Higgs Boson Pair Production:
Total XS at NNLO+NNLL in the EFT

Javier Mazzitelli - *Universidad de Buenos Aires*

in collaboration with **Daniel de Florian**

HH subgroup meeting – November 2015, CERN

CONICET

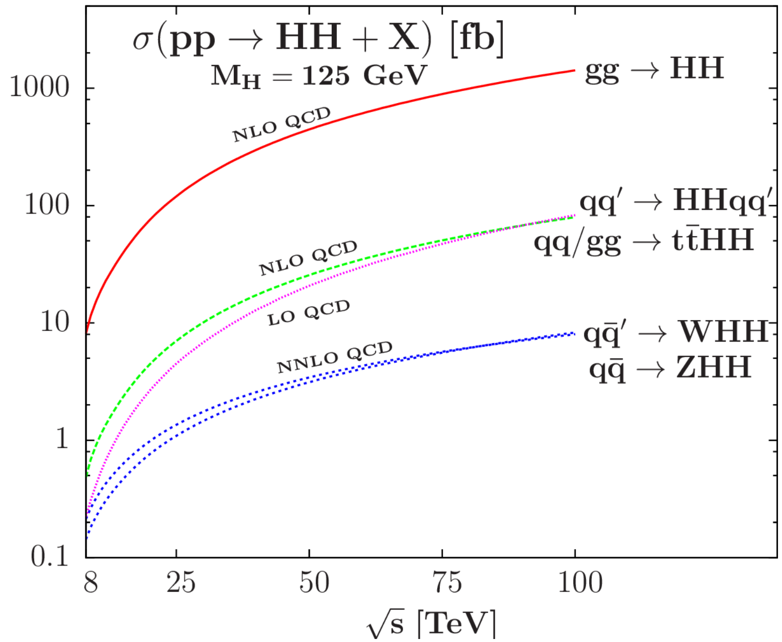
Motivation

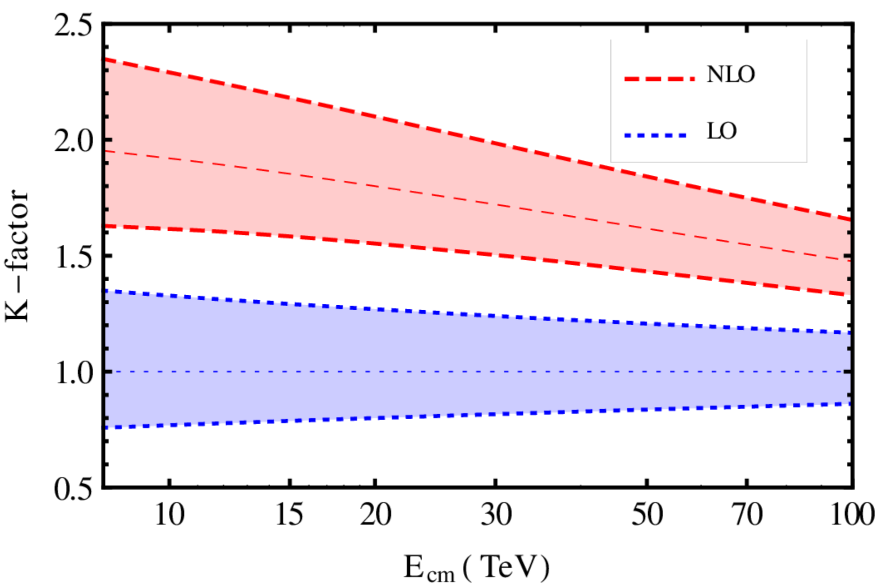
- **Why computing HH production via gluon fusion at NNLO+NNLL in the EFT?**

  - Gluon fusion is the main HH production channel

  - NLO corrections in the EFT are large
    K factor close to 2
    Large theoretical uncertainties

  - We need to improve both precision and accuracy of the prediction
    Finite top mass effects at NLO (Eleni-Marco's talk)
    NNLO (and NNLL) in the EFT ←



