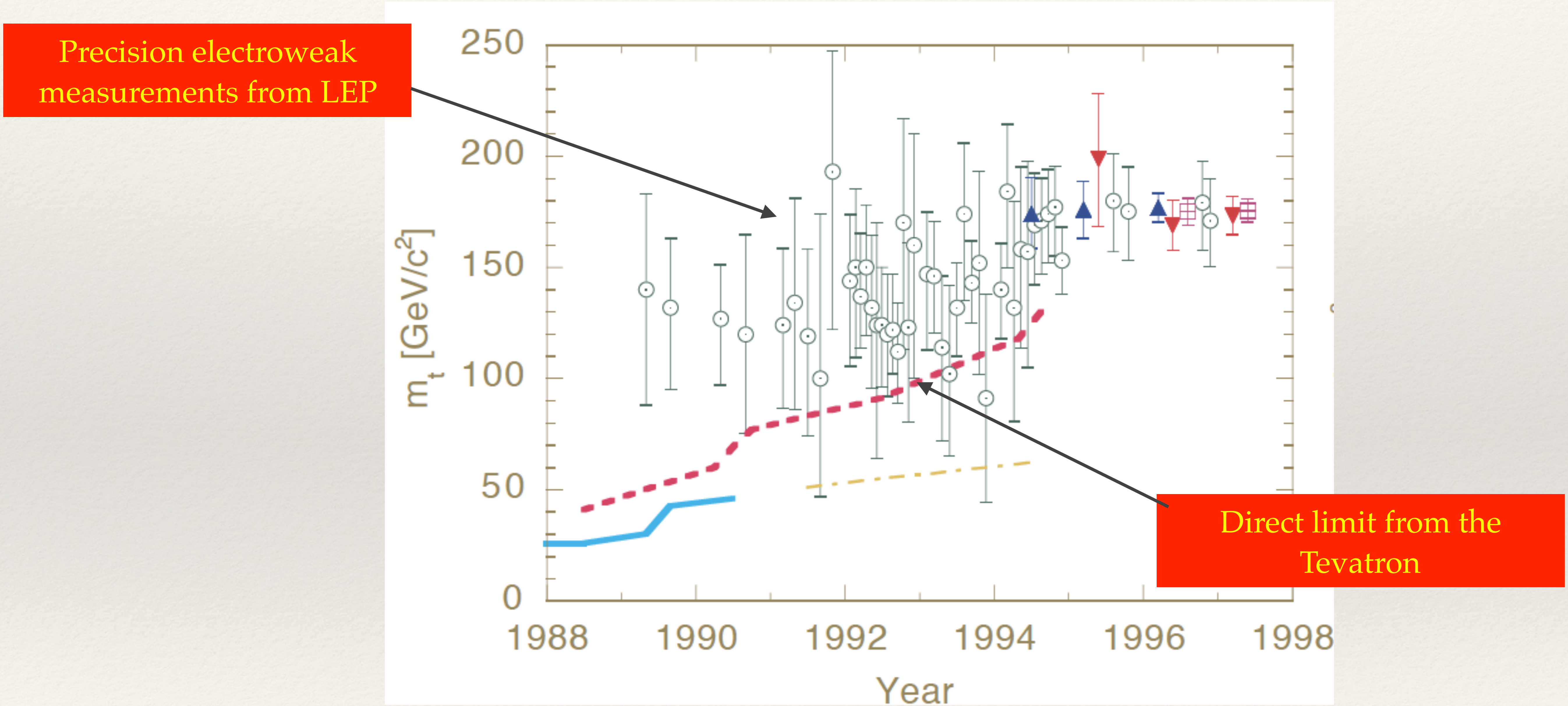
- Jet events with a large missing energies, not described by standard model sources.

The Altarelli cocktail

- The first attempt to estimate backgrounds to these events was using shower Monte Carlos.
- Without matrix element corrections, Monte Carlos give a good description of collinear emission, but seriously underestimate events at large p_{T}.
- This was probably responsible for the original underestimate of one of the standard model backgrounds for mono jets, $Z(\rightarrow \nu\ \nu)$+jet
- Eventually explained by Altraelli as a “cocktail” of $Z(\rightarrow \nu\ \nu)$+jet events, misidentified electron, cracks, jet fluctuations,W->tau ν events….at St. Vincent in 1985

Constraints on top quark mass

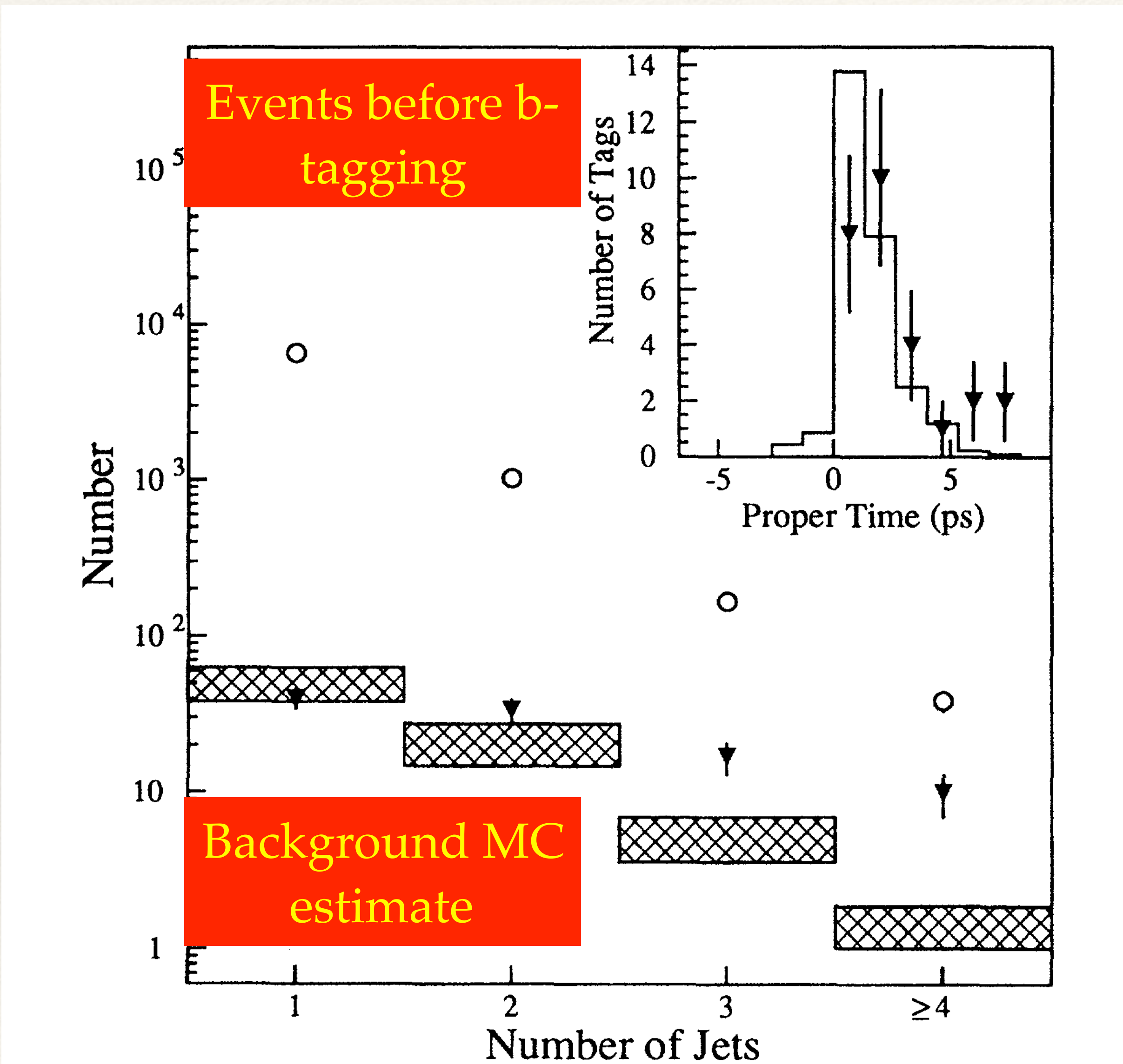
Quigg, arXiv:hep-ph/9704332



- Indirect precision limits track direct bounds, or is it vice versa?

Top quark at the Tevatron

CDF, PRL74, 1995



Berends et al , PLB224, 1989

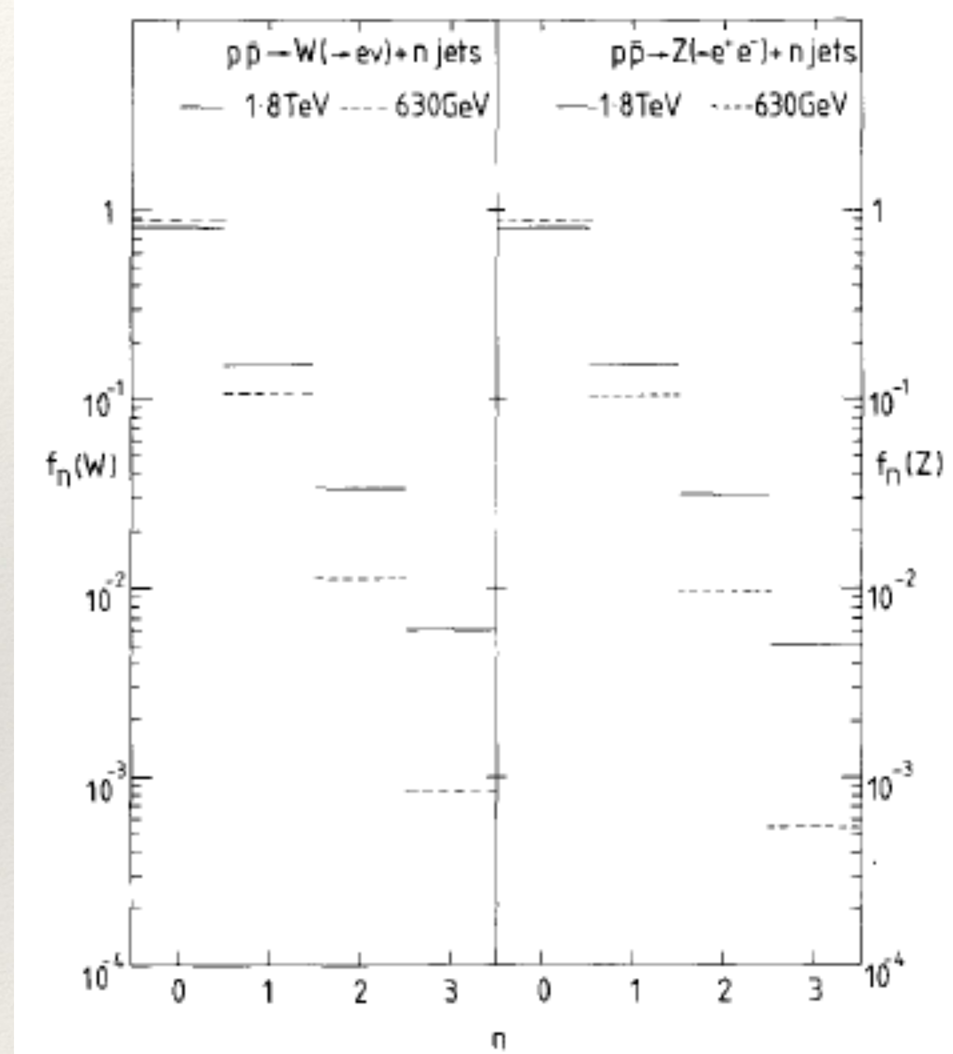


Fig. 2. Jet multiplicities at $\sqrt{s}=630$ GeV (dashed lines) and 1.8 TeV (solid lines) for (a) $W\to e\nu$ and (b) $Z\to e^+e^-$, with the full set of lepton and jet cuts defined in eqs. (3.1), (3.2).

- Estimated of b-tagged W+jets background relies on W+jet Monte Carlo, incorporating, in some measure, Berends-Giele scaling.

WW-pair cross section

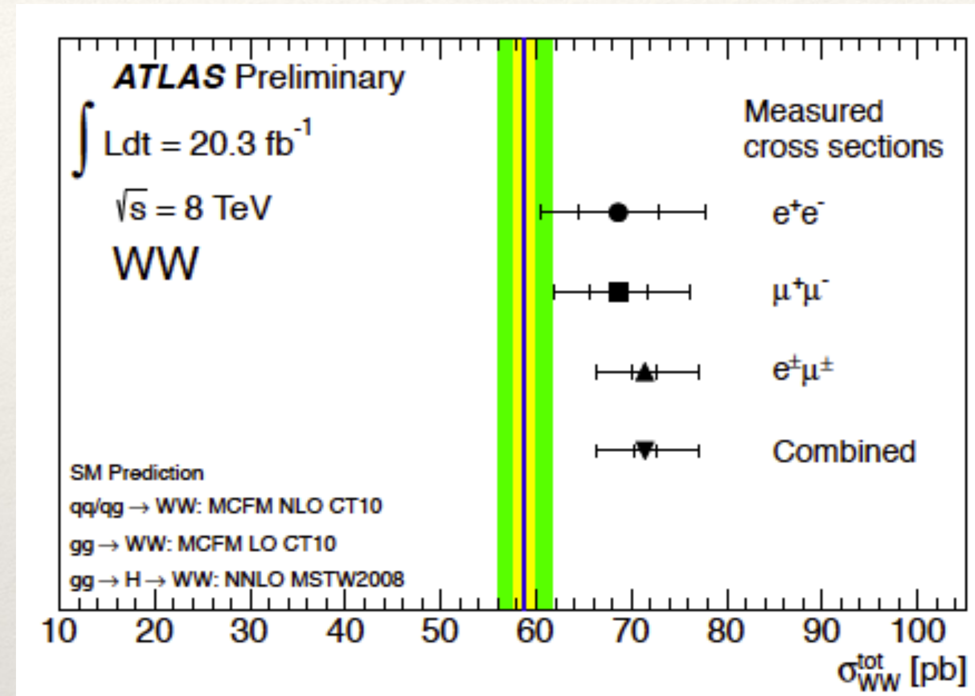
ATLAS-CONF-2014-033

- Total cross section for WW found in 2014 to be 2.1σ high.
- However no sizeable disagreement at the level of fiducial cross section.

Monni et al, 1410.4745v1

decay mode	$\sigma_{\text{fid.}}^{\text{exp.}}$ [fb]	$\sigma_{\text{fid.}}^{\text{th.}}$ [fb]
$e^+\mu^- + e^-\mu^+$	$377.8^{+6.9}_{-6.8}(\text{stat.})^{+25.1}_{-22.2}(\text{syst.})^{+11.4}_{-10.7}(\text{lumi.})$	$357.9^{+14.4}_{-14.4}$
e^+e^-	$68.5^{+4.2}_{-4.1}(\text{stat.})^{+7.7}_{-6.6}(\text{syst.})^{+2.1}_{-2.0}(\text{lumi.})$	$69.0^{+2.7}_{-2.7}$
$\mu^+\mu^-$	$74.4^{+3.3}_{-3.2}(\text{stat.})^{+7.0}_{-6.0}(\text{syst.})^{+2.3}_{-2.1}(\text{lumi.})$	$75.1^{+3.0}_{-3.0}$

- Monte Carlo (POWHEG) result for the jet veto efficiency is found to overestimate the Sudakov suppression effects, wrt analytic resummation.



arXiv:1603.01702

An apparent BSM effect, defused by comparison of analytic and Monte Carlo results.

