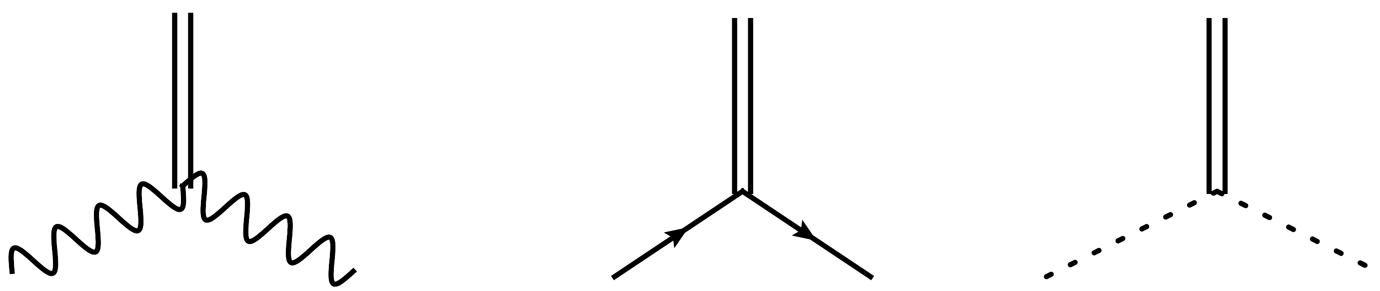
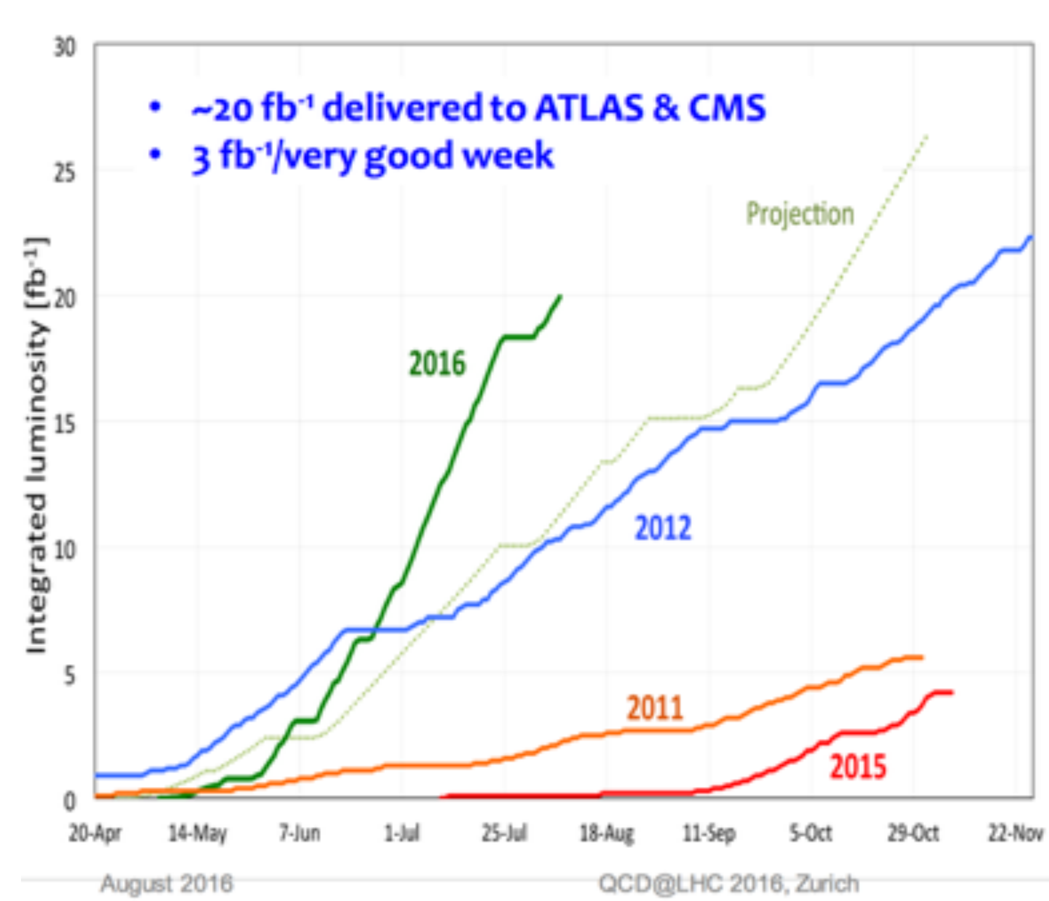
BERNHARD MISTLBERGER

QCD IN HIGGS PHYSICS

- 4th of July 2012: The begin of the precision physics age of Higgs boson phenomenology
- Immediately after the discovery of the Higgs boson we started to ask questions about it's nature:
  Couplings, spin, parity, mass, cross sections …

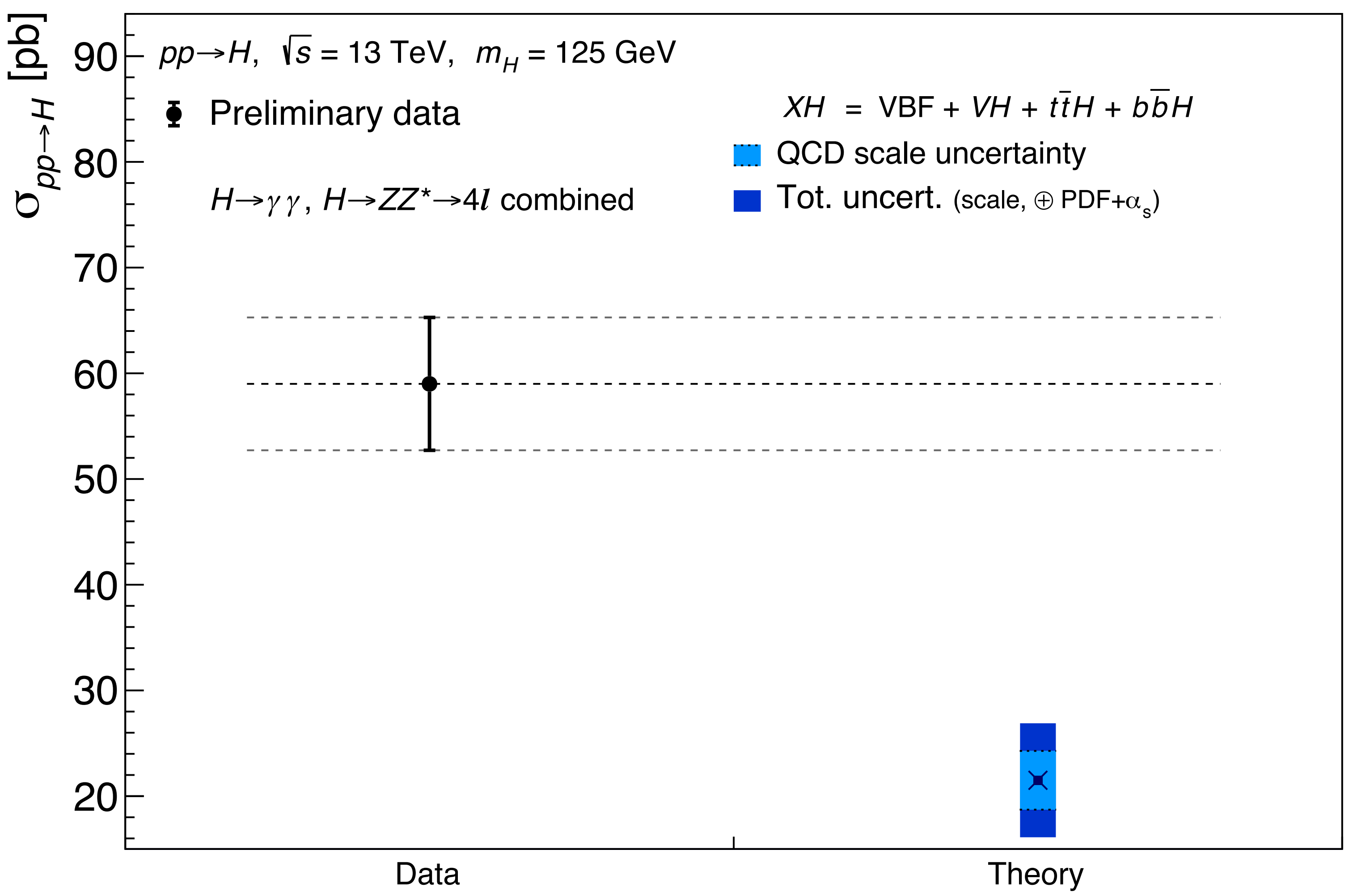


- The basis for testing our understanding of nature is on the one side precise measurements that are sensitive to the Higgs boson properties.



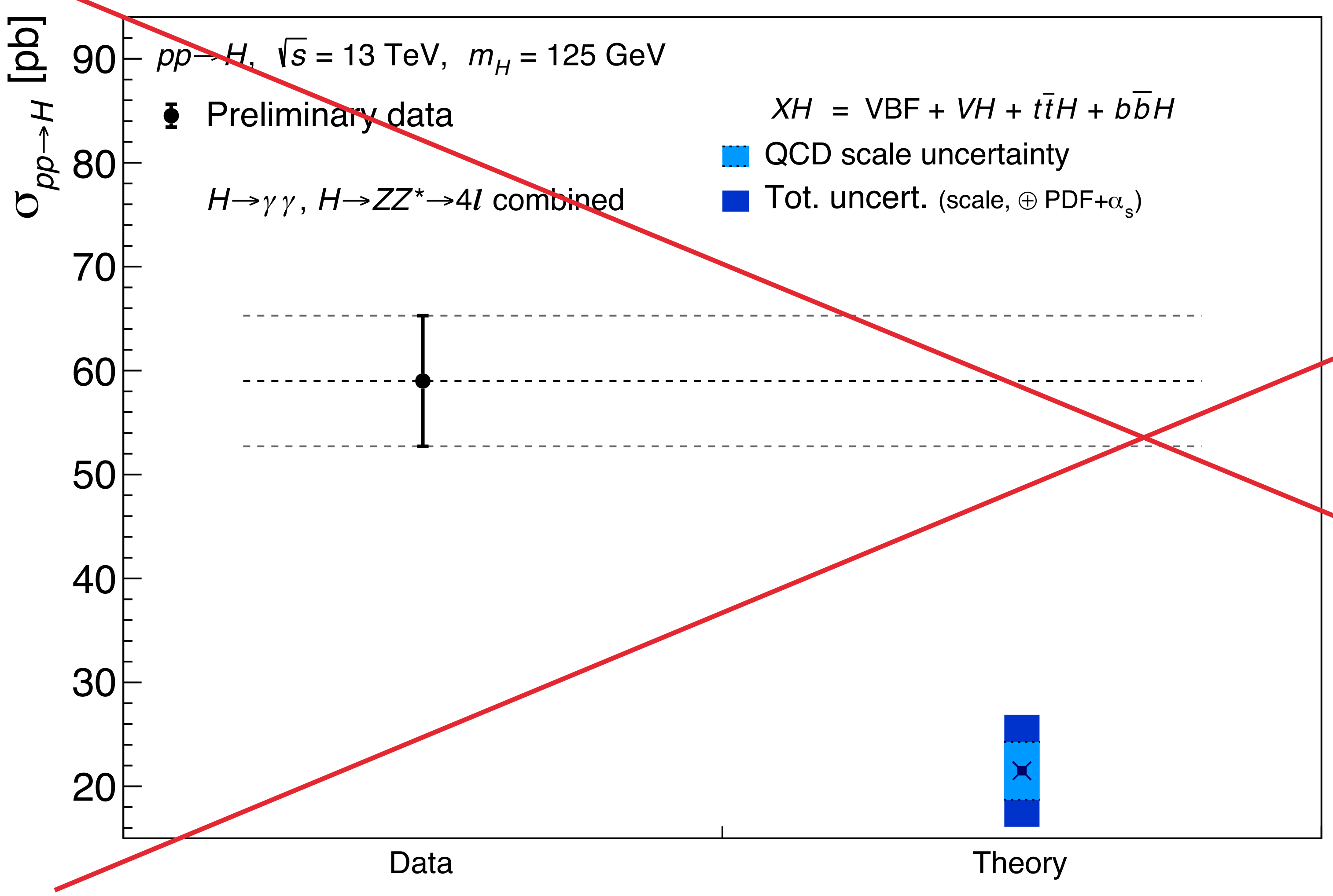
- LHC provides the input!
  Run 2: Data, data, data

COMPARE DATA TO PREDICTION



- Precise measurement
- 3.8 sigma deviation
- 1500 papers about new physics on the arXiv
- SM fails