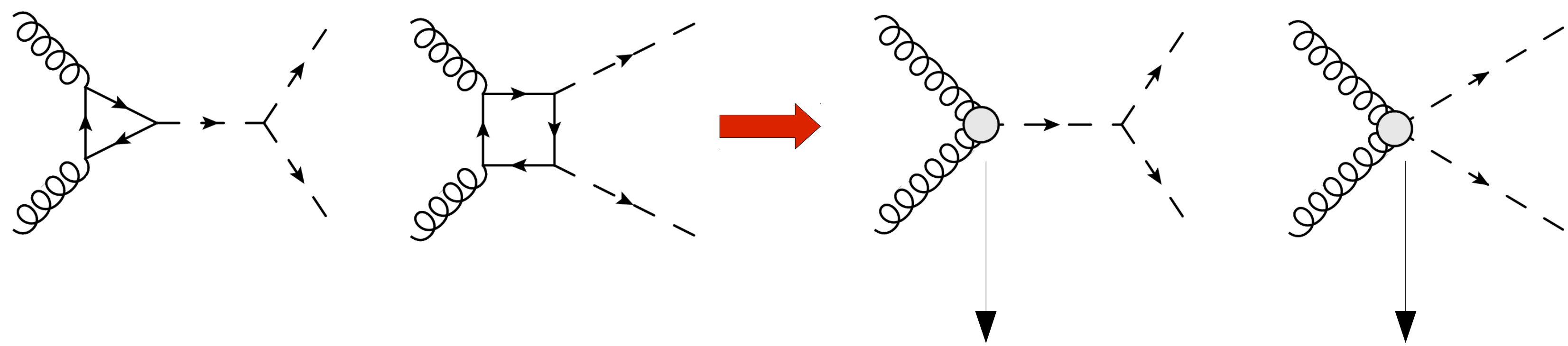


Calculation in the EFT

- **Calculation is much simpler! Loop induced in the full theory, tree level in the EFT**

Full Theory (1-loop) | Eff. Theory (tree level)

Leading Order



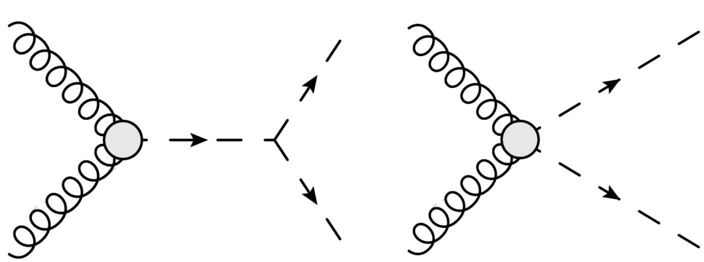
- **Even more, the vertices have the same structure!**

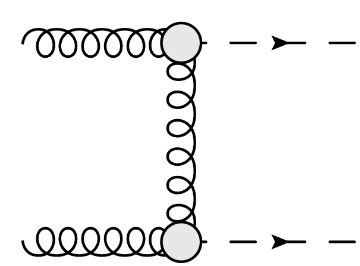
$$\mathcal{L}_{ggH} \propto G_{\mu\nu}G^{\mu\nu} H/v \qquad \mathcal{L}_{ggHH} \propto G_{\mu\nu}G^{\mu\nu} (H/v)^2$$

- We split the calculation: $$Q^2 \frac{d\hat{\sigma}}{dQ^2} = \hat{\sigma}^a + \hat{\sigma}^b$$

Single-Higgs like

New topologies with two effective vertices





- We obtained the NNLO cross section

[arXiv:1309.6594]

Threshold Resummation

- **All-order summation of threshold enhanced contributions**

Higgs pair invariant mass

$$z = \frac{Q^2}{\hat{s}}$$

Threshold:

$$z \to 1 \iff N \to \infty$$

- **Resummation is performed in Mellin space**
- **Threshold enhanced contributions:** $(\ln N)^k$
- **Originated by soft gluon emissions**
- **Resummation formula:**

$$G^{(\mathrm{res})}_{gg,N} = \Delta_N \times C_{gg} + \mathcal{O}(1/N)$$

Partonic cross section (in Mellin space)

Sudakov factor
Exponentiates the large log corrections

Constant contributions

Threshold Resummation

- **Sudakov factor:**

Known (same as for single Higgs prod)

$$\Delta_N = \exp\Big(\underbrace{\underbrace{\underbrace{\ln N\, g^{(1)}(\lambda)}_{\text{LL}} + g^{(2)}(\lambda)}_{\text{NLL}} + \alpha_S\, g^{(3)}(\lambda)}_{\text{NNLL}} + \dots \Big), \quad \lambda = \beta_0 \alpha_S \ln N$$

Leading Log →	$\alpha_S^n \ln^{n+1} N$
Next-to-Leading Log →	$\alpha_S^n \ln^n N$
Next-to-Next-to-Leading Log →	$\alpha_S^n \ln^{n-1} N$

- **Constant contributions:**

Virtual and non-logarithmic soft contributions →

$$C_{gg} = 1 + \sum_{n=1} \left(\frac{\alpha_S}{2\pi}\right)^n C_{gg}^{(n)}$$

$$\text{N}^i\text{LL} \xleftarrow{\text{Needed for}} C_{gg}^{(i)} \xrightarrow{\text{Obtained from}} \text{N}^i\text{LO}$$

