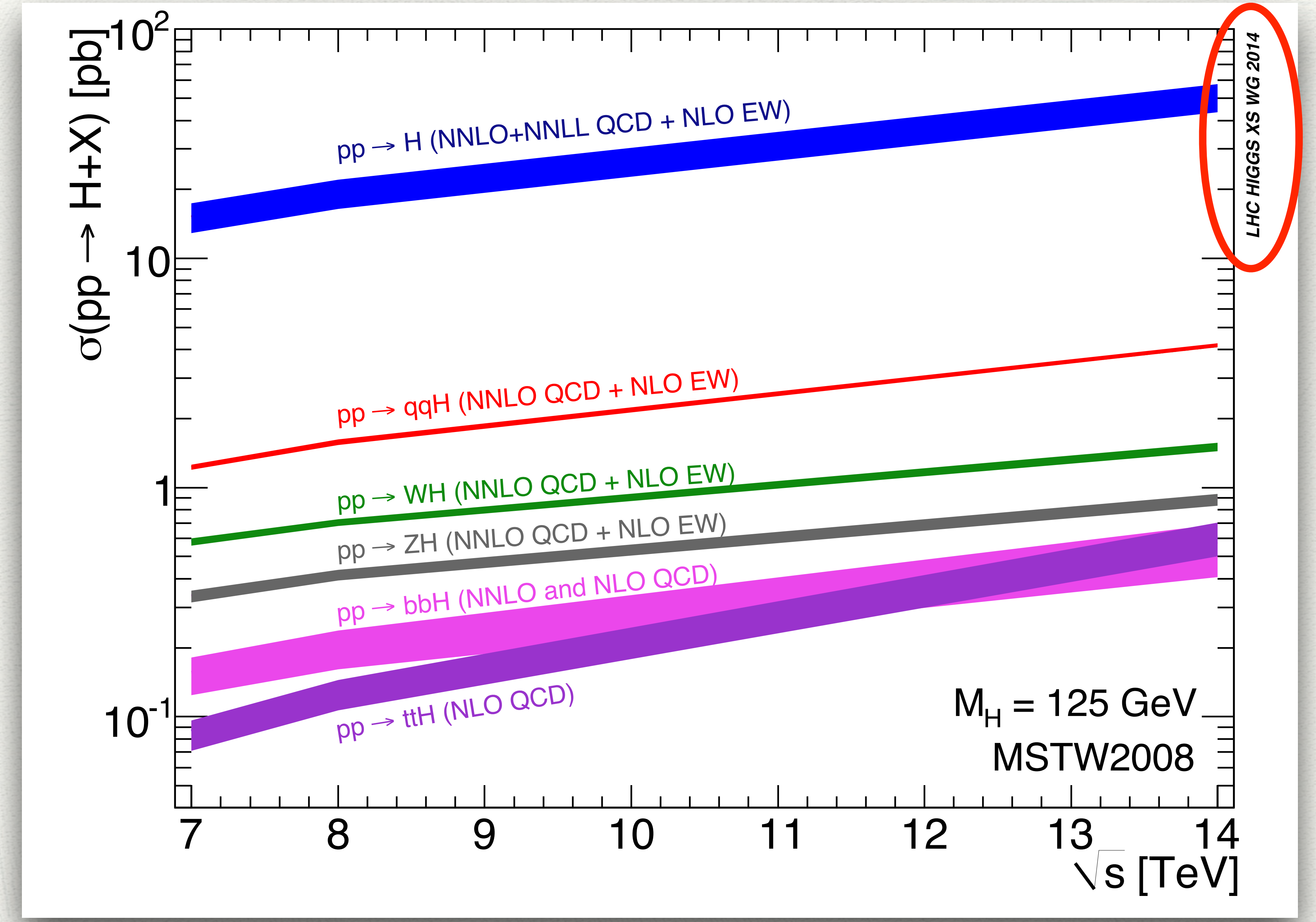
SM$_{\text{(-like)}}$ Higgs production: theoretical progress

John Campbell, Fermilab

Aspen Winter Conference in Particle Physics, Jan. 10-16, 2016

State of play in 2014



How could this figure be updated now?

What about knowledge beyond $\sigma(pp \to H+X)$?

What good is it all?

(and apologies to all work that I have overlooked in this subjective review)

2015: a banner year

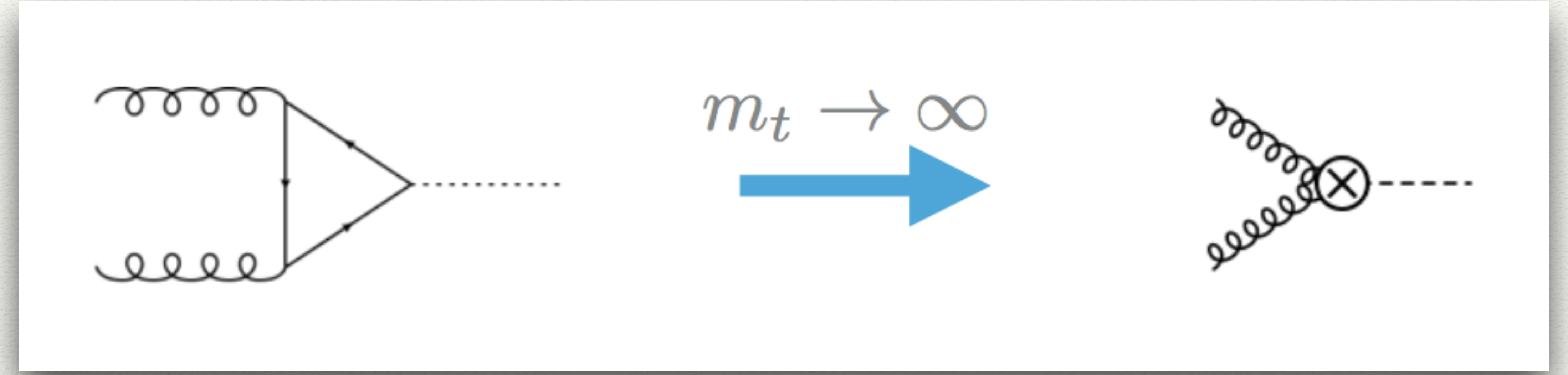
- A fantastic year that has led to a significantly better theoretical understanding of Standard Model Higgs boson production at the LHC.
  - improved predictions for cross-sections and observables;
  - development of better Monte Carlo tools;
  - new ideas for additional channels and improved analyses.
- Headlined by new theoretical calculations of Higgs boson processes at NNLO and beyond.
  - both total cross-sections and accounting for required fiducial cuts.
  - control of both absolute normalization and remaining uncertainty.
- Bottom line: extraction of Higgs boson couplings and properties at an unprecedented level of precision.

Headlines

Gluon-fusion production at N^{3}LO

Anastasiou, Duhr, Dulat, Furlan, Gehrmann, Herzog, Lazopoulos, Mistlberger

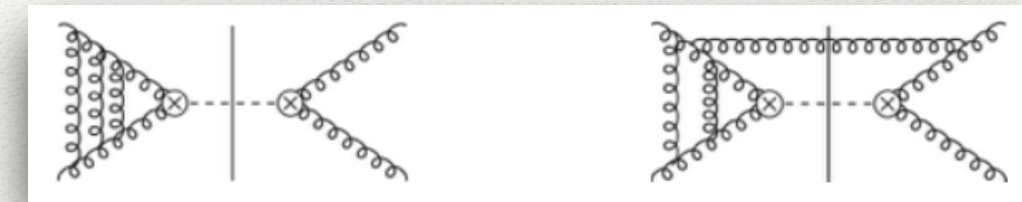
- Focus of great theoretical scrutiny.
  - dominant production mode at the LHC;
  - a "simple" 2→1 process.
- Exact calculation only known to NLO at present; higher orders tractable through EFT.
- Capture dominant effects through scaling with exact treatment at LO.

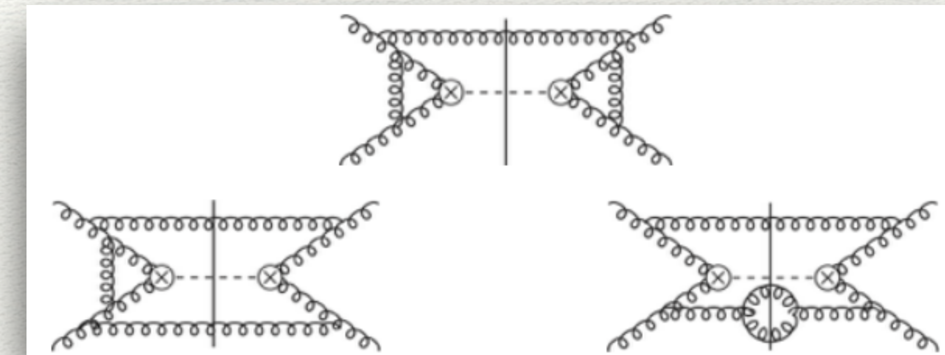


➢Compute N^{3}LO cross-section as an expansion around the soft limit, to arbitrary order.

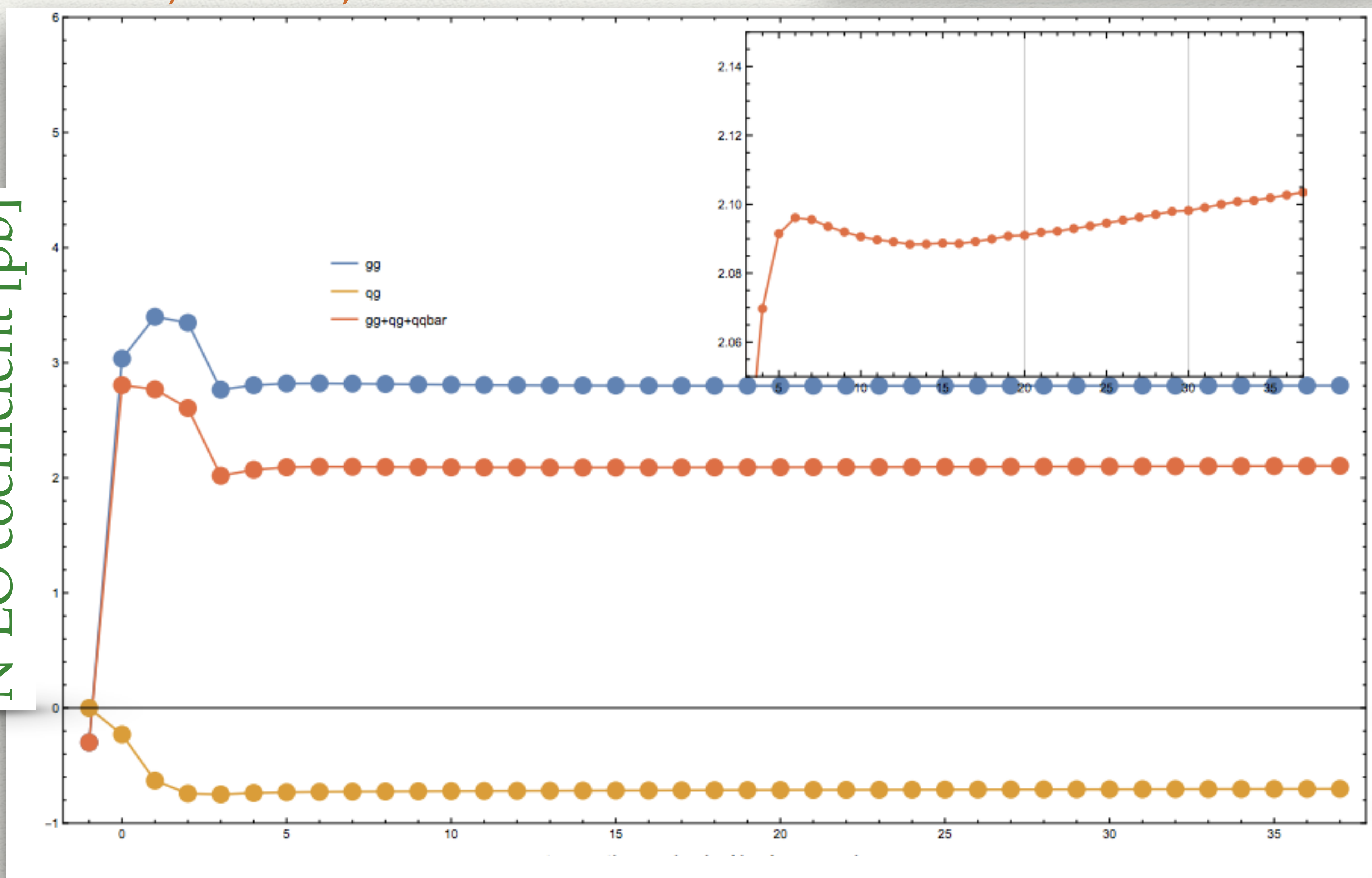
$$z = m_H^2/\hat{s} \quad \longrightarrow \quad (1-z) \text{ is distance from threshold}$$

Convergence of soft expansion





F. Dulat, Dec 2015, CERN



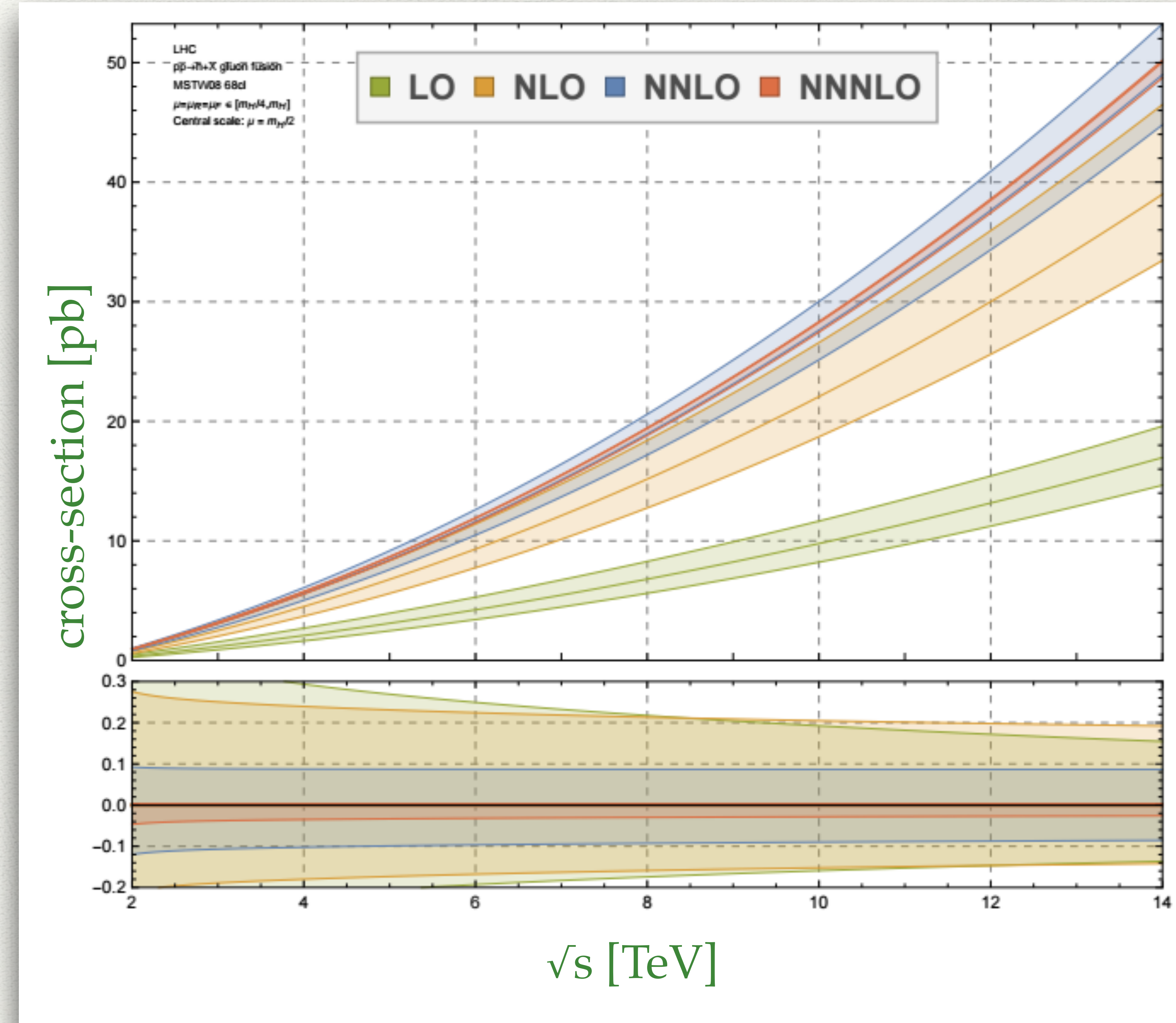
N^{3}LO coefficient [pb]

terms in expansion

small residual effect in low-z (high-energy) region

excellent convergence

Fruits of theoretical labor: scale uncertainty



Anastasiou, Duhr, Dulat, Herzog, Mistlberger, arXiv: 1503.06056

Impact: latest results

- Cross-section increases by ~2% compared to NNLO and within scale uncertainty → negligible impact on value of coupling extracted so far.

- Level of precision mandates careful analysis of other effects, approximations and remaining sources of uncertainty.

→ F. Dulat Dec 2015, CERN

  - N^3LO pdfs not available and not accounted for by pdf uncertainties; can estimate uncertainty by equivalent at NNLO: ~1%.

  - finite mass effects only known approximately beyond NLO, do not include all important interference effects;
    estimate of total uncertainty: ~2%.