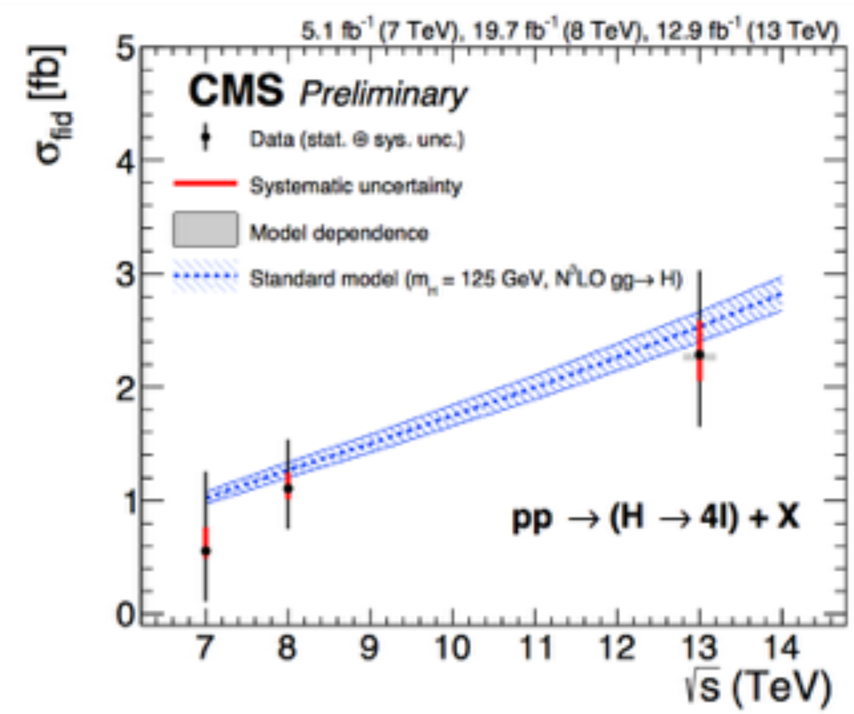
COMPARE DATA TO PREDICTION AT LO

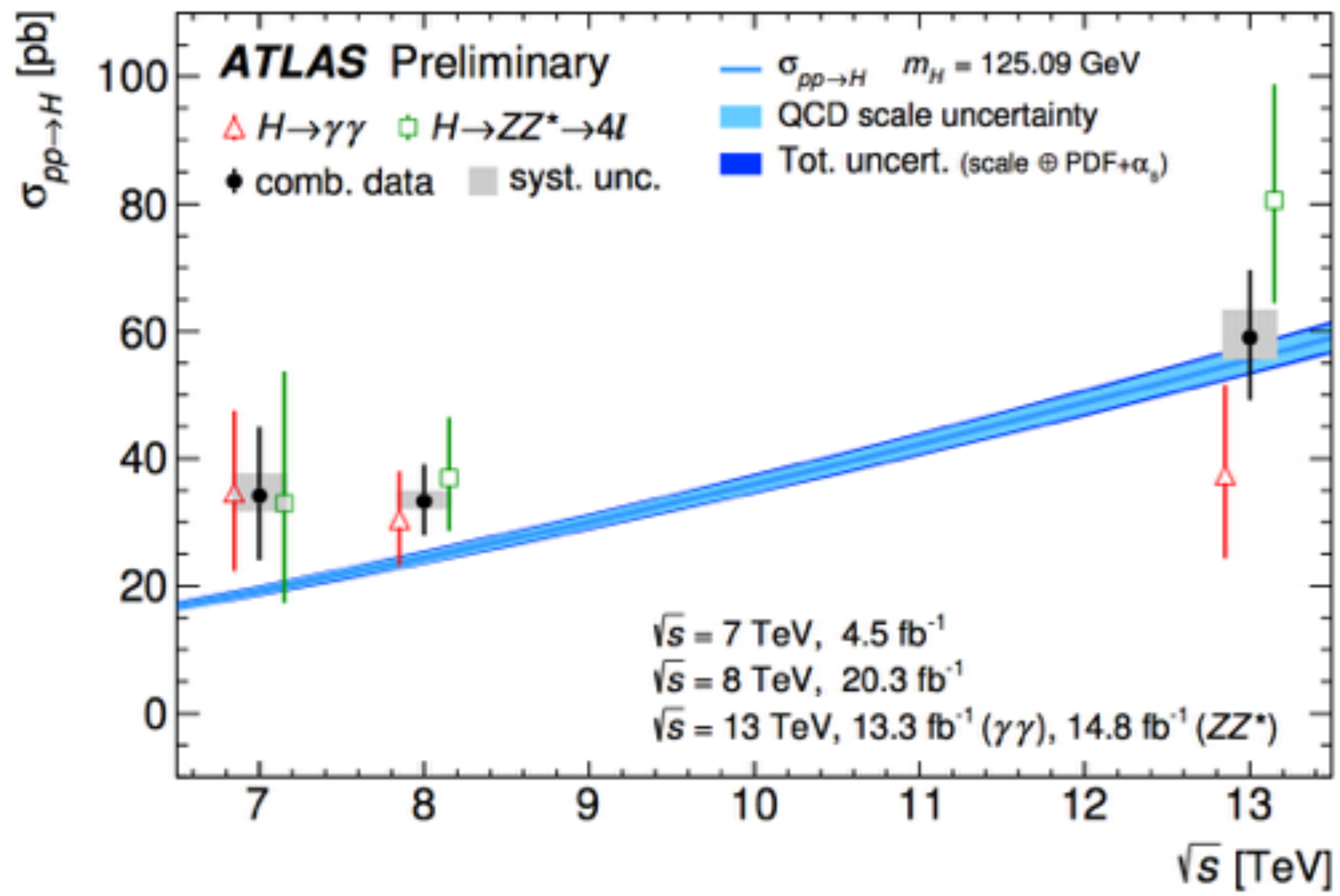


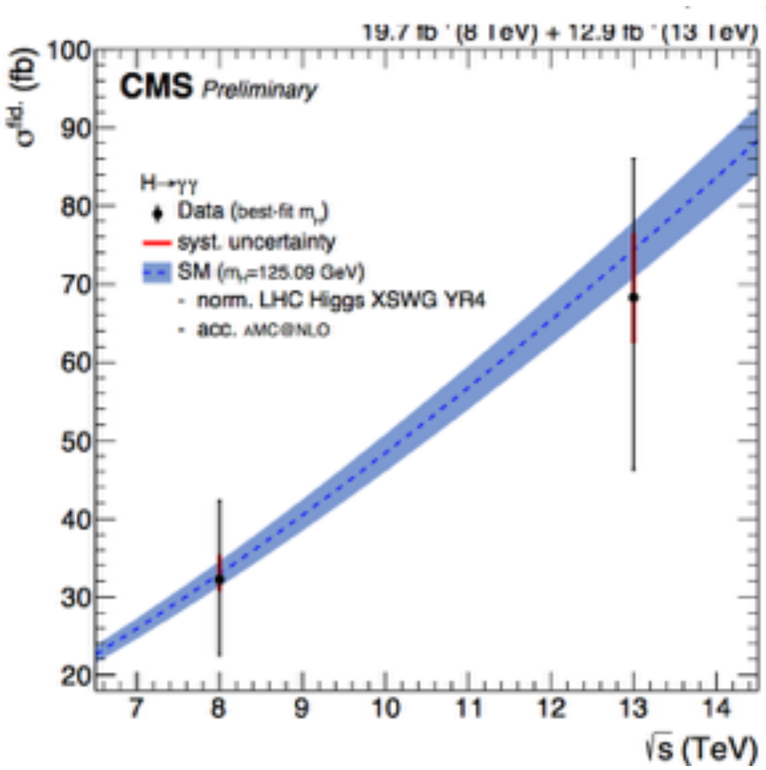
- Precise measurement
- 3.8 sigma deviation
- 1500 papers about new physics on the arXiv
- SM fails

THIS IS WHY WE NEED CORRECTIONS

WHAT ACTUALLY HAPPENED







- Incredible agreement of data and theory
- Triumph of SM predictions
- Higgs production ~10 sigma observed

- Testing our understanding of nature is dependent on being able to falsify our descriptions by comparing to experiment

- Our ability to predict collider experiment outcome is largely based on

$$d\sigma \sim \int dx dy f(x) f(y) d\hat{\sigma} \mathcal{J}_{\mathcal{O}} + \mathcal{O}\left(\frac{\Lambda}{Q}\right)$$

- Factorisation allows predictions to % level precision Challenge to improve!

- Experimental systemics will allow us to measure cross sections to an accuracy of a few percent!

Predictions have to supersede this bound!

MANY INTERESTING THINGS

- Background predictions / Interference

  See Lorenzo's & Marius' talk
- Resummation in Higgs physics

  See Pier's, Thomas' & Marco's talk
- Double Higgs production

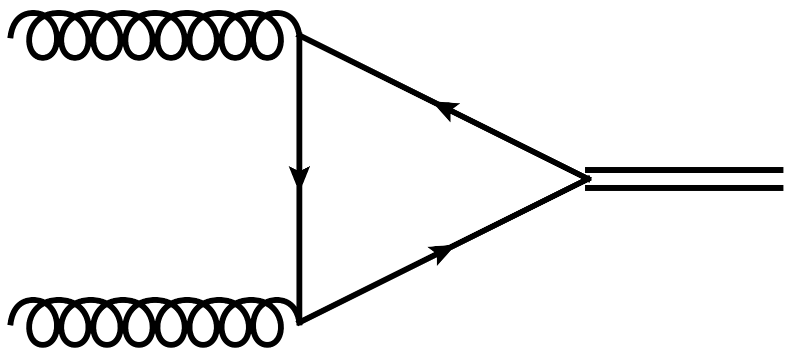
  [Borowka,Greiner,Heinrich,Jones,Kerner,Schlenk,Schubert,Zirke]

  Fantastic numerical approach!

  See Stephen's & Jonas' talk

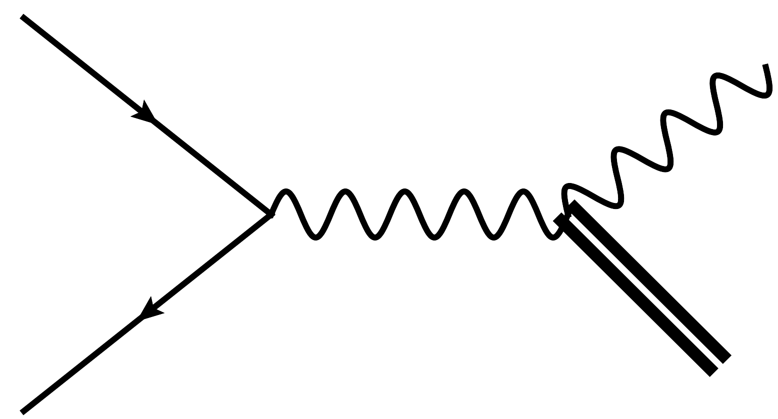
- I will talk about some selected topics regarding Higgs boson signal processes

4 WAYS TO PRODUCE A HIGGS



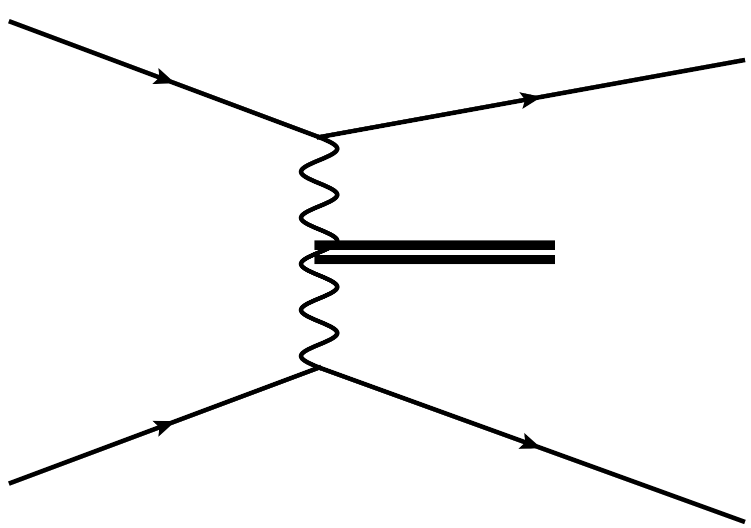
ggF

~88.2%



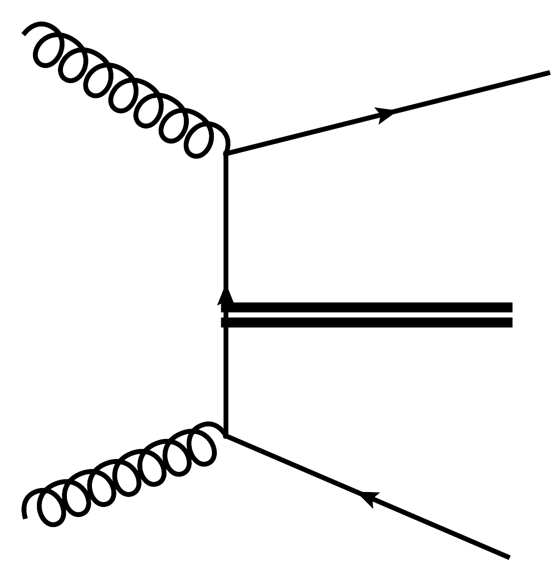
Associated

~4.1%



VBF

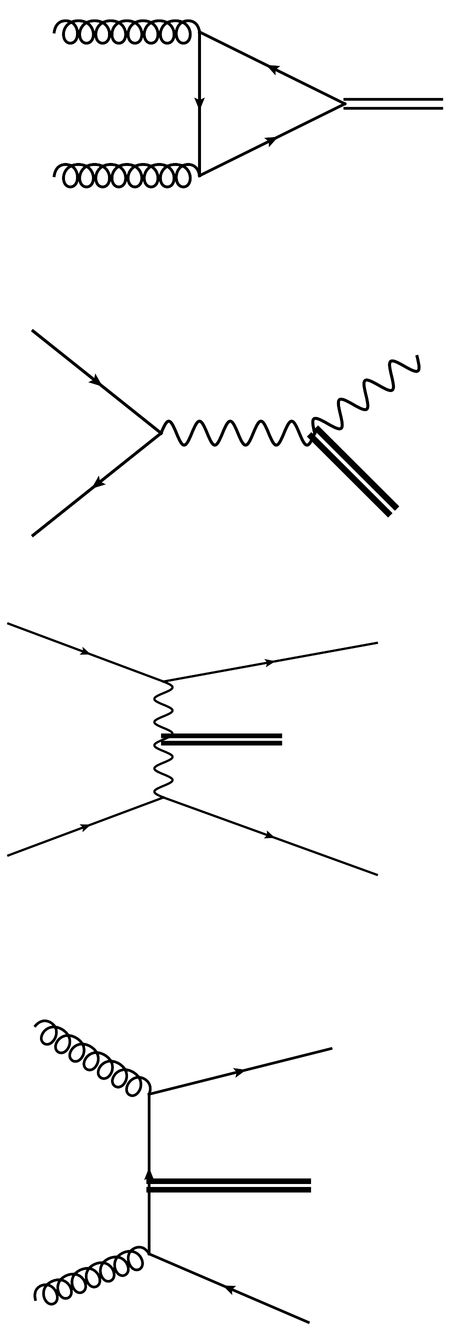
~6.8%



ttH

~0.9%

4 WAYS TO PRODUCE A HIGGS

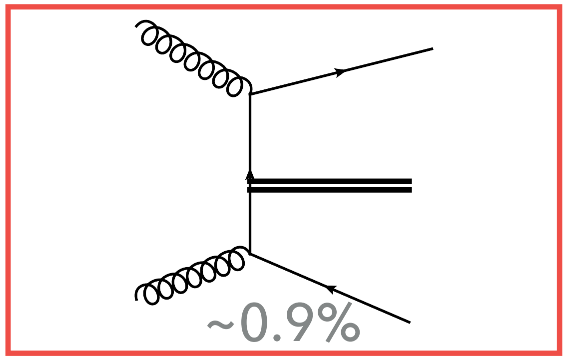


- Separation into different production modes
- Experimentally accessible due to significantly different contributions to observable signatures
- Despite small contributions to production cross section