P5-Science Drivers

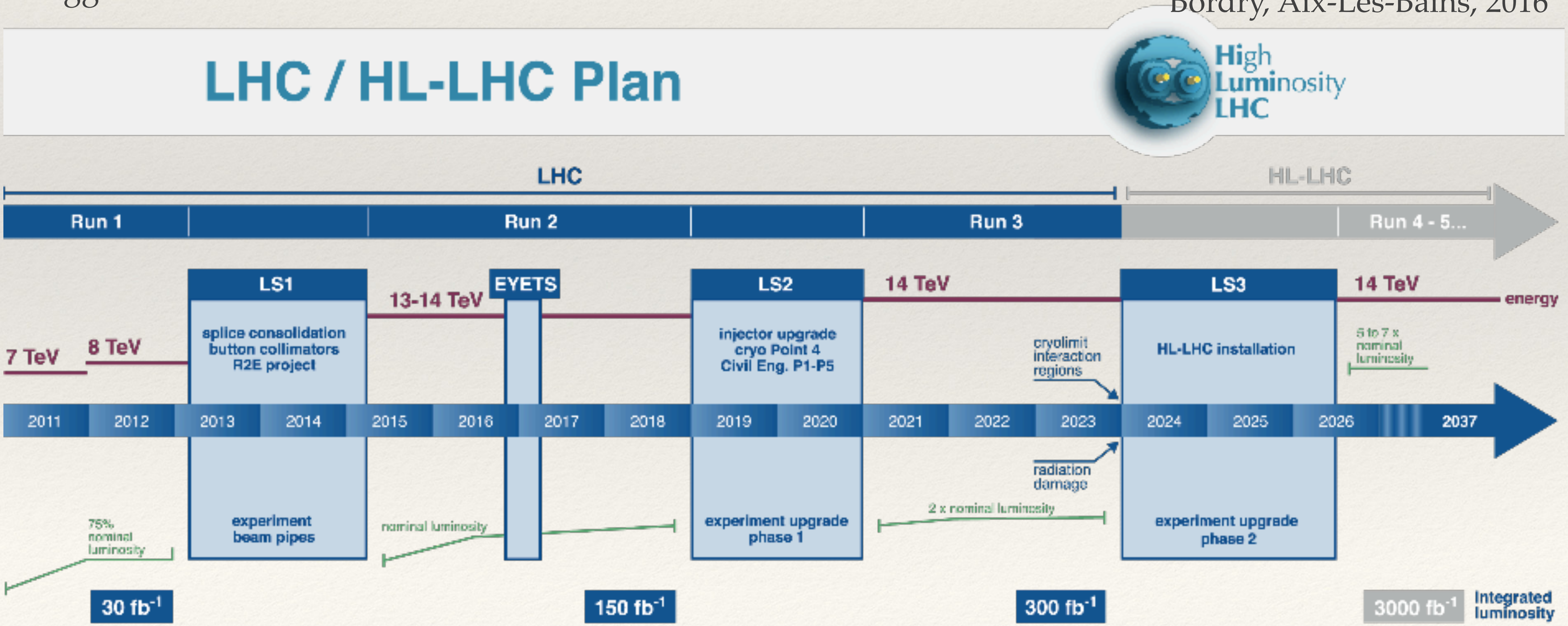
- Use the Higgs boson as a new tool for discovery
- Pursue the physics associated with neutrino mass
- Identify the new physics of Dark Matter
- Understand cosmic acceleration: dark energy and inflation
- Explore the unknown: new particles, interactions and physical principles

A top priority for LHC

High priority measurements at HL-LHC

- Higgs p_T distribution
- Higgs pair production
- Vector boson fusion and WW scattering
- Higgs couplings to fermions
- Higgs total cross section

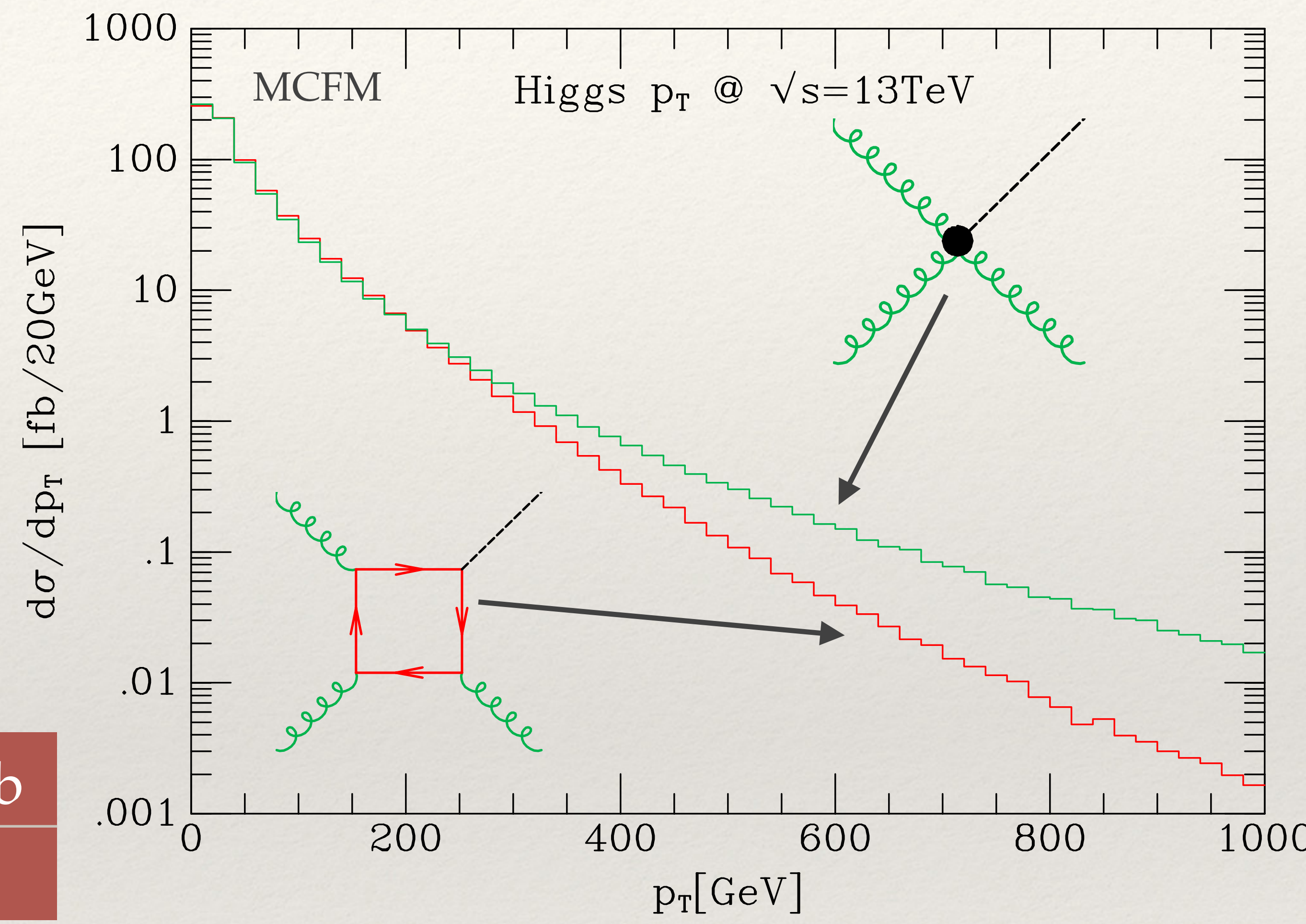
Bordry, Aix-Les-Bains, 2016



Higgs p_T distributions

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.



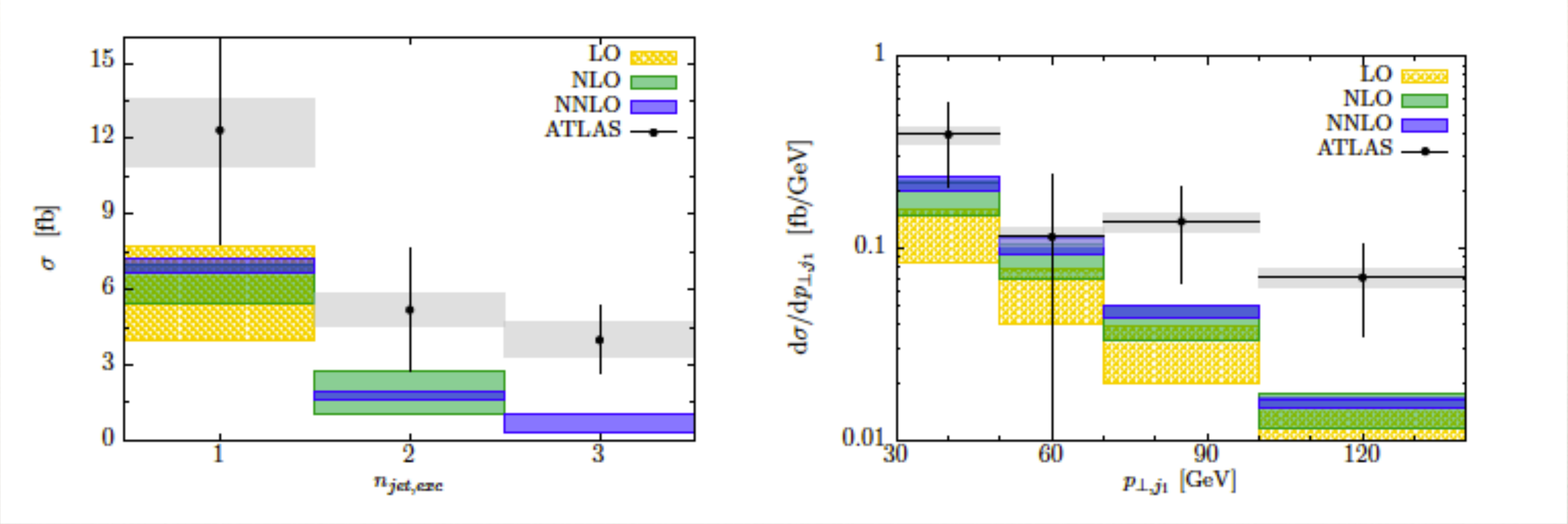
- Lowest order cross sections only

	$\sigma(p_T>p_{cut})$=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

Higgs+1jet @ NNLO (8TeV)

Caola et al, 1508.02684

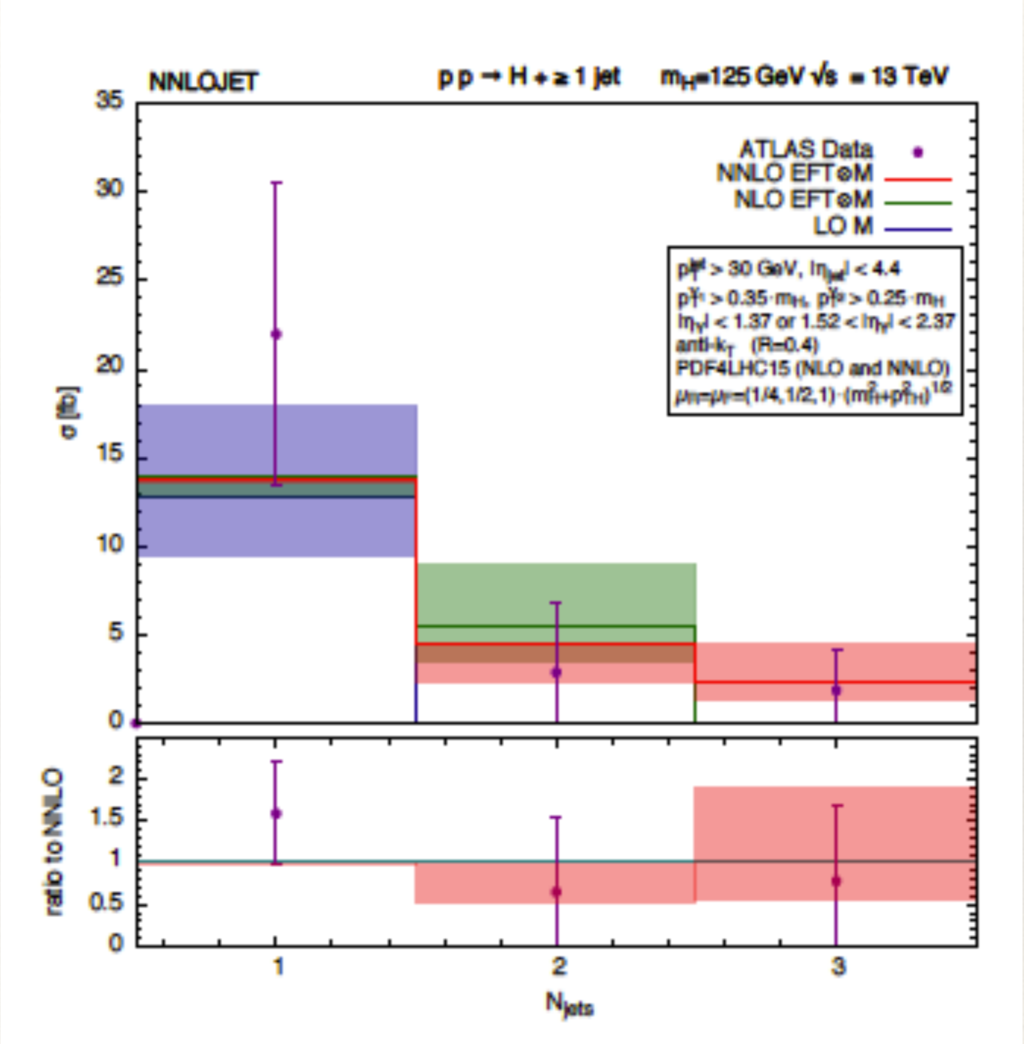


- differential NNLO calculation allows cuts to be applied.
- Apply ATLAS style cuts for $\gamma\gamma$ final state at 8 TeV
- NNLO corrections (blue) are appreciable, but controlled in size.
- $3ab^{-1}$ would reduce statistical error by a factor of 12

Higgs+1jet @ NNLO (13TeV)

- Calculation is done in the effective theory, rescaled bin-by-bin with LO calculation.
- Good agreement with in all jet bins

Chen et al,1607.08817



Higgs pair production

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

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

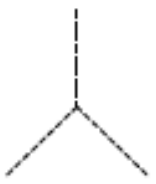
- Effective field theory for soft multi-Higgs production

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

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

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

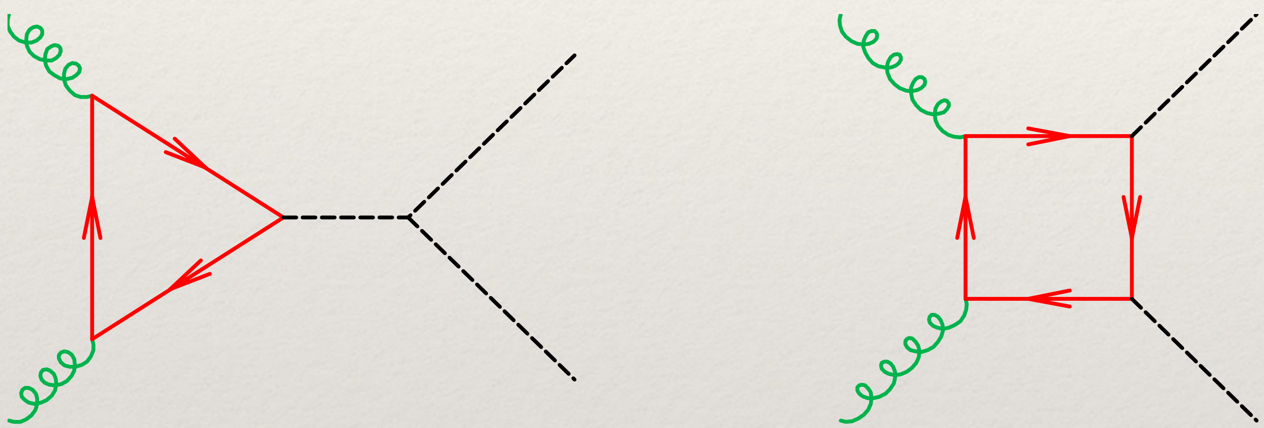
$$= \left[\frac{g_{ggH}}{v}\frac{3m_h^2}{[s-m_h^2]}\frac{1}{v} + \frac{g_{ggHH}}{v^2}\right]$$