  - electroweak corrections to the LO process known, dominant mixed NLO effects computed in EFT;
    estimated uncertainty from missing NLO: ~1%

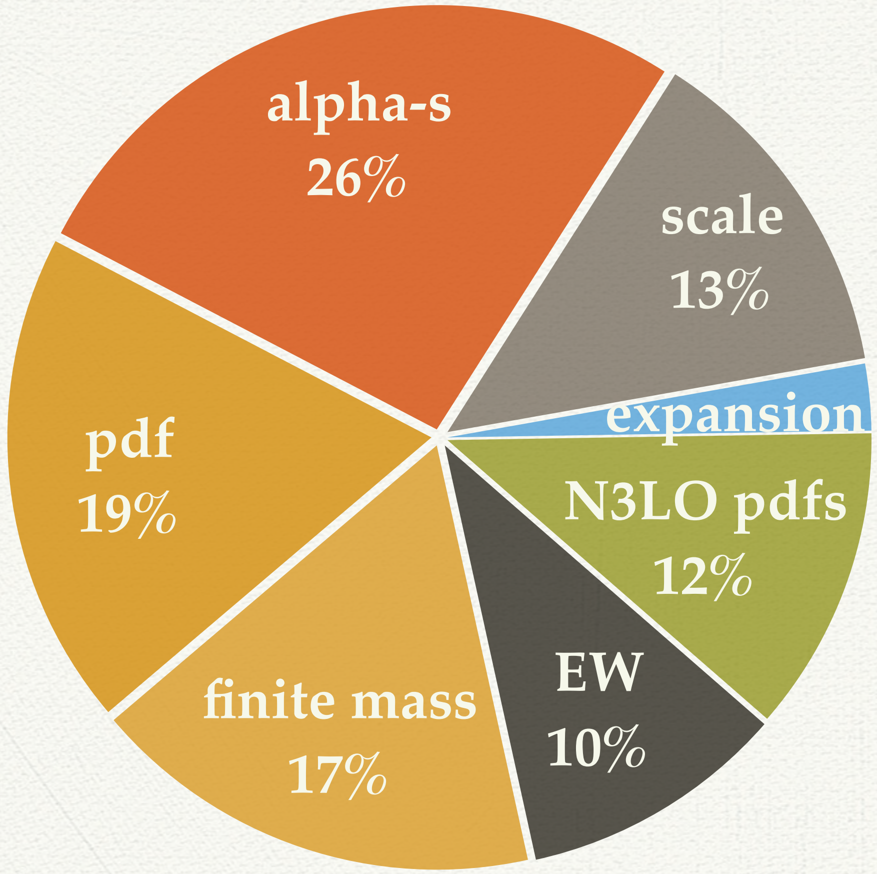
Impact and outlook

- Best prediction at 13 TeV, combining all sources of uncertainty, promises spectacular precision:

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

- Current uncertainty budget points the way for further theoretical improvements.

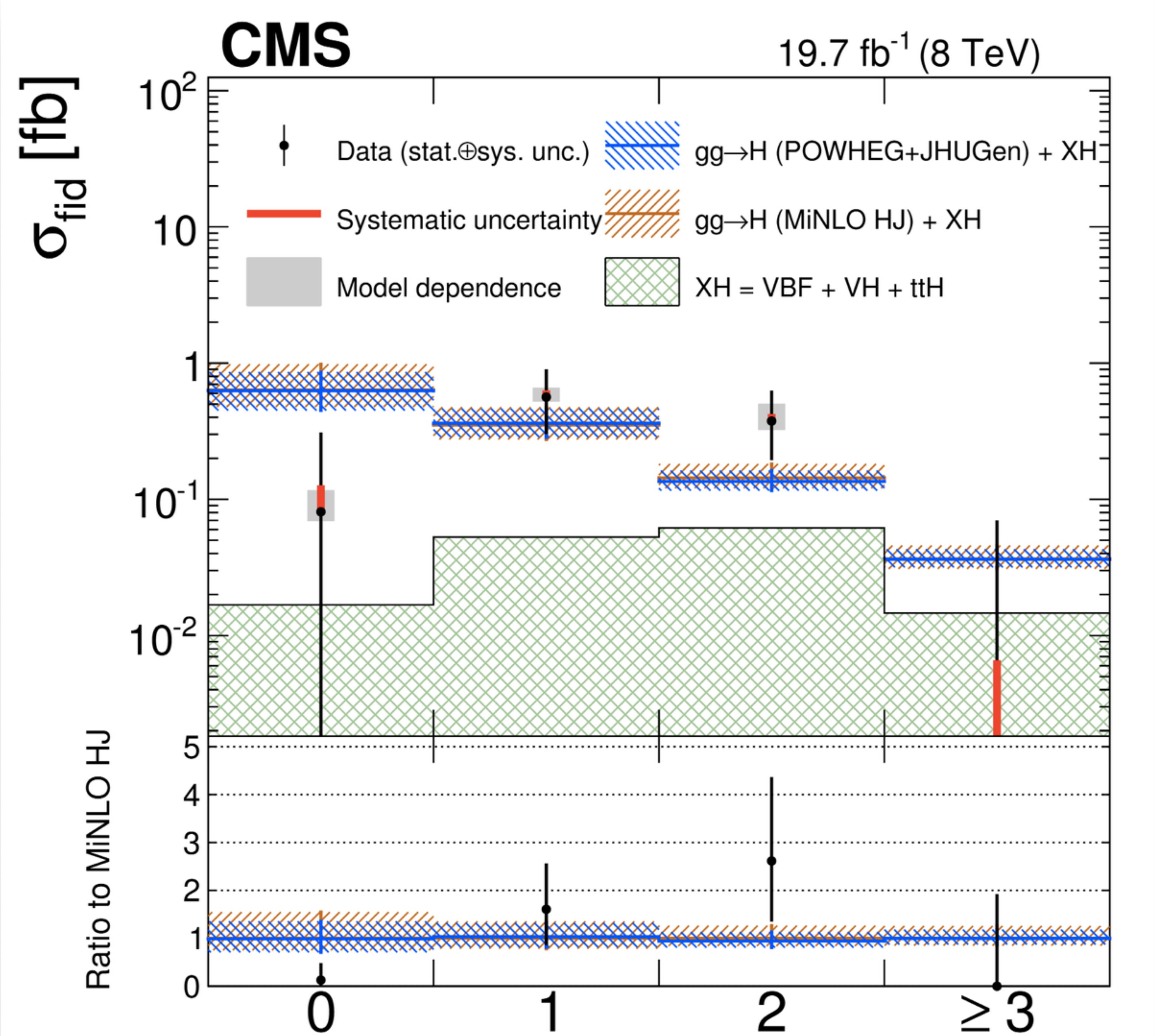
- In addition:
  - paves way for similar approaches to related Higgs processes, e.g. associated production.
  - application to rapidity distributions too?



The Higgs boson and QCD

- The Higgs boson radiates additional jets prolifically …
  - according to our theoretical tools;
  - and (even more so?) in the 7 and 8 TeV data taken so far.
- Important source of additional events;
  - to exploit, need more differential information.

CMS-HIG-14-028, Dec 2015

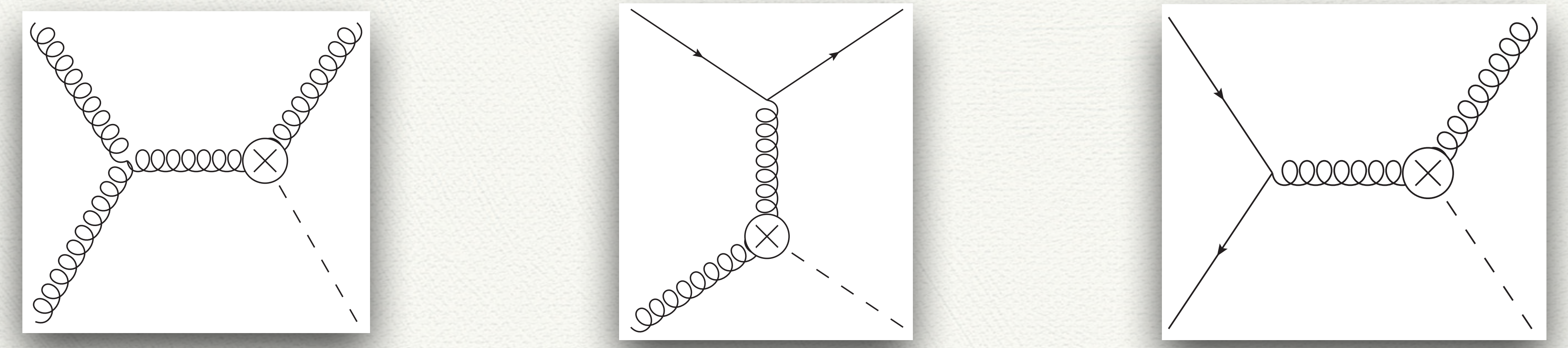


H→ZZ→ 4ℓ decays

Higgs+jet production at NNLO

- Previous approximate results included only NNLO corrections to gluonic channels.

  Boughezal, Caola, Melnikov, Petriello, Schulze (2013)
  Chen, Gehrmann, Glover, Jaquier (2014)



- This year, multiple new fully-differential results at NNLO:
  - dominant gg and qg channels, sub-dominant (1% effect) qq at NLO;

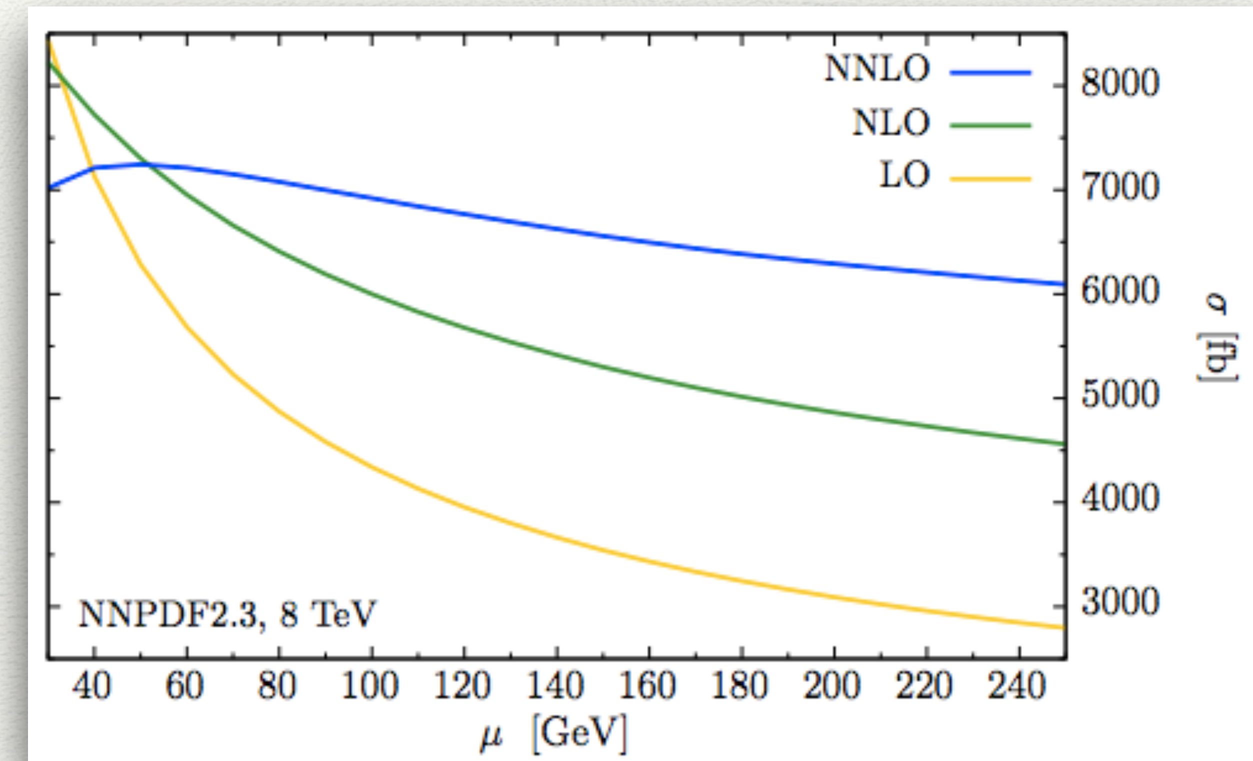
    Boughezal, Caola, Melnikov, Petriello, Schulze, arXiv: 1504.07922
  - extension to include Higgs boson decays for fiducial comparisons;

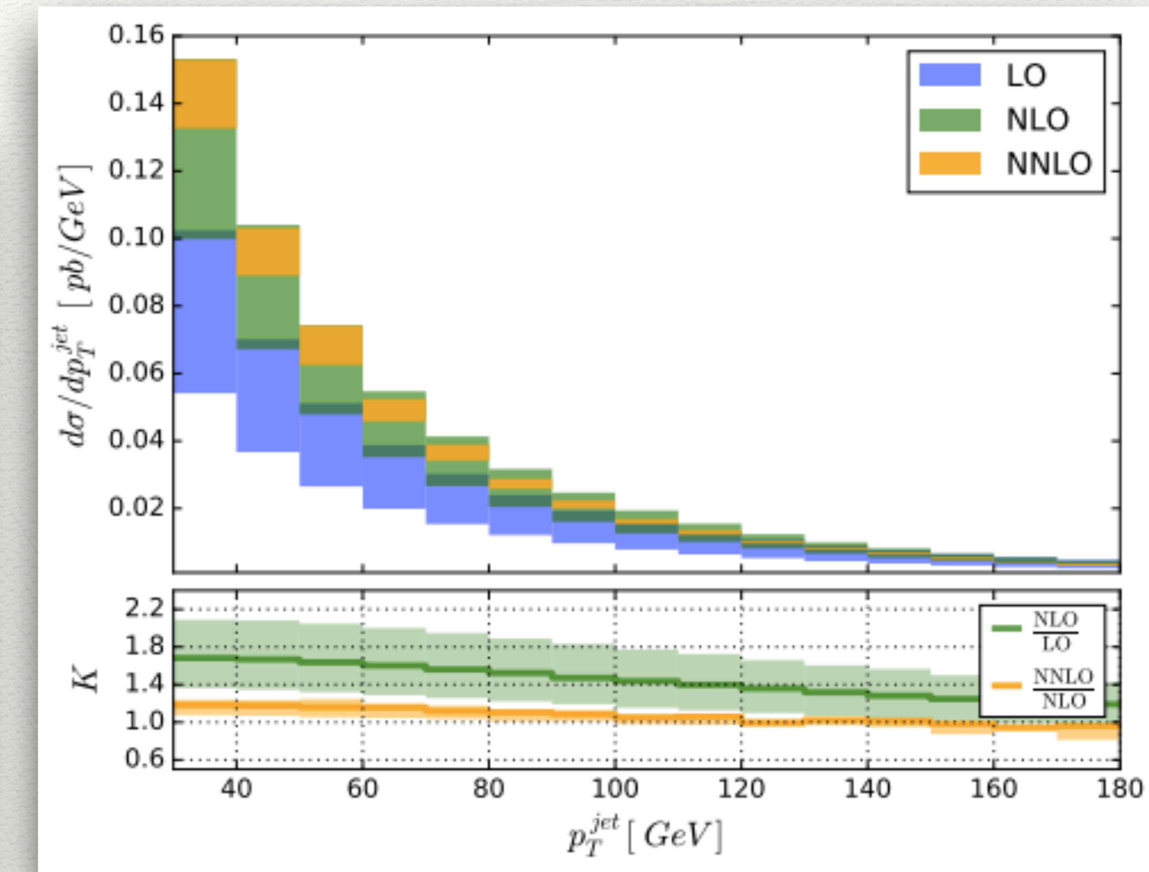
    Caola, Melnikov, Schulze, arXiv: 1508.02684
  - all channels included at NNLO.