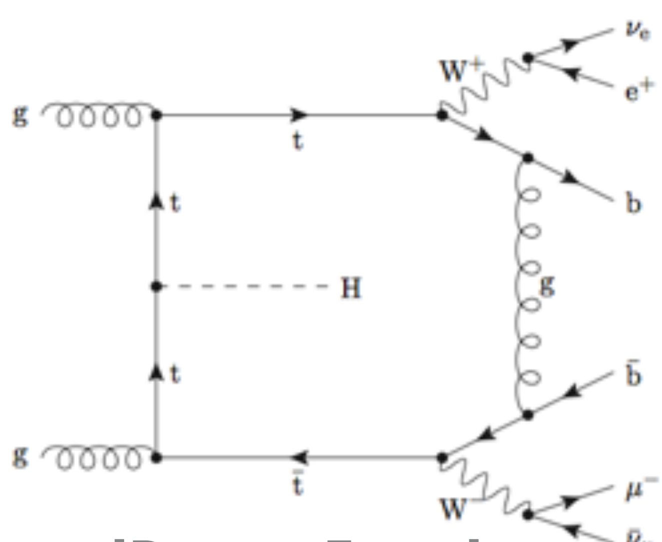
Precision in Demand for all of them

TTH

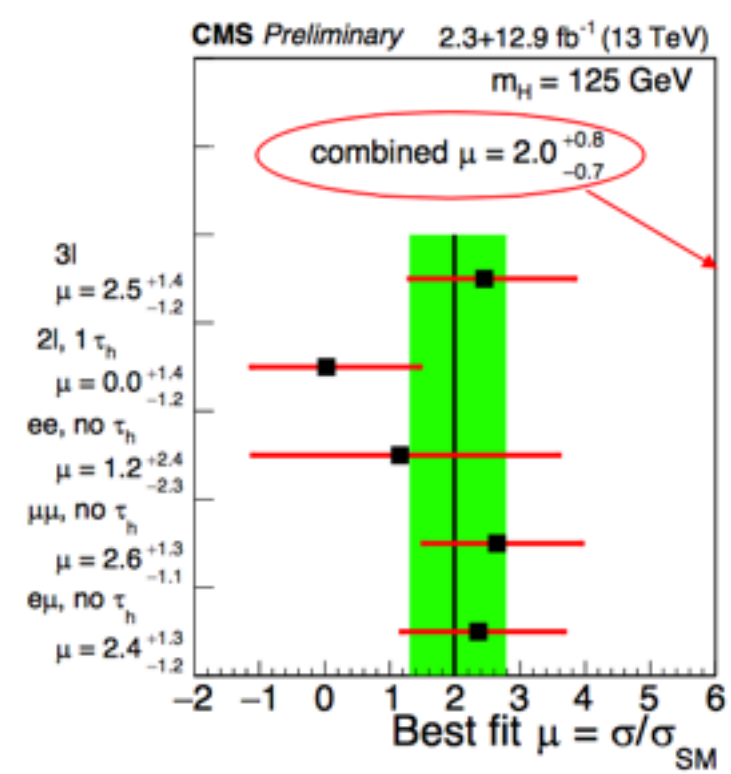
See Stefano's talk



- Direct measurement of Y_t
- Complex final state
- Pushing the boundaries of NLO to the limits
- Automation at NLO requires deep understanding!
- Example signal:

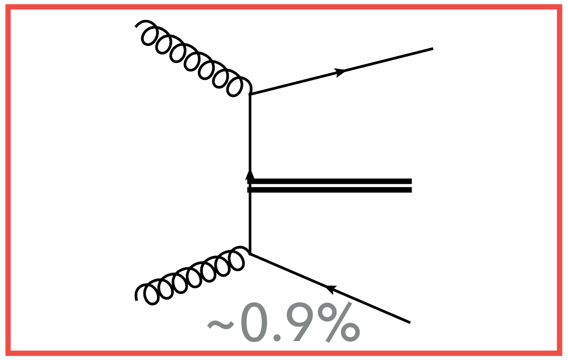


[Denner,Feger]

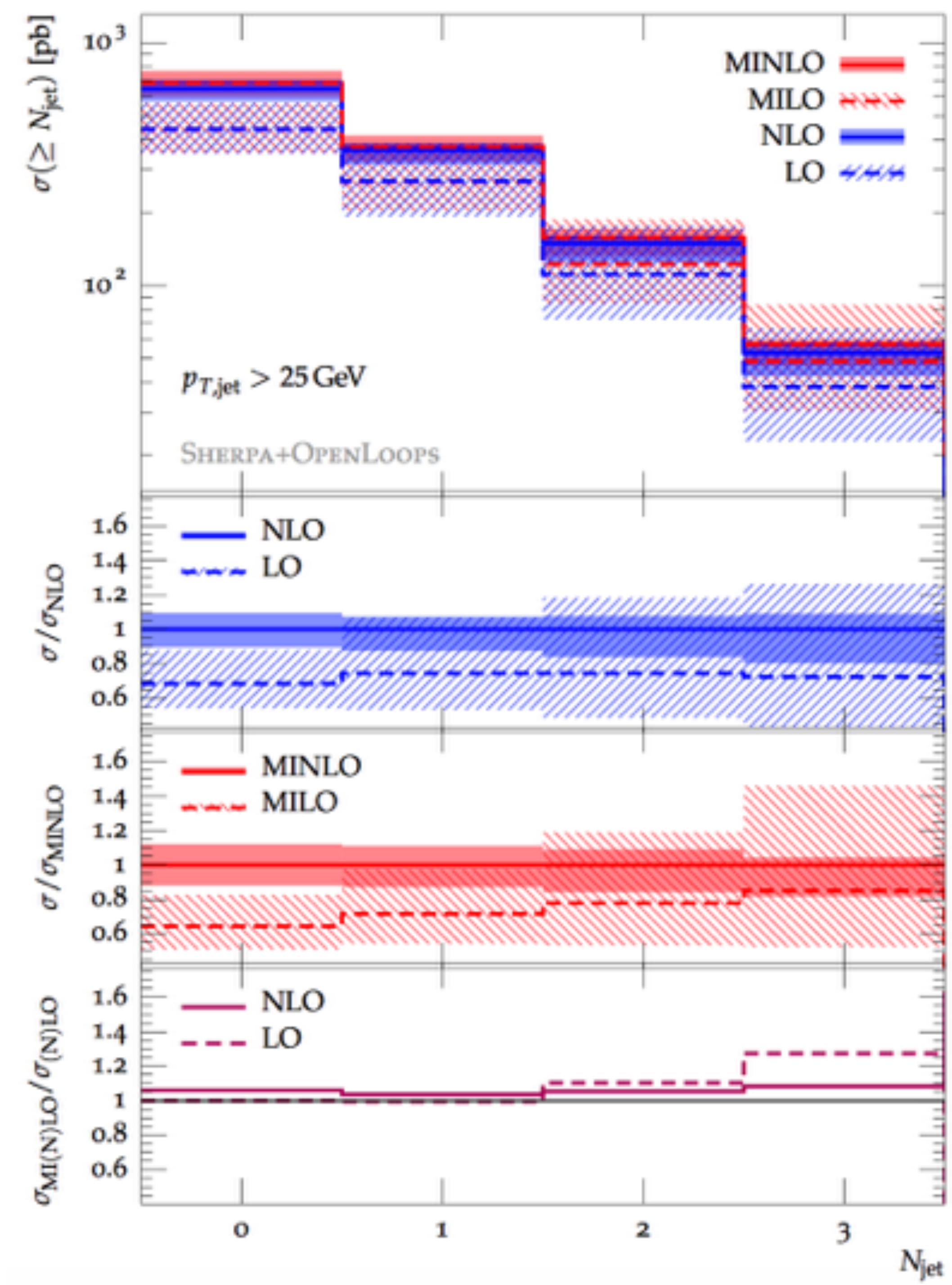


TTH

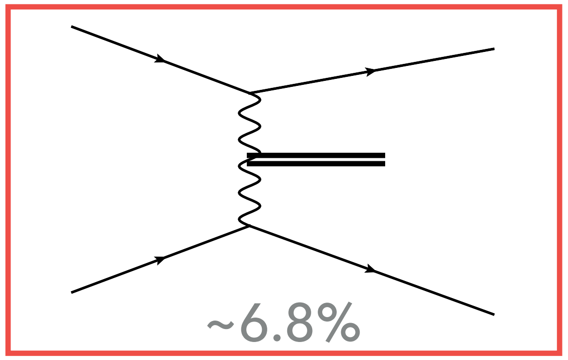
See Stefano's talk



- Interference effects, tH production
- Electro weak corrections
- Off-Shell effects
- Backgrounds
  large source of uncertainty
  Example: tt+3 Jets [Moretti, et al.]

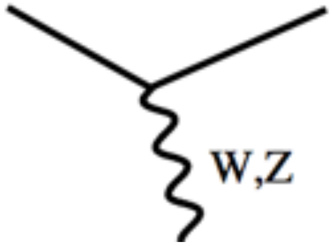


VECTOR BOSON FUSION



- Complicated 2 -> 3 process already at Born level!

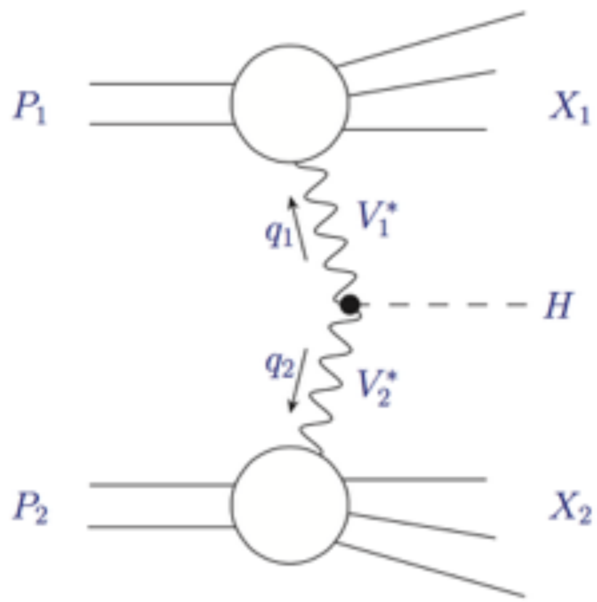
- The way out: Think of it as DIS^2

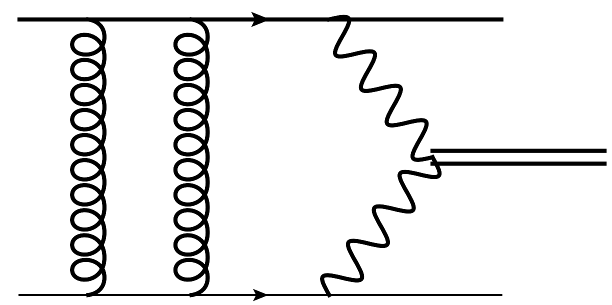


- Computation of DIS structure functions possible to N3LO accuracy [Moch, Vogt, Vermaseren]

- Sew together structure functions to produce a high loop level cross section

VECTOR BOSON FUSION: STRUCTURE FUNCTION APPROACH



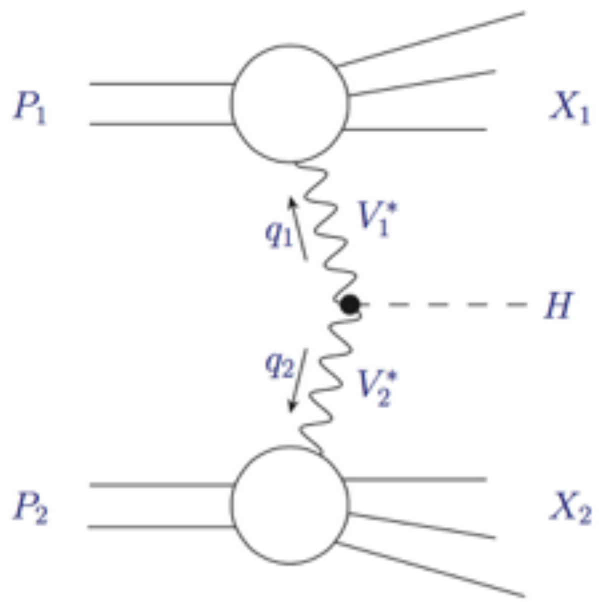


$$\frac{\alpha_s^2}{n_c^2}$$

- Color-suppressed!

- Inclusive NNLO cross section in the structure function approach in 2012 [Bolzoni, Maltoni, Moch, Zaro]
- Possible corrections estimated to be < 1%
- Perturbative corrections small

VECTOR BOSON FUSION: STRUCTURE FUNCTION APPROACH

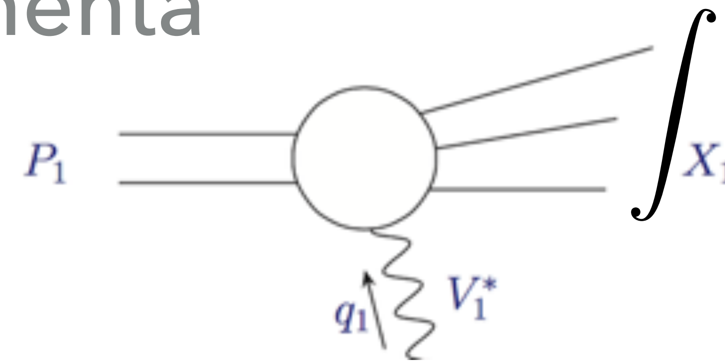


- But: True power of VBF lies in the possibility to distinguish the production mode by tagging very forward jet configurations
- Select events with at least two jets with large rapidity separation

$$\Delta_{y_1 y_2} \sim 4.5$$

- Problem: Structure functions computed integrated over final state parton momenta

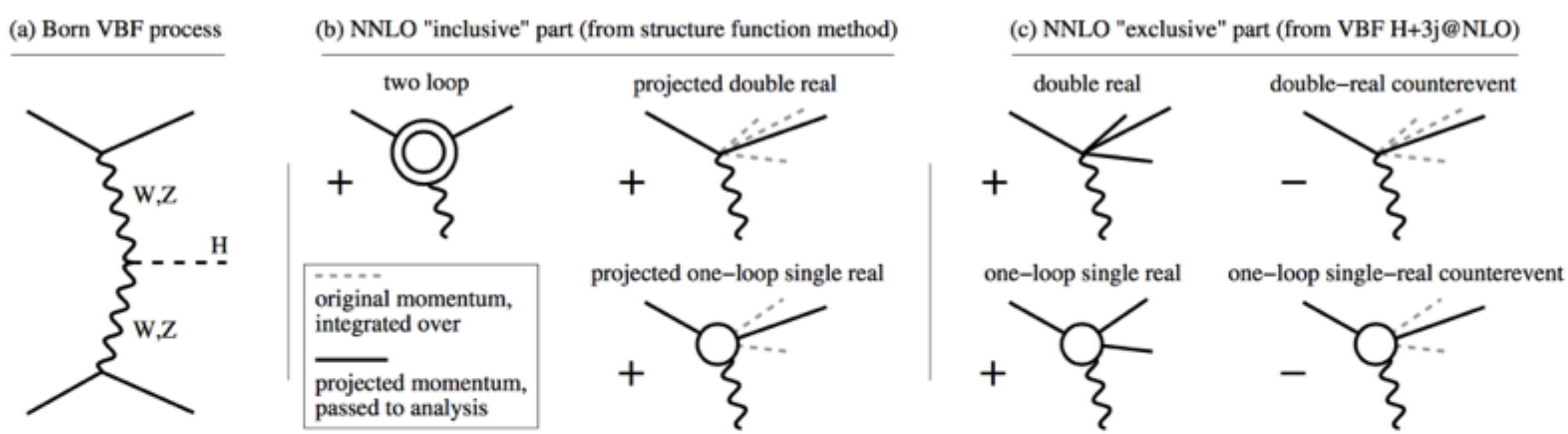
Inherently non differential!