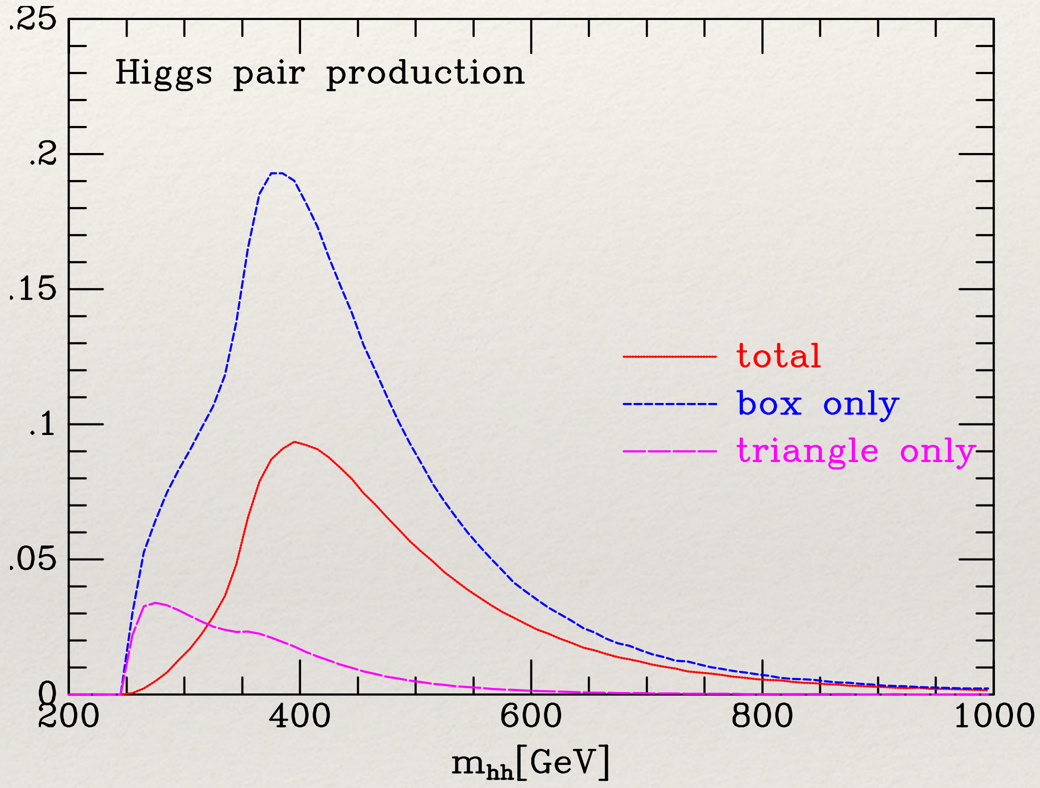


$-6i\lambda v = -3im_H^2/v$

LO Higgs pair production - full theory

- Sensitivity to triple Higgs coupling comes from threshold region



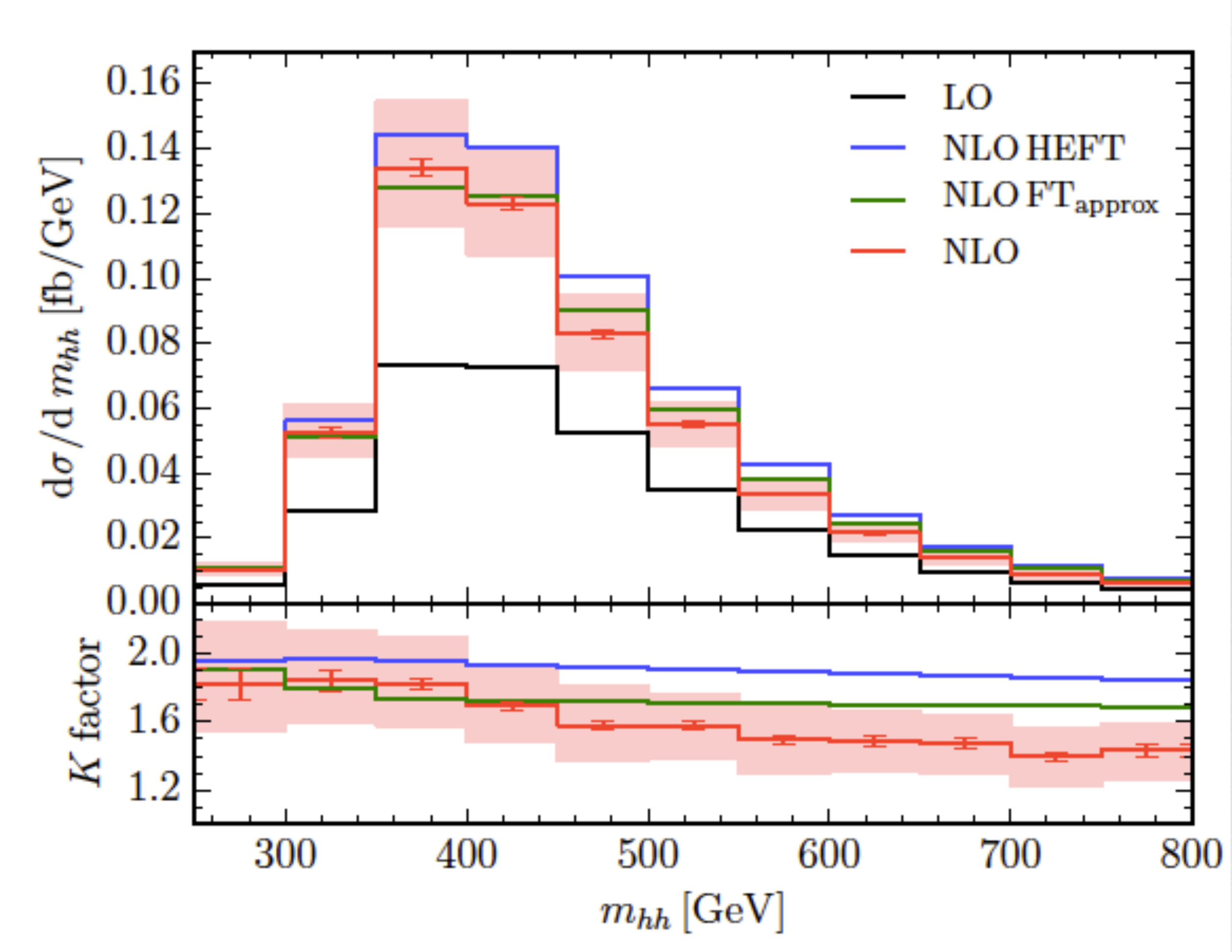


- As m_{hh} becomes large s-channel propagator suppresses first diagram.

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).



$\sqrt{s} = 13\,\text{TeV}$

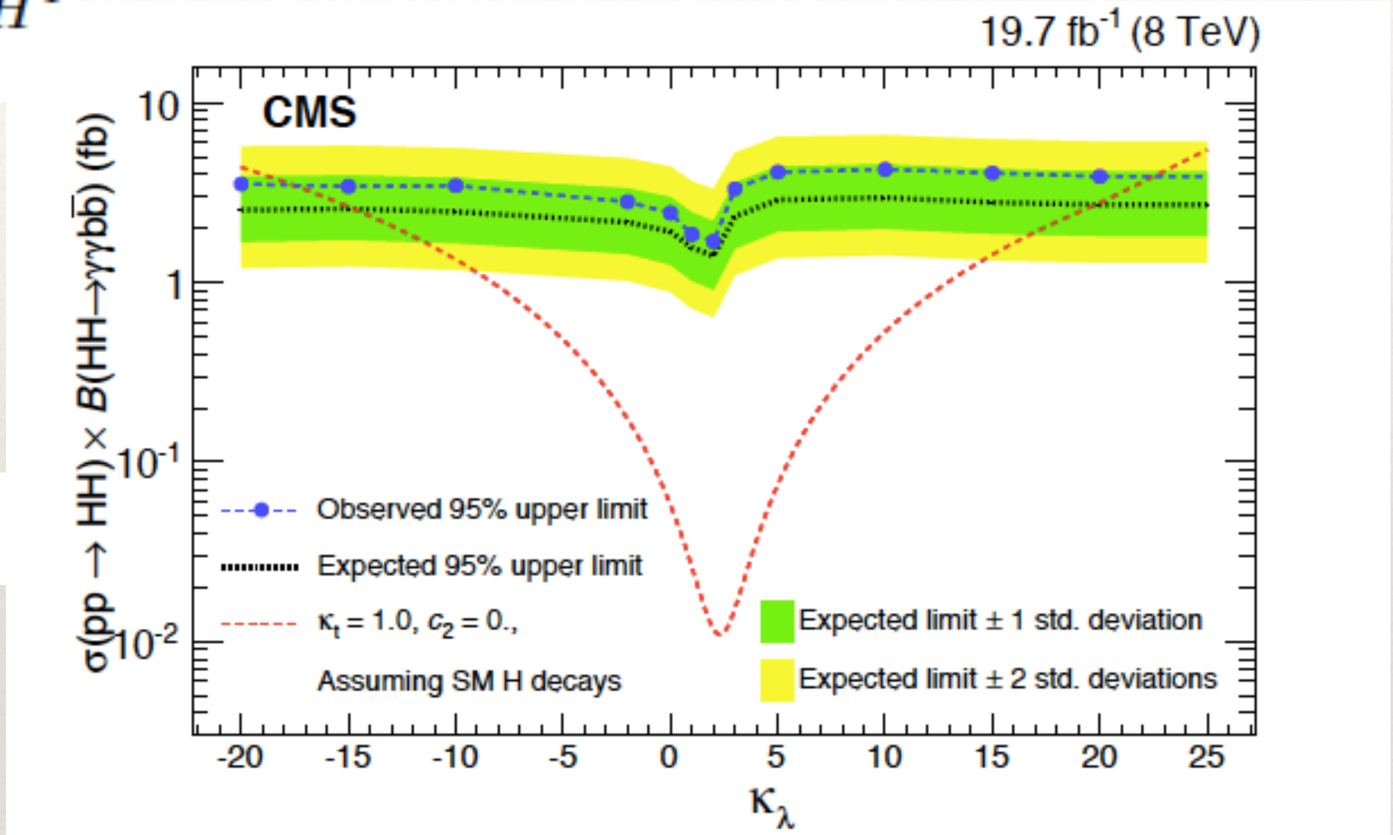
$$\sigma^{\rm NLO} = 27.80^{+13.8\%}_{-12.8\%}\,\text{fb} \pm 0.3\%\,(\text{stat.}) \pm 0.1\%\,(\text{int.})\ .$$

Tiny cross section after Higgs branching ratios applied.

Current bounds on the effective Higgs self-coupling

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

arXiv:1603.06896

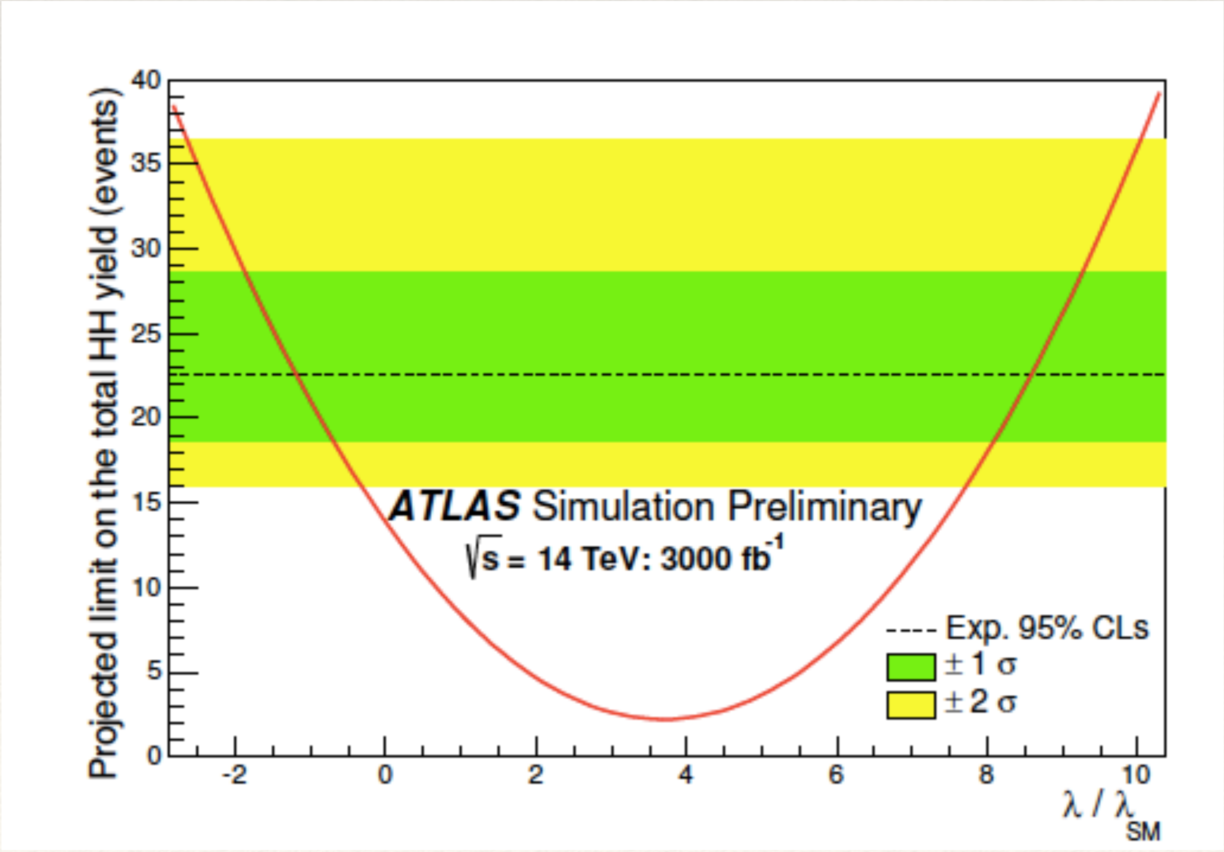


- Using the final state $\gamma\gamma b\bar{b}$
- bound on effective couplings are $\kappa_3 \leq -17.5$ and $\kappa_3 \geq 22.5$
- Most promising channels for the future $b\bar{b}b\bar{b},\ \tau\tau b\bar{b},\ \gamma\gamma b\bar{b},\ WWb\bar{b}$