    Boughezal, Focke, Giele, Liu, Petriello, arXiv: 1505.03893

Impact of NNLO corrections

BCMPS, arXiv: 1504.07922



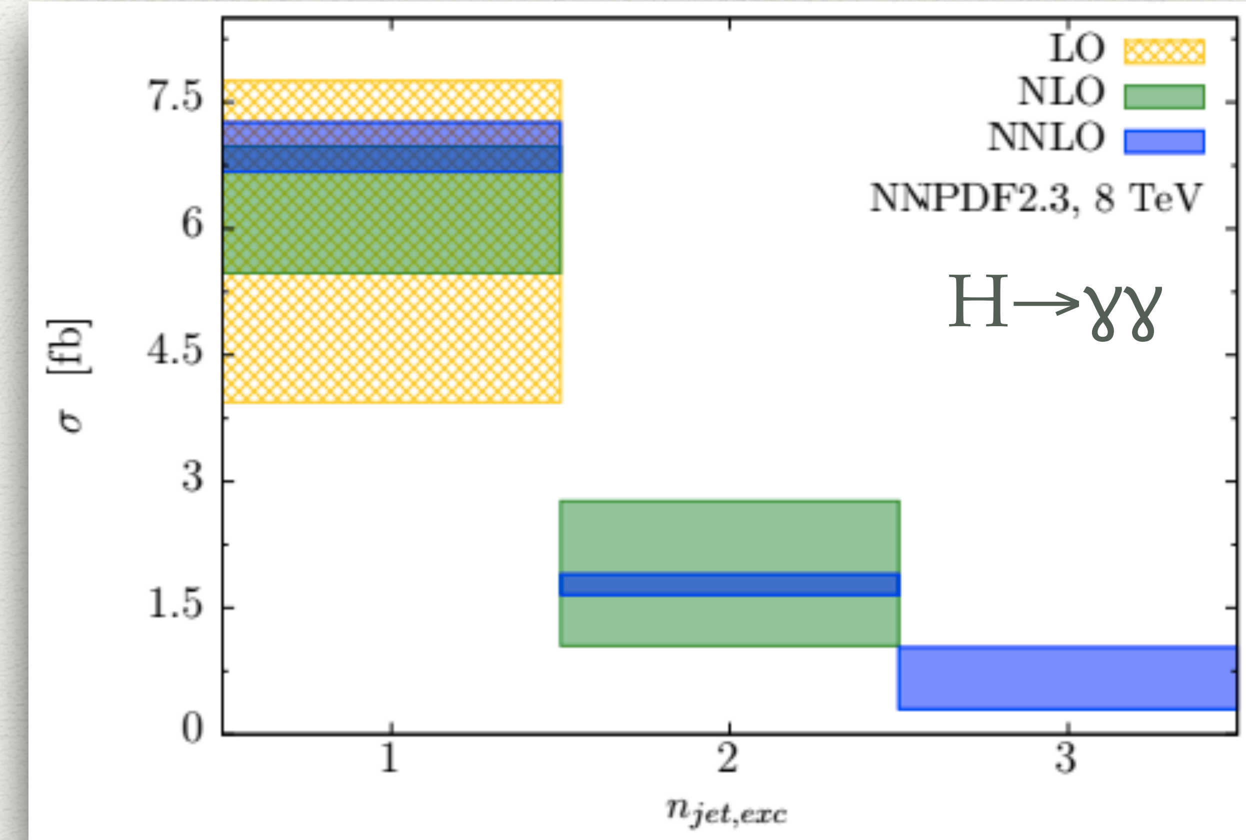


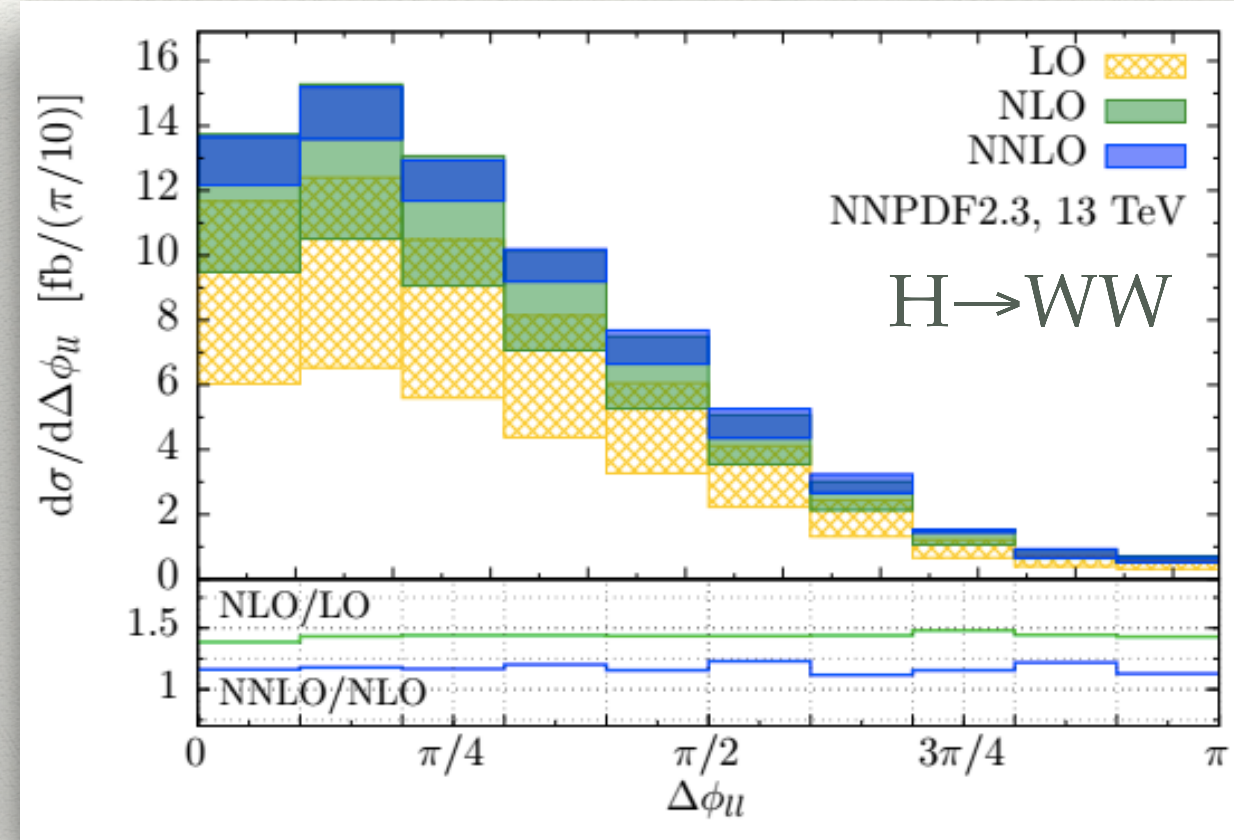
BFGLP, arXiv: 1505.03893

- Corrections modest, dominant effects already captured at NLO.; predictions already stabilized (c.f. inclusive production).
  - NNLO ~15% for typical LHC cuts (p_T~30 GeV), decrease as p_T increases.
  - Residual scale uncertainty ~ 5%.
- Calculation uses powerful new SCET-based technique, “jettiness subtraction”.

Fiducial Higgs+jet at NNLO

(the other) CMS, arXiv: 1508.02684





- Consistent calculation, O(α_s^5), for jet multiplicities from one to three.
  - *k*-jet rate known to N$^{(3\text{-}k)}$LO.
  - also true for zero-jet bin in absence of fiducial cuts.

- Key observables, e.g. dilepton azimuthal separation in H→WW decays: not significantly changed.
- Ratios of fiducial cross-sections display excellent convergence.

$$R_{WW/\gamma\gamma} = \frac{\sigma_{H+j}^{WW\to e^+\mu^-\nu\bar{\nu},13\ \text{TeV}}}{\sigma_{H+j}^{\gamma\gamma,8\ \text{TeV}}} = 2.39^{-0.06}_{+0.04},\quad 2.33^{-0.04}_{+0.05},\quad 2.32^{-0.04}_{+0.02}$$

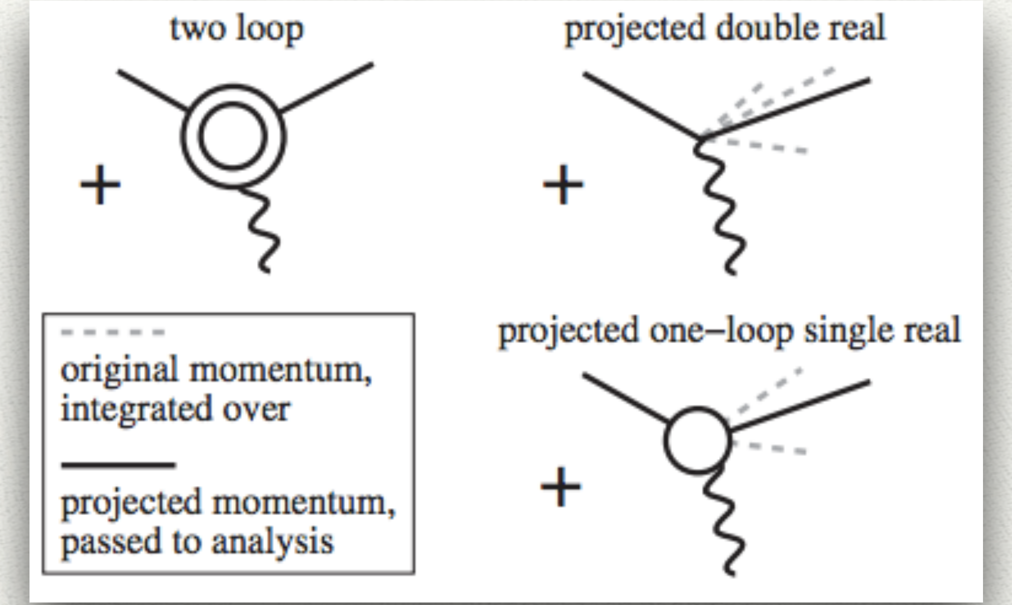
LO **NLO** **NNLO**

Differential VBF production at NNLO

Cacciari, Dreyer, Karlberg, Salam, Zanderighi, arXiv: 1506.02660

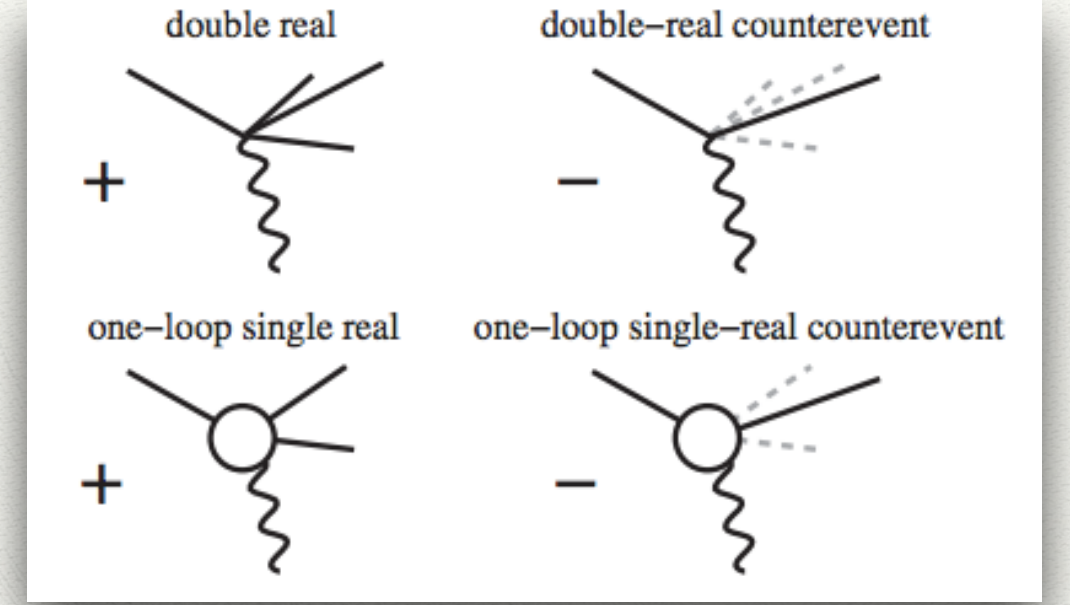
- Critical test of the Standard Model: largest production process that involves tree-level interactions. Bolzoni, Maltoni, Moch, Zaro (2010, 2012) Figy, Zeppenfeld, Oleari (2003)
- Cross-section known at NNLO (total) and NLO (differential).
- Innovative "projection-to-Born" method that exploits structure function approach to merge two existing calculations:

NNLO inclusive rate



NLO VBF+jet

Figy, Hankele, Zeppenfeld (2008) Jager, Schissler, Zeppenfeld (2014)



Impact: differential VBF at NNLO

- Can now assess effect of NNLO corrections under fiducial cuts used to tag VBF events; contrast with inclusive case.

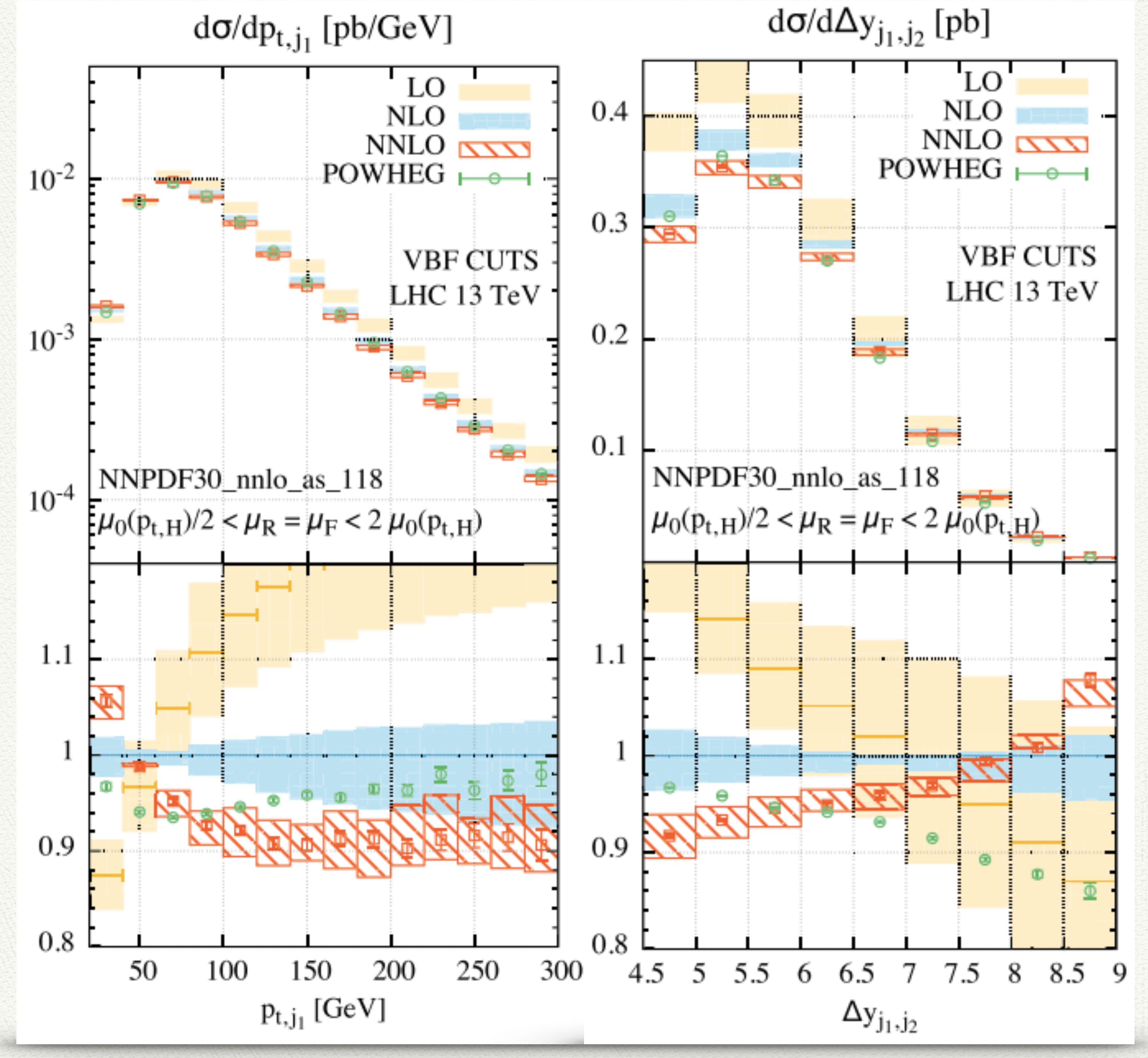
	inclusive	fiducial
	$\sigma^{(\text{no cuts})}$ (pb)	$\sigma^{(\text{VBF cuts})}$ (pb)
LO	$4.032^{+0.057}_{-0.069}$	$0.957^{+0.066}_{-0.059}$
NLO	$3.929^{+0.024}_{-0.023}$	$0.876^{+0.008}_{-0.018}$
NNLO	$3.888^{+0.016}_{-0.012}$	$0.826^{+0.013}_{-0.014}$

Effect of NNLO	inclusive	fiducial
	normalization: -1%	normalization: -6%
	uncertainty: 0.4%	uncertainty: 1.7%

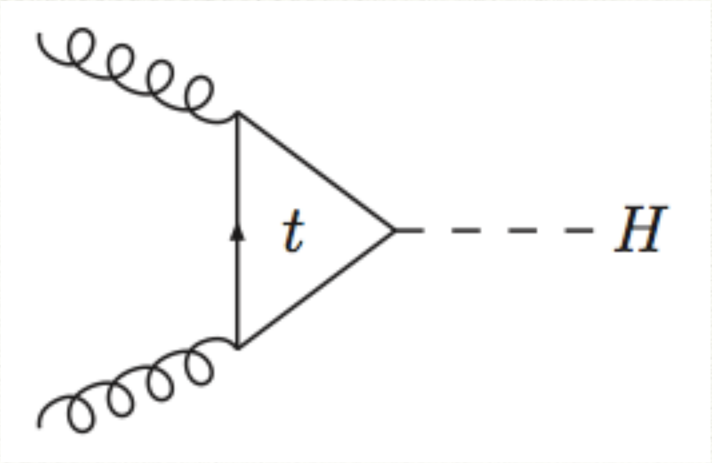
- Invaluable information for future precision studies of this process.

Distributions and outlook

- Even bigger impact on differential distributions
  - corrections up to O(10%);
  - outside NLO uncertainty estimate from scale variation.
- Motivation for N^3LO calculation; may be possible with this technique.



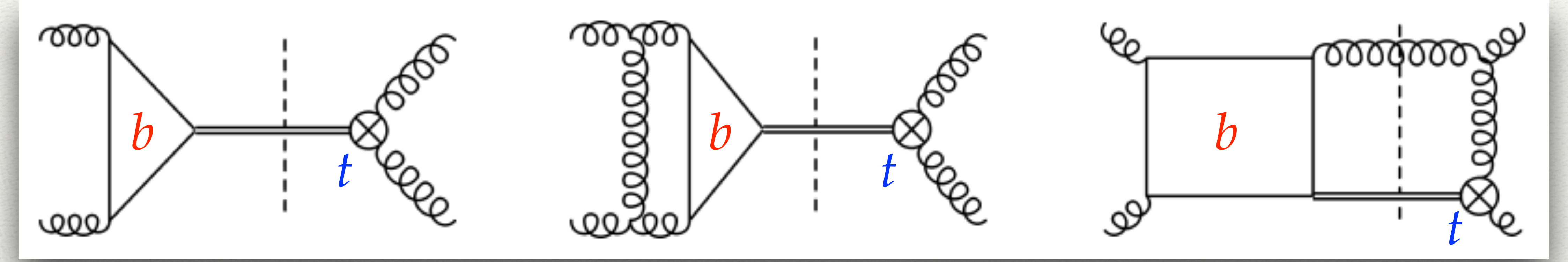
Gluon-fusion



Finite-mass effects

- Inclusion of finite mass effects (top and bottom loops) at NLO in NNLOPS generator: effects of order a few percent.
  Hamilton, Nason, Zanderighi, arXiv: 1501.04637

- New analytic calculation of leading interference effects at NLO, as expansion in powers of m_b.
  Mueller, Ozturk, arXiv: 1512.08570



- Opens up possibility of similar method at NNLO, to reduce one of the leading uncertainties that remains.

The Higgs boson p_T and jets

- Investigations of the Higgs transverse momentum distribution in parton showers, at NNLO+NNLL and including some BSM effects.

Neill, Rothstein, Vaidya, arXiv: 1503.00005

Bagnaschi, Vicini, arXiv: 1505.00735

Bagnaschi, Harlander, Mantler, Vicini, Wiesemann, arXiv: 1510.08850

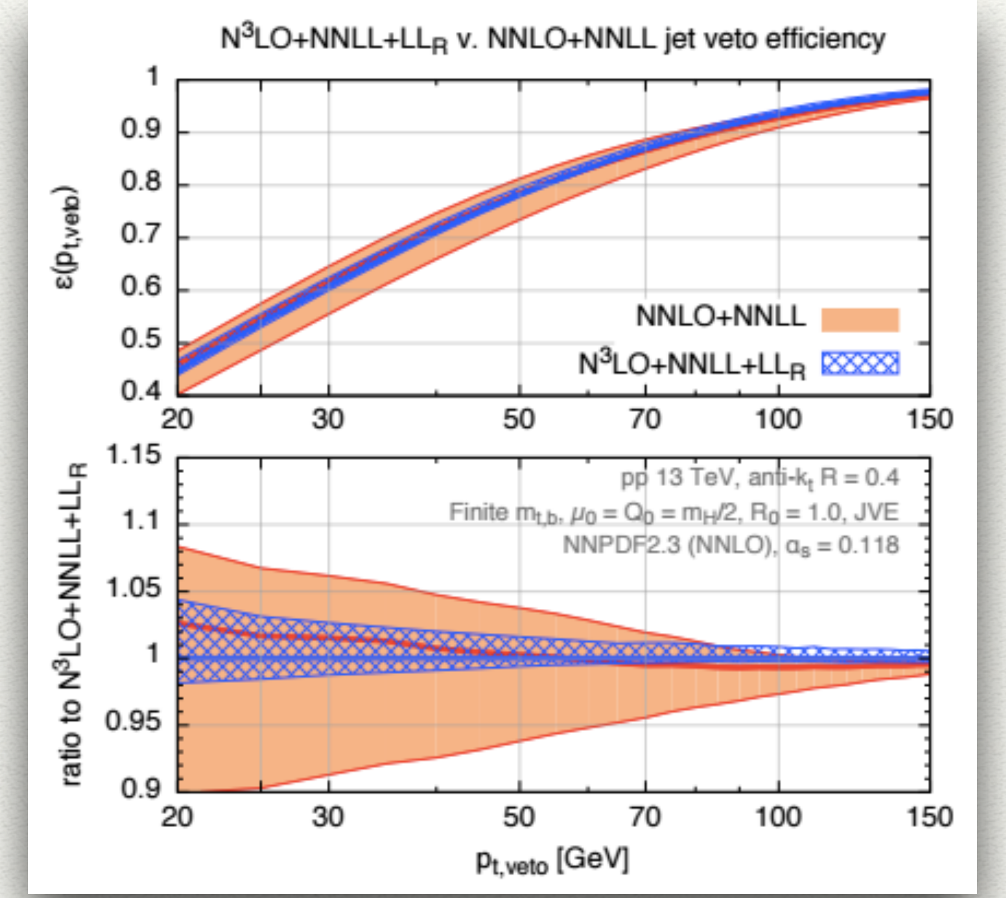
- Phenomenology of H+2/3 jets (GF and VBF) in GOSAM/SHERPA.