VECTOR BOSON FUSION: PROJECTION TO BORN

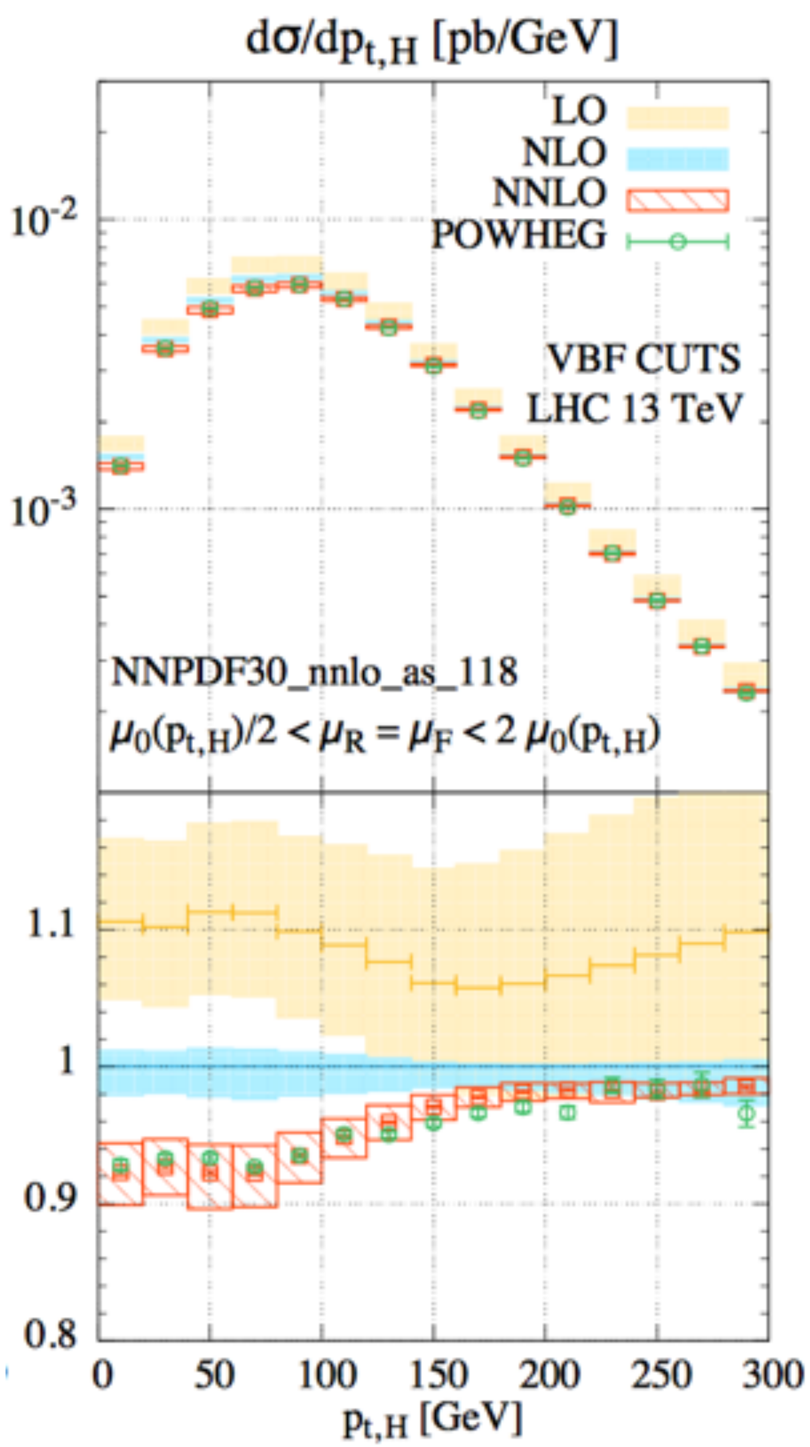
[Cacciari,Dreyer,Karlberg,Salam,Zanderighi]

- New method to perform fully differential QCD computation
- Clever combination of NLO computation [POWHEG] and inclusive NNLO cross section
- Get everything with resolved +J kinematics from NLO + unresolved kinematics from combining inclusive and „unresolved“ NLO



VECTOR BOSON FUSION: PROJECTION TO BORN

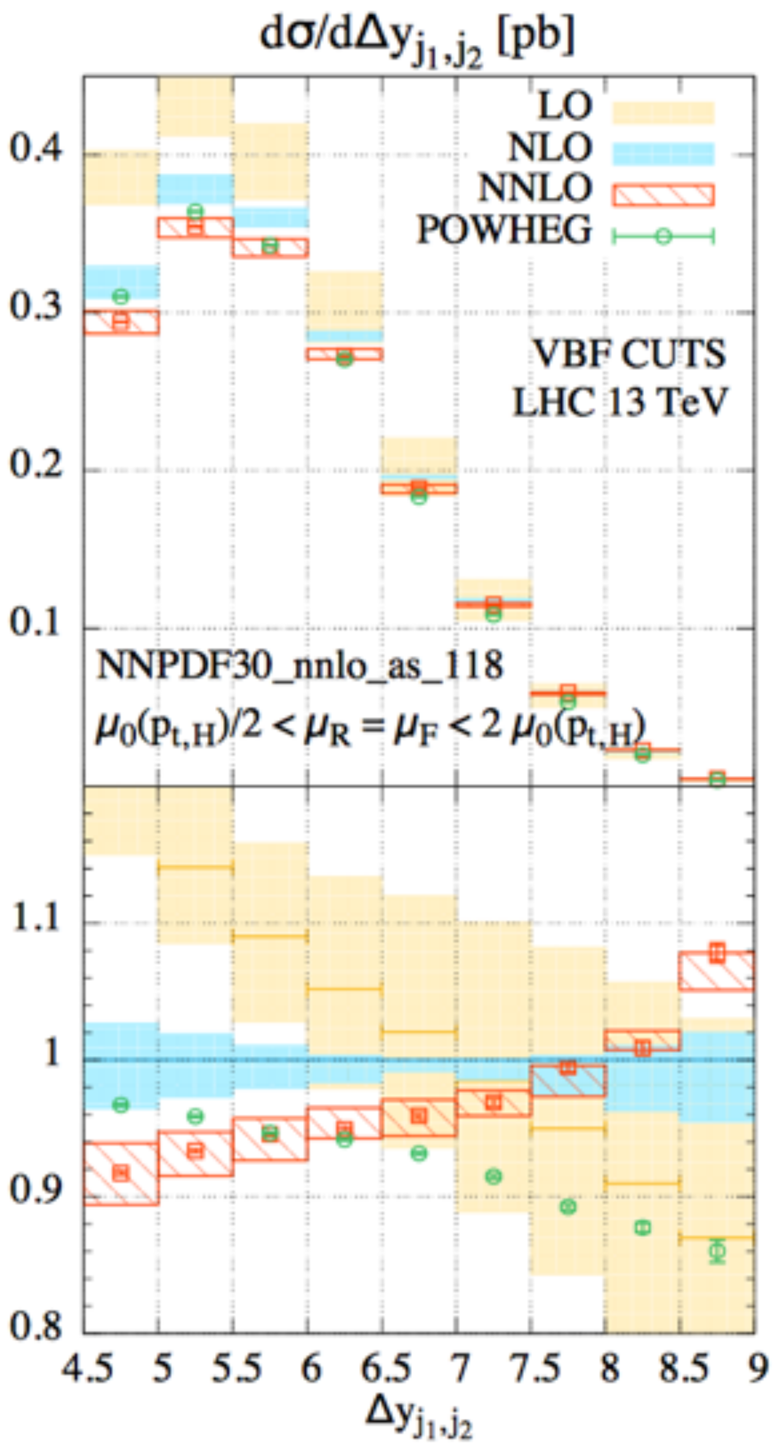
[Cacciari,Dreyer,Karlberg,Salam,Zanderighi]



- Sizable (~10 %) corrections for fiducial cross sections / distributions at NNLO
- Significant reduction in perturbative uncertainties
- pT Higgs distribution shows agreement with NLOPS

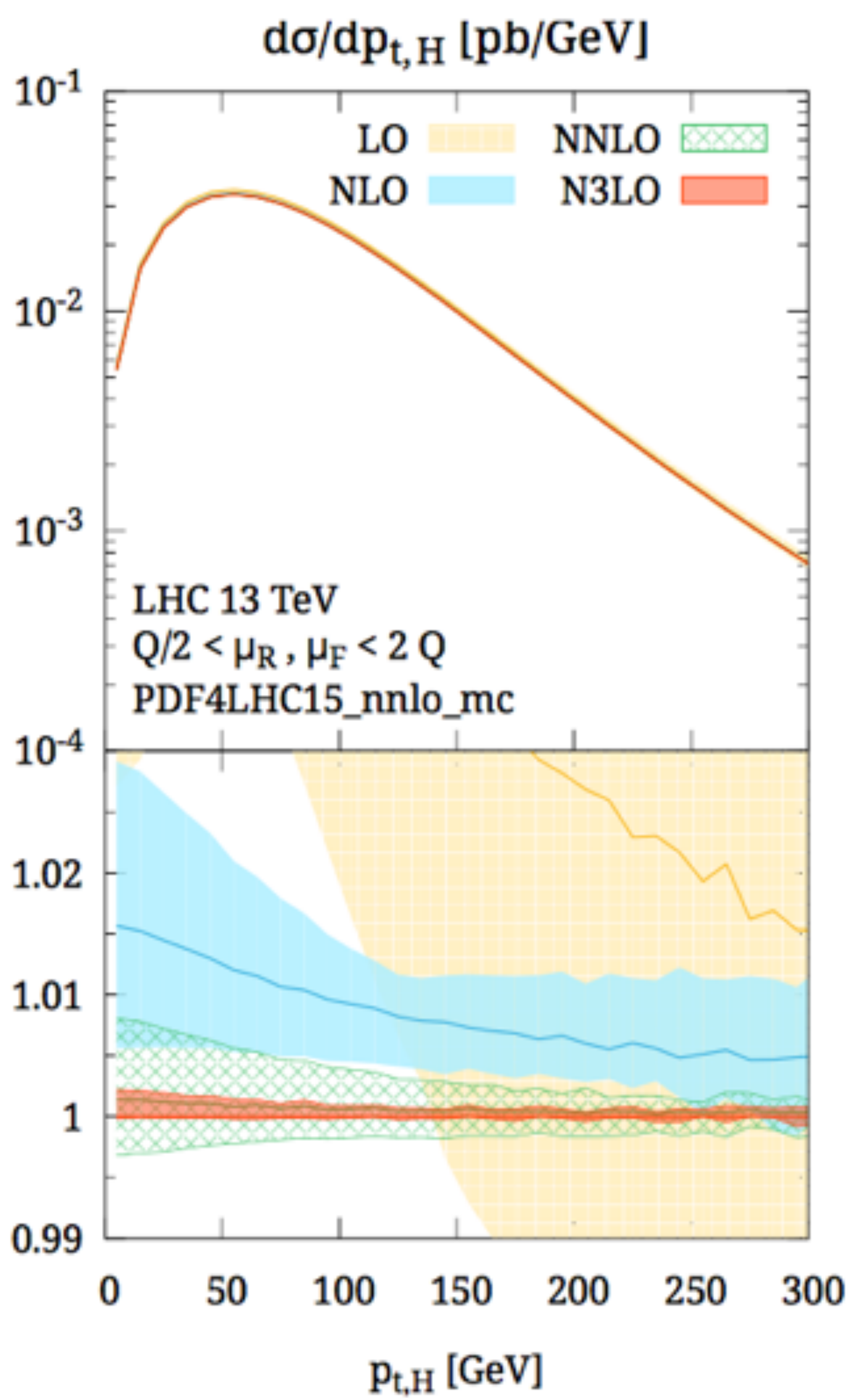
VECTOR BOSON FUSION: PROJECTION TO BORN

[Cacciari,Dreyer,Karlberg,Salam,Zanderighi]



- Other observables show sizable corrections beyond NLOPS
- Convergence of perturbative series? Uncertainty estimates?
- Extension of P2B Framework to N3LO for VBF?

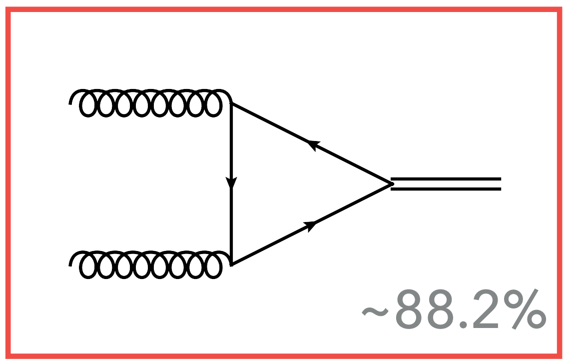
VECTOR BOSON FUSION: PROJECTION TO BORN



[Dreyer,Karlberg]

- Inclusive VBF at N3LO in structure function approach
- Remaining Scale uncertainty 1.4 ‰
- Perturbative convergence indicated by scale variation
- Tagging Jets not accessible
- DIS^2 is an approximation!

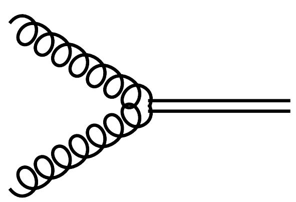
GLUON FUSION



- 2 to 1 Born
- Loop induced
- Dominant Production mode
- Large QCD corrections

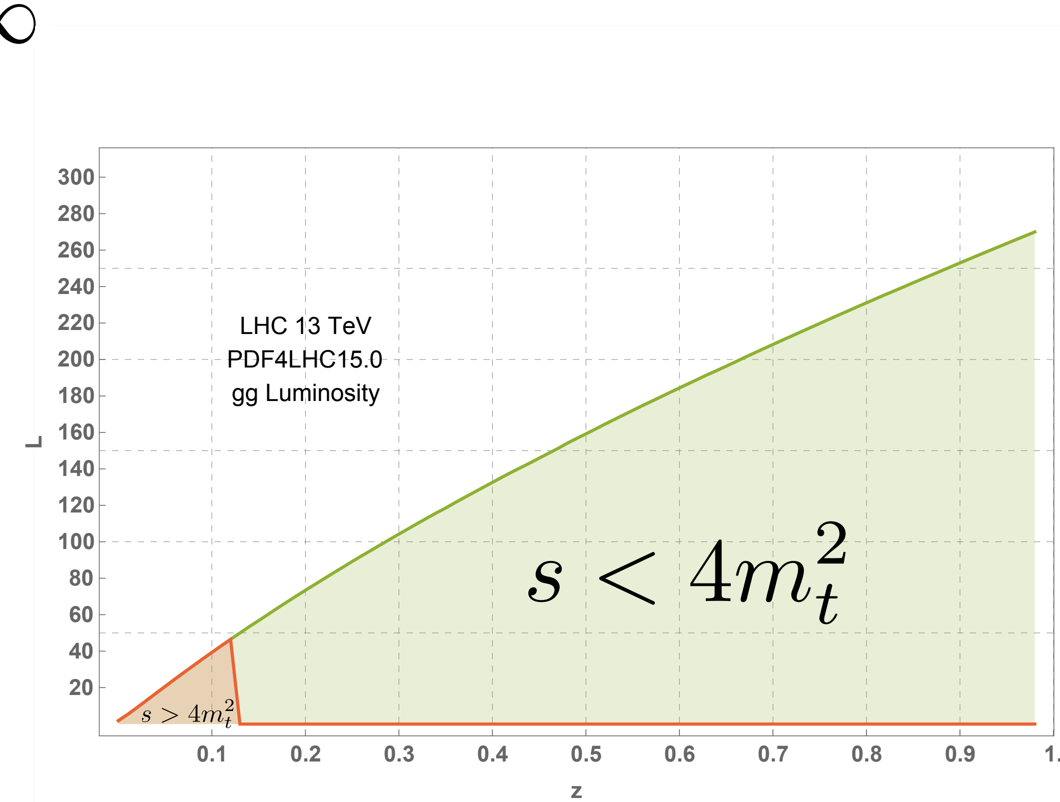
- Heavy-top effective theory

$$\delta = \frac{\hat{s}}{4m_t^2}$$

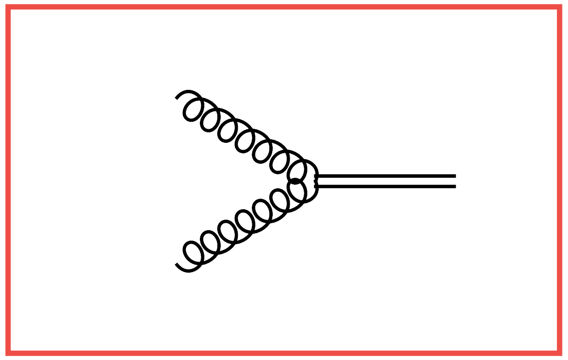


Remove 1 loop $\quad m_t \to \infty$

- Get access to very high loop computations



GLUON FUSION – INCLUSIVE CROSS SECTION



- Probability to produce at least the Higgs boson in P P collisions

$$\hat{\sigma}(z) = \hat{\sigma}^{LO}(z) + \alpha_S \hat{\sigma}^{NLO}(z) + \alpha_S^2 \hat{\sigma}^{NNLO}(z) + \alpha_S^3 \hat{\sigma}^{N3LO}(z) + \mathcal{O}(\alpha_S^4)$$