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



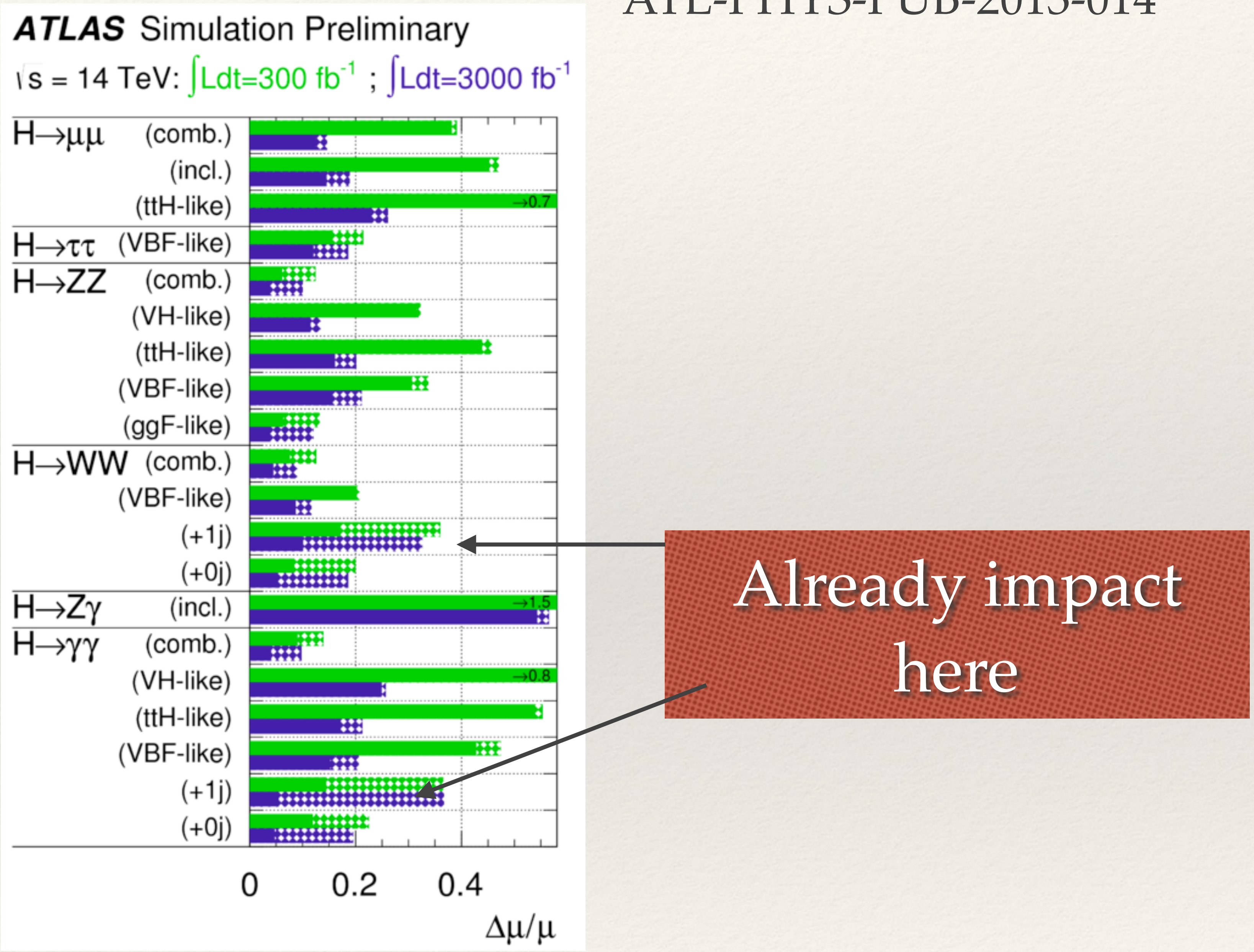
ATL-PHYS-PUB-2014-019

Signal strengths

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.



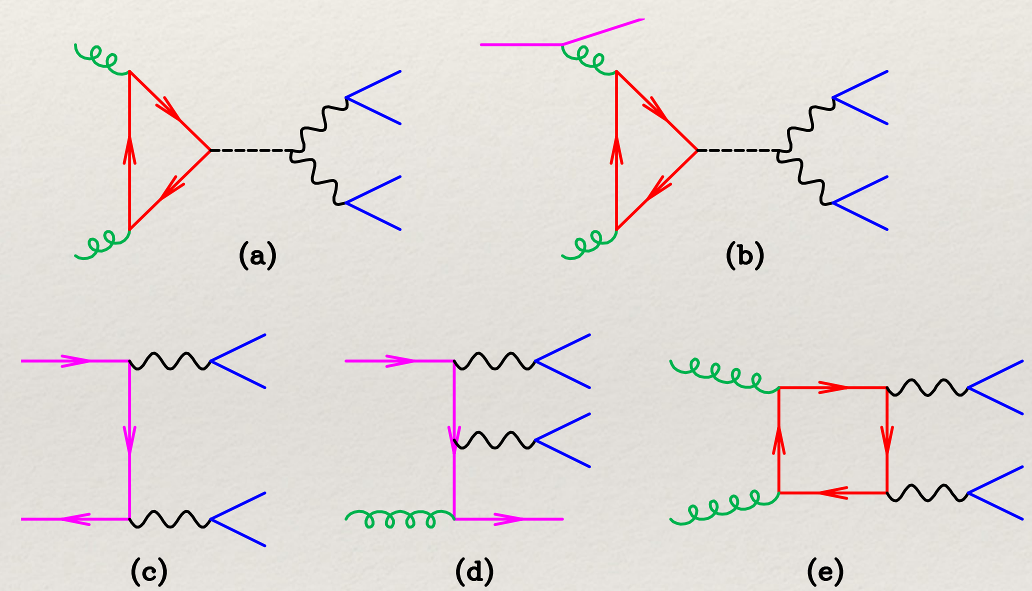
ATLAS: Syst. errors as run 1, with (without) theory errors

Off-shell Higgs

pp→$e^-e^+\mu^-\mu^+$ in the standard model

- Mishmash of orders in perturbation theory

$(a): g(-p_1) + g(-p_2) \to H \to e^-(p_3) + e^+(p_4) + \mu^-(p_5) + \mu^+(p_6)$	$O(g_s^2 e^4)$
$(b): q(-p_1) + g(-p_2) \to H \to e^-(p_3) + e^+(p_4) + \mu^-(p_5) + \mu^+(p_6) + q(p_7)$	$O(g_s^3 e^4)$
$(c): q(-p_1) + \bar{q}(-p_2) \to e^-(p_3) + e^+(p_4) + \mu^-(p_5) + \mu^+(p_6)$	$O(e^4)$
$(d): q(-p_1) + g(-p_2) \to e^-(p_3) + e^+(p_4) + \mu^-(p_5) + \mu^+(p_6) + q(p_7)$	$O(g_s e^4)$
$(e): g(-p_1) + g(-p_2) \to e^-(p_3) + e^+(p_4) + \mu^-(p_5) + \mu^+(p_6)$	$O(g_s^2 e^4)$



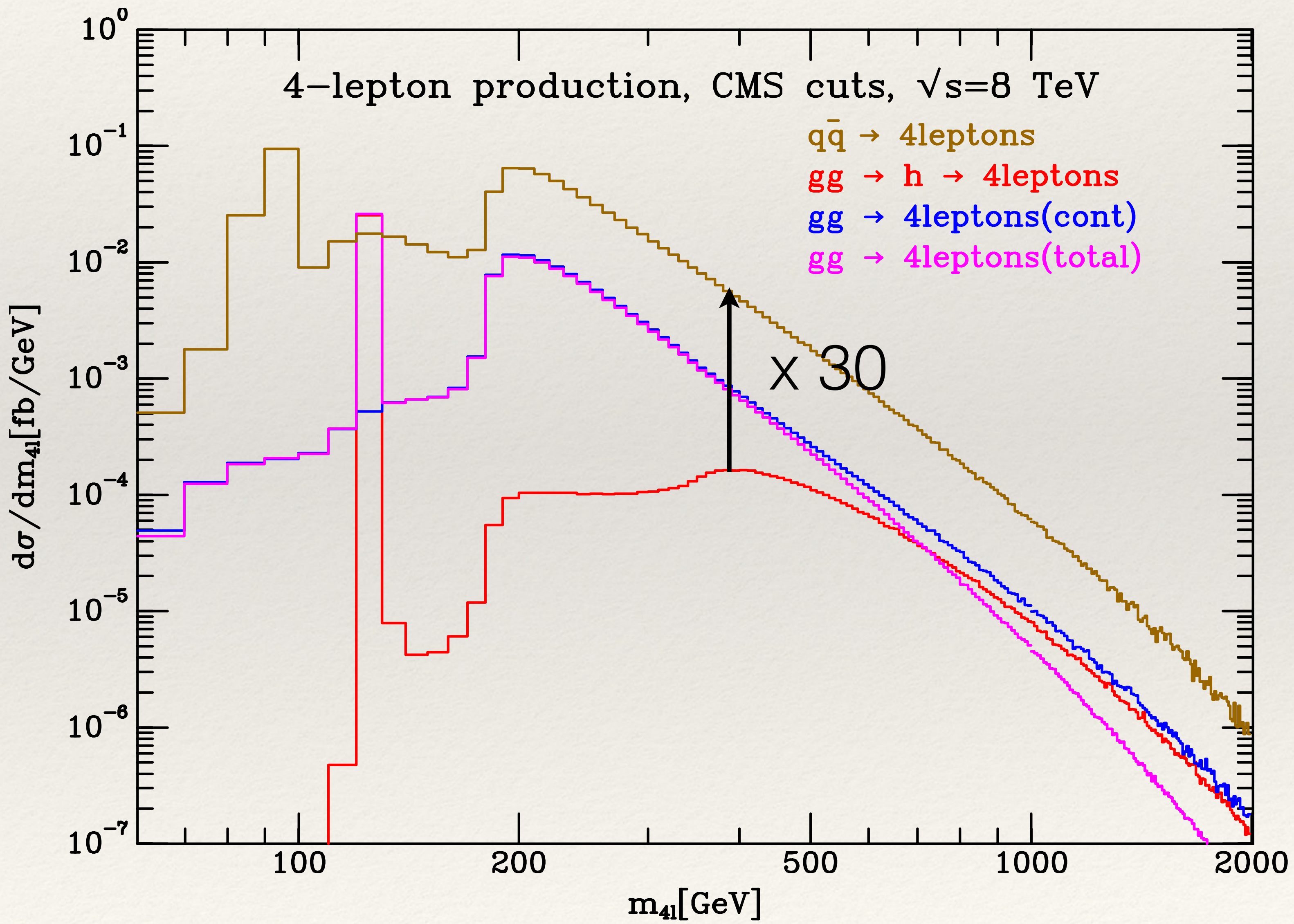
- Representative diagrams are:-
- (a) and (e), (b) and (d) can interfere.
- (b-d) interference does not overwhelm (a-e).

The big picture @ 8TeV

- Peak at Z mass due to singly resonant diagrams.
- Interference is an important effect off-resonance.
- Destructive at large mass, as expected.
- With the standard model width, Γ_H, challenging to see enhancement/deficit due to Higgs channel.
- 3 phenomena happening in the tail.

$$p_{T,\mu} > 5 \text{ GeV}\,, \quad |\eta_\mu| < 2.4\,,$$
$$p_{T,e} > 7 \text{ GeV}\,, \quad |\eta_e| < 2.5\,,$$
$$m_{ll} > 4 \text{ GeV}\,, \quad m_{4\ell} > 100 \text{ GeV}\,.$$

CMS cuts
CMS PAS HIG-13-002



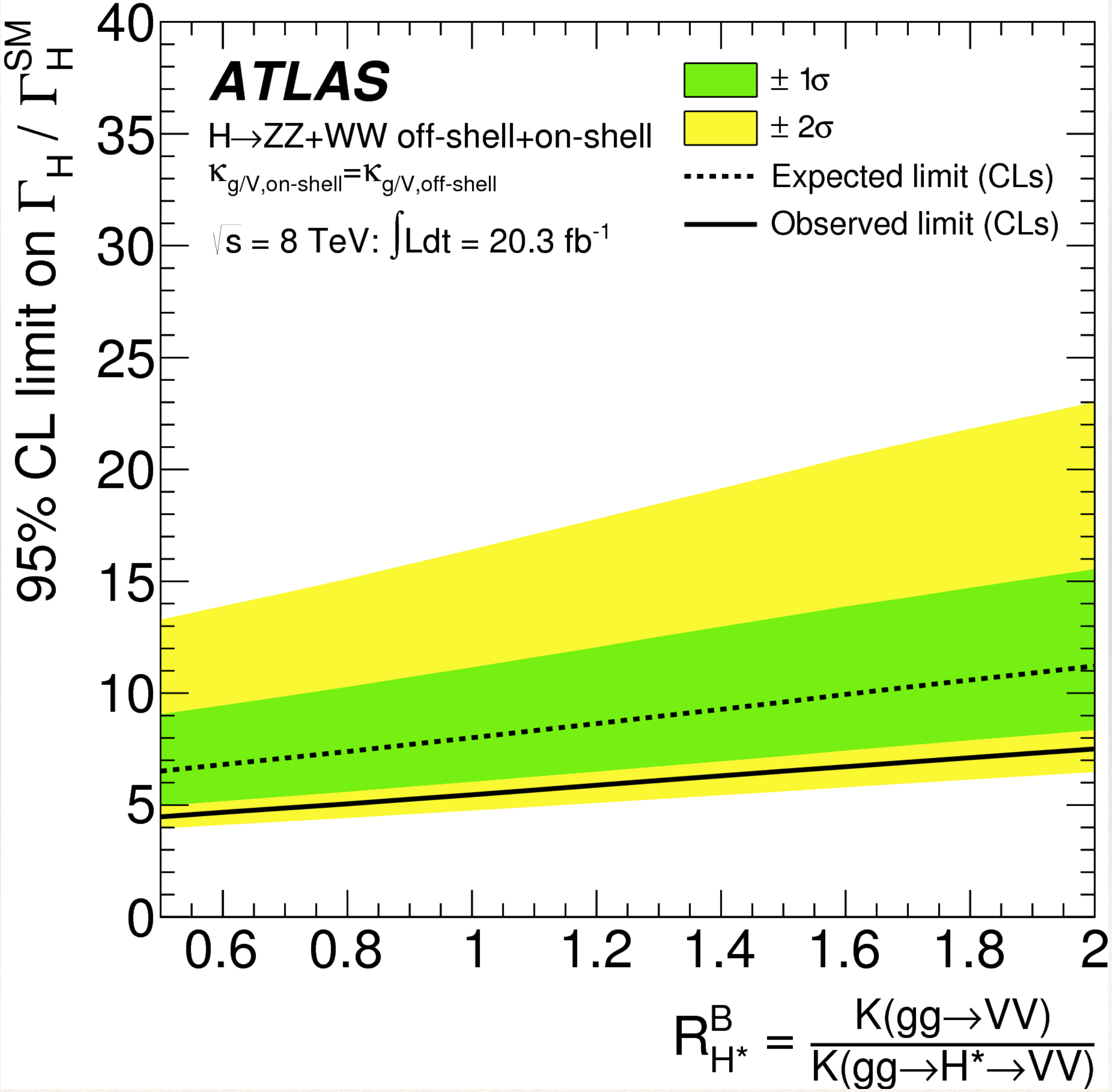
Higgs couplings and width

- Off-shell tail is a valuable source of information about the Higgs production and decay couplings $\sigma_{\text{off}} \propto g_i^2 g_f^2$
- Higgs cross section under the peak depends on ratio of couplings and width. $\sigma_{\text{peak}} \propto \frac{g_i^2 g_f^2}{\Gamma}$
- So measurements at the peak cannot untangle couplings and width.
- Off-peak cross section is independent of the width, but still depends on $g_i^2 g_f^2$ (modulo interference, see later).
- Taking ratio $$\frac{\left(\frac{\sigma_{\text{off}}}{\sigma_{\text{peak}}}\right)_{\text{experimental gg}}}{\left(\frac{\sigma_{\text{off}}}{\sigma_{\text{peak}}}\right)_{\text{theoretical SM}}} = \frac{\Gamma}{\Gamma^{\text{SM}}}$$
- Ratio depends linearly on the Higgs boson width.
- Assumption that on- and off-shell couplings are the same, introduces model dependence.