Greiner, Hoeche, Luisoni, Schoenherr, Winter, Yundin, arXiv: 1506.01016

- Very recently, jet-veto analysis taking into account new N^3LO inclusive result.
  - also includes NNLL jet pt and LL jet radius resummation.

Banfi, Caola, Dreyer, Monni, Salam, Zanderighi, Dulat, arXiv: 1511.02886

increase in central value and new scale uncertainty both 2%



Beyond a scalar Higgs and related processes

- Primarily of interest for BSM but closely related to other developments discussed here.

- N^{3}LO predictions for a pseudoscalar Higgs in the threshold limit.

  Ahmed, Kumar, Mathews, Rana, Ravindran, arXiv: 1510.02235

- NNLL soft/collinear resummation for pseudoscalar Higgs boson (N^{3}LL for scalar).

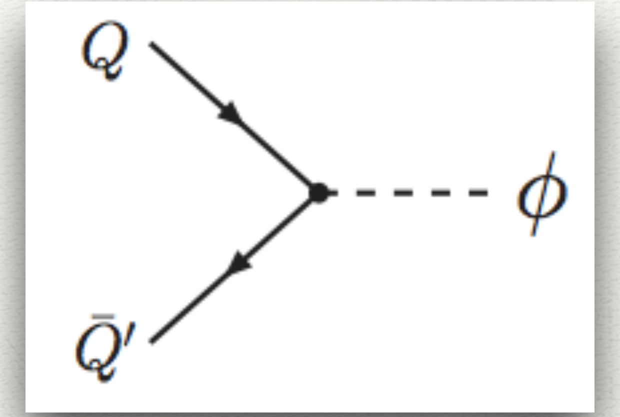
  Schmidt, Spira, arXiv: 1509.00195

- Heavy-quark annihilation channels:
  - FONLL scheme for bb annihilation;

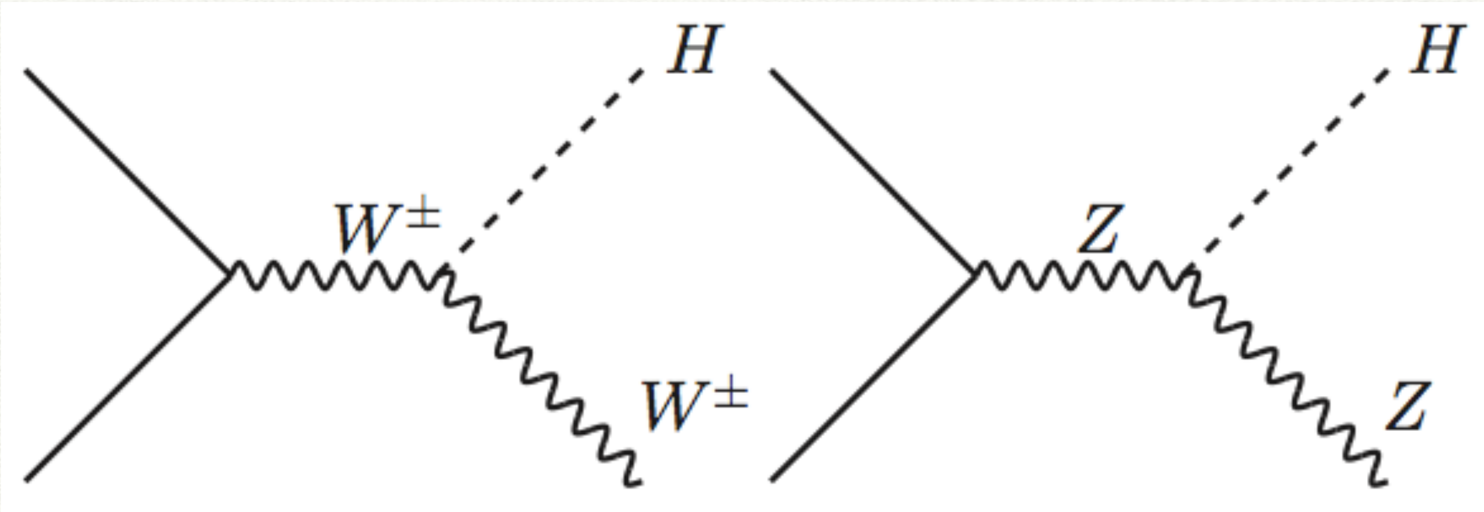
    Forte, Napoletano, Ubiali, arXiv: 1508.01529

  - NNLO for neutral, charged Higgs production.

    Harlander, arXiv: 1512.04901

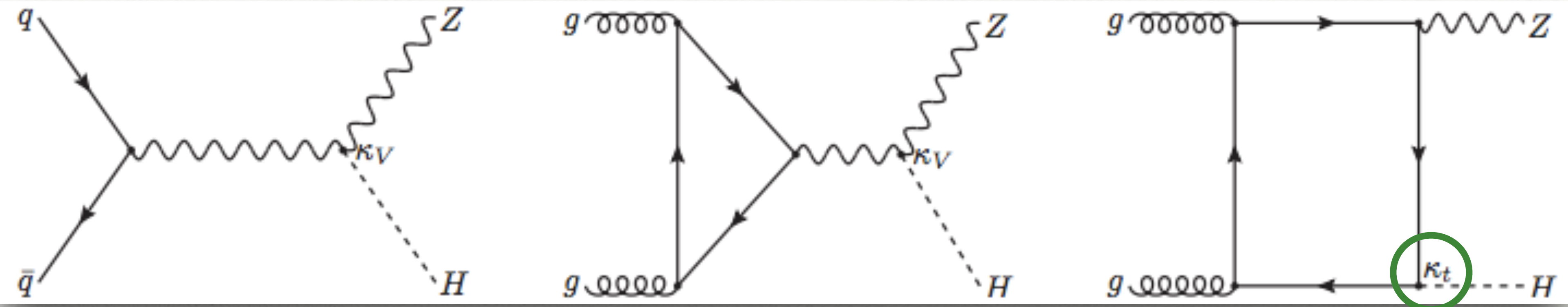


Associated VH production



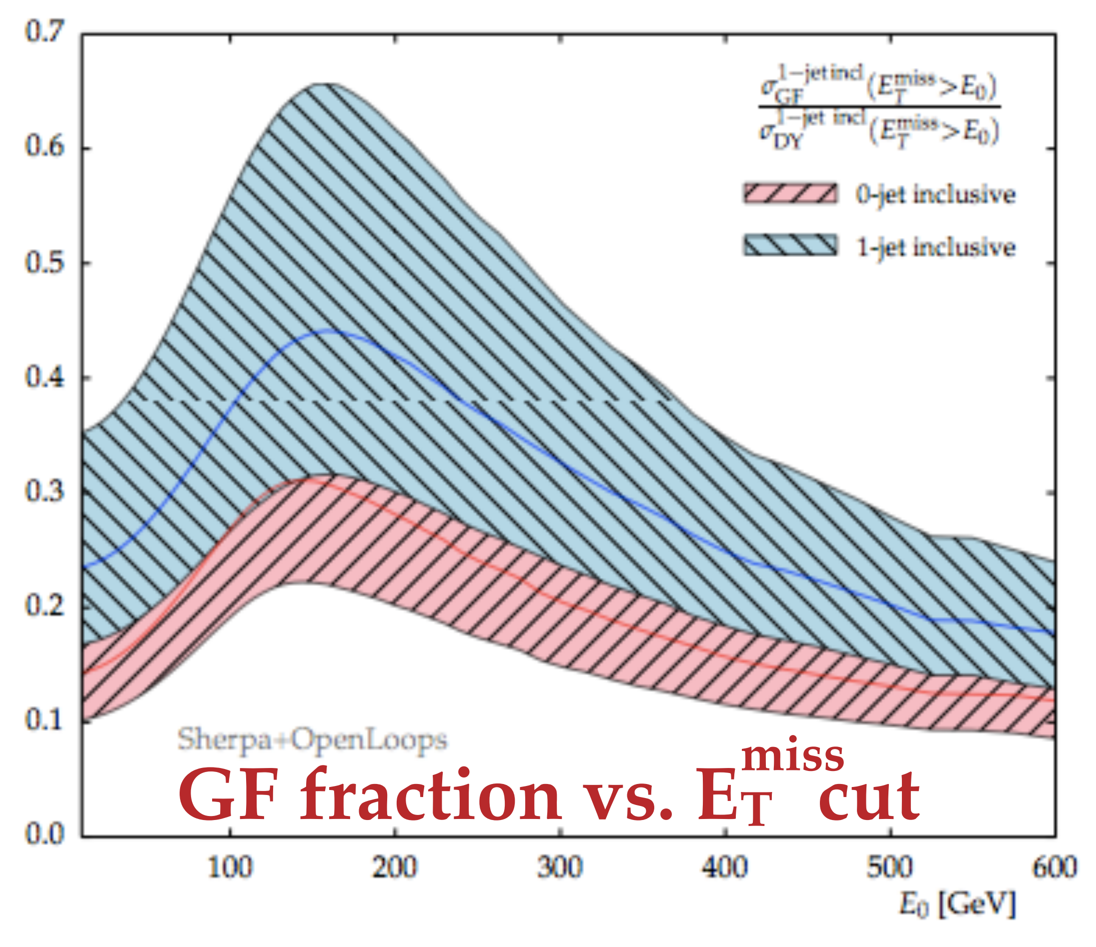
Improved Monte Carlo modelling

Goncalves, Krauss, Kuttimalai, Maierhofer, arXiv: 1509.01597
(see also: Hespel, Maltoni, Vryonidou, arXiv: 1503.01656)



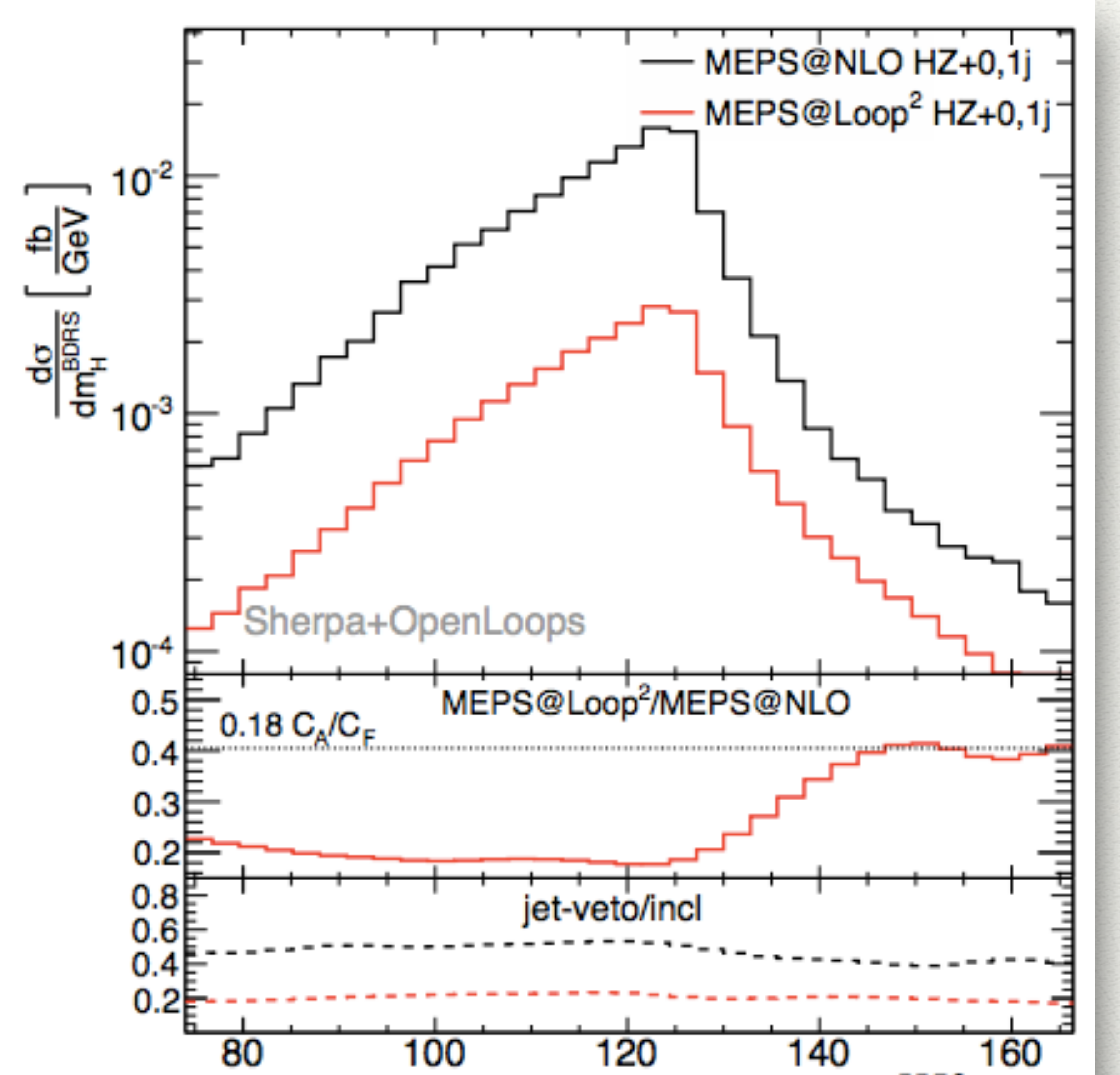
Drell-Yan like   gg→VH, formally NNLO

- Useful to consider contributions separately for purposes of MC multi-jet merging (different QCD emission patterns).
- gg→VH enhanced by gluon pdf, large top Yukawa and effect of $2m_t$ threshold;
  - especially important for invisible decays, e.g. Higgs-portal models.

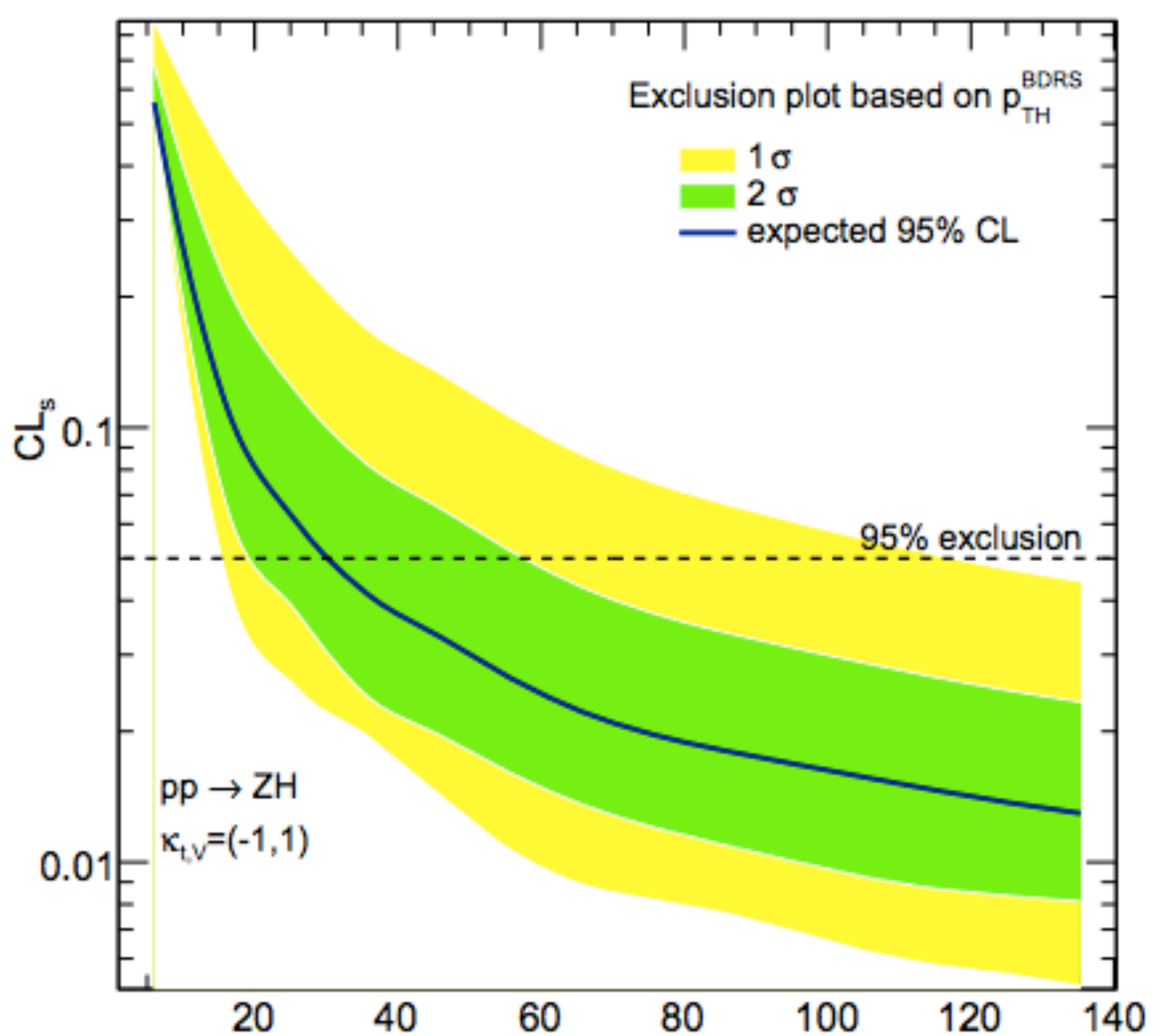


Impact

- Important for application of jet veto, e.g. to suppress background.
- Imperative for application to boosted search for H→bb decays.