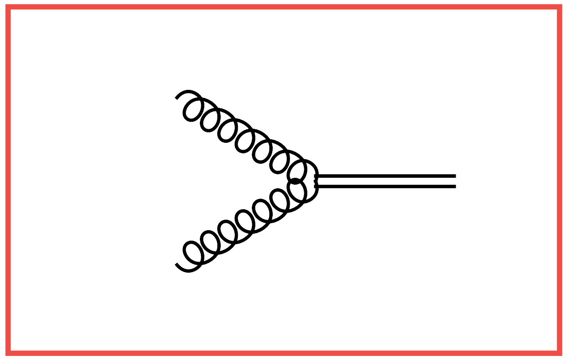
✓ ✓ ✓ ✓

LO	$15.05 \pm 14.8\%$
NLO	$38.2 \pm 16.6\%$
NNLO	$45.1 \pm 8.8\%$
N3LO	$45.2 \pm 1.9\%$

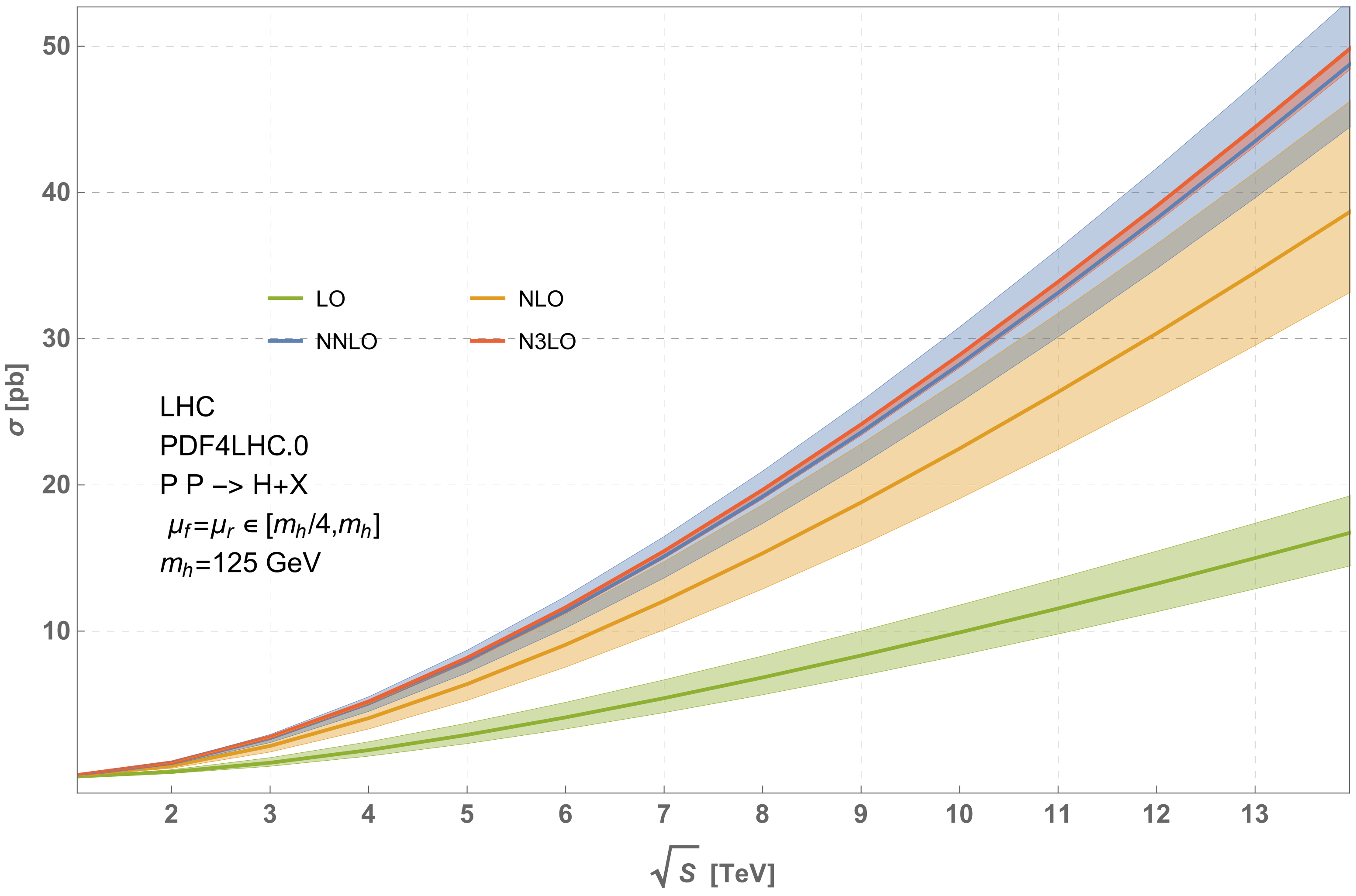
- Stabilisation of perturbative series
- Drastic reduction in scale variation uncertainty estimate

[Anastasiou, Duhr,Dulat,Furlan,Gehrmann,Herzog,Lazopoulos,BM]

GLUON FUSION – INCLUSIVE CROSS SECTION

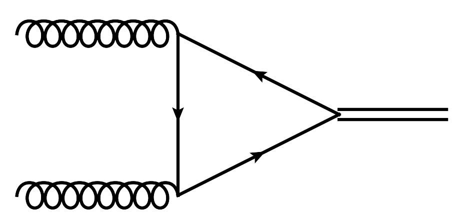


- Analytic computation
- Challenge for current loop computation technology



[Anastasiou, Duhr,Dulat,Furlan,Gehrmann,Herzog,Lazopoulos,BM]

GLUON FUSION – INCLUSIVE CROSS SECTION

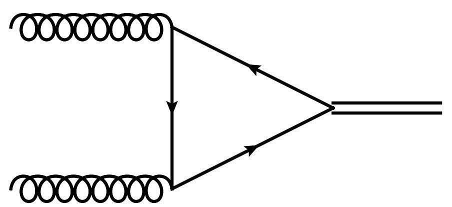


$$\sigma = 48.58\,\mathrm{pb}^{+2.22\,\mathrm{pb}\,(+4.56\%)}_{-3.27\,\mathrm{pb}\,(-6.72\%)}\ (\mathrm{theory}) \pm 1.56\,\mathrm{pb}\,(3.20\%)\ (\mathrm{PDF}+\alpha_s)\,.$$

$$\begin{aligned}
48.58\,\mathrm{pb} = \quad & 16.00\,\mathrm{pb} & (+32.9\%) \quad & (\mathrm{LO,\ rEFT})\\
& +20.84\,\mathrm{pb} & (+42.9\%) \quad & (\mathrm{NLO,\ rEFT})\\
& -\ \ 2.05\,\mathrm{pb} & (-4.2\%) \quad & ((t,b,c),\ \mathrm{exact\ NLO})\\
& +\ \ 9.56\,\mathrm{pb} & (+19.7\%) \quad & (\mathrm{NNLO,\ rEFT})\\
& +\ \ 0.34\,\mathrm{pb} & (+0.7\%) \quad & (\mathrm{NNLO},\ 1/m_t)\\
& +\ \ 2.40\,\mathrm{pb} & (+4.9\%) \quad & (\mathrm{EW,\ QCD\text{-}EW})\\
& +\ \ 1.49\,\mathrm{pb} & (+3.1\%) \quad & (\mathrm{N^3LO,\ rEFT})
\end{aligned}$$

- LHC predictions demand effects beyond pure EFT
- Mass corrections & EWK effects

GLUON FUSION – INCLUSIVE CROSS SECTION

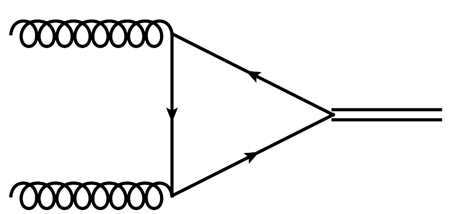


$$\sigma = 48.58\,\text{pb}^{+2.22\,\text{pb}\,(+4.56\%)}_{-3.27\,\text{pb}\,(-6.72\%)}\,(\text{theory}) \pm 1.56\,\text{pb}\,(3.20\%)\,(\text{PDF}+\alpha_s)\,.$$

- Many residual uncertainties of comparable importance
- Todo List:
  - Full mass dependent NNLO
  - Mixed $\mathcal{O}(\alpha\alpha_S)$ corrections
  - N3LO PDFs
  - ....

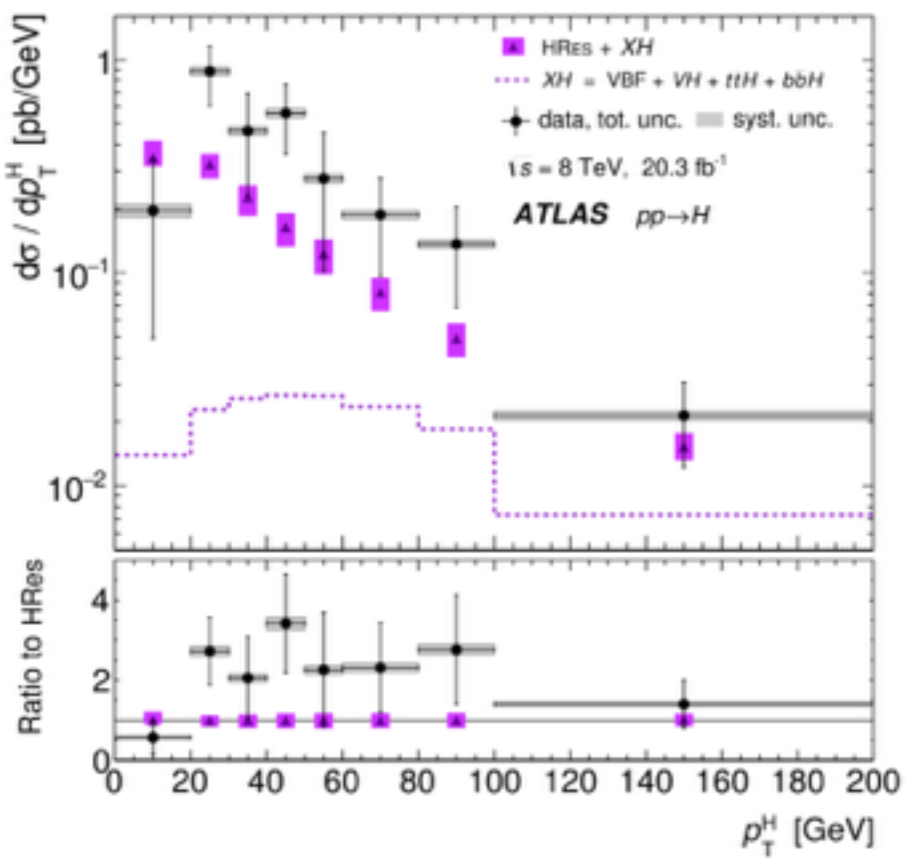
δ(scale)	δ(trunc)	δ(PDF-TH)	δ(EW)	$\delta(t,b,c)$	$\delta(1/m_t)$
$^{+0.10\text{ pb}}_{-1.15\text{ pb}}$	±0.18 pb	±0.56 pb	±0.49 pb	±0.40 pb	±0.49 pb
$^{+0.21\%}_{-2.37\%}$	$\pm0.37\%$	$\pm1.16\%$	$\pm1\%$	$\pm0.83\%$	$\pm1\%$