Caola-Melnikov 1307.4935

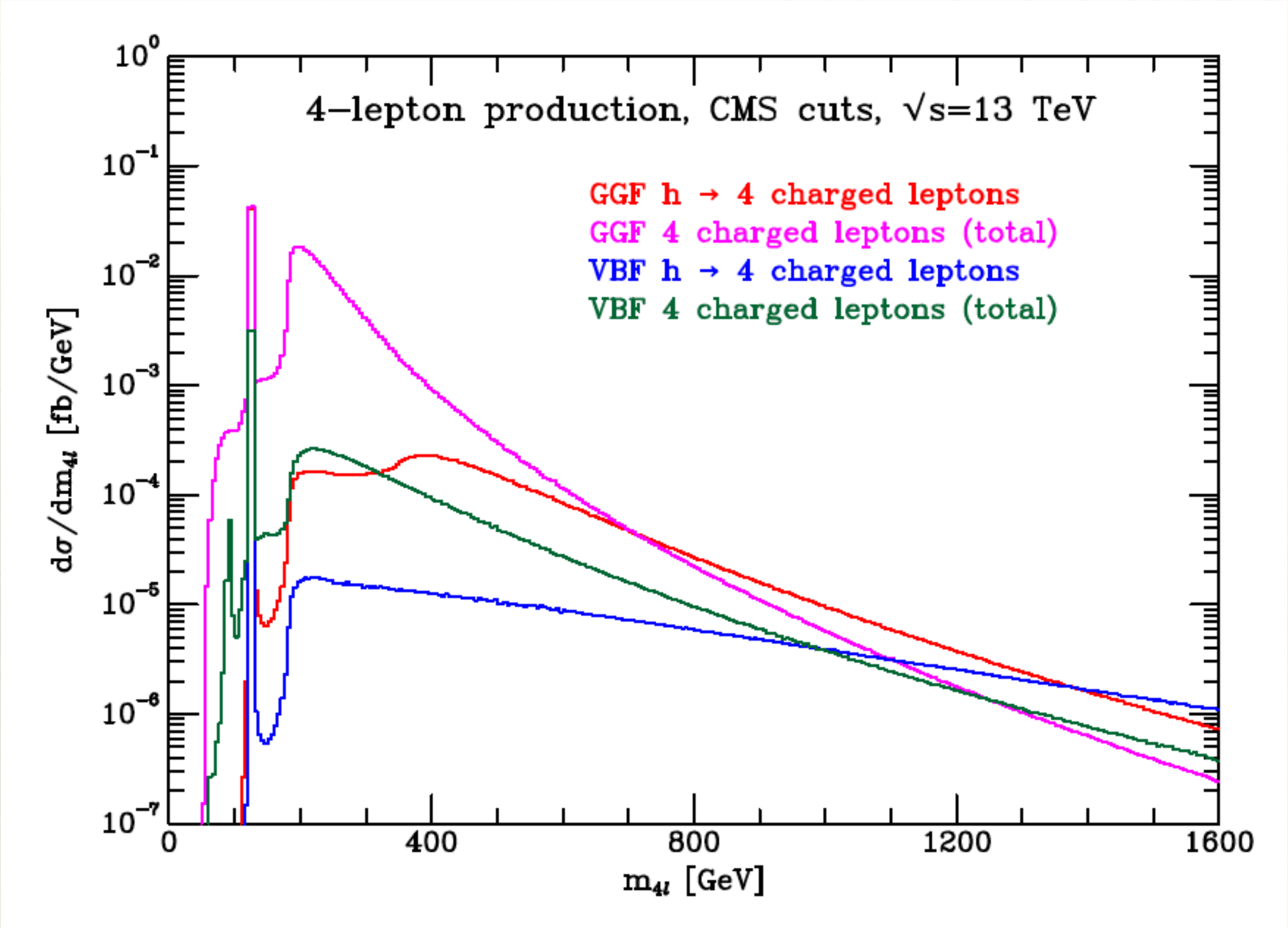
Atlas result for Higgs width

- Γ_{SM}=4.2 MeV
- Atlas bound between 5 and 7 times standard model value



Gluon-gluon fusion vs Vector boson fusion

- (pp → $e^-e^+\mu^-\mu^+$) vs (pp→ jet+jet+$e^-e^+\mu^-\mu^+$ with VBF cuts)



- EW cross section for Higgs ~10% of gg fusion (before VBF cuts)
- Higgs tail relatively more important in pp → jet+jet+$e^-e^+\mu^-\mu^+$
- Different slope for VBF tail.

Englert,Spannowsky, 1405.0285, Campbell, RKE 1502.02990

Diagrams for pp → jet+jet+$e^-e^+\mu^-\mu^+$

- Off-shell behaviour for VBF subject of much theoretical study.

- Jet cuts

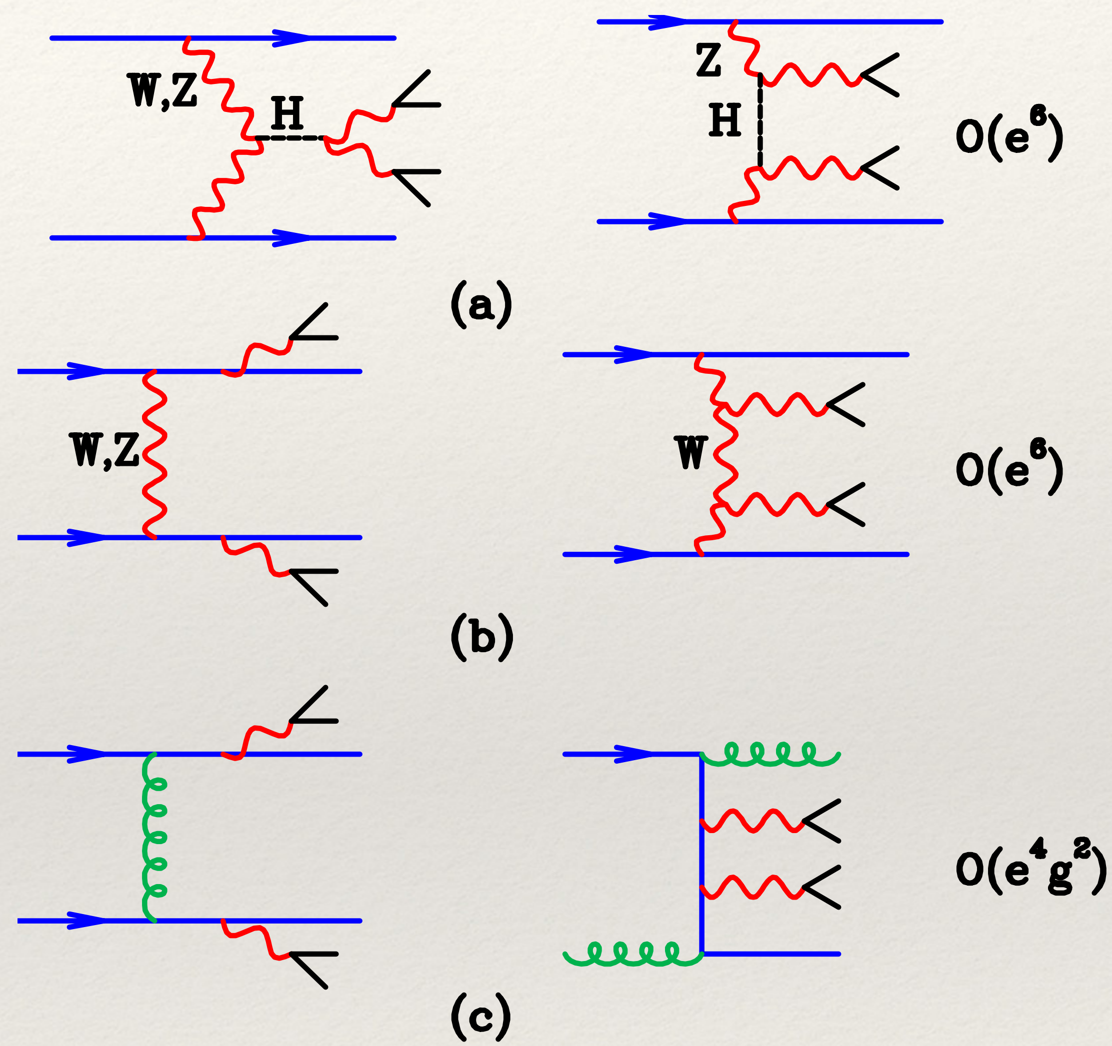
$$p_{T,J} > 30 \text{ GeV}\,, |\eta_J| < 4.5\,, R = 0.4$$

- CMS lepton cuts

$$p_{T,\mu} > 5 \text{ GeV}\,,\ |\eta_\mu| < 2.4\,,$$
$$p_{T,e} > 7 \text{ GeV}\,,\ |\eta_e| < 2.5\,,$$
$$m_{ll} > 4 \text{ GeV}\,,\ m_{4\ell} > 100 \text{ GeV}\,.$$

- Additional VBF cuts

$$y_{gap} > 2.4$$
$$\eta_1 \times \eta_2 < 0$$
$$m_{j_1 j_2} > 500 \text{ GeV}$$



Rates for signal and background

Signal, O(α^6)

Process	Nominal process	Cut	σ [fb] $\mathcal{O}(\alpha^6)$	Factor	Events in 100 fb^{-1}
$pp \to e^- \mu^+ \nu_\mu \bar{\nu}_e jj$	W^-W^+	$m_T^{WW} > 300$ GeV	0.2378	x4	95
$pp \to \nu_e e^+ \nu_\mu \mu^+ jj$	W^+W^+	$m_T^{WW} > 300$ GeV	0.1358	x2	27
$pp \to e^- \bar{\nu}_e \mu^- \bar{\nu}_\mu jj$	W^-W^-	$m_T^{WW} > 300$ GeV	0.0440	x2	9
$pp \to \nu_e e^+ \mu^- \mu^+ \mu^+ jj$	W^+Z	$m_T^{WZ} > 300$ GeV	0.0492	x4	20
$pp \to e^- \bar{\nu}_e \mu^- \mu^+ jj$	W^-Z	$m_T^{WZ} > 300$ GeV	0.0242	x4	10
$pp \to l^- l^+ \nu_l \bar{\nu}_l jj$	ZZ	$m_T^{ZZ} > 300$ GeV	0.0225	x6	14
$pp \to l^- l^+ \nu_l \bar{\nu}_l jj$	ZZ	$m_T^{WW} > 300$ GeV	0.0181	x6	11
$pp \to e^- e^+ \mu^- \mu^+ jj$	ZZ	$m_{4l} > 300$ GeV	0.0218	x2	4

Table 3. Electroweak ($\mathcal{O}(\alpha^6)$) cross sections at $\sqrt{s} = 13$ TeV, under the cuts given in Eqs. (2.2)–(2.6) and the off-shell definition specified in the table. The factor gives the approximate number by which the result shown for specific lepton flavours must be multiplied to account for two flavours of charged leptons, e, μ and three flavours of neutral leptons, ν_e, ν_μ, ν_τ.

W^+W^+

Factor takes into account sum over e,μ and ν_e,ν_μ,ν_τ

c.f. ttbar 254 events

Background, O($\alpha^4\alpha_s^2$)

Process	Nominal process	Cut	σ [fb] $O(\alpha^4\alpha_s^2)$	Factor	Events in 100 fb^{-1}
$pp \to e^- \mu^+ \nu_\mu \bar{\nu}_e jj$	W^-W^+	$m_T^{WW} > 300$ GeV	0.2227	x4	89
$pp \to \nu_e e^+ \nu_\mu \mu^+ jj$	W^+W^+	$m_T^{WW} > 300$ GeV	0.0079	x2	2
$pp \to e^- \bar{\nu}_e \mu^- \bar{\nu}_\mu jj$	W^-W^-	$m_T^{WW} > 300$ GeV	0.0025	x2	0
$pp \to \nu_e e^+ \mu^- \mu^+ \mu^+ jj$	W^+Z	$m_T^{WZ} > 300$ GeV	0.0916	x4	37
$pp \to e^- \bar{\nu}_e \mu^- \mu^+ jj$	W^-Z	$m_T^{WZ} > 300$ GeV	0.0454	x4	18
$pp \to l^- l^+ \nu_l \bar{\nu}_l jj$	ZZ	$m_T^{ZZ} > 300$ GeV	0.0143	x6	9
$pp \to l^- l^+ \nu_l \bar{\nu}_l jj$	ZZ	$m_T^{WW} > 300$ GeV	0.0118	x6	7
$pp \to e^- e^+ \mu^- \mu^+ jj$	ZZ	$m_{4l} > 300$ GeV	0.0147	x2	3

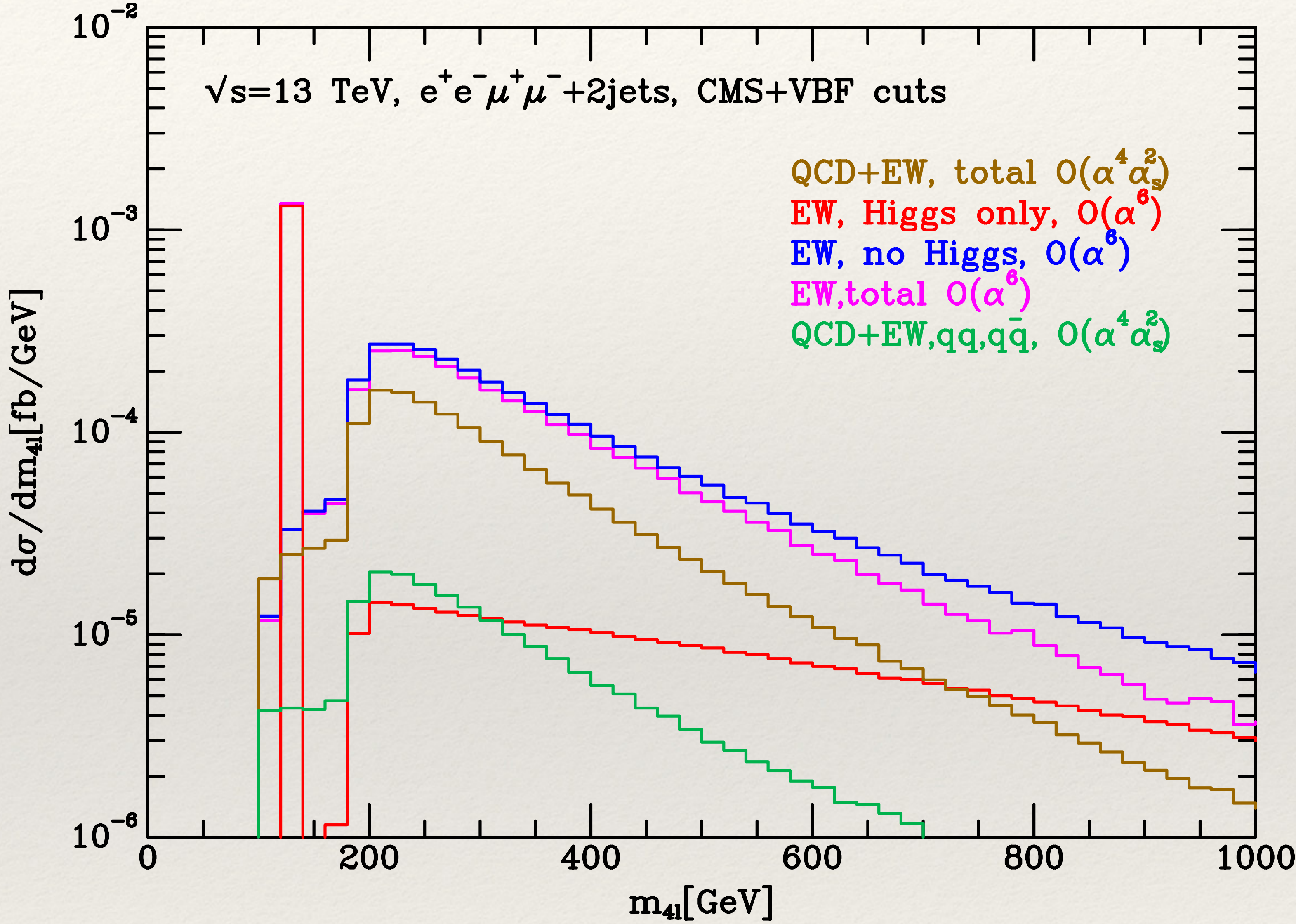
Table 4. Mixed QCD-electroweak ($\mathcal{O}(\alpha^4\alpha_s^2)$) cross sections at $\sqrt{s} = 13$ TeV, under the cuts given in Eqs. (2.2)–(2.6) and the off-shell definition specified in the table.