Threshold Resummation

- **Inverse Mellin transform performed numerically**
- **Matching with the FO**

$$\sigma^{NNLL} = \underbrace{\sigma^{res} - \sigma^{res}\big|_{\mathcal{O}(\alpha_S^4)}}_{\text{Resummed contributions starting at } \mathcal{O}(\alpha_S^5)} + \sigma^{NNLO}$$

$$\Longrightarrow \quad \sigma^{NNLL}\big|_{\mathcal{O}(\alpha_S^4)} = \sigma^{NNLO}$$

- **Resummed contributions should account for the dominant effect of the uncalculated missing higher orders**

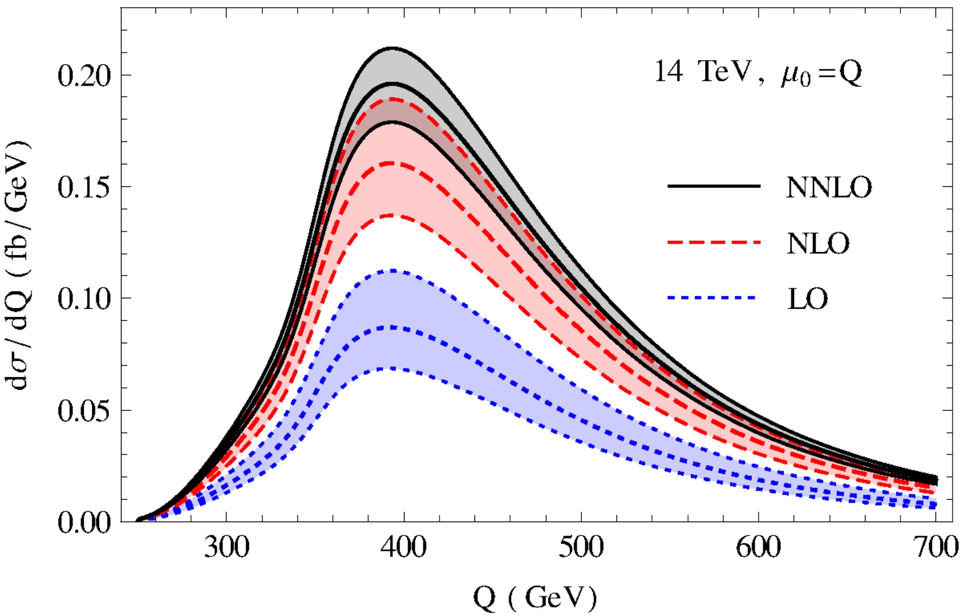
  - Relatively large invariant mass → Corrections dominated by threshold contributions
  - Explicitly checked up to NNLO computing the soft-virtual approximation

Numerical results for the LHC

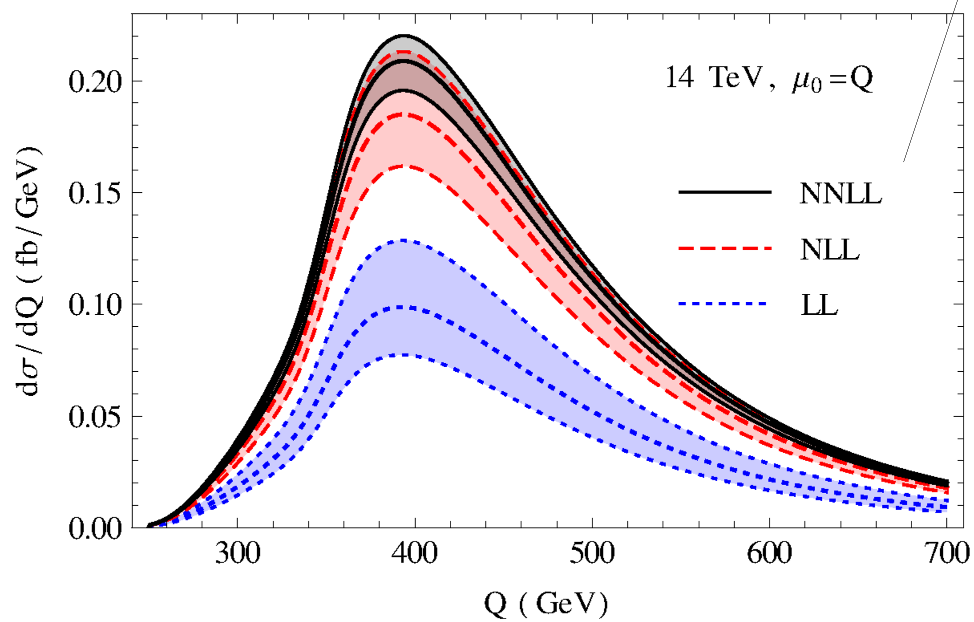
- **HH invariant mass distribution XS**
- **Bands** ──► **Scale uncertainty**
- Central scale: HH invariant mass Q