GLUON FUSION – INCLUSIVE/EXCLUSIVE CROSS SECTION

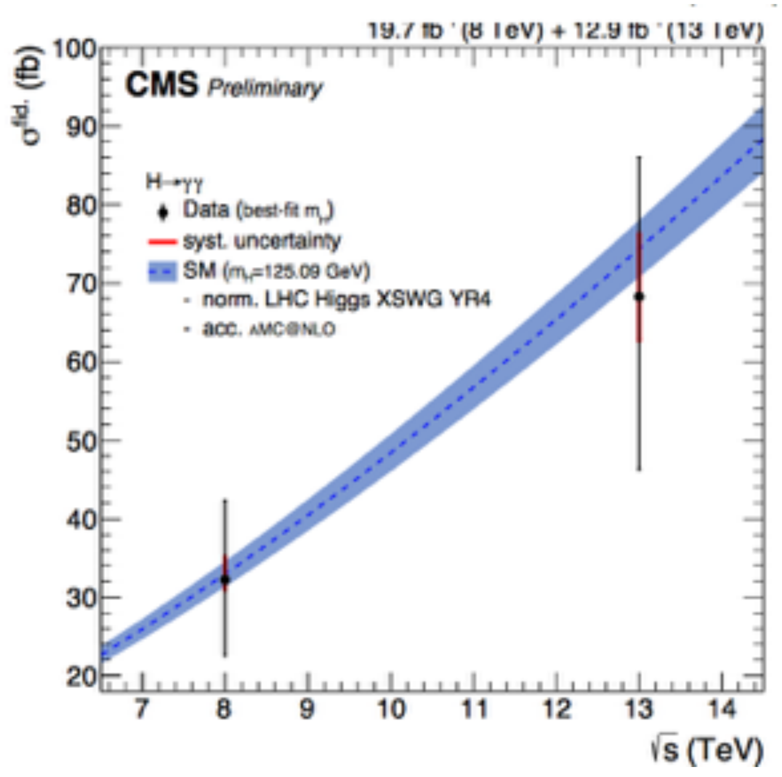


~88.2%

- Real measurements happen in fiducial volumes
- Inclusive cross section: Derived quantity with input from many measurements
- We require high precision predictions for observables as close to experimental outcome as possible



$$H \to \gamma\gamma$$



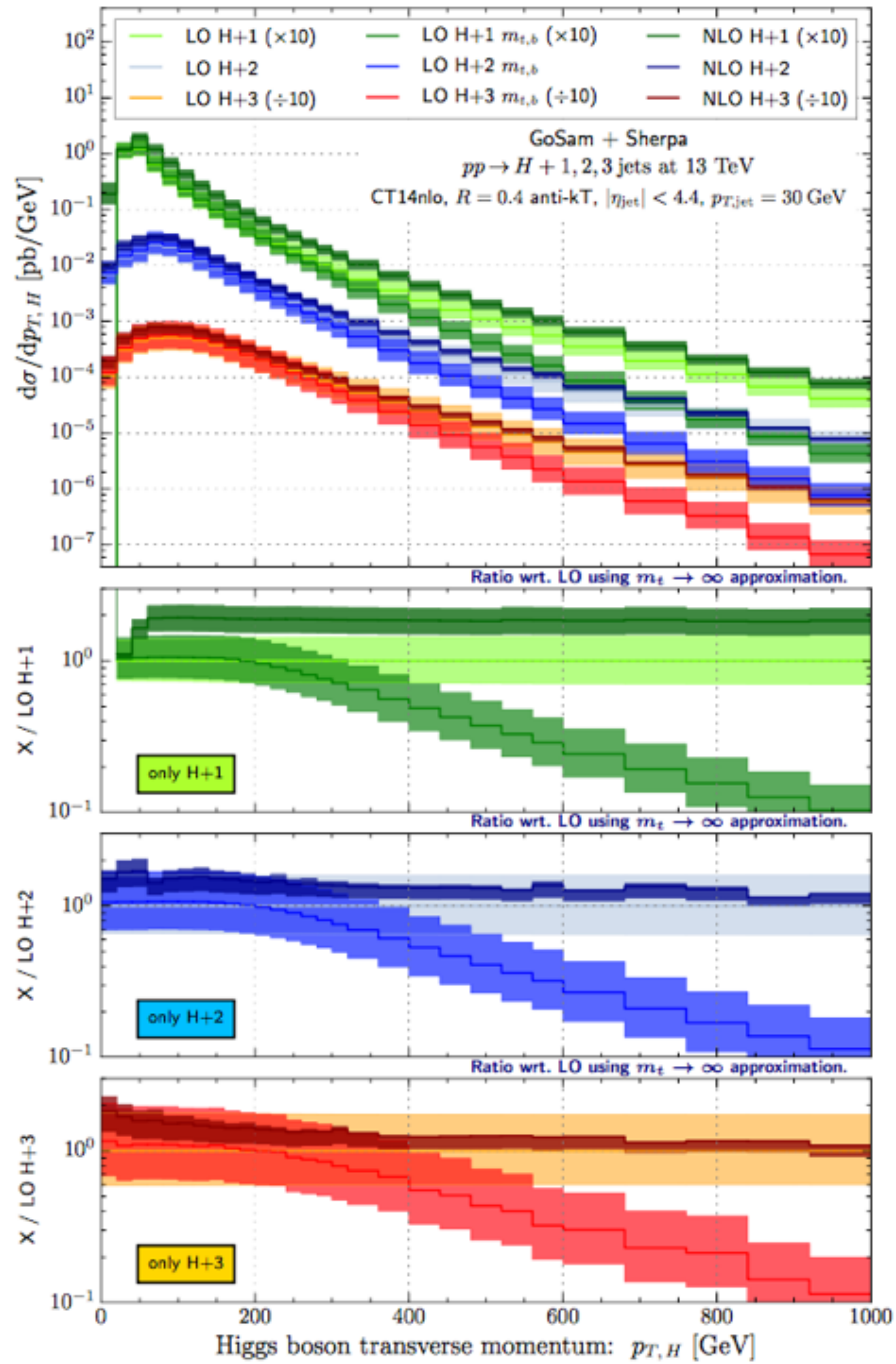
CMS

$$\sigma^{\mathrm{fid}}_{\mathrm{tot}} = 69^{+16}_{-22}(\mathrm{stat.})^{+8}_{-6}(\mathrm{syst})\ \mathrm{fb}$$

H + 3 JETS AT NLO

[Greiner,Hoeche,Luisoni,Schoenherr,Winter,(Yundin)]

- Up to 7 particle amplitudes
- Background for VBF
- Mass Corrections at LO
- Good agreement for
  pt< 200 GeV
  Resolve effective vertex
  by hardest single pT
- Mass effects grow with pT
  400 GeV $K_t \sim 0.6$
  1TeV $K_t \sim 0.1$



PRECISION FOR HIGGS PLUS JET

Fully differential NNLO for 2 -> 2 scattering

- Successful treatment of double real radiation
- Applied to colored final state
- Higgs+1 Jet NNLO computed with three different methods

  [Chen,Gehrmann,Glover,Jaquier]

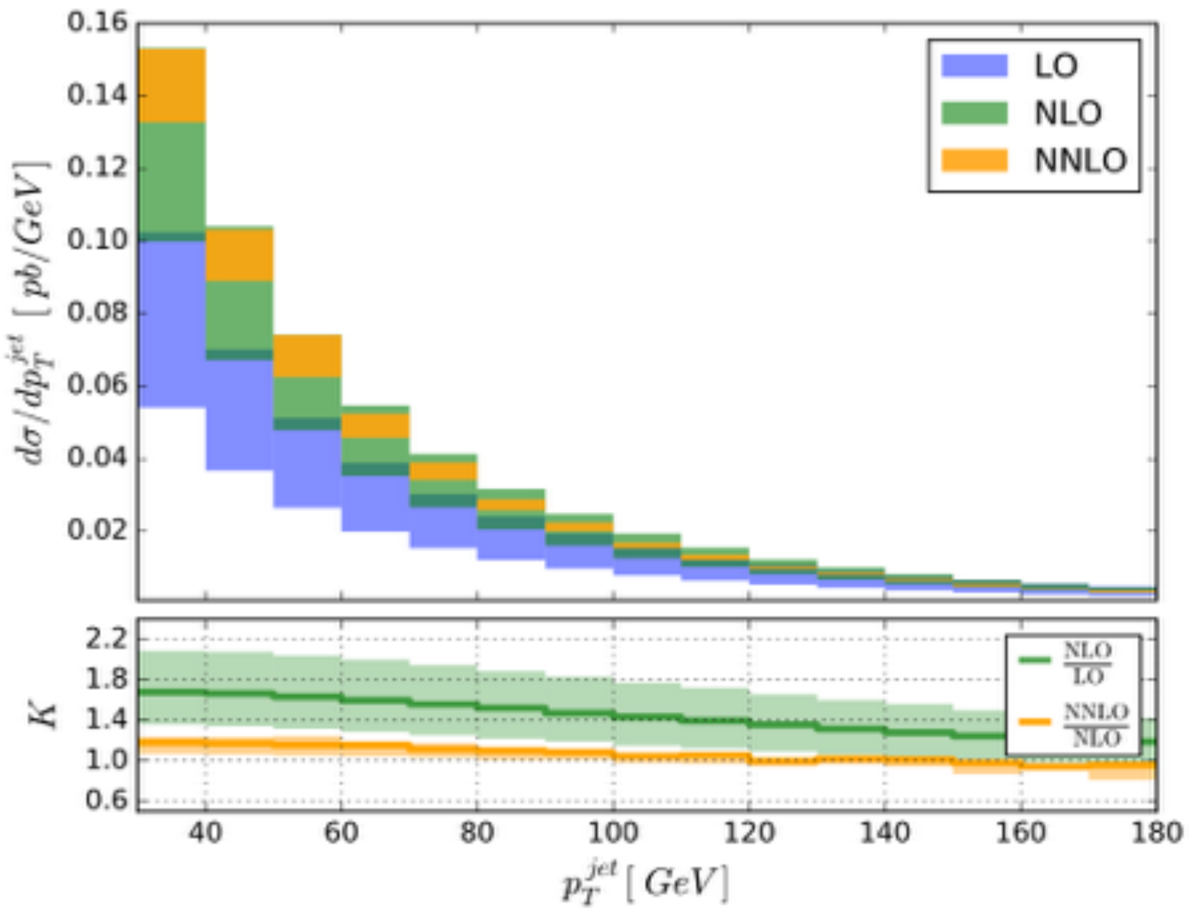
  [Boughezal,Caola,Melnikov,Petriello,Schulze]

  [Boughezal,Focke,Giele,Liu,Petriello]

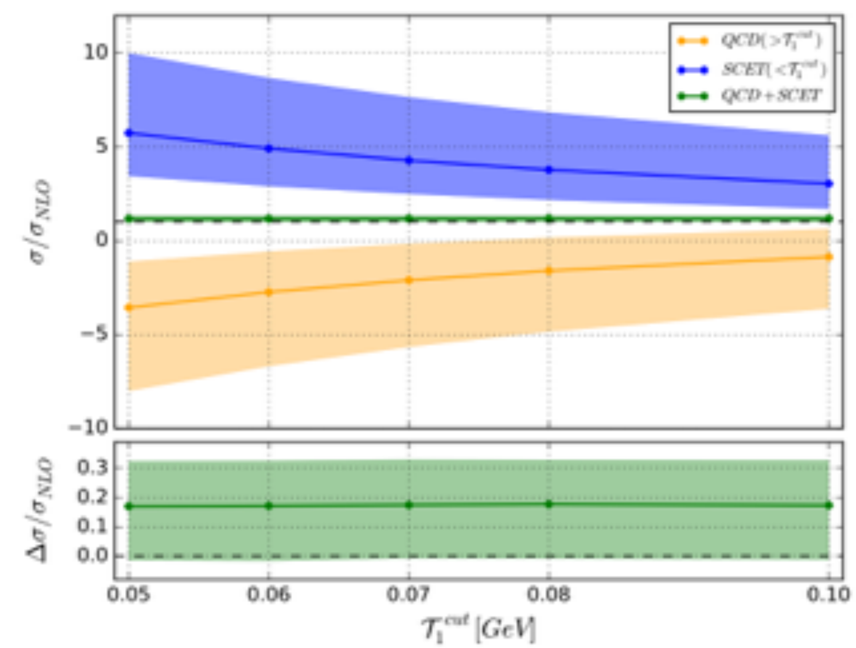
- **Sector decomposition**
- **Non-Linear Mappings**
- **qT**
- **FKS+**
- **N-Jettiness**
- **Antenna**
- **Colourful**
- **Projection-To-Born**
- **...**

[Chen,Gehrmann,Glover,Jaquier]

PRECISION FOR HIGGS PLUS JET



- Complexity of differential NNLO requires validation by multiple methods
- Exploratory phase: What works best in which framework?



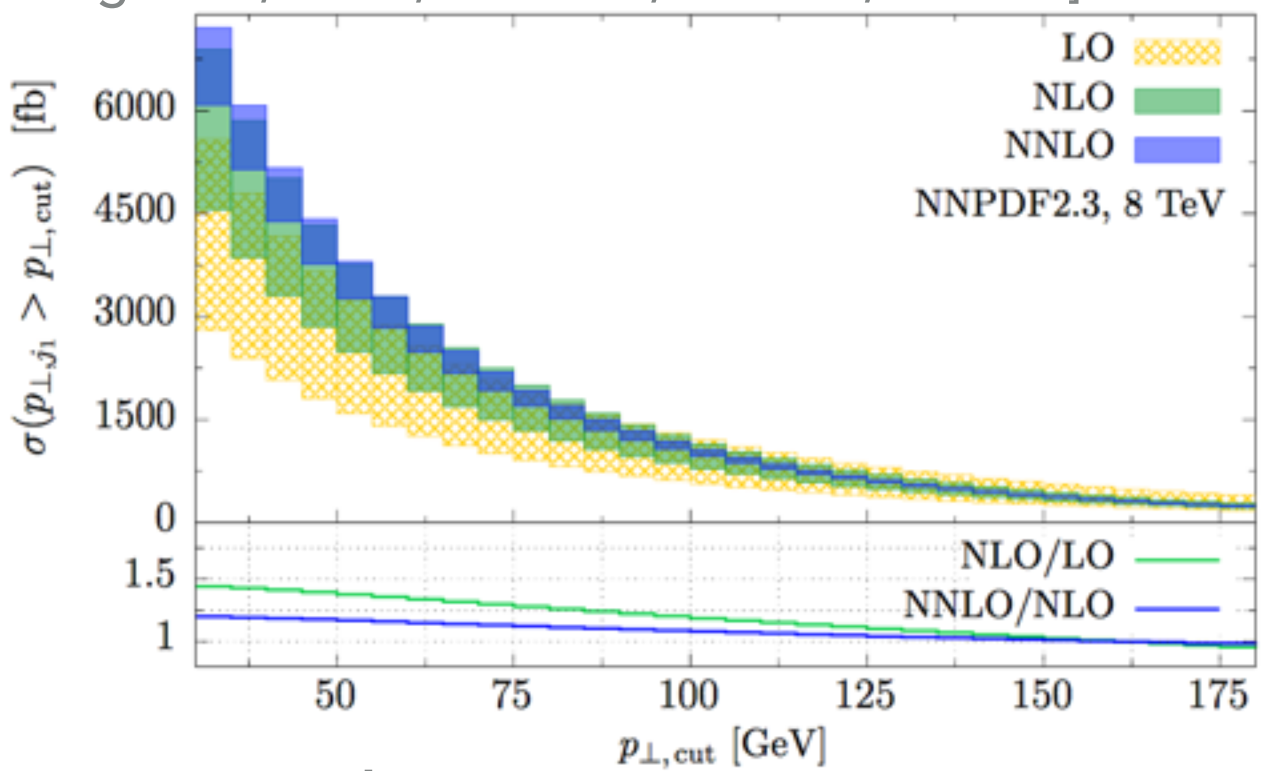
- N-Jettiness Slicing:
  Clever parameter to separate resolved
  from unresolved phase space for colored final state
  Resolved: Automated, stable NLO
  Unresolved: SCET approximation to cross section

[Boughezal,Focke,Giele,Liu,Petriello]

N-Jettiness see also:[Gaunt,Stahlhofen,Tackmann,Walsh]

PRECISION FOR HIGGS PLUS JET

[Boughezal,Caola,Melnikov,Petriello,Schulze]