W^+W^+

Ignore other sources of background, W+jet, QCD…..

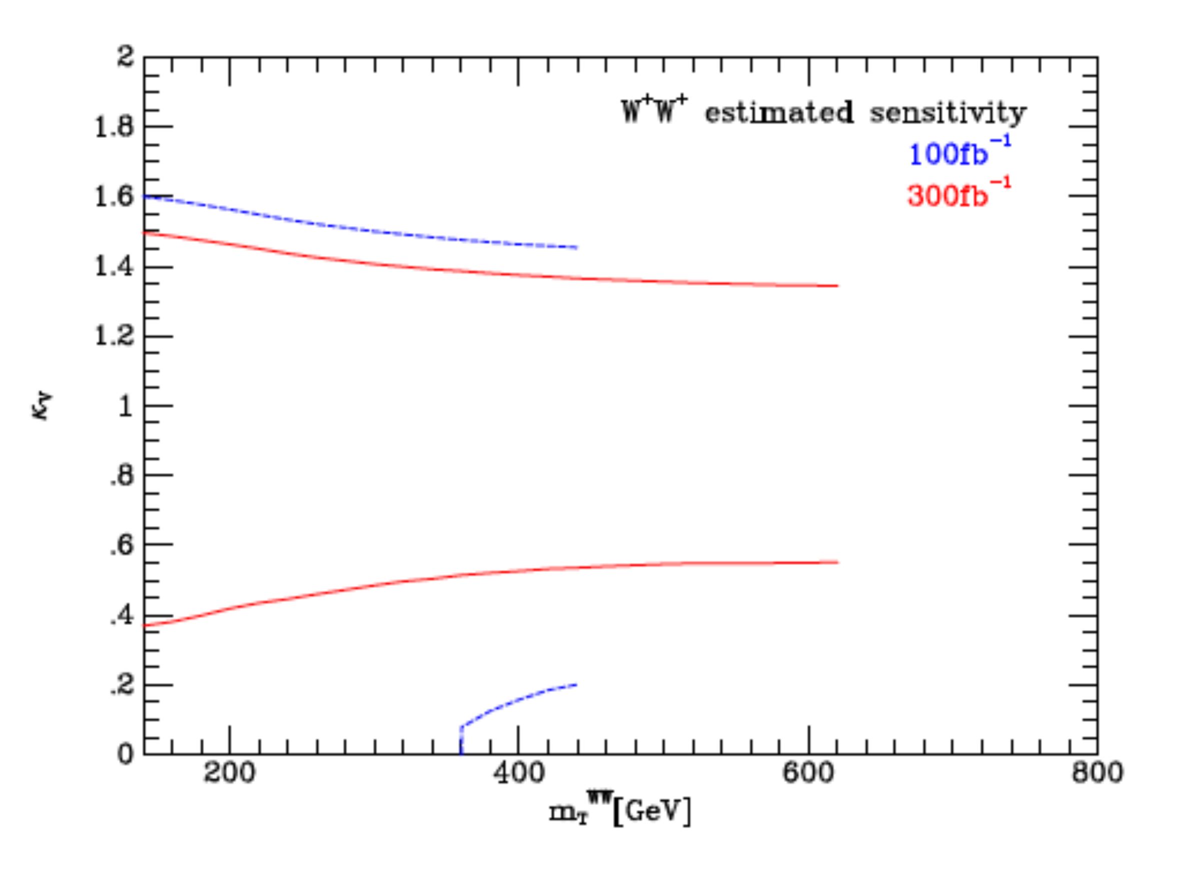
VBF cuts @ 13 TeV

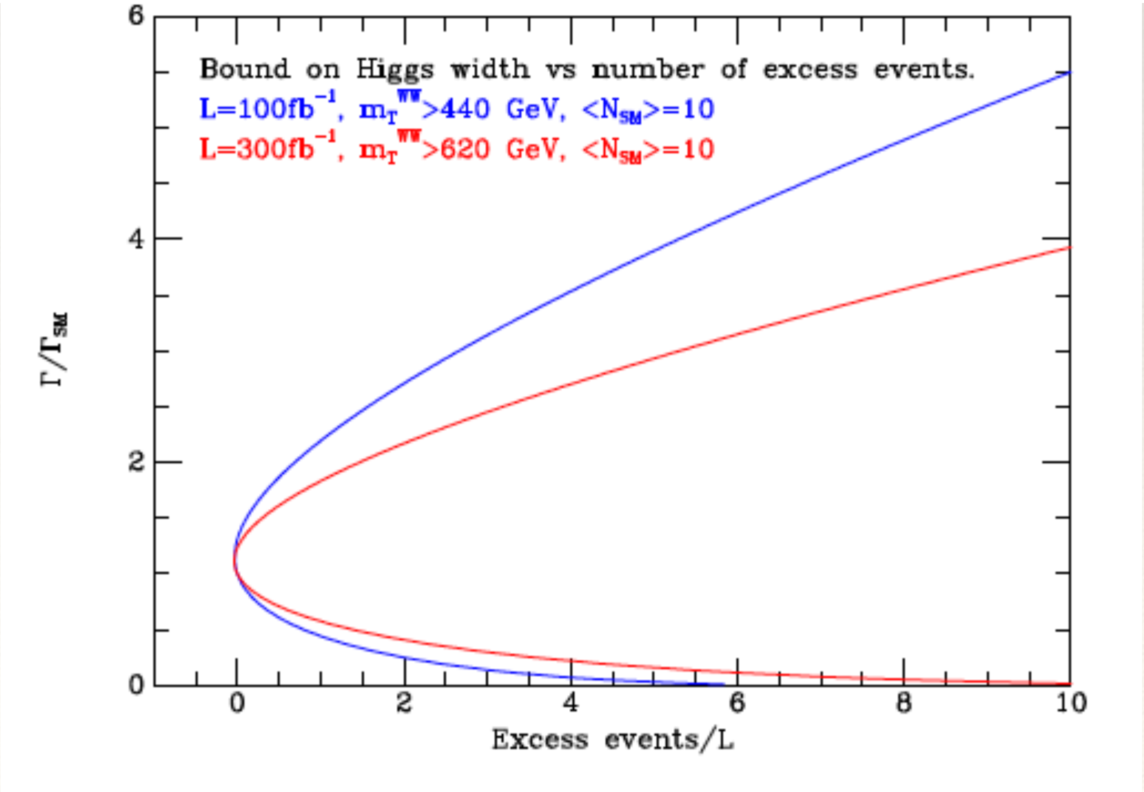
- Run II will give us access to VBF
- VBF cuts reduce the strong background, $O(\alpha^4\,\alpha_s{}^2)$, but gq -> gq $e^-e^+\mu^-\mu^+$ still significant.
- This same statement holds for W^+W^-,$W^\pm Z$,ZZ



Improvement with 100, 300fb^{-1} at $\sqrt{s}$=13TeV

- Expected upper and lower bounds on κ_V obtained from W^+W^+ events as a function of the transverse mass.
- Bounds are cut off when SM prediction falls below 10 events.
- In all cases the best bounds are achieved, taking the highest possible cut on the transverse mass.
- Possible width bounds with (100, 300fb^{-1}) are similar to those currently obtained from gg fusion (20fb^{-1}).





NNLO

Processes currently known through NNLO

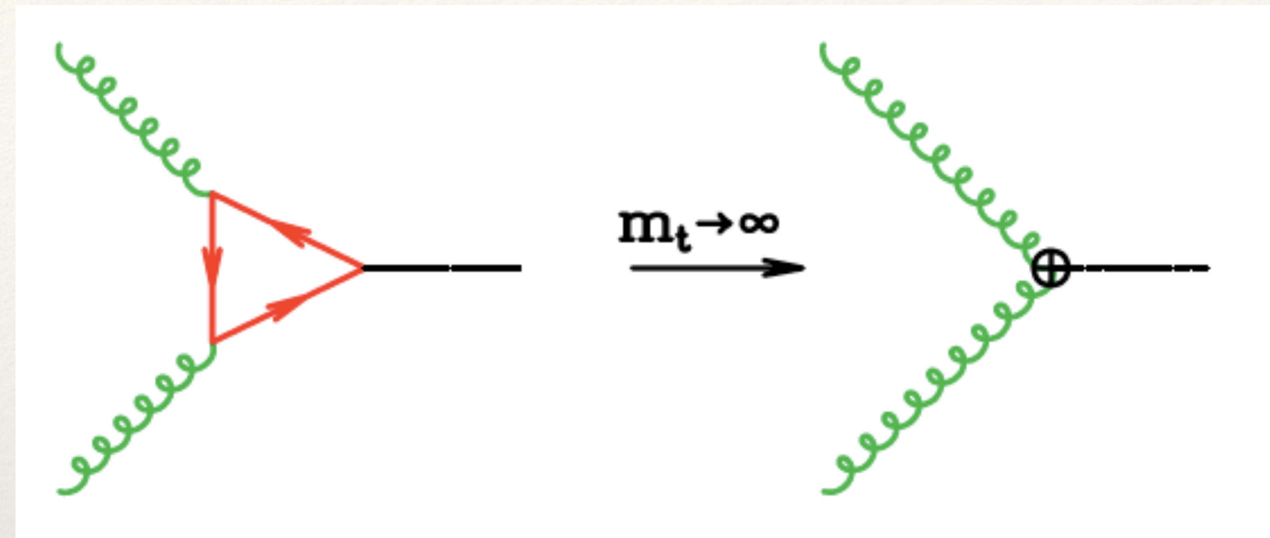
dijets	gluon-gluon	PDFs,strong couplings,BSM	1407.5558
H+0jet	fully inclusive N^3LO	Higgs couplings	1503.06056,
H+1jet	fully exclusive	Higgs couplings,probing GGH	1408.5325,1504.07922, 1505.03893
tt pair	fully exclusive, stable tops	top cross section ,mass pt, FB	1601.05375
single top	fully exclusive, stable tops, t-	Vtb,width, PDfs	1404.7116
WBF	exclusive VBF cuts	Higgs couplings	1506.02660
W+j	fully exclusive, decays	PDFs	1504.02131
Z+j	decay, off-shell effects	PDFs	1601.04569,1507.20850, 1507.02850
ZH	decays to bb at NLO	Higgs couplings	1407.4747,1601.00658
WH	fully exclusive	Higgs couplings	1312.1669, 1601.00658
ZZ	fully exclusive, off-shell	trilinear gauge couplings,BSM	1405.2219, 1507.06257
WW	fully inclusive	trilinear gauge couplings,BSM	1408.5243
$W\gamma$,$Z\gamma$	fully exclusive	trilinear gauge couplings,BSM	1601.06751
$\gamma\gamma$	fully differential	Background studies	1110.2375,1603.02663
top decay	exclusive	Top couplings	1301.7133
H-bb	exclusive, massless	Higgs couplings boosted	1110.2368

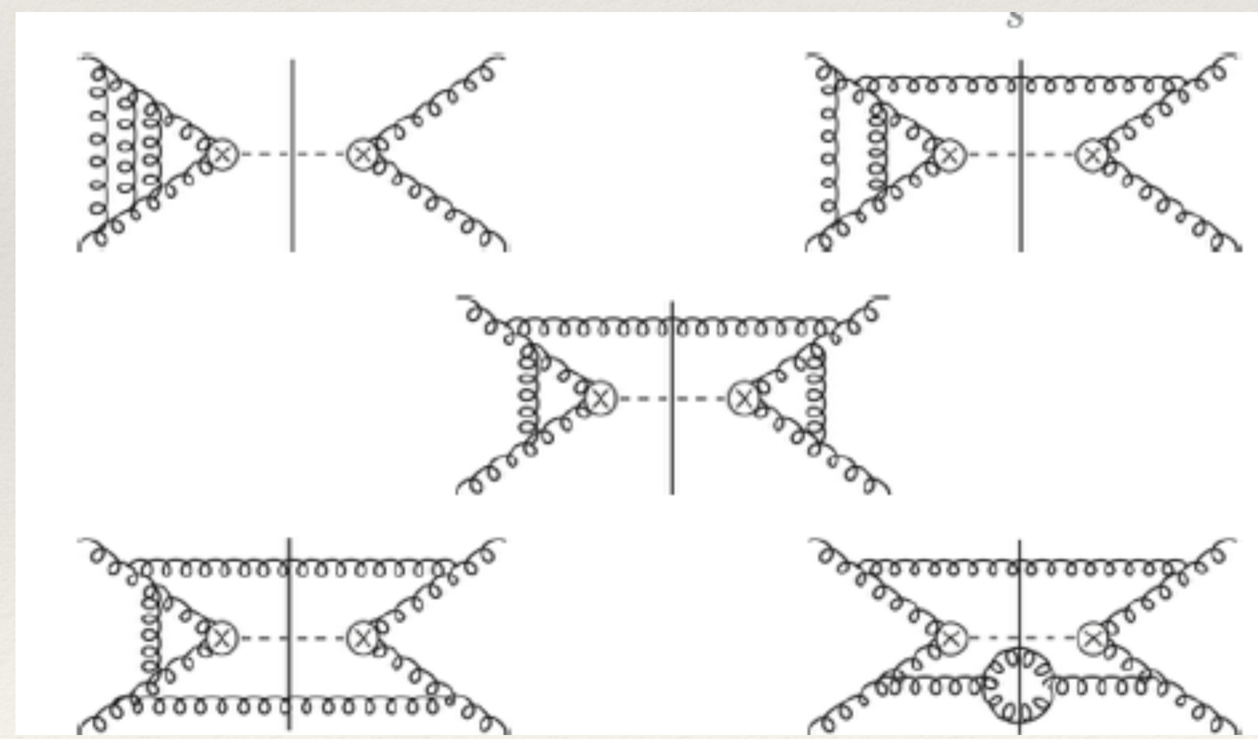
- It is important at NNLO, as it was at NLO that we can go beyond total cross sections.
- This is necessary so that we can calculate fiducial cross section for limited detector coverage.