mass of Higgs candidate



luminosity [fb^{-1}]

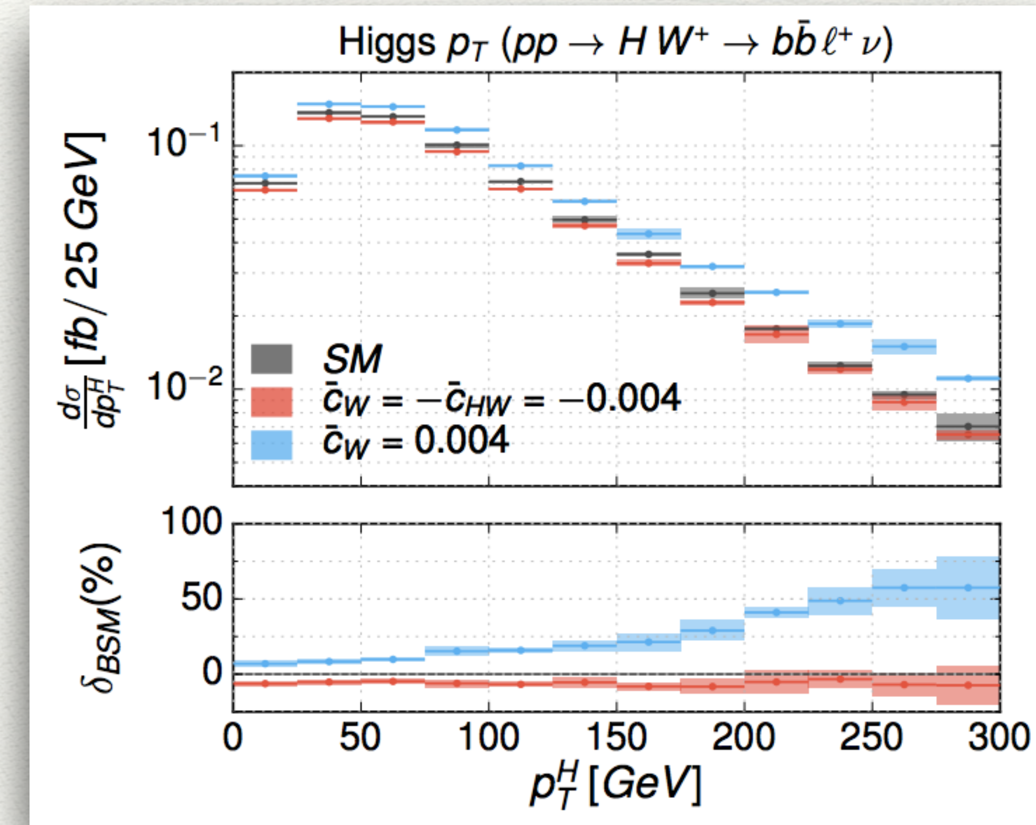
~ 30fb^{-1} data required to exclude opposite-sign y_t

Other new tools

- NLO parton shower (POWHEG) including effects of anomalous couplings in linear EFT:

  Mimasu, Sanz, Williams, arXiv: 1512.02572

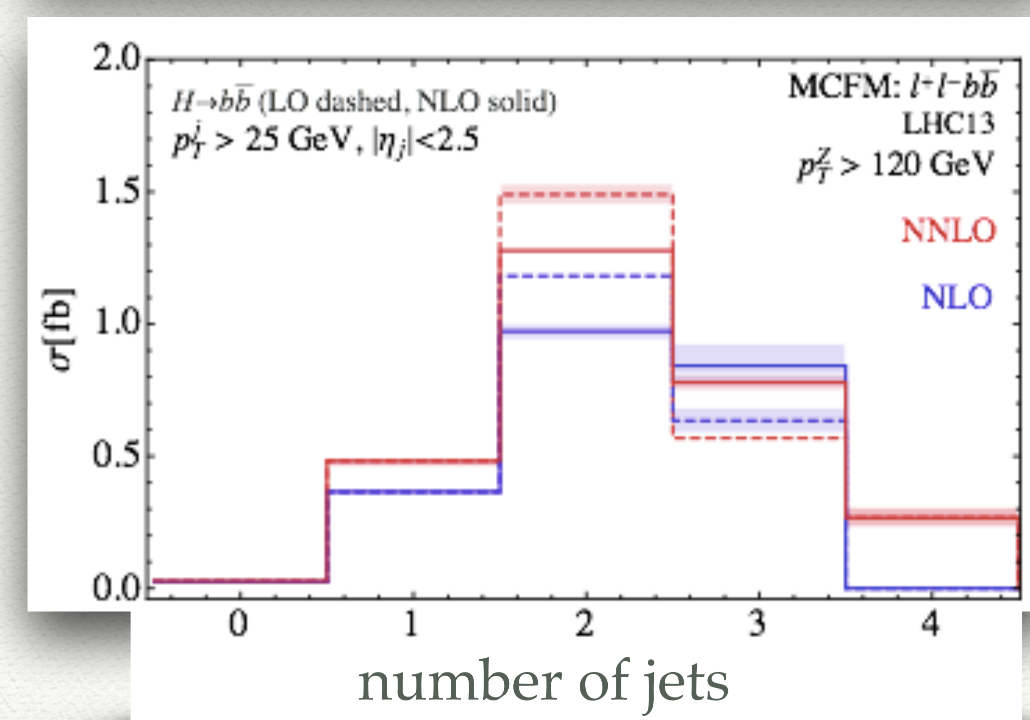
$$\frac{ig\ \bar{c}_W}{m_W^2}\left[\Phi^\dagger T_{2k}\overleftrightarrow{D}^\mu\Phi\right]D^\nu W^k_{\mu\nu}+\frac{2ig\ \bar{c}_{HW}}{m_W^2}\left[D^\mu\Phi^\dagger T_{2k}D^\nu\Phi\right]W^k_{\mu\nu}$$



- Fully-differential NNLO including both DY and y_t contributions.

  Ellis, JC, Williams, arXiv: 1601.00658

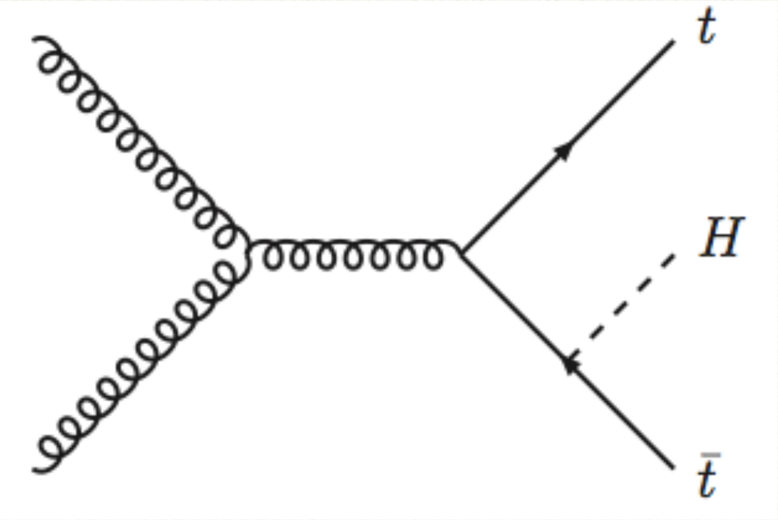
  - also includes effects of radiation in decay at NLO for H→bb.



- Recalculation of H→bb at NNLO.

  Del Duca et al, arXiv: 1501.07226

Associated top production



Beyond NLO: parton showers and resummation

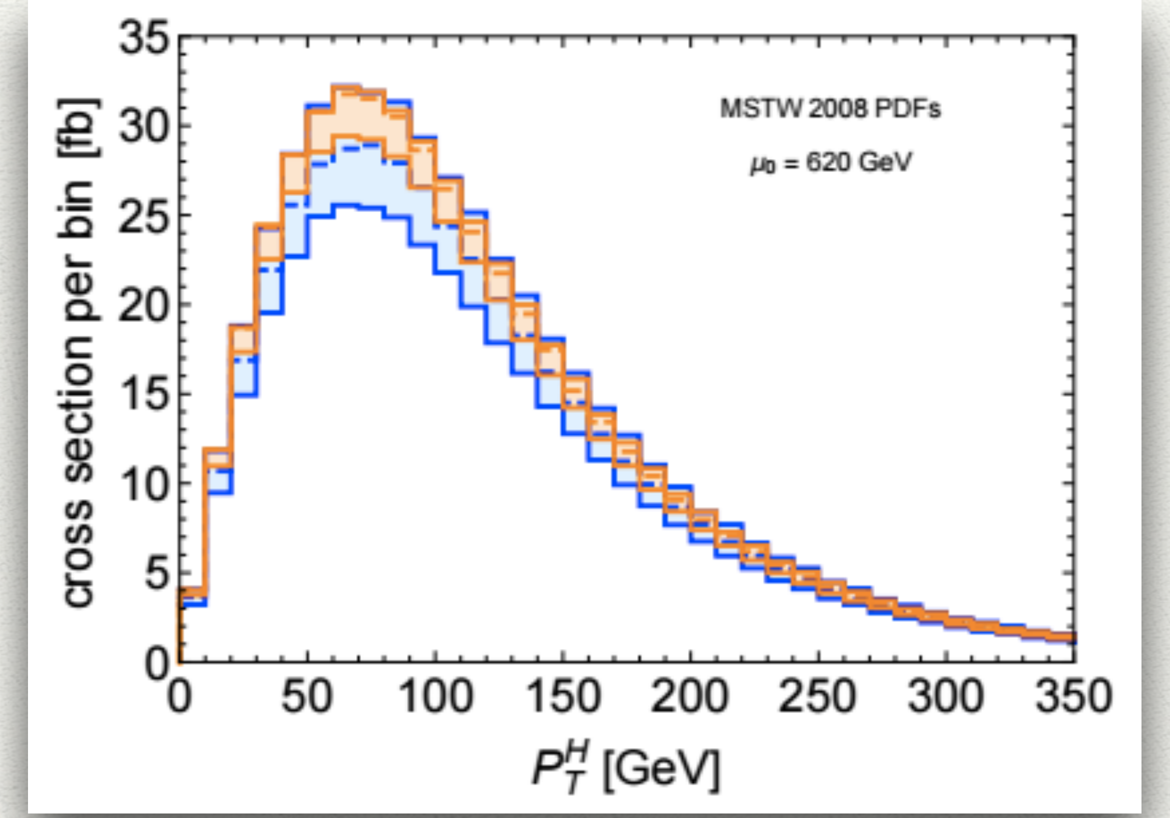
- Public NLO parton shower available in POWHEG-BOX.

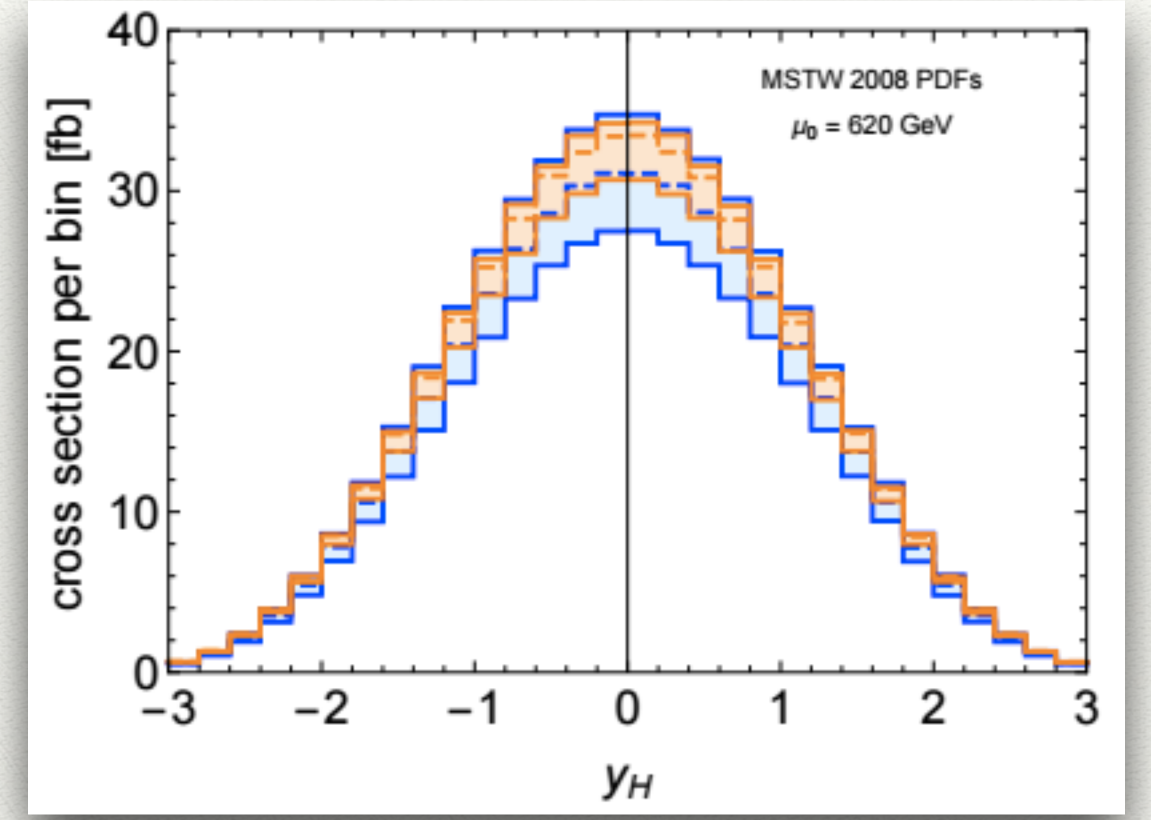
  Hartanto, Jager, Reina, Wackeroth, arXiv: 1501.04498

- First steps beyond NLO: soft-gluon resummation for approximate NNLO.

  Broggio, Ferroglia, Pecjak, Signer, Yang, arXiv: 1510.01914

  - caveat: how well does this capture behavior of full corrections?
  - estimate of uncertainty by including additional contributions that are formally sub-leading in the soft limit.
  - justified by comparison of exact and approximate NLO.

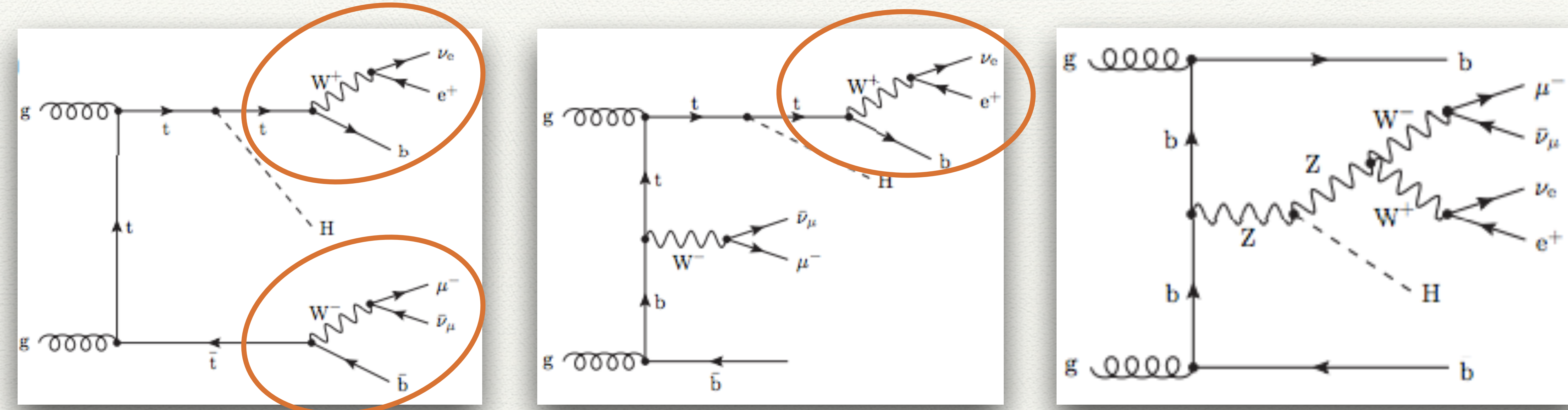




Less approximations at NLO

Denner, Feger, arXiv: 1506.07448

- Full treatment of all diagrams that lead to the same final state: non-resonant contributions, off-shell and interference effects.



- Calculation performed in limit of massless b-quarks; infrared safety therefore requires two hard b-jets.
  - difference with on-shell calculation $< 1\%$.
  - would be much bigger in regions where one bottom quark is not observed, but requires massive b-quarks.

Fun facts about dogs

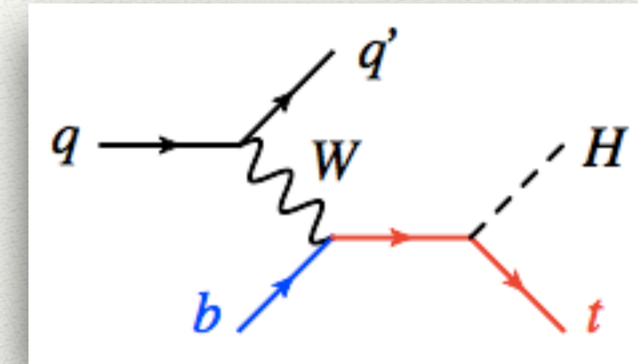
- The largest breed of dog is the Irish Wolfhound.
- Puppies do not know how to walk when first born; they usually learn when they are 2-5 weeks old.
- Two nose prints are never exactly alike.
- More than 50 dogs have lived in the White House!
- Dogs are able to smell things that we can't.
- They can see much better in the dark than we can.

Humans do have more taste buds than dogs- in fact, we have about 9,000 of them!