Antenna Subtraction

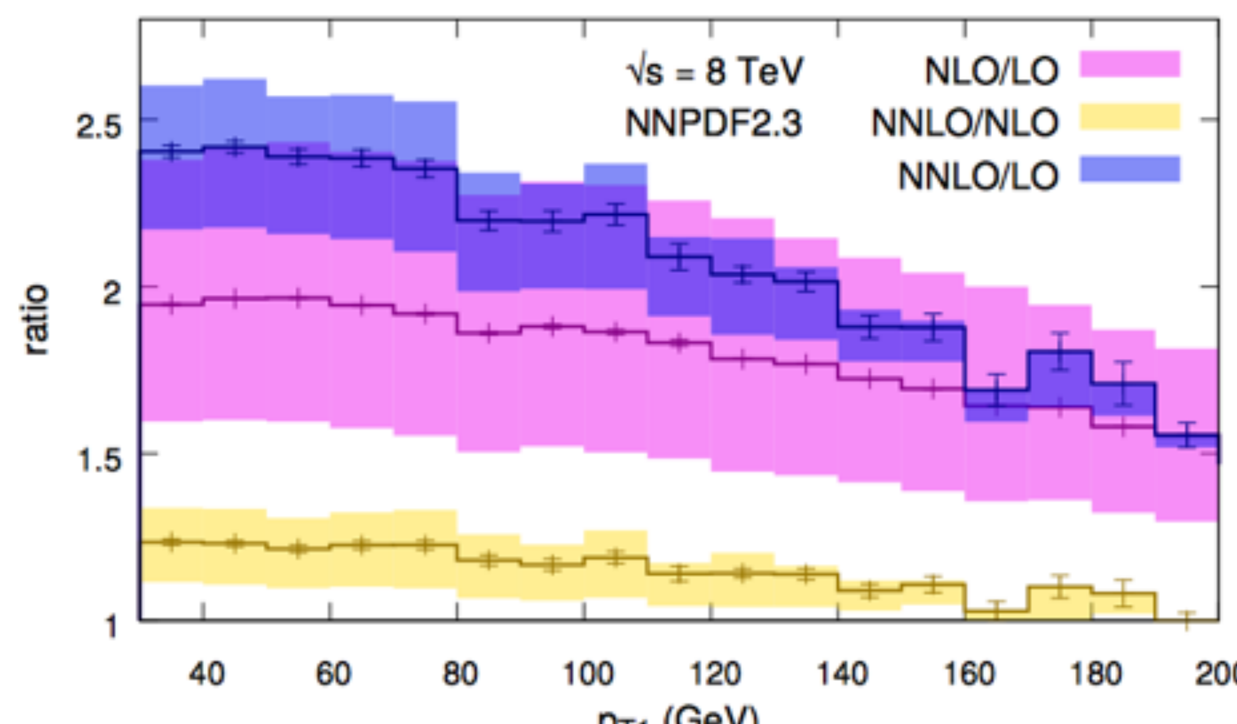
- Exploit universal IR singular behavior of amplitudes
  Simpler amplitudes as subtraction terms
- Analytic cancellation of IR singularities - Integrated counter terms

Subtraction: No Approximation

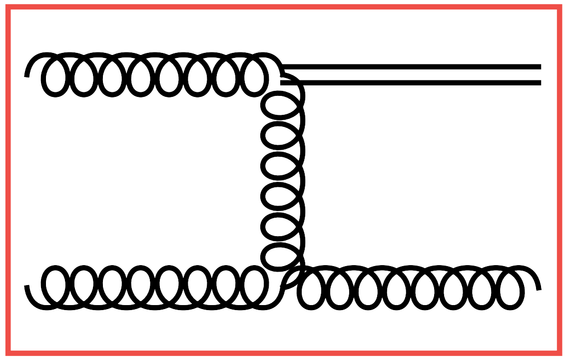
Sector improved residue subtraction

- Phase-Space partitioning to isolate IR singularities
- Automatic generation of subtraction terms
- Numerical Integration of singularities

[Chen,Gehrmann,Glover,Jaquier]



PRECISION FOR HIGGS PLUS JET



- Good agreement among different methods
- Stabilisation of perturbative series for differential cross sections
- Sizable contributions from NNLO

LO	$3.9^{1.7}_{-1.1} pb$	
NLO	$5.6^{1.3}_{-1.1} pb$	$+44\%$
NNLO	$6.7^{0.5}_{-0.6} pb$	$+72\%$

[Boughezal,Caola,Melnikov,Petriello,Schulze]

$\Delta R = 0.5$

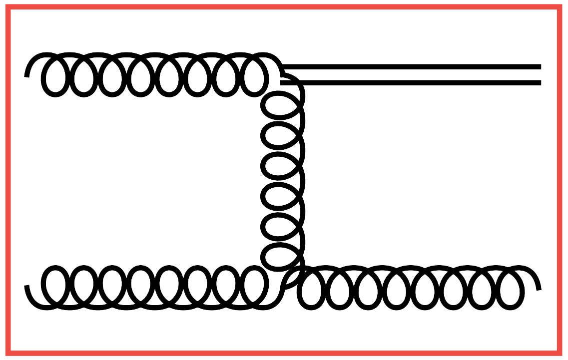
$p_T^j > 30\text{GeV}$

$S = 8\text{TeV}$

$\mu = m_h$

- Better convergence for lower scale $\mu = \frac{m_h}{2}$
- Perturbative results precise for $p_T^j > 30\text{GeV}$

PRECISION FOR HIGGS PLUS JET

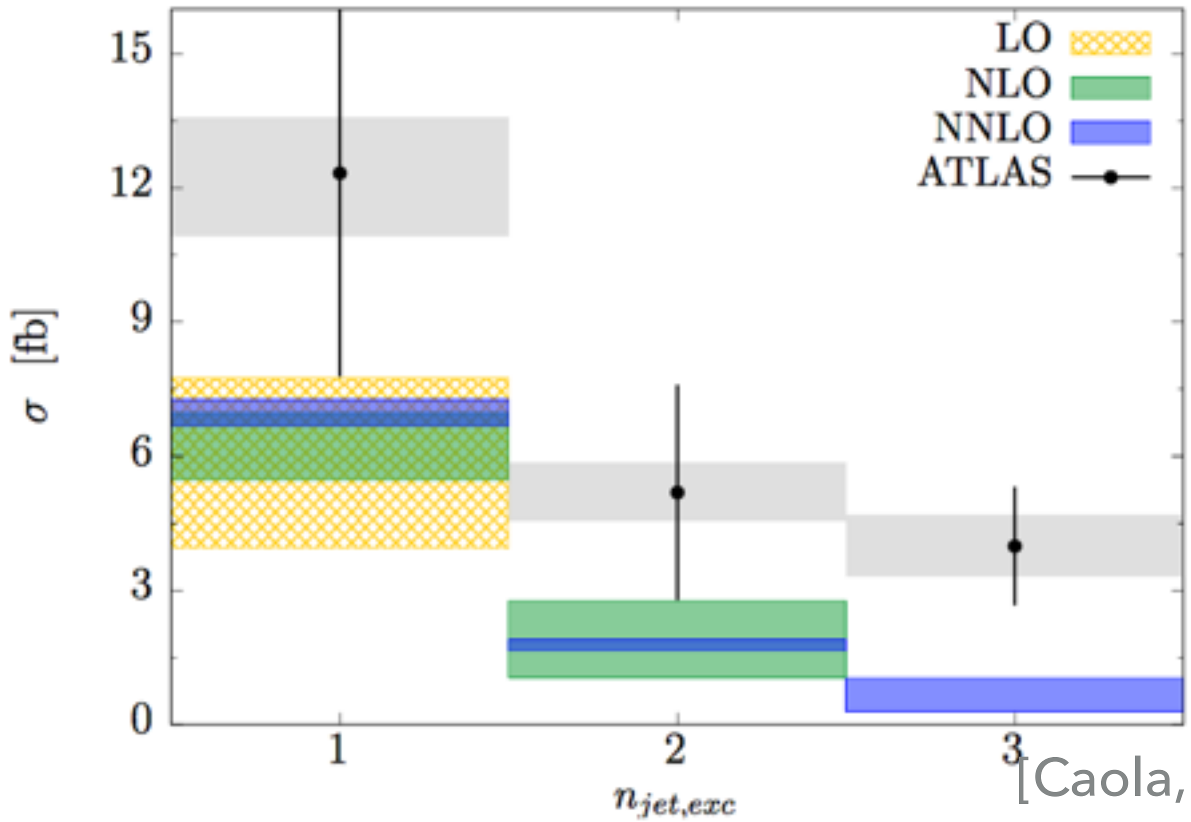


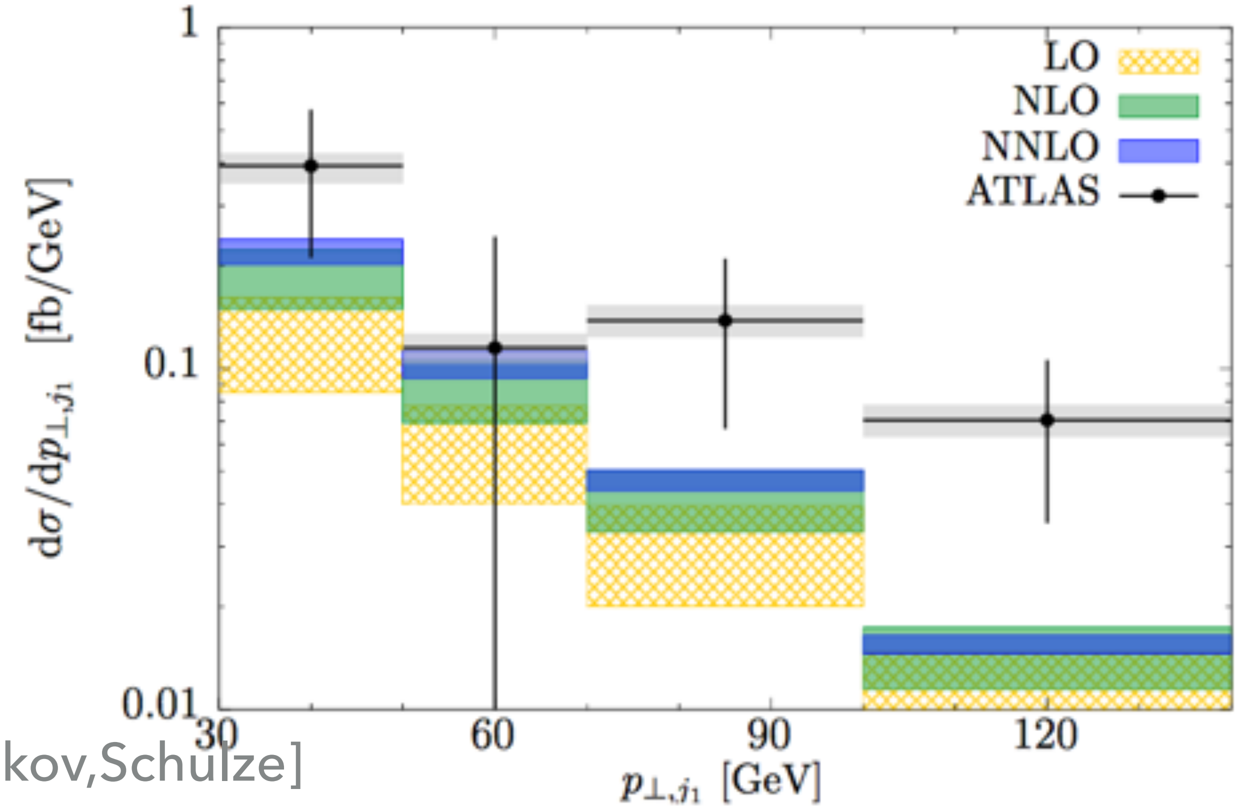
- Fiducial cross sections + distributions

$H \to \gamma\gamma$

S=8TeV

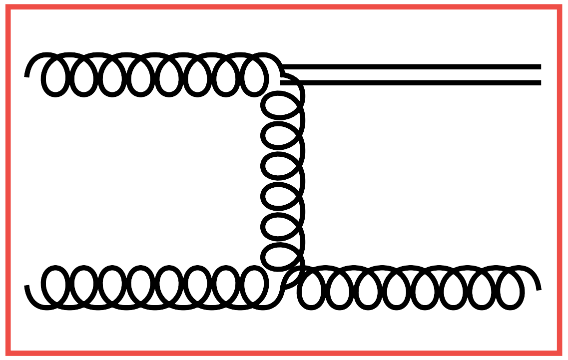
- Still large statistical uncertainties
- Observed a bit high …





[Caola,Melnikov,Schulze]