N^3LO

The new frontier N^{3}LO

- 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

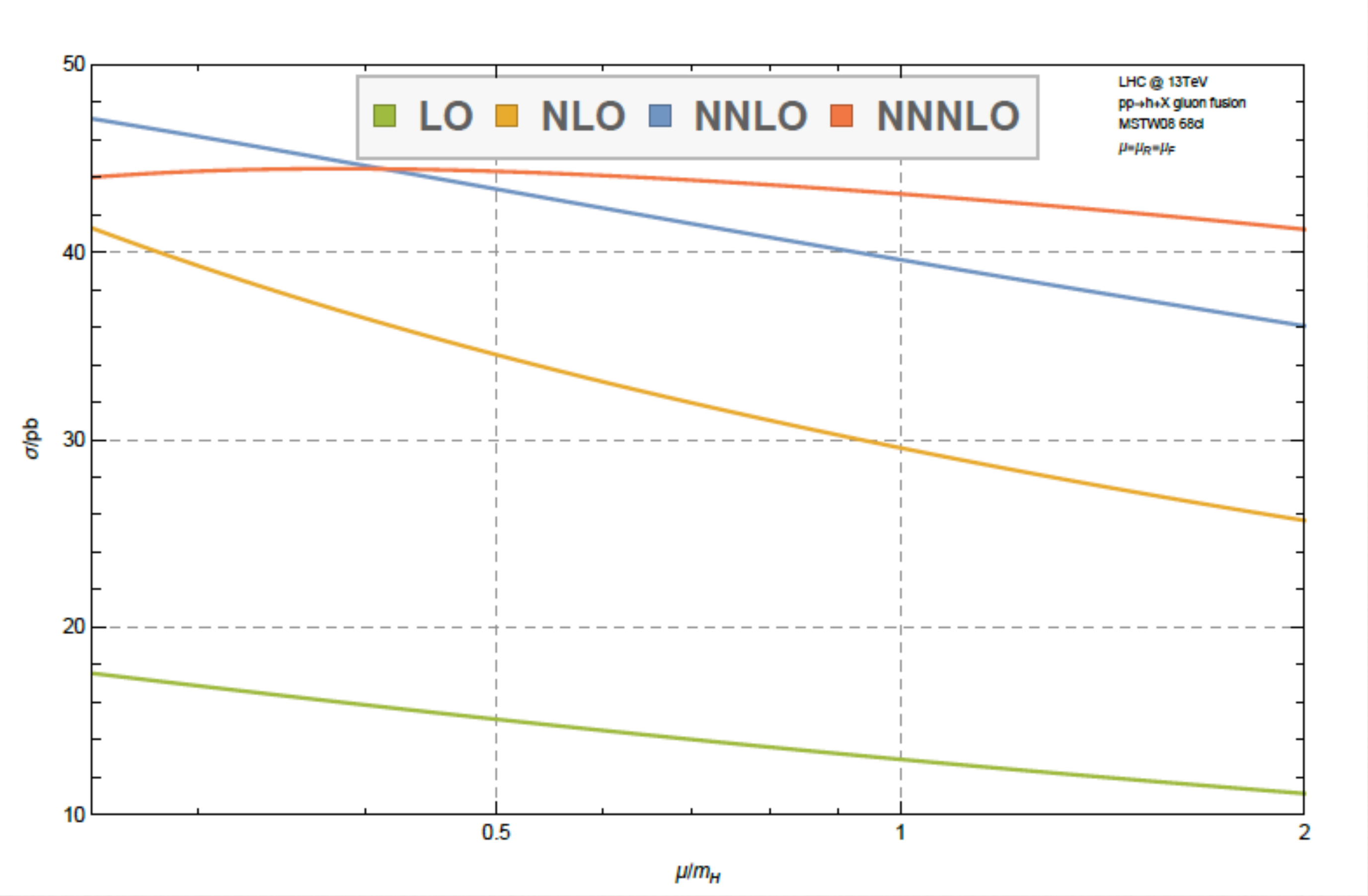




N^3LO: Higgs total cross section at N^3LO

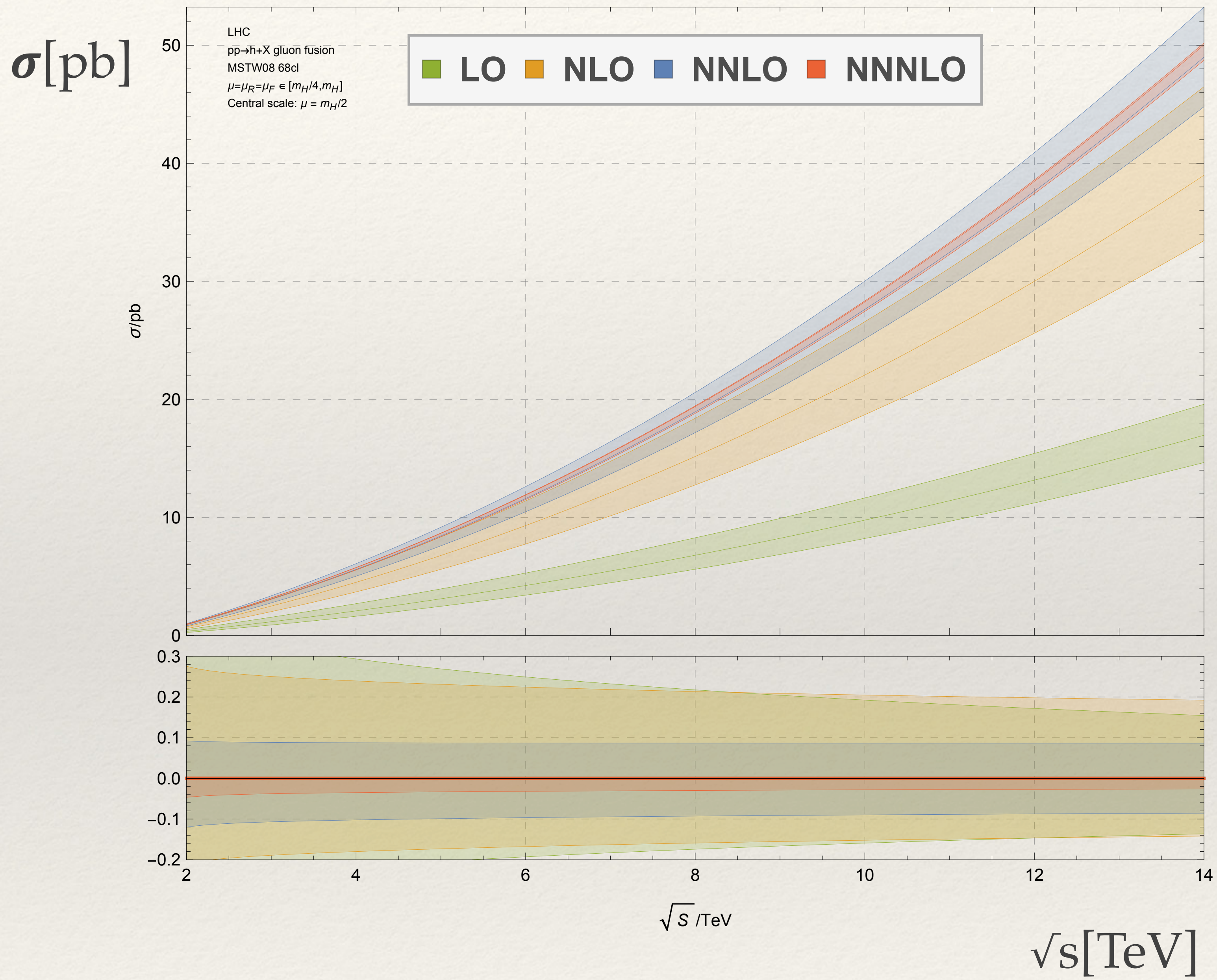
- Result in 1503.06056 is σ= 44.31+0.31%-2.64%pb for $\mu \in [m_H/4, m_H]$ at N^3LO
- At N^2LO this uncertainty is ±9%
- Assume effective expansion parameter is $\alpha_s C_A \sim 0.3$.
- Therefore size of N4LO correction would notionally be of order (0.3)^4=1%
- Instead scale uncertainty gives an error of 3%

1503.06056,1505.04110



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 N4LO correction would notionally be of order (0.3)^4=1%
- Instead scale uncertainty gives an error of 3%



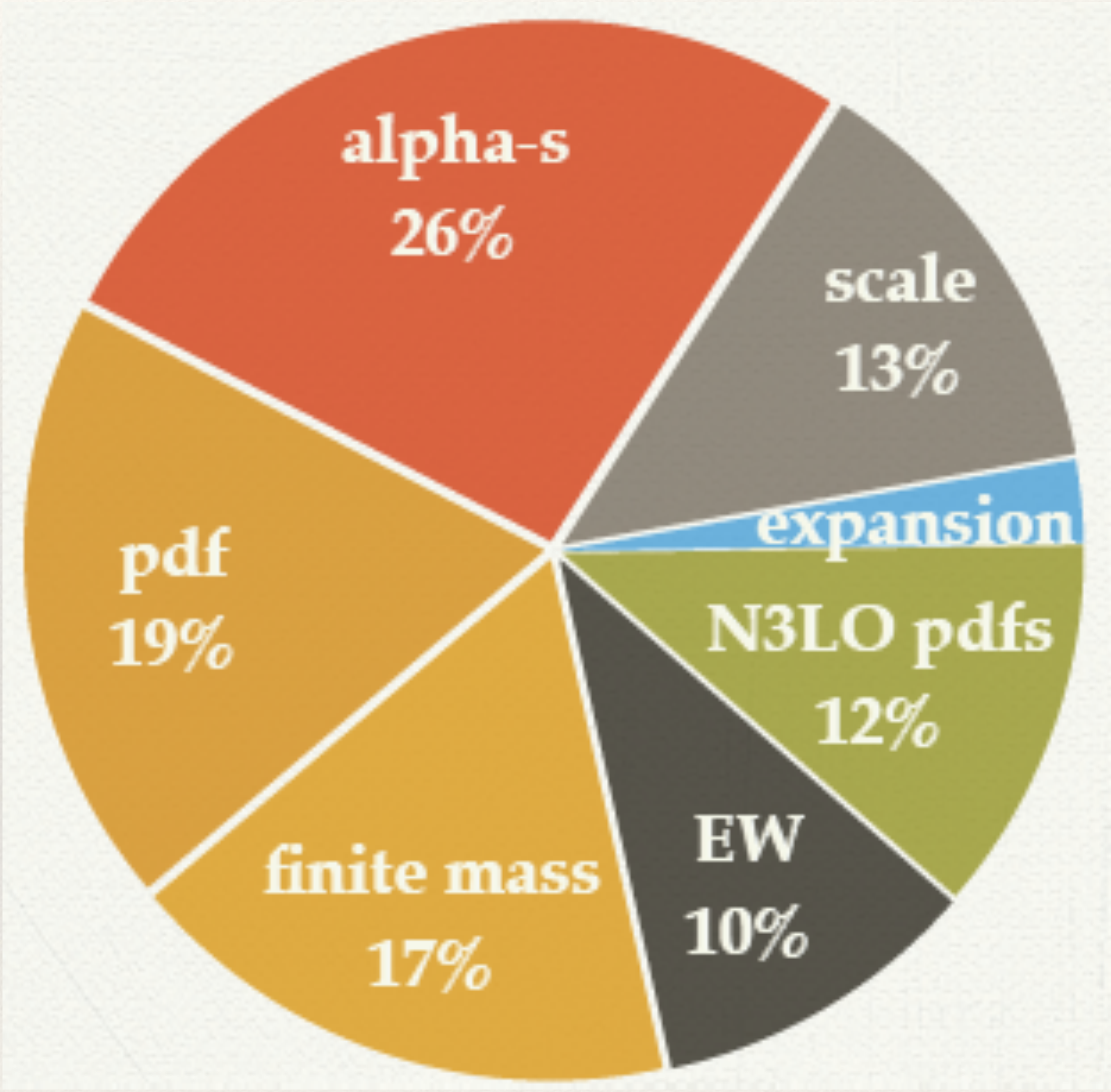
Best prediction at 13 TeV

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.



Outlook

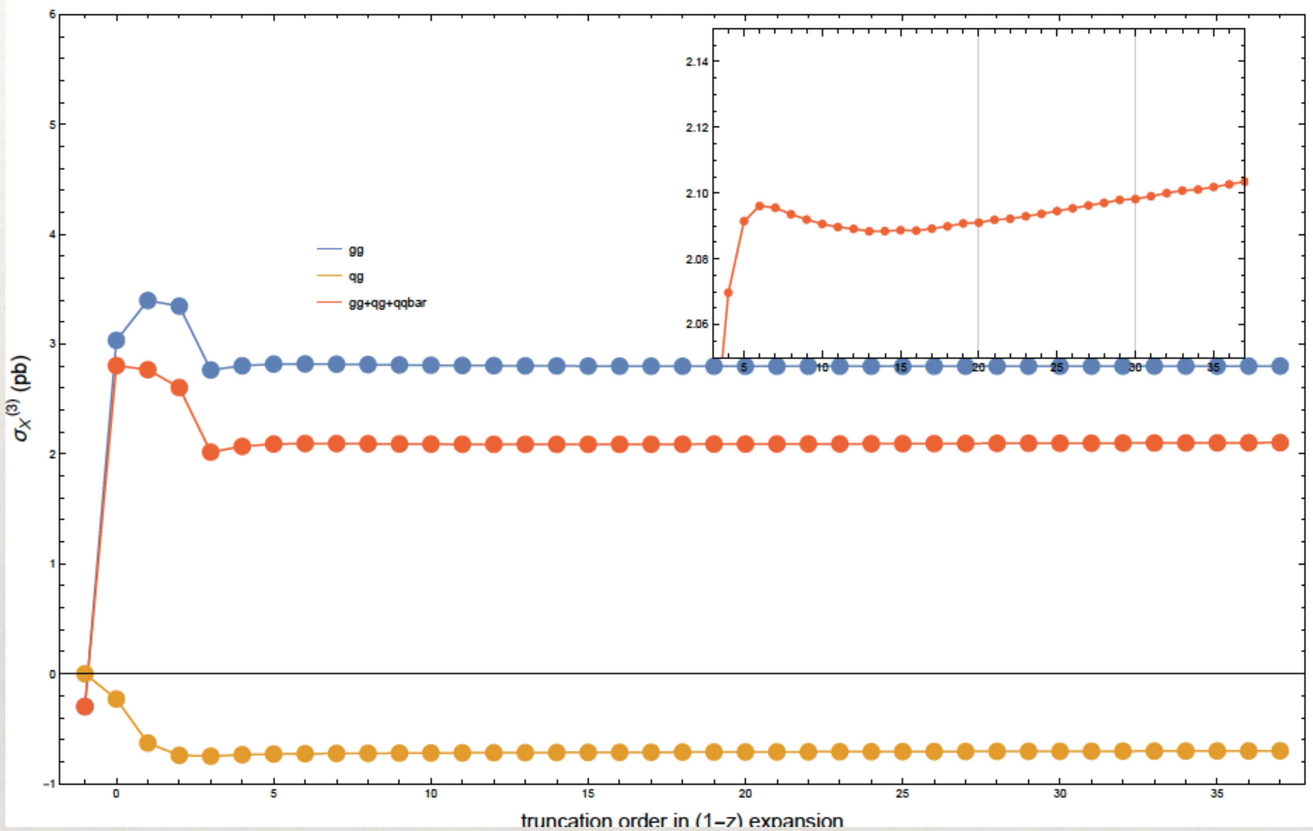
- It might seem that precision QCD is a game of diminishing returns; higher orders terms are harder to calculate and, if the perturbative series is well-tempered, less important.
- On the contrary it is a great time to work on radiative corrections. The Higgs boson is a central theme of run II at the LHC; it radiates copiously.
- To achieve percent level accuracy one needs at least NNLO, plus improvements in the PDF's, α_S
- There has been an astonishing development of theoretical tools, both software and "wetware" which help us in the task.

Backup

N^3LO : the total Higgs production cross section

- Compute N^3LO cross section as an expansion around the soft limit (1-z), $z=m_H^2/s$
- Achieve excellent convergence with small residual growth due to high energy log z
- Plausibly claim to have calculated the total cross section.

Anastasiou et al, 1503.06056



Truncation order of (1-z) expansion

Effective coupling dependence of other processes

- $\sqrt{s}$=13TeV in 100fb^{-1}
- $M_{(T)}$>300GeV
- Note that numbers are not so different for κ_V=0 (no Higgs) and κ_V=1 (SM)
- For this energy and luminosity we cannot place the cut sufficiently high that the non-cancelling terms dominate.