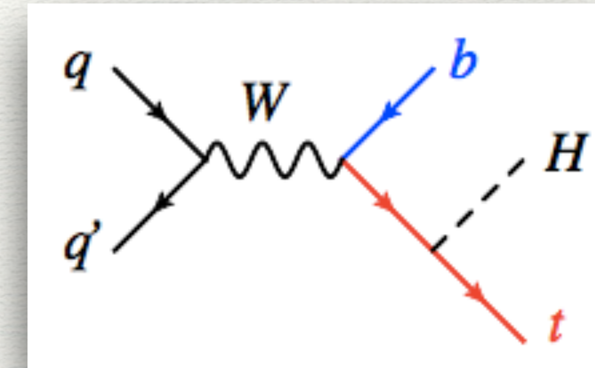
Other production modes

Single top + Higgs

t-channel



s-channel



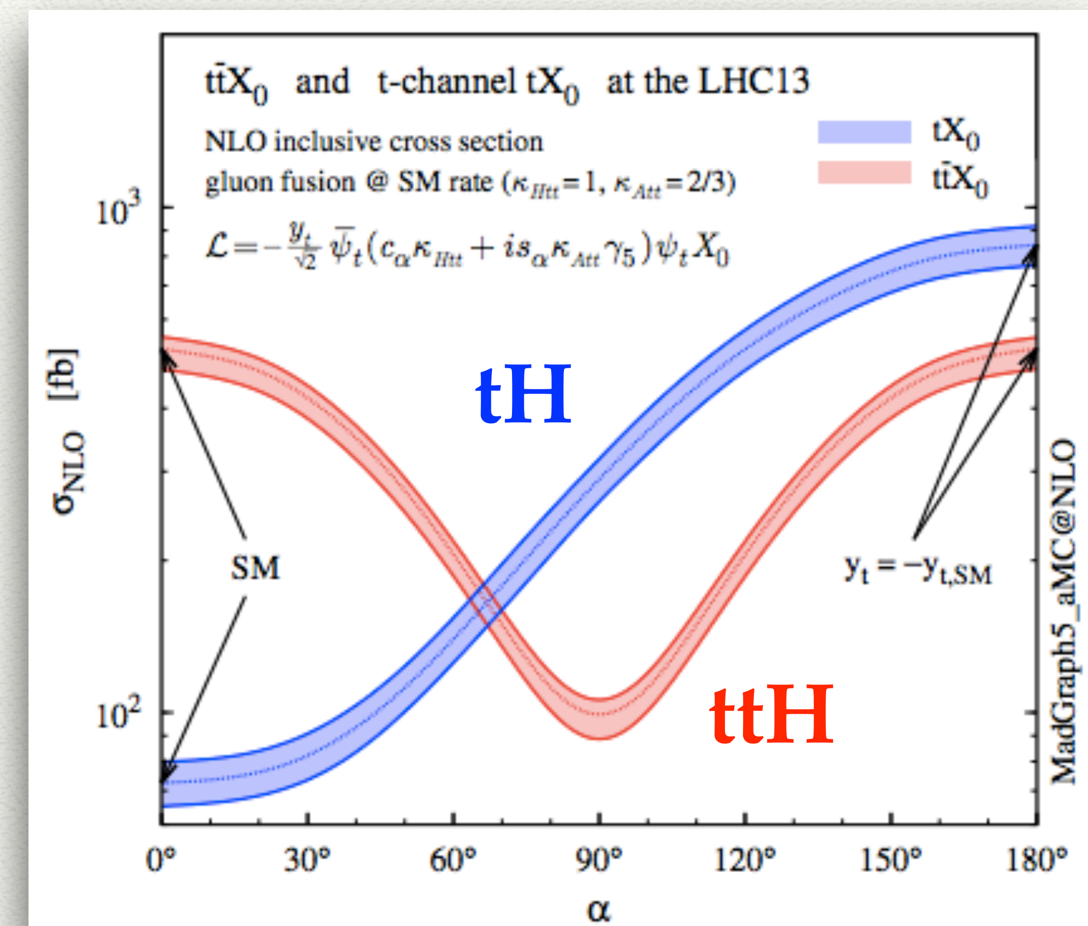
- Small total cross-section ~ 75fb at 13 TeV (mostly t-); strong destructive interference due to unitarity, very sensitive to non-standard couplings.

- Thorough analysis of theoretical uncertainty and sensitivity to CP-violating Yukawa in aMC@NLO.

Demartin, Maltoni, Mawatari, Zaro, arXiv: 1504.00611

$$\mathcal{L} = -\frac{y_t}{\sqrt{2}}\bar{\psi}_t\left(\cos\alpha + i\gamma_5\frac{2}{3}\sin\alpha\right)\psi_t X_0$$

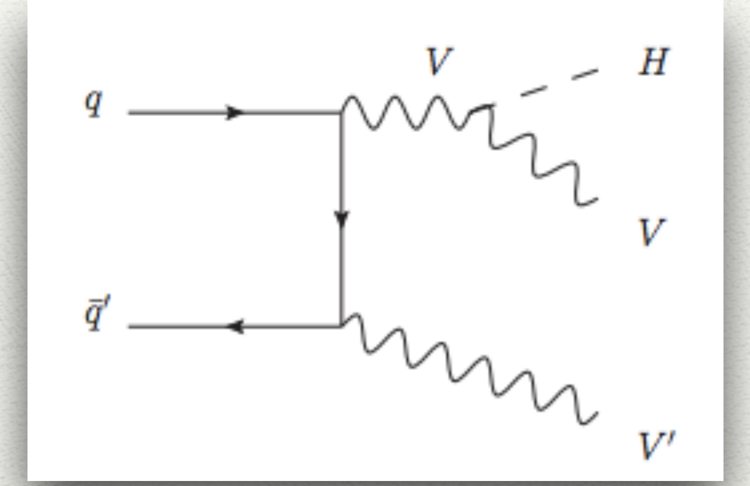
ensures GF cross-section remains at observed SM level

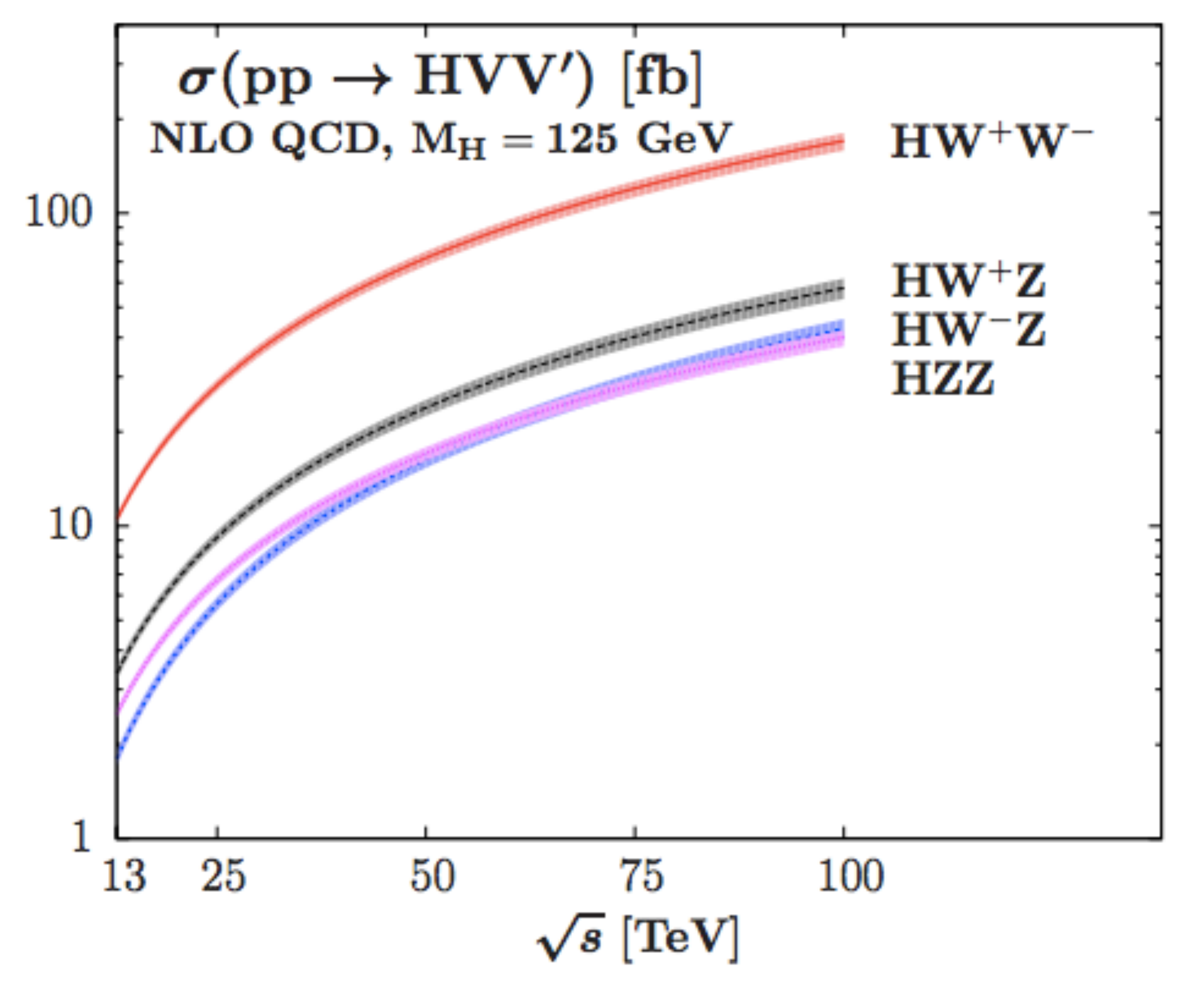


New modes in POWHEG-BOX

- Associated production with a pair of weak bosons.

  Baglio, arXiv: 1512.05787





  - rates at 13 TeV in *2-10 fb* range, better prospect for FCC …

- Production in association with b-jets: probe of extended Higgs sectors.

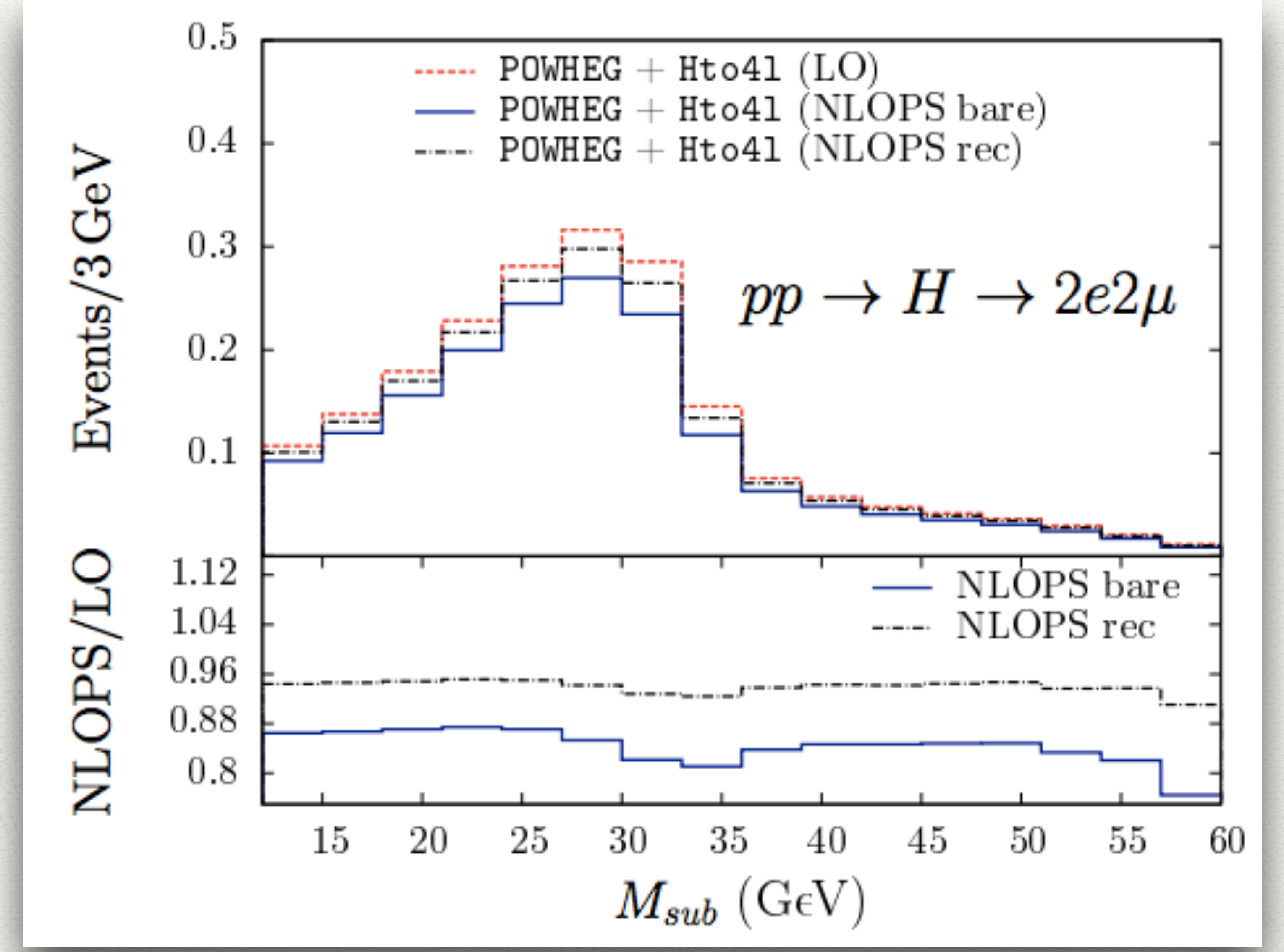
  Jager, Reina, Wackeroth, arXiv: 1509.05843

Decays

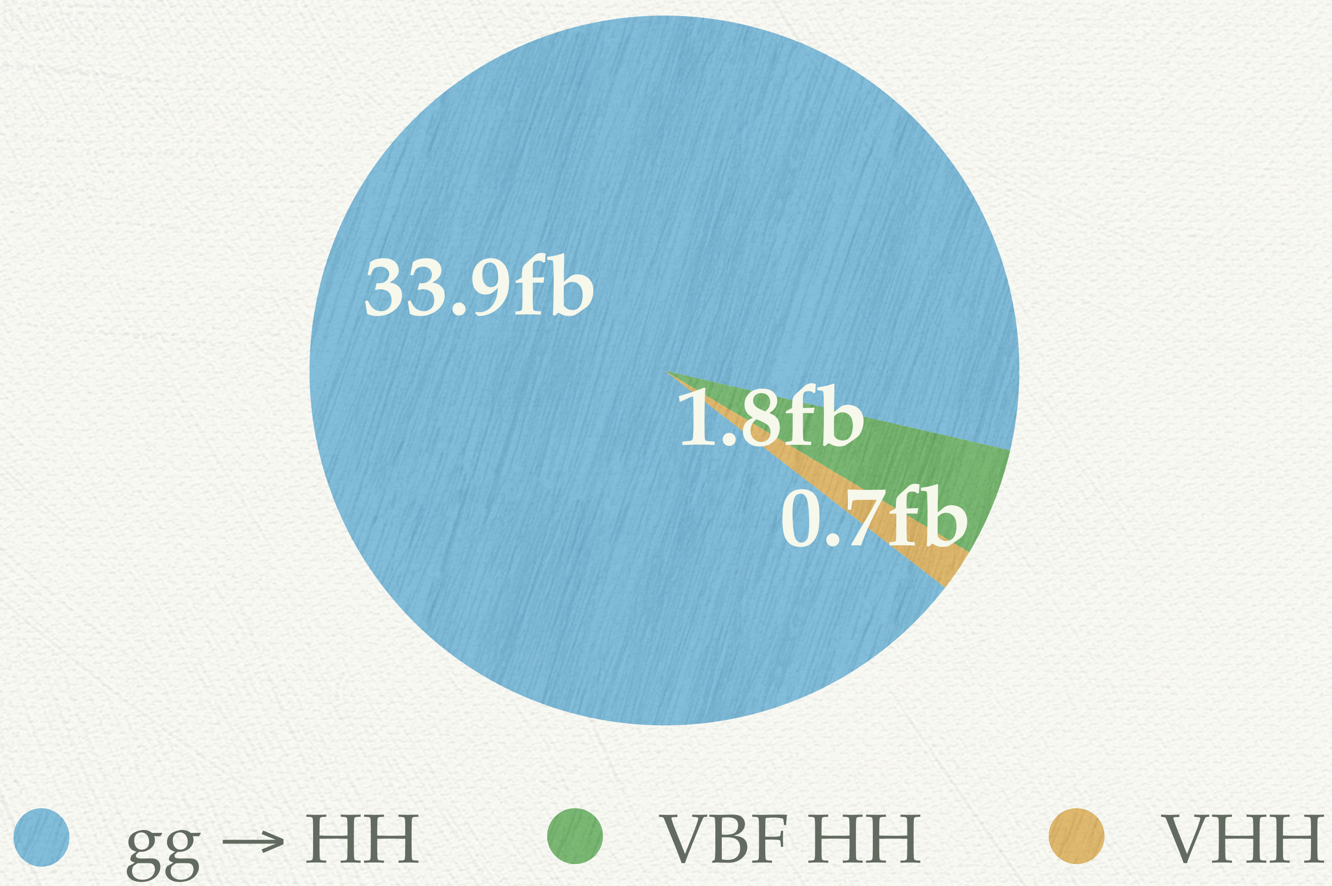
Electroweak NLO+PS corrections to H→4ℓ

Boselli, Carloni Calame, Montagna, Nicrosini, Piccinini, arXiv: 1503.07394

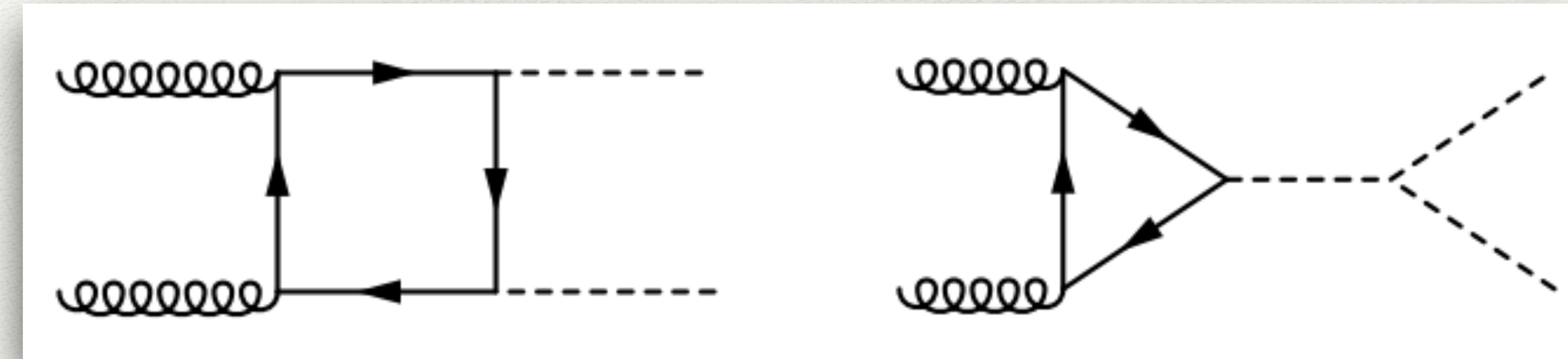
- Full calculation of complete NLO weak and QED corrections, combined with multiple-photon emission through QED parton shower.
    - stand-alone package can be interfaced with any generator.