PRECISION FOR HIGGS PLUS JET

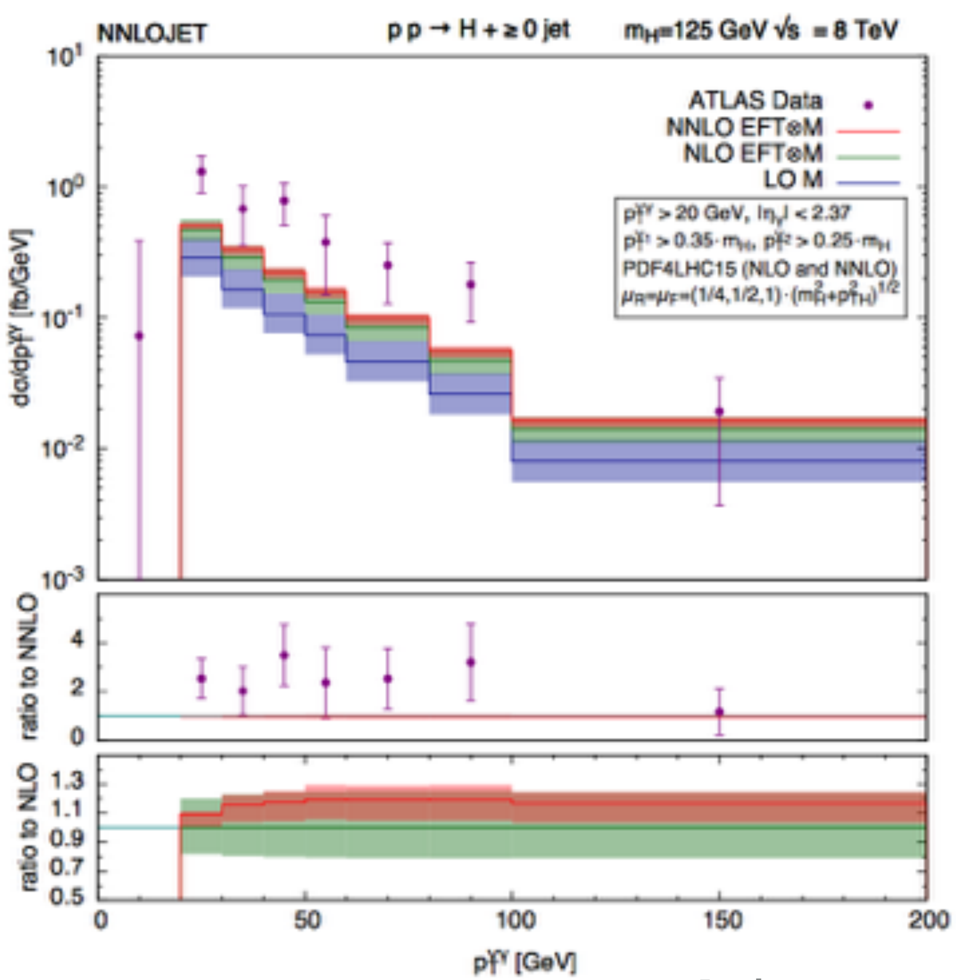


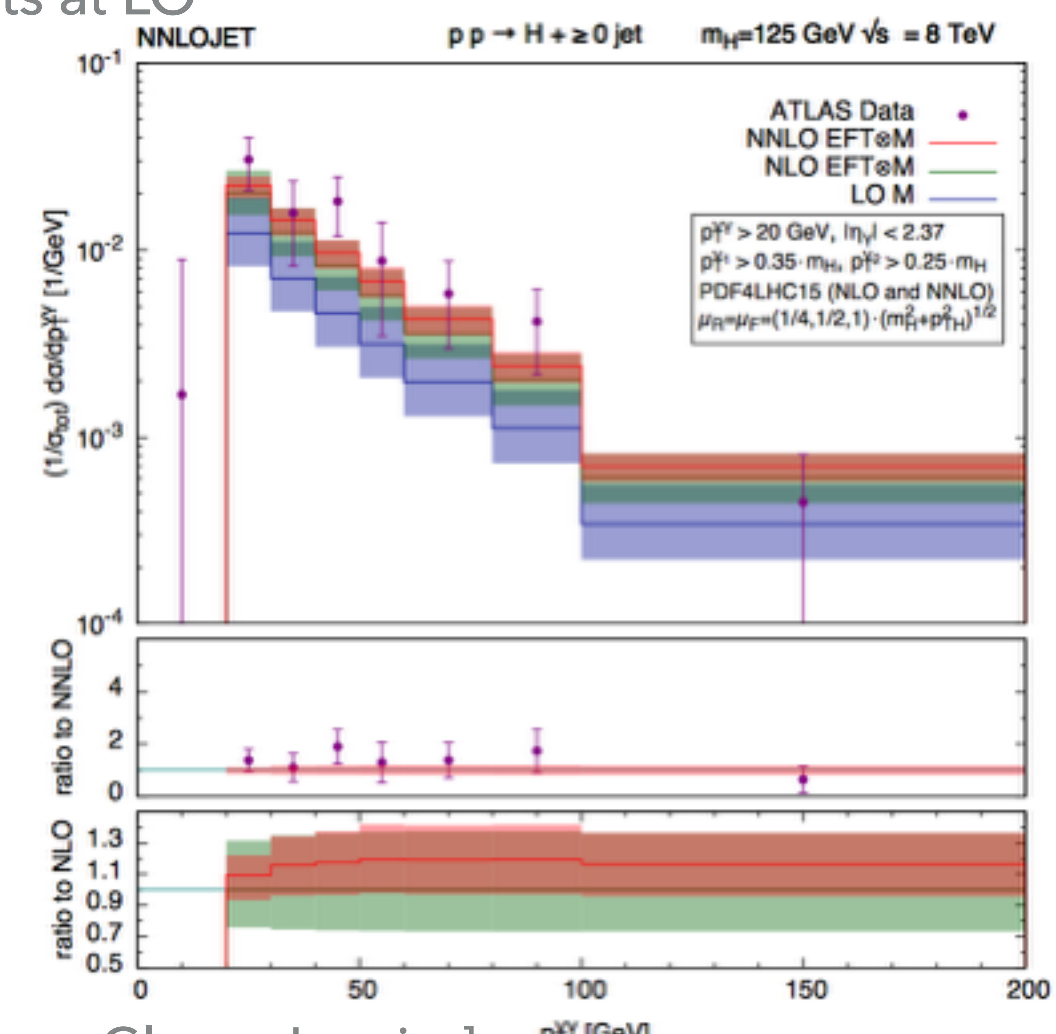
- Fiducial cross sections + distributions

$H \to \gamma\gamma$

S=8TeV

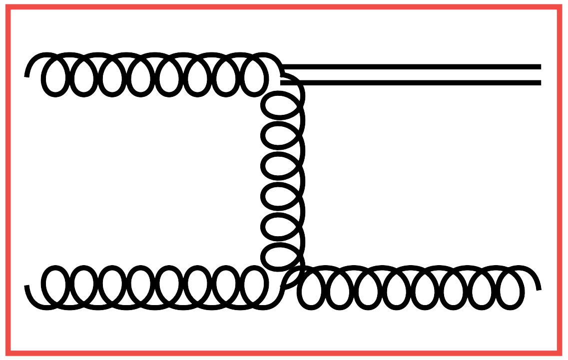
- Normalisation to total cross section improves agreement: Shapes! Worse scale uncertainty
- Mass effects at LO



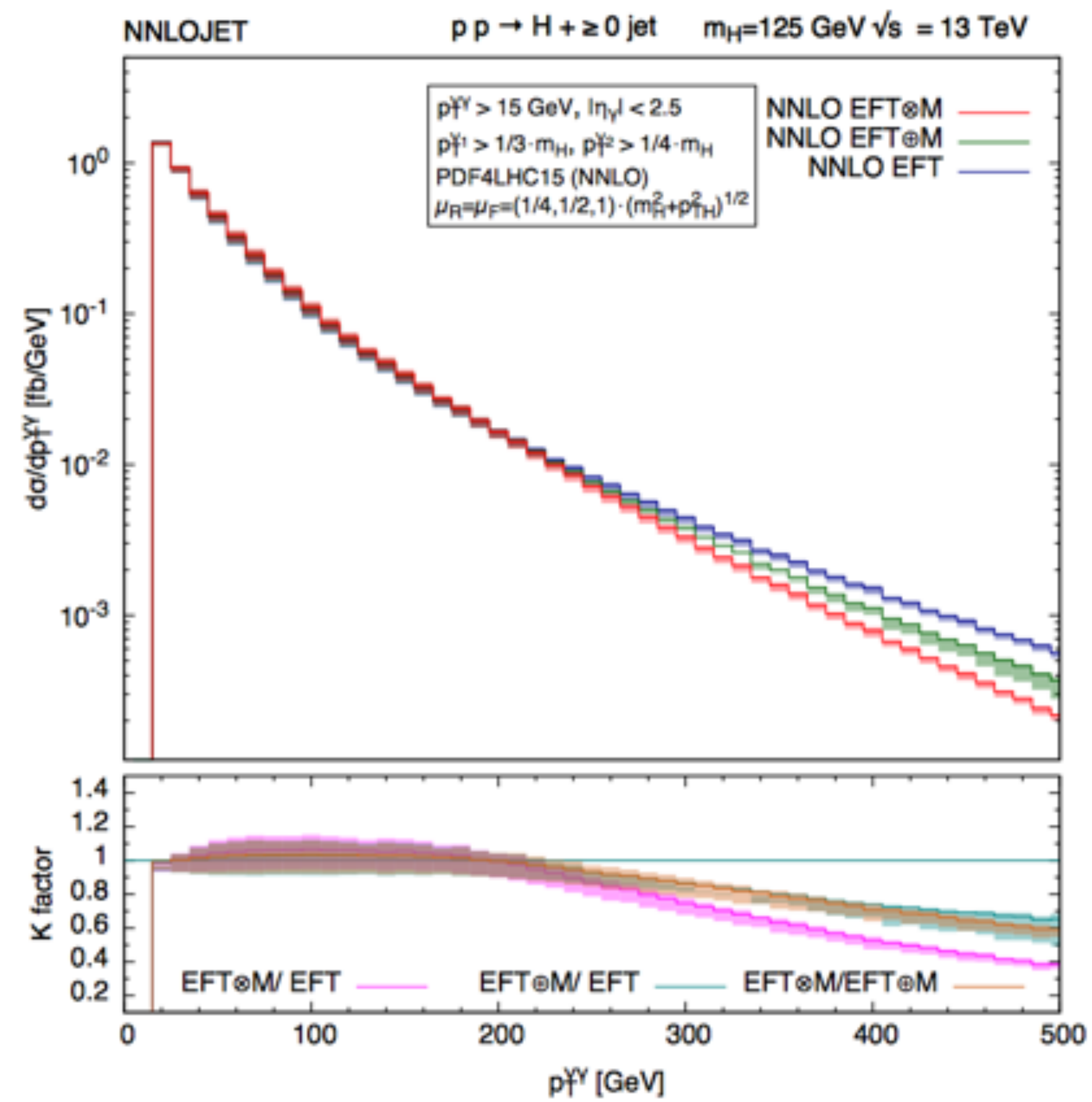


[Chen,Cruz-Martinez,Gehrmann,Glover,Jaquier]

PRECISION FOR HIGGS PLUS JET



- Fiducial cross sections + distributions



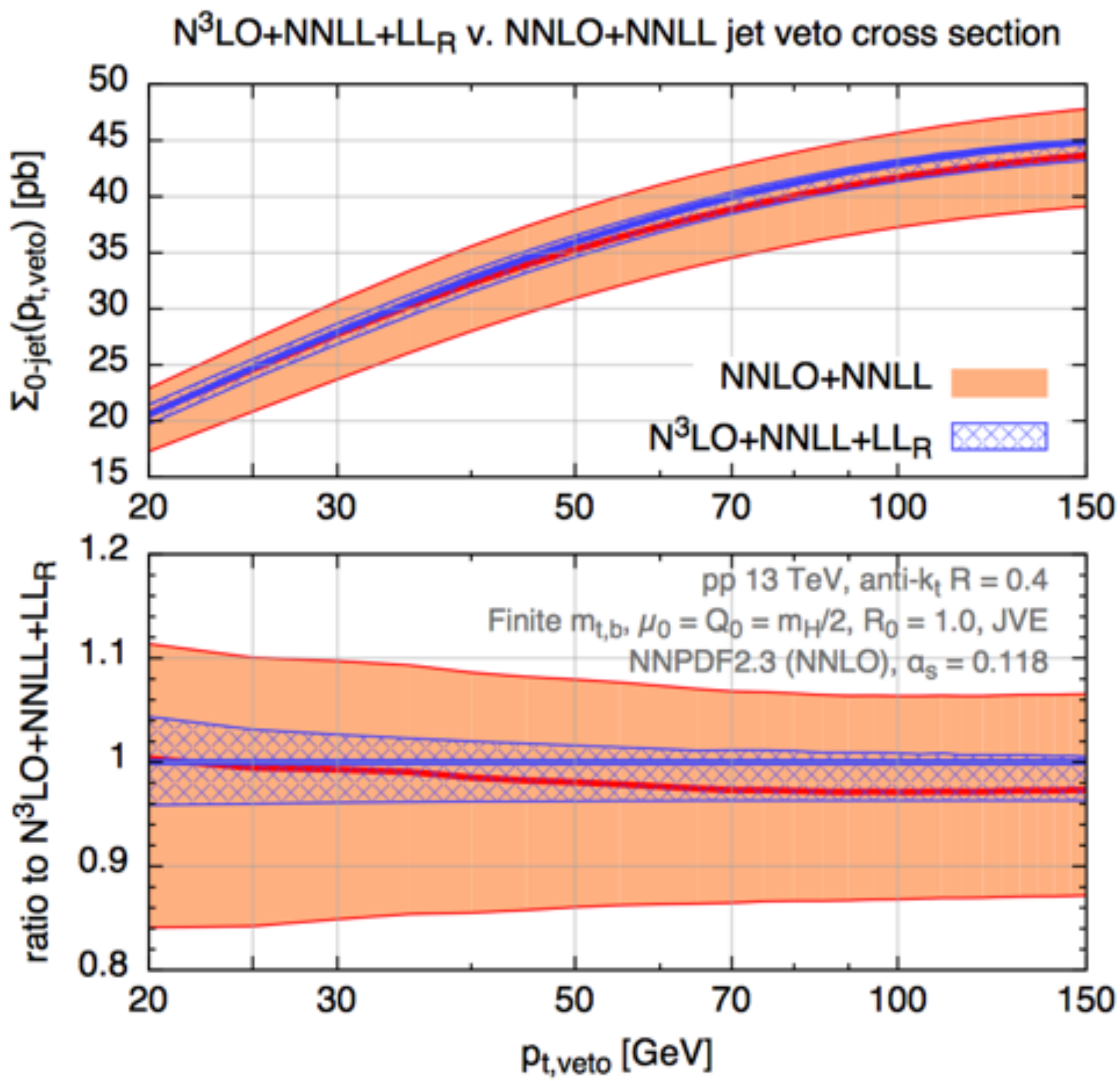
[Chen,Cruz-Martinez,Gehrmann,Glover,Jaquier]

- NNLO EFT for small pT
- pT=400 GeV: 50 % uncertainty due to masses at LO
- full NLO H+J desired

  Interesting: b-masses: [Melnikov,Penin]
- EFT works well for pT< ~200 GeV

JET VETO CROSS SECTION

See talks by Fabrizio Caola and Pier Monni



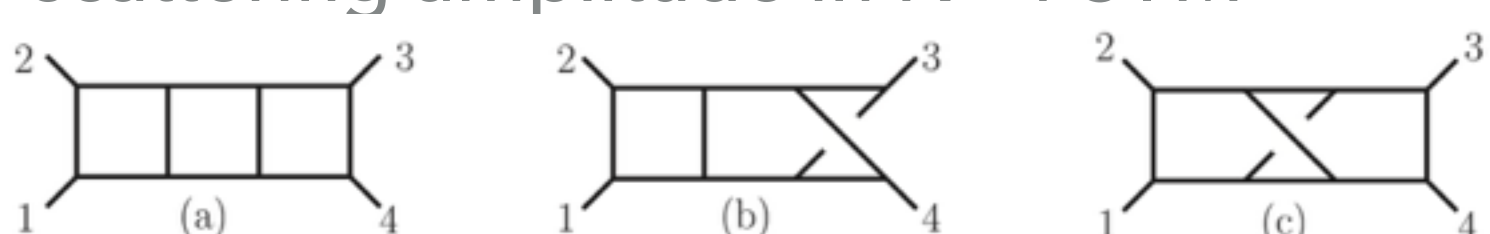
[Banfi,Caola,Dreyer,Dulat,Monni,Salam,Zanderighi]

- Subtracting H+J from inclusive N3LO
- Differential observable at N3LO
- Combine with small R and pT-veto resummation
- QCD perturbation theory at fixed order does a good job

PROGRESS IN QFT

- Progress in formal QFT can lead to application for predictions
- But: Our desire to predict drives us to further develop formal aspects of QFT
  - Understand better what we compute to get faster (NLO)
  - Uncover beautiful mathematical structures
  - Understand deeper structures of QFT

Example: Recently computed
4-particle 3-loop scattering amplitude in N=4 SYM



[Henn,BM]

CONCLUSIONS

- QCD precision predictions for Higgs boson physics are inseparably intertwined with the success of Higgs boson phenomenology at the LHC
- Remarkable progress in precision computation
- Desire to predict better inspires to develop our understanding of QFT
- Large room for improvement
  Precision standard of the future: Differential N3LO