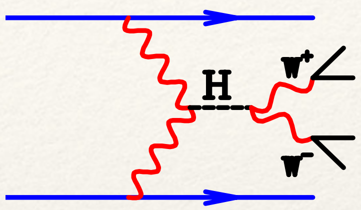
Signal

$$\begin{aligned}
l^-l^+\nu\bar{\nu}: &\quad N^{\text{off}} = 127.9 - 42.8\,\kappa_V^2 + 20.8\,\kappa_V^4 \\
l^+l^+\nu\nu: &\quad N^{\text{off}} = 37.2 - 18.3\,\kappa_V^2 + 8.3\,\kappa_V^4 \\
l^-l^-\bar{\nu}\bar{\nu}: &\quad N^{\text{off}} = 11.0 - 4.1\,\kappa_V^2 + 1.8\,\kappa_V^4 \\
l^+l^-l^+\nu: &\quad N^{\text{off}} = 23.5 - 6.8\,\kappa_V^2 + 3.2\,\kappa_V^4 \\
l^+l^-l^-\bar{\nu}: &\quad N^{\text{off}} = 11.3 - 3.3\,\kappa_V^2 + 1.6\,\kappa_V^4 \\
l^-l^+l^-l^+: &\quad N^{\text{off}} = 6.0 - 3.0\,\kappa_V^2 + 1.5\,\kappa_V^4
\end{aligned}$$

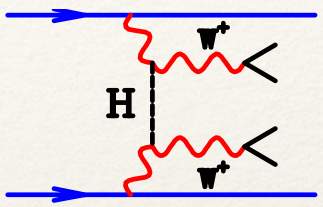
Signal + Background

$$\begin{aligned}
l^-l^+\nu\bar{\nu}: &\quad N^{\text{off}} = 224.8 - 42.8\,\kappa_V^2 + 20.8\,\kappa_V^4 \\
l^+l^+\nu\nu: &\quad N^{\text{off}} = 38.8 - 18.3\,\kappa_V^2 + 8.3\,\kappa_V^4 \\
l^-l^-\bar{\nu}\bar{\nu}: &\quad N^{\text{off}} = 11.5 - 4.1\,\kappa_V^2 + 1.8\,\kappa_V^4 \\
l^+l^-l^+\nu: &\quad N^{\text{off}} = 60.1 - 6.8\,\kappa_V^2 + 3.2\,\kappa_V^4 \\
l^+l^-l^-\bar{\nu}: &\quad N^{\text{off}} = 29.5 - 3.3\,\kappa_V^2 + 1.6\,\kappa_V^4 \\
l^-l^+l^-l^+: &\quad N^{\text{off}} = 9.0 - 3.0\,\kappa_V^2 + 1.5\,\kappa_V^4
\end{aligned}$$

Most useful channel is W^+W^- vs W^+W^+



W+W-On-shell



W+W+ Off-shell

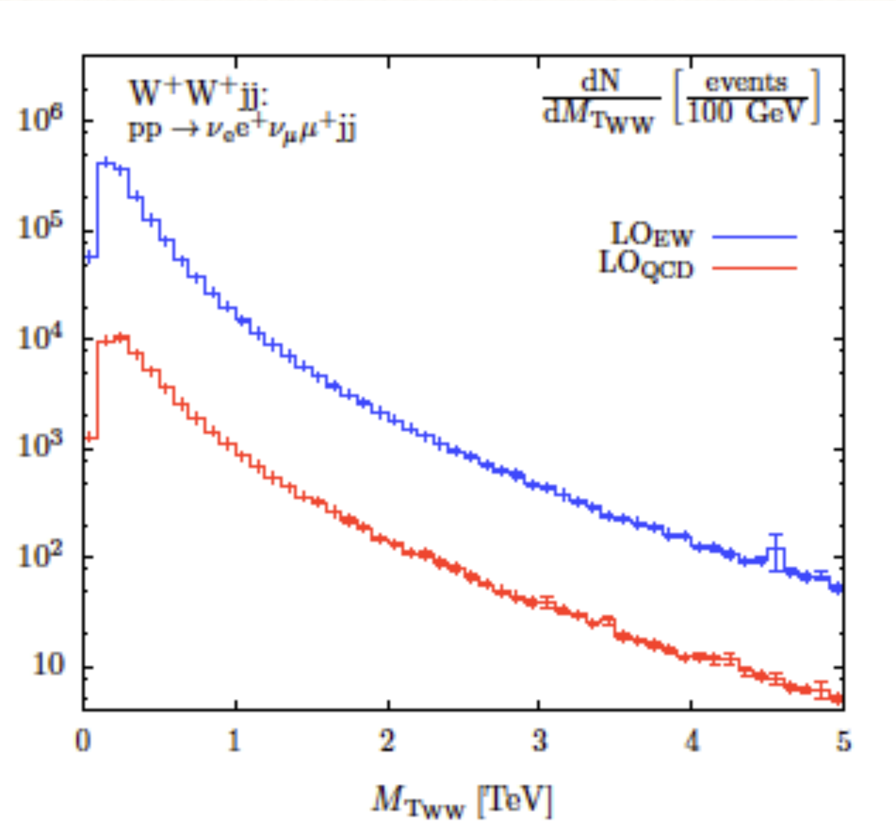
- In the first instance, we work in the effective coupling framework, where standard couplings are rescaled by κ_V.
- At $\sqrt{s}$=8TeV, SM prediction displays a dependence on κ_V

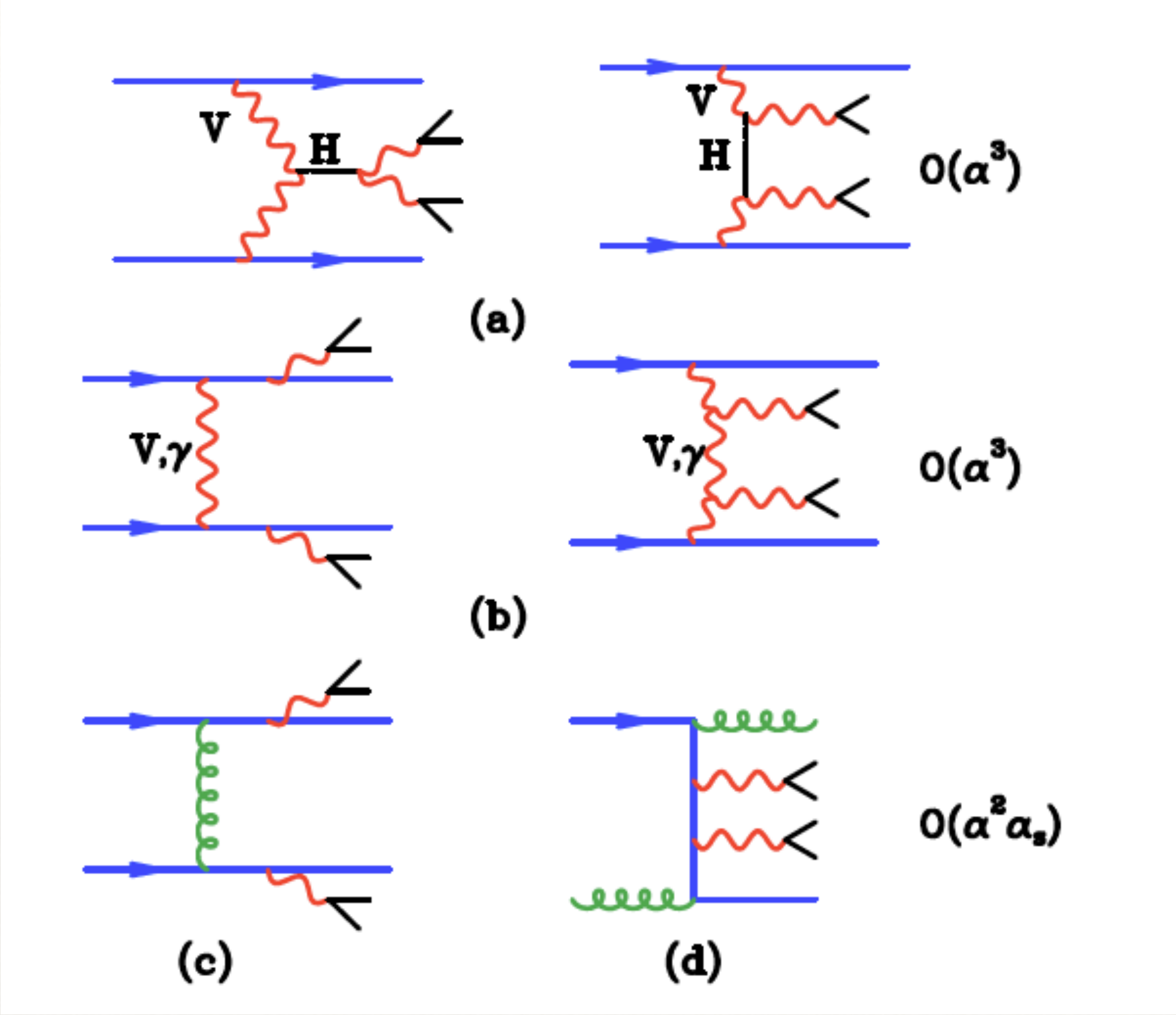
$$\sigma^{same-sign}_{fiducial} = 1.015 - 0.106\,\kappa_V^2 + 0.040\,\kappa_V^4 \text{ fb}\,.$$

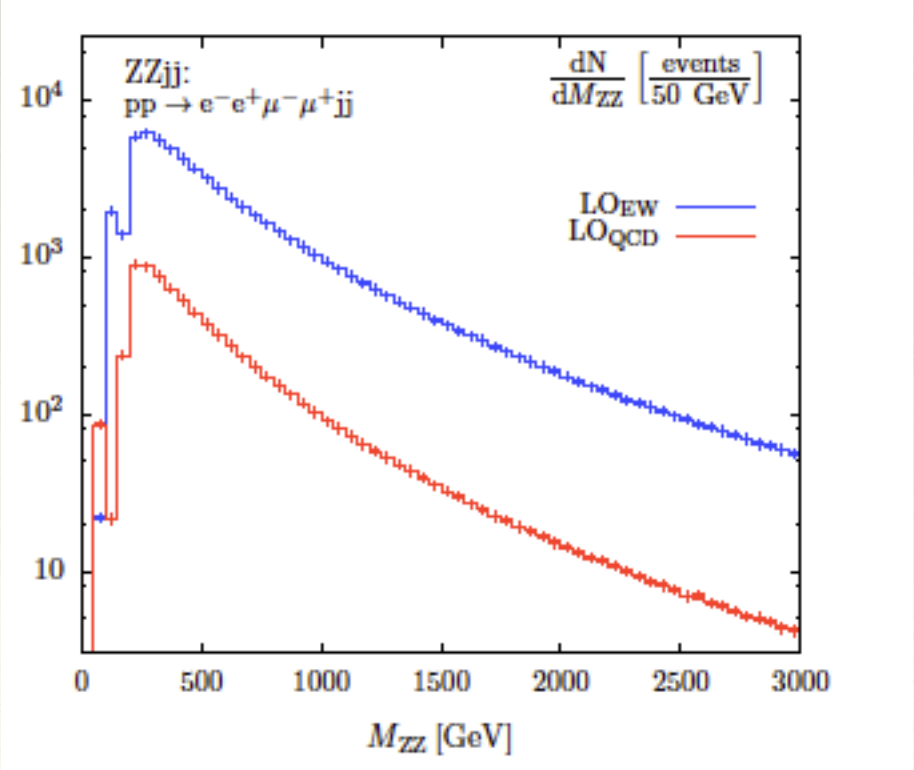
- ATLAS on-shell signal-strength $\mu^{ATLAS}_{VBF} = 1.27^{+0.53}_{-0.45}$
- ATLAS W^+W^+ measurement $\sigma^{measured} = 1.3 \pm 0.4(stat) \pm 0.2(syst) \text{ fb}\,.$
- Bound is $\kappa_V < 7.8\,.$
- current notional width bound $\Gamma_H < 60.8 \times \Gamma_H^{SM}\,.$

Current result

Vector boson fusion and scattering







Rates for 3 inverse attobarns 1607.0183

Latest word on Higgs cross section error budget

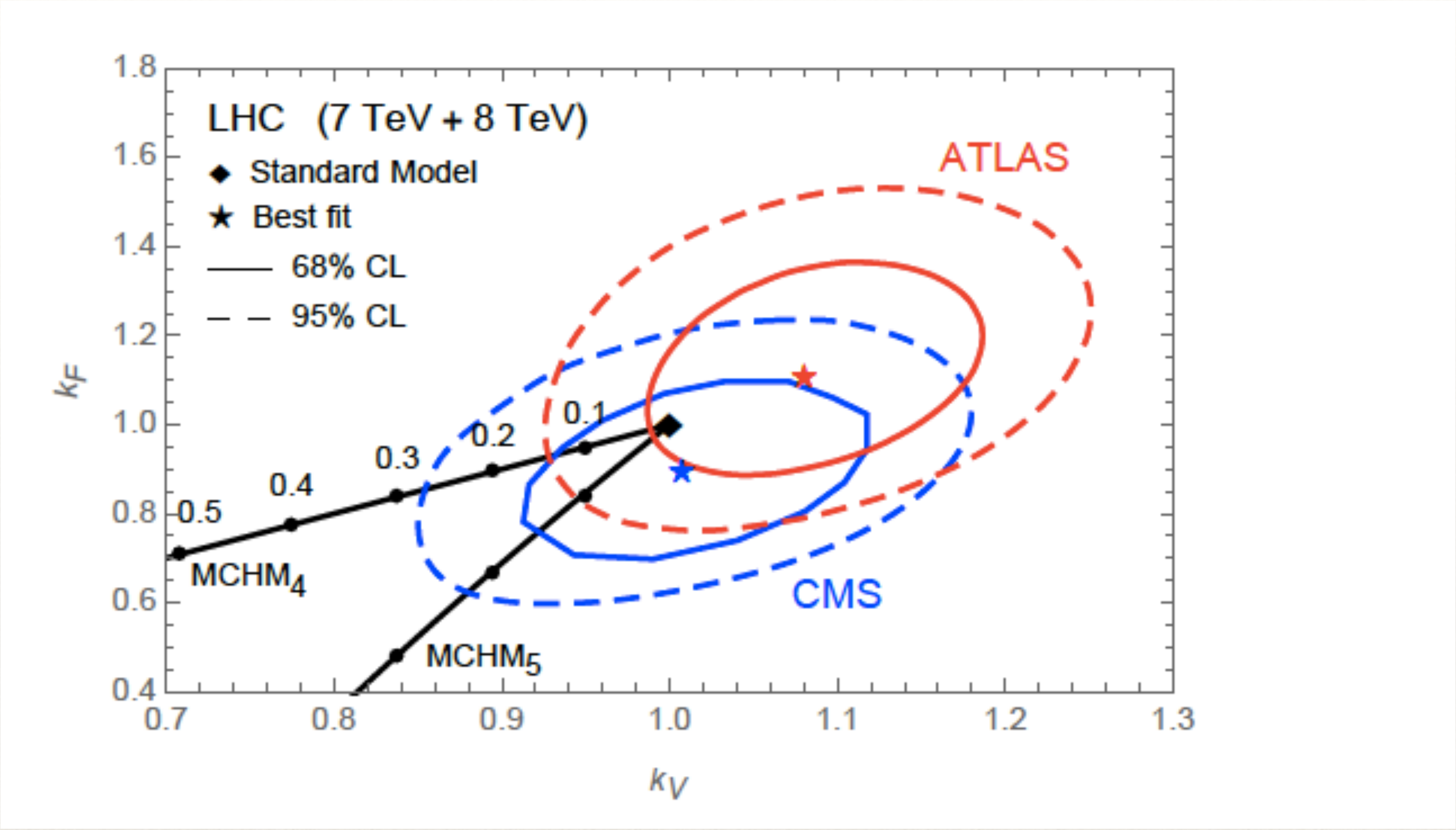
F. Dulat, CERN, December 2015, https://indico.cern.ch/event/462111/

σ/pb	δ_{PDF}/pb	δ_{α_s}/pb	δ_{scale}/pb	δ_{trunc}/pb	δ_{pdfTH}/pb	δ_{EW}/pb	δ_{tb}/pb	δ_{1/m_t}/pb
48.48	± 0.90	± 1.26	$^{+0.09}_{-1.11}$	± 0.12	± 0.56	± 0.48	± 0.34	± 0.48
48.48	$\pm 1.86\%$	$\pm 2.60\%$	$^{+0.2}_{-2.3}\%$	$\pm 0.25\%$	$\pm 1.15\%$	$\pm 1.00\%$	$\pm 0.70\%$	$\pm 1.00\%$

- N^3LO pdfs are not available and not accounted for by pdf uncertainties
- Finite mass effects only known approximately beyond NLO, do not include all important interference effects
- Electroweak corrections at LO known, dominant mixed effects calculated in EFT.

Effective coupling parameters and composite Higgs models

- Paramter ξ of composite Higgs models related to Naturalness.



Wulzer, 1510.05159