Higgs pair production



Beyond NNLO in gluon fusion

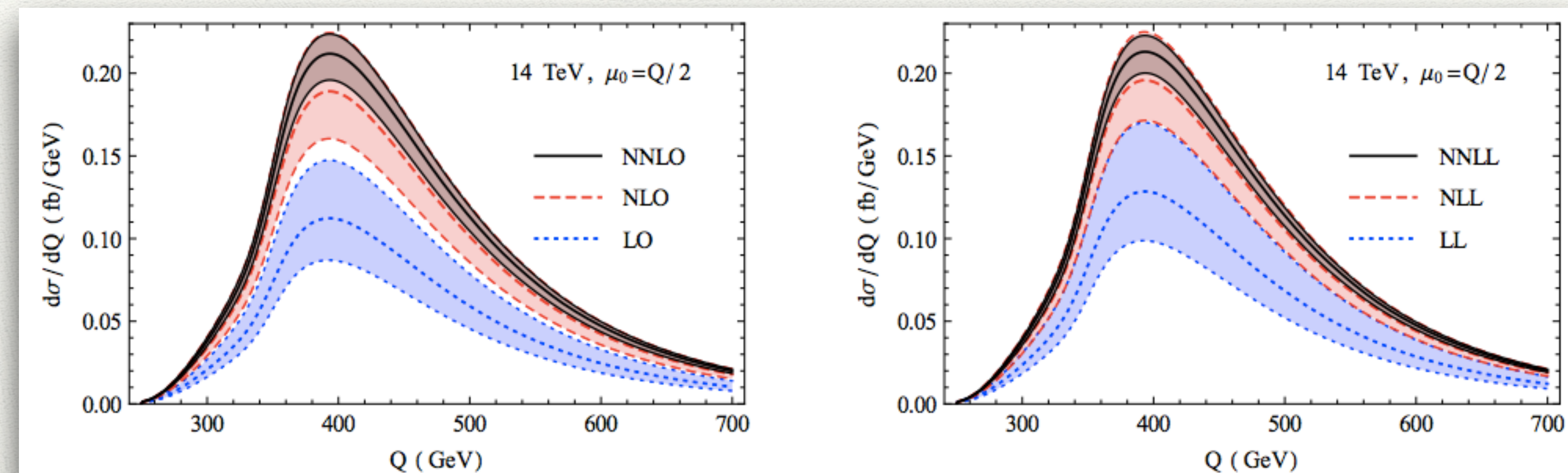


probe of Higgs potential (self-coupling)

- Cross-section known at NNLO in infinite top quark mass limit; now extended by threshold resummation to NNLL.

de Florian, Mazzitelli
arXiv: 1505.07122

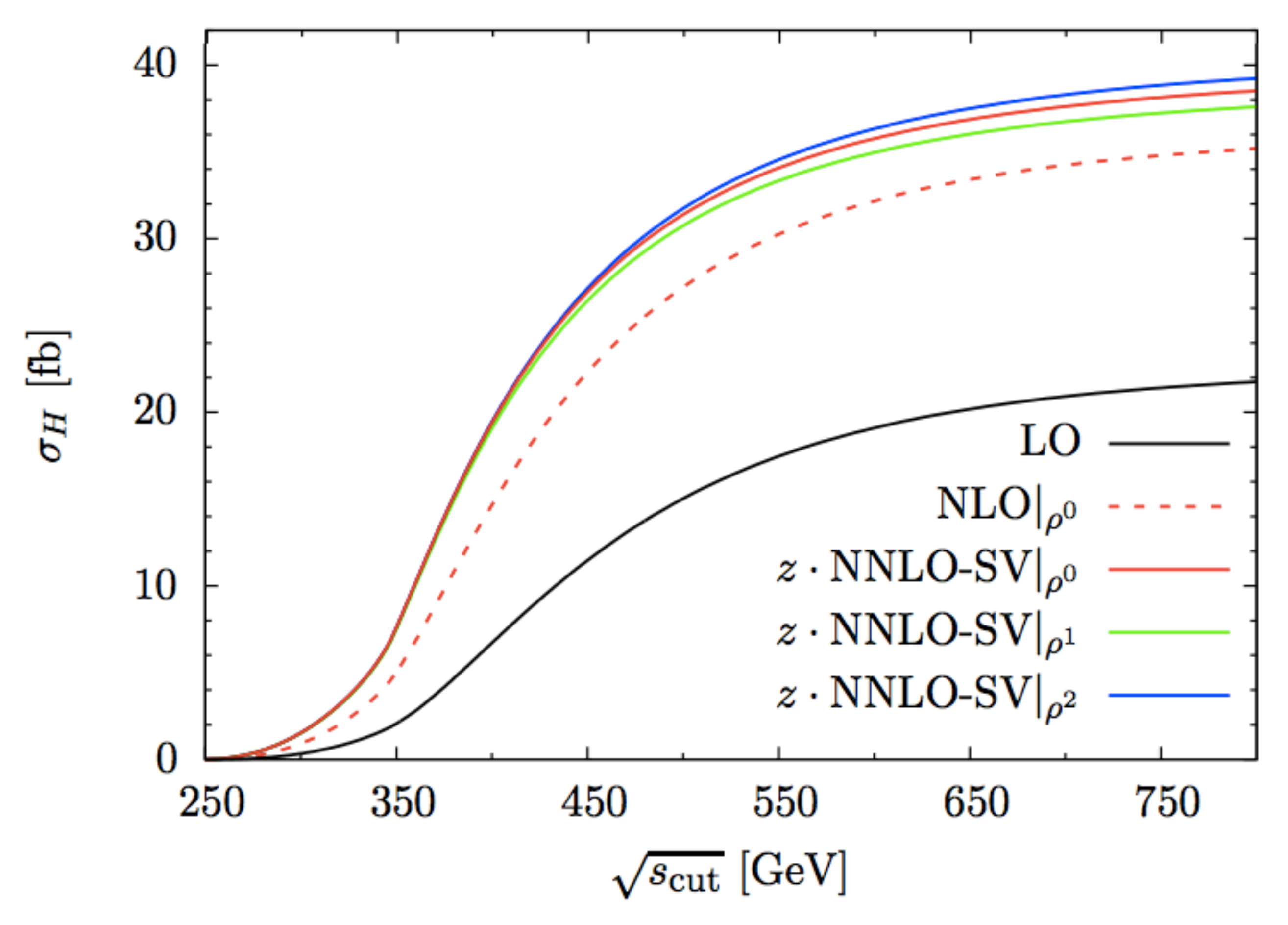
fixed order | resummed



Top mass corrections

- Exact dependence on top mass only known at LO;
  at NLO, expansion to $(1/m_t)^{12}$ supplemented by factoring LO result.

- Exact calculation feasible at NLO but out of reach at NNLO;
  - improved NNLO approximation including mass effects to $(1/m_t)^4$; strictly valid only for $\sqrt{\hat{s}} \lesssim 2m_t$



Grigo, Hoff, Steinhauser, arXiv: 1508.00909

estimate of remaining finite-mass uncertainty:

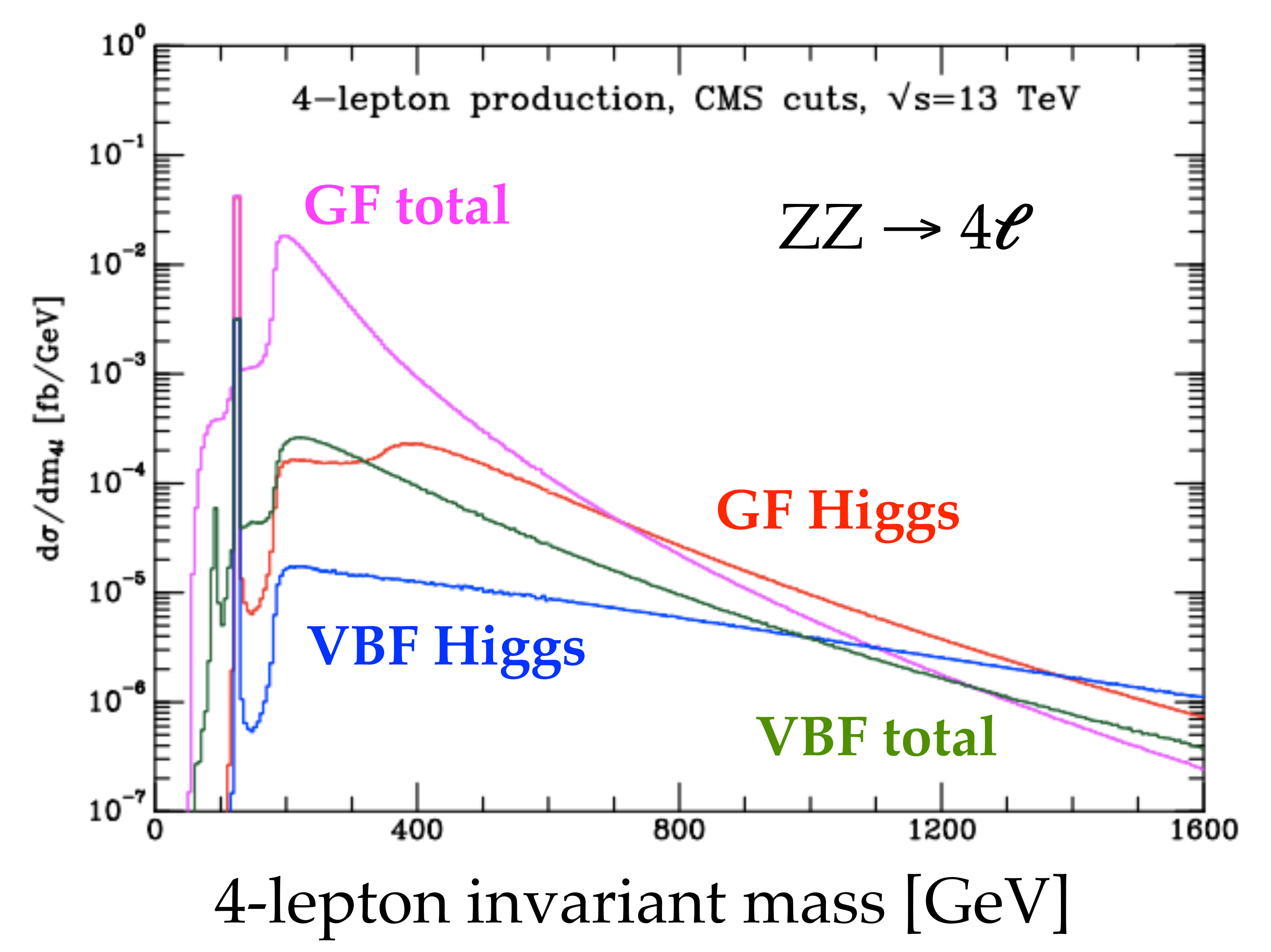
NLO $\pm 10\%$

NNLO $\pm 5\%$

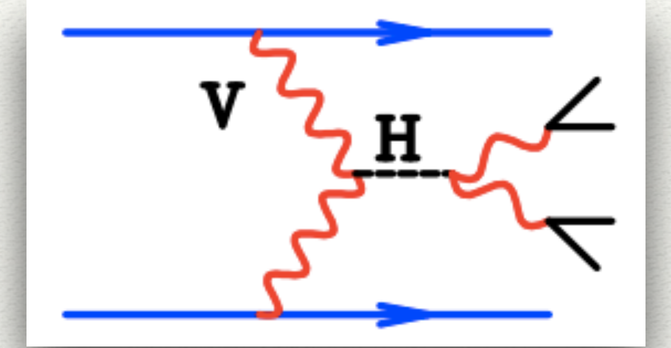
Off-shell / interference effects

Higgs boson line-shape in H→VV decays

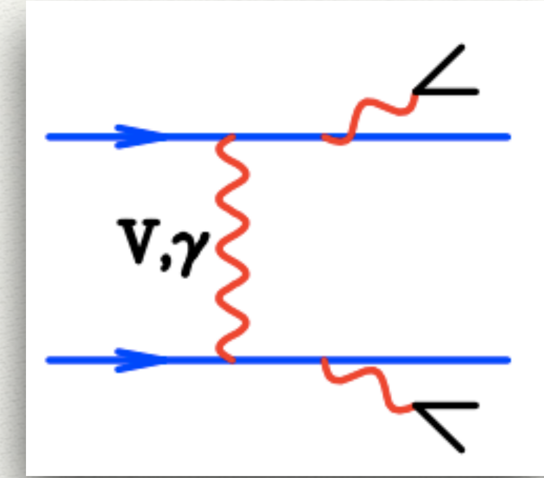
- Reveals a significant off-shell component (real vector bosons, top threshold).
  - sensitive to cancellation of longitudinal modes in SM.



VBF Higgs

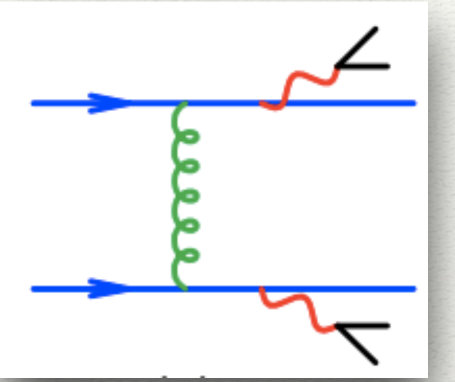


"VBF" total



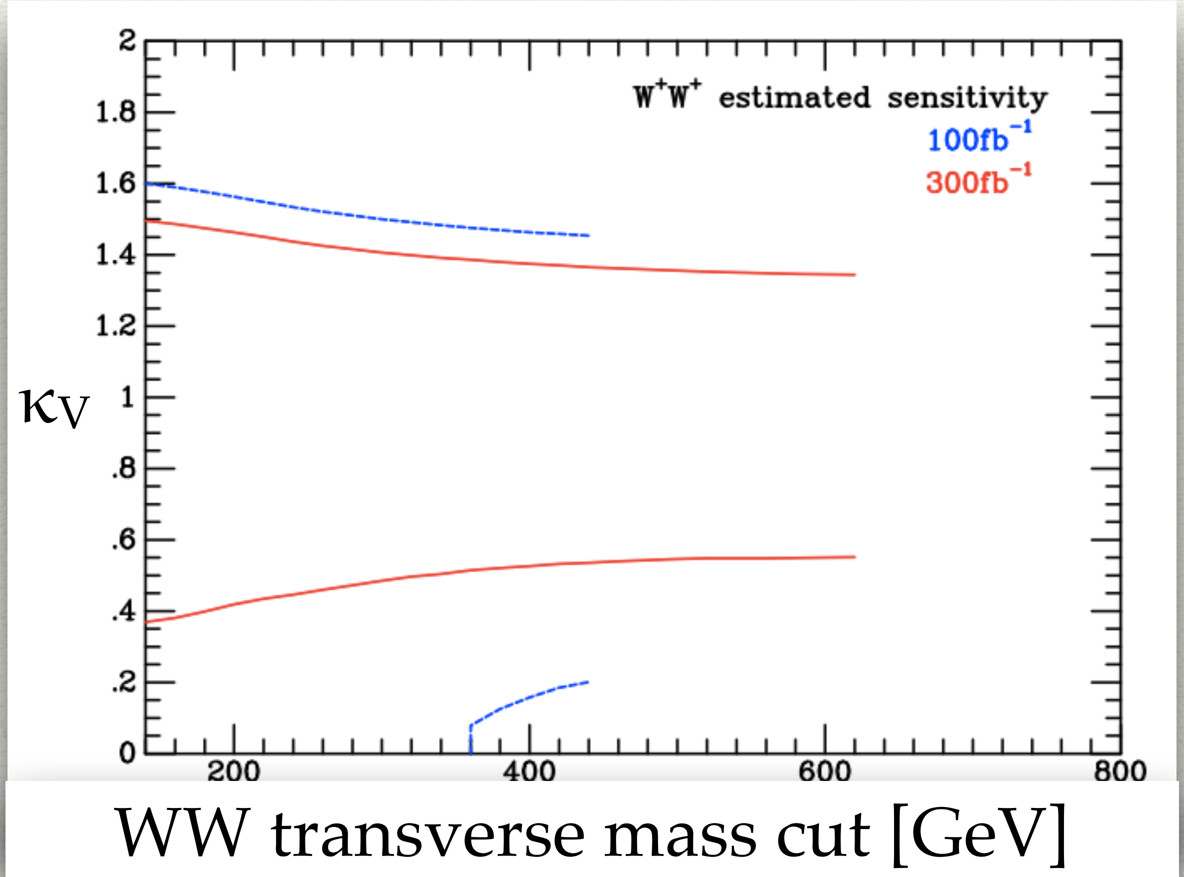
Bounds on off-shell Higgs couplings/width

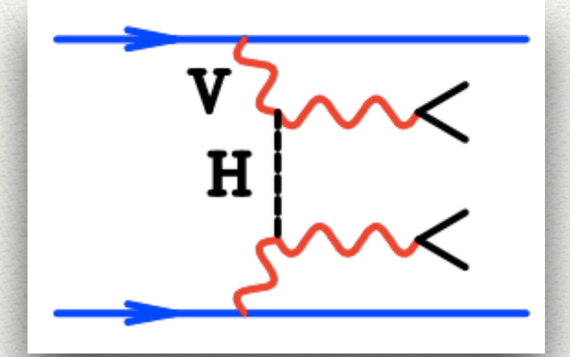
- Use high-mass events to bound off-shell Higgs couplings/width.
  - larger rate in GF, requires additional theoretical assumptions (particles in the loop).
  - constraints in Run 2 from tree-level vector boson scattering processes (not just VBF), significant backgrounds from QCD.



- Best information from like-sign W channels that have only small backgrounds.

JC, Ellis, arXiv: 1502.02990





sensitivity to Higgs coupling through t-channel

Run I estimate (ATLAS data): $\kappa_V < 2.8$

Ballestrero, Maina, arXiv: 1506.02257 — SM+singlet extension

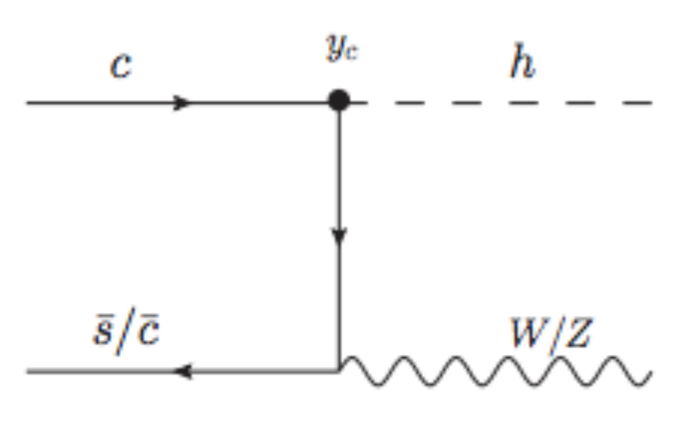
Englert, McCullough, Spannowsky, arXiv: 1504.02458 — combination with LEP

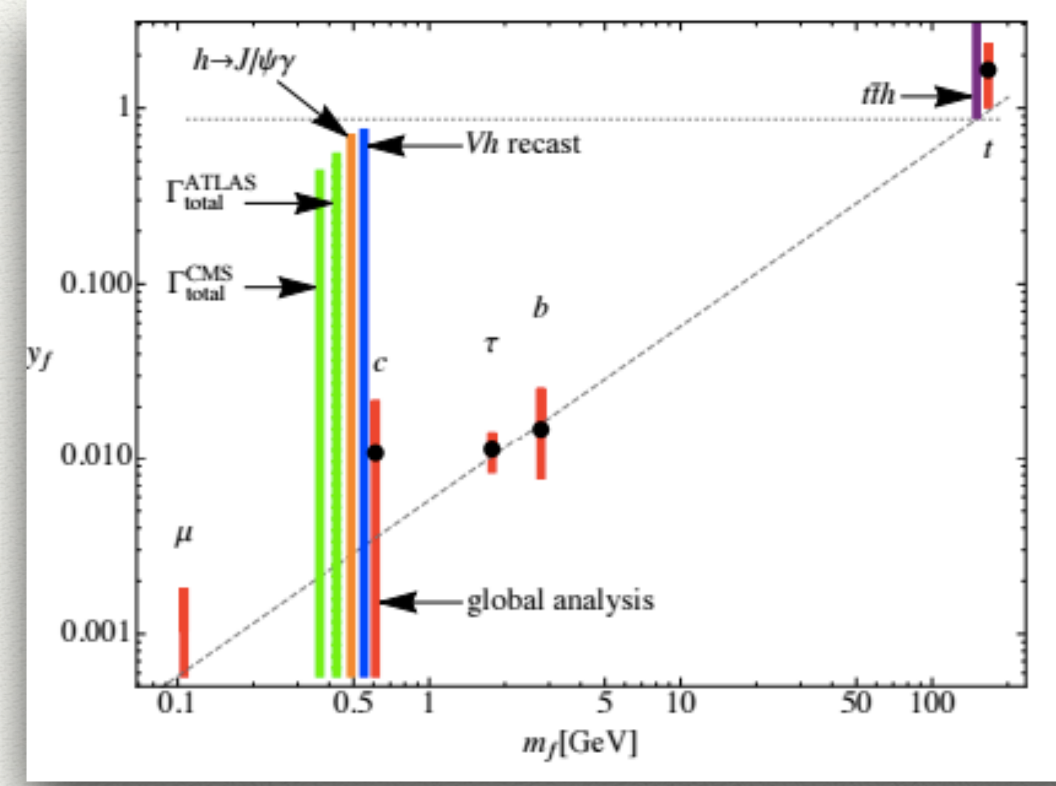
Higgs couplings

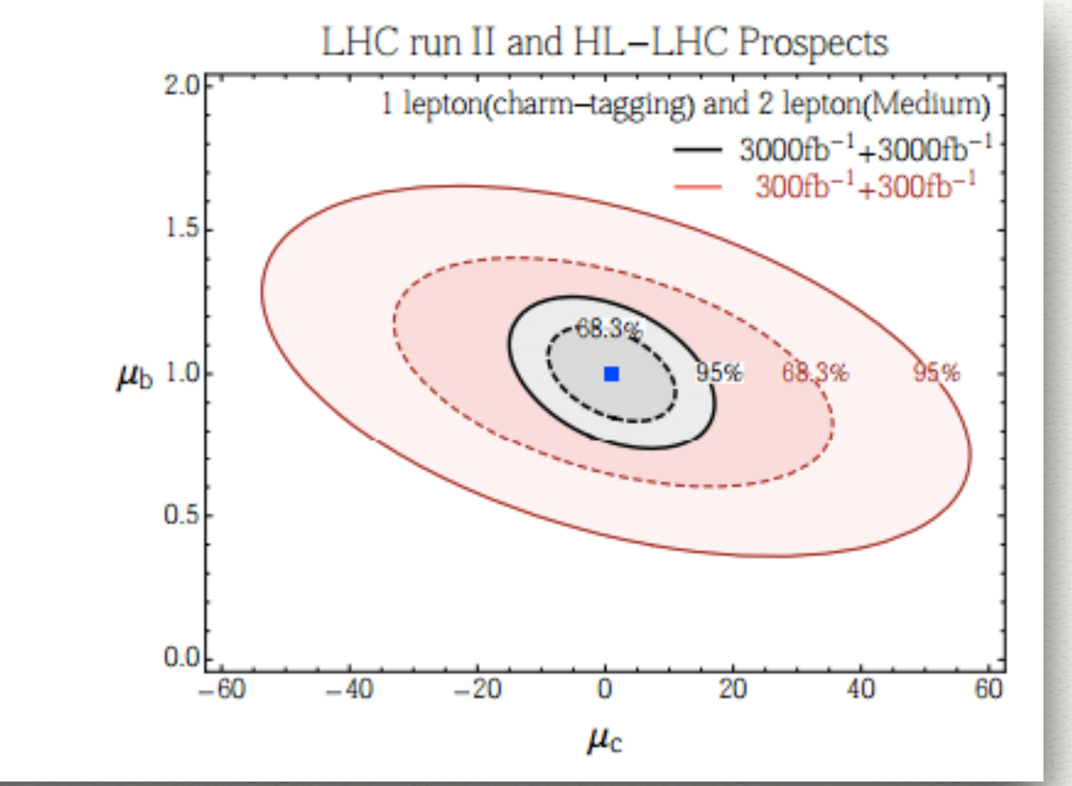
Coupling to charm quarks

Perez, Soreq, Stamou, Tobioka, arXiv: 1503.00290

- Novel ideas for constraining the charm Yukawa coupling.
  - recasting $VH(\to bb)$, taking advantage of bottom/charm mis-tagging and new production channels that are normally pdf-suppressed;
  - re-interpreting direct bound on total width;
  - bounds on exclusive decay, $H \to J/\psi\gamma$
  - indirect bound from global analysis of Higgs couplings.





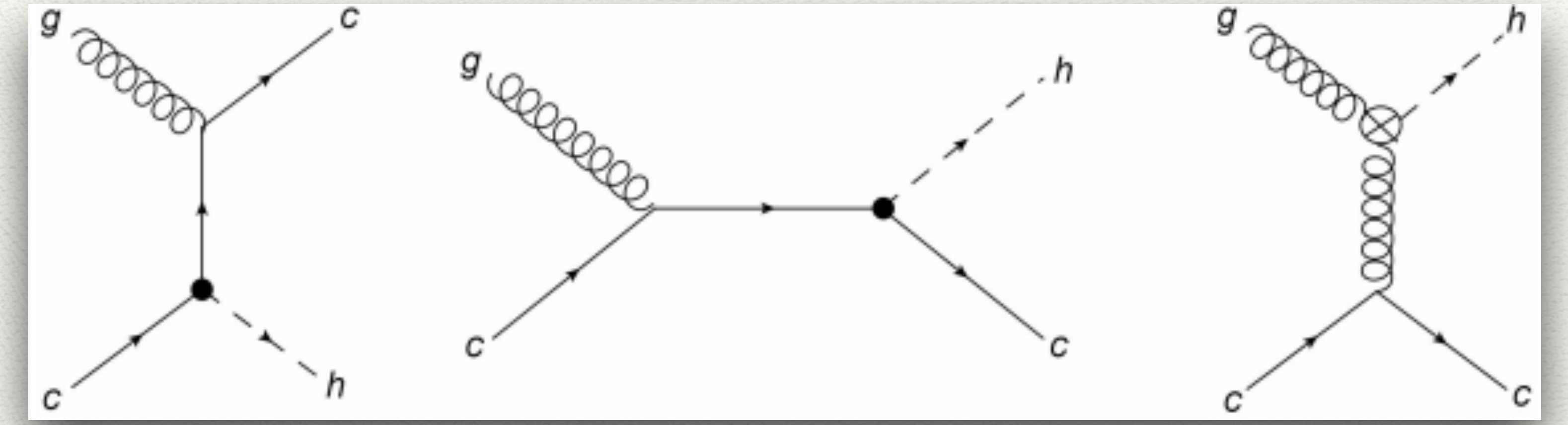


… or through Higgs + charm

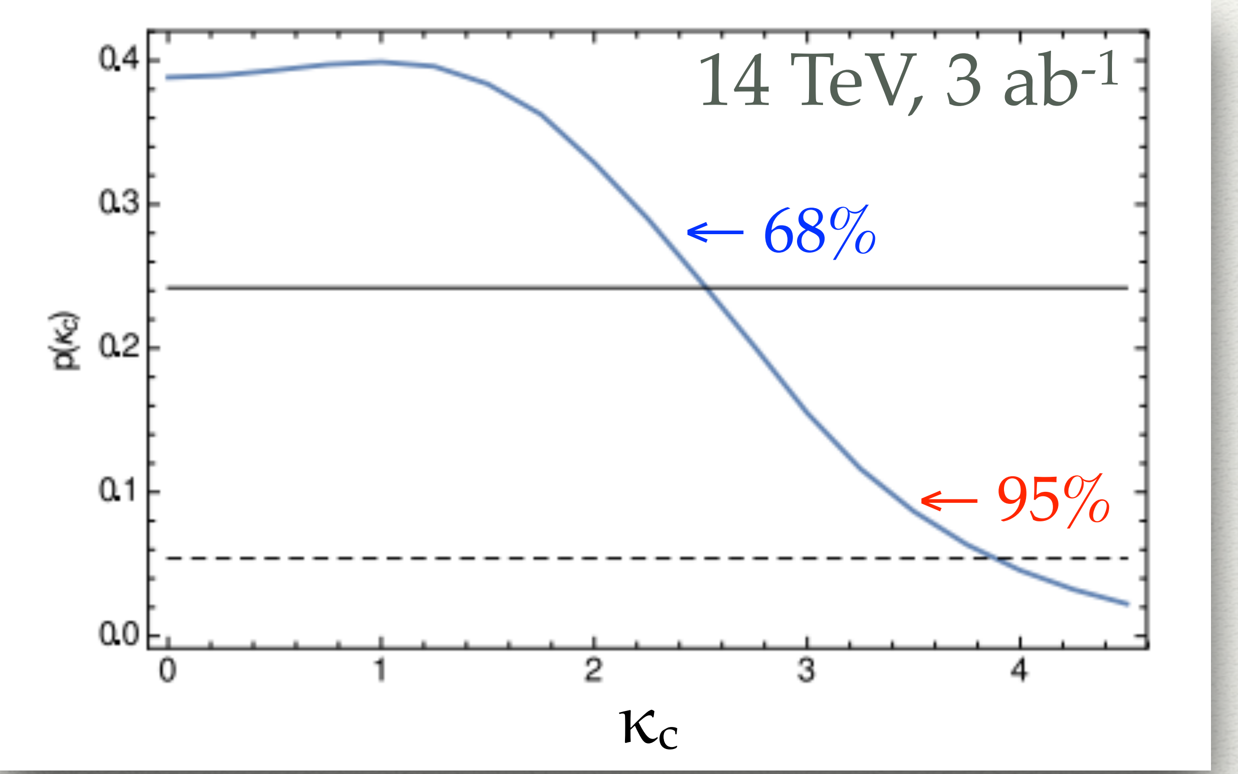
Brivio, Goertz, Isidori, arXiv: 1507.02916

- Can take advantage of clean Higgs decay modes and only need to tag one charm jet.

- More events, but larger intrinsic "background".



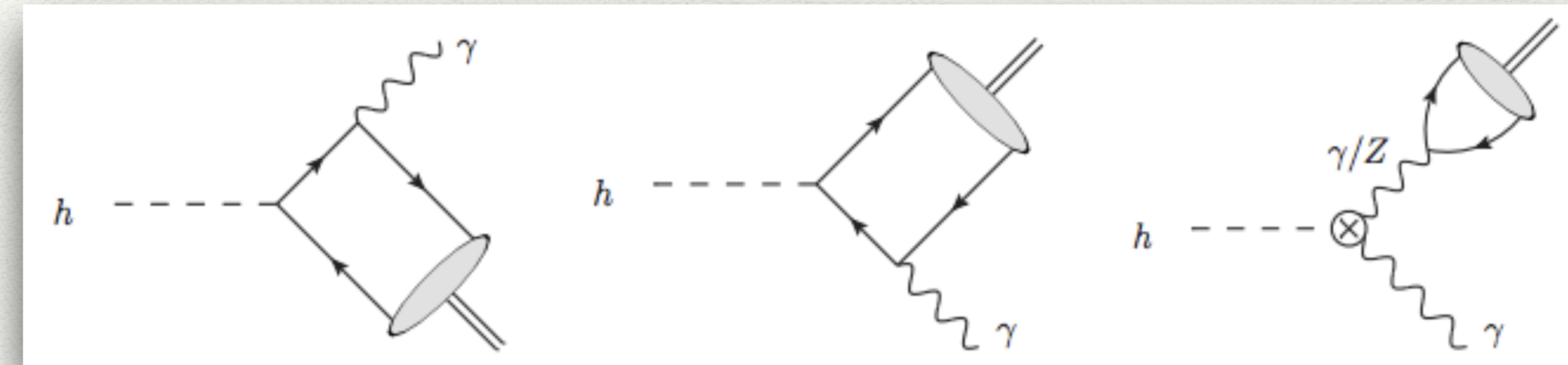
- Expected constraint from HL-LHC similar to previous slide.
    - theoretical uncertainty based on NLO calculation ~ 20%



New analysis of exclusive decays

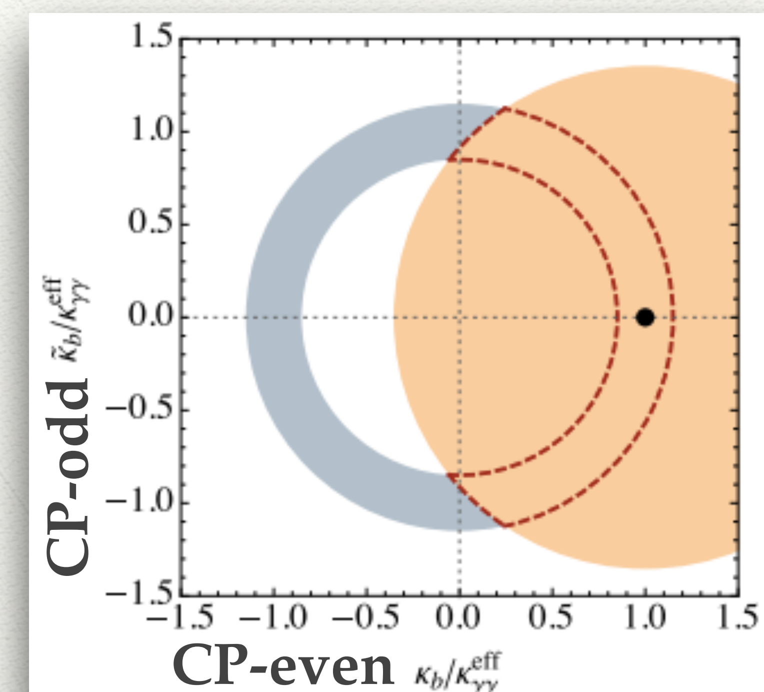
direct indirect

Koenig, Neubert, arXiv: 1505.03870



original idea in:
Bodwin et al, 1306.5770
Kagan et al, 1406.1722

- Include radiative corrections, resum large logarithms, account for flavor mixing.
- Indirect contributions must be predicted with precision and accounted for, without assuming SM, in order to extract information on Yukawa; achieve by taking ratio: Br$(h\to V\gamma)$/Br$(h\to\gamma\gamma)$.
- SM branching ratios of order 10^{-6} or smaller; long-term prospects (3000fb^{-1}):
  - $h\to\ \phi\gamma$ yields O(30) constraint on y_s
  - $h\to J/\psi\gamma$ gives O(1) constraint on y_c
  - $h\to\Upsilon(nS)\gamma$ and $h\to bb$ complementary.



Complementary information on bottom Yukawa

- Weak boson fusion with Higgs decays to bottom quarks.
  - small signal to background ratio
  - lack of typical cuts to ameliorate analysis, e.g. central jet veto.
- New proposal to use:
  - fat jets to identify $H \rightarrow bb$ decay;
  - matrix element method combined with shower deconstruction;
  - data-driven approach.

  Englert, Mattelaer, Spannowsky, arXiv: 1512.03429

- Sensitivity to SM value after LHC accumulates ~ $100 fb^{-1}$;
  - with $600 fb^{-1}$, constrain SM value at ~20% level.


theoretical progress on SM Higgs production
precision total cross-sections
LO NLO NNLO NNNLO
α 26%
scale 13%
expansion
LO pdfs 12%
10%
precision fiducial predictions
N3LO+NNLL+LLR v. NNLO+NNLL jet veto efficiency
ratio to N3LO+NNLL+LLR
LO
NLO
NNLO
NNPDF2.3, 13 TeV
σ(VBF cuts) (pb)
4.032 +0.057 −0.069
3.929 +0.024 −0.023
3.888 +0.016 −0.012
0.957 +0.066 −0.059
0.876 +0.008 −0.018
0.826 +0.013 −0.014
improved Monte Carlo tools
MEPS@NLO HZ+0,1j
MEPS@Loop2 HZ+0,1j
Sherpa+OpenLoops
POWHEG + Hto4l (LO)
POWHEG + Hto4l (NLOPS bare)
POWHEG + Hto4l (NLOPS rec)
pp → H → 2
tX0 and t-channel tX0 at the LHC13
NLO inclusive cross section
gluon fusion @ SM rate
SM
MadGraph5_aMC@NLO
α
new ideas to test SM Higgs
V
H
κb/κγγ eff

Outlook

- (Un-)fortunately this talk has a short shelf-life, due to the rapid pace of theoretical developments.

- Huge, ongoing effort in the LHC Higgs Cross Section Working Group.
  https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWG

  - next meeting later this week, Jan 13-15 at CERN.
    http://indico.cern.ch/event/407347/overview

- The great strides being made now will surely be reflected in sharper constraints on the Higgs boson, and in greater number, later this year.