Here NNLL means NNLL+NNLO, etc

Fixed order

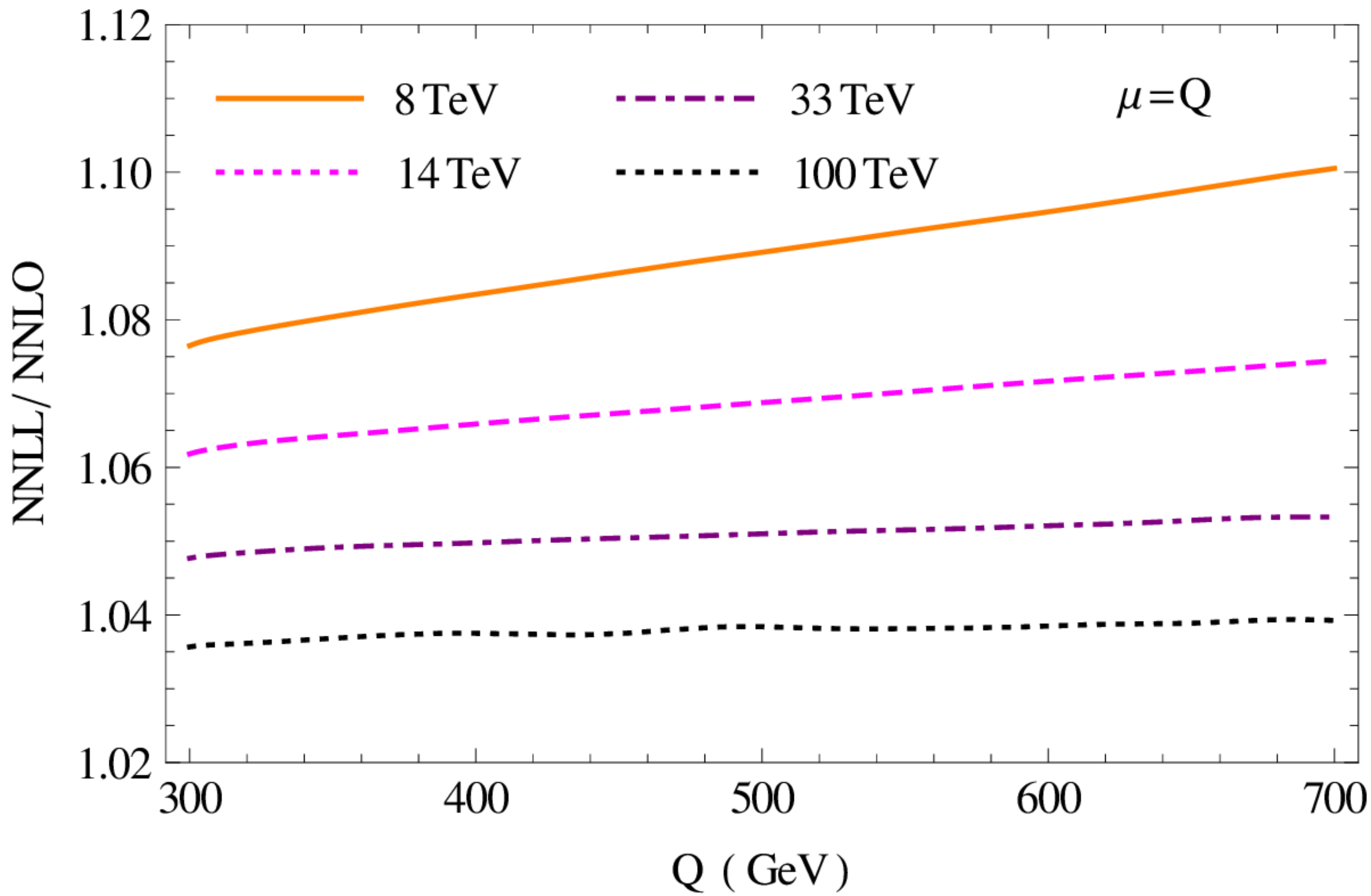


Resummed



- Overlap only between NLO (NLL) and NNLO (NNLL)
- Resummed contributions ──► increase of the cross section
- Uncertainty reduction from NNLO to NNLL
- Shape: very small differences between FO and resummed distributions

NNLL/NNLO ratio vs. HH invariant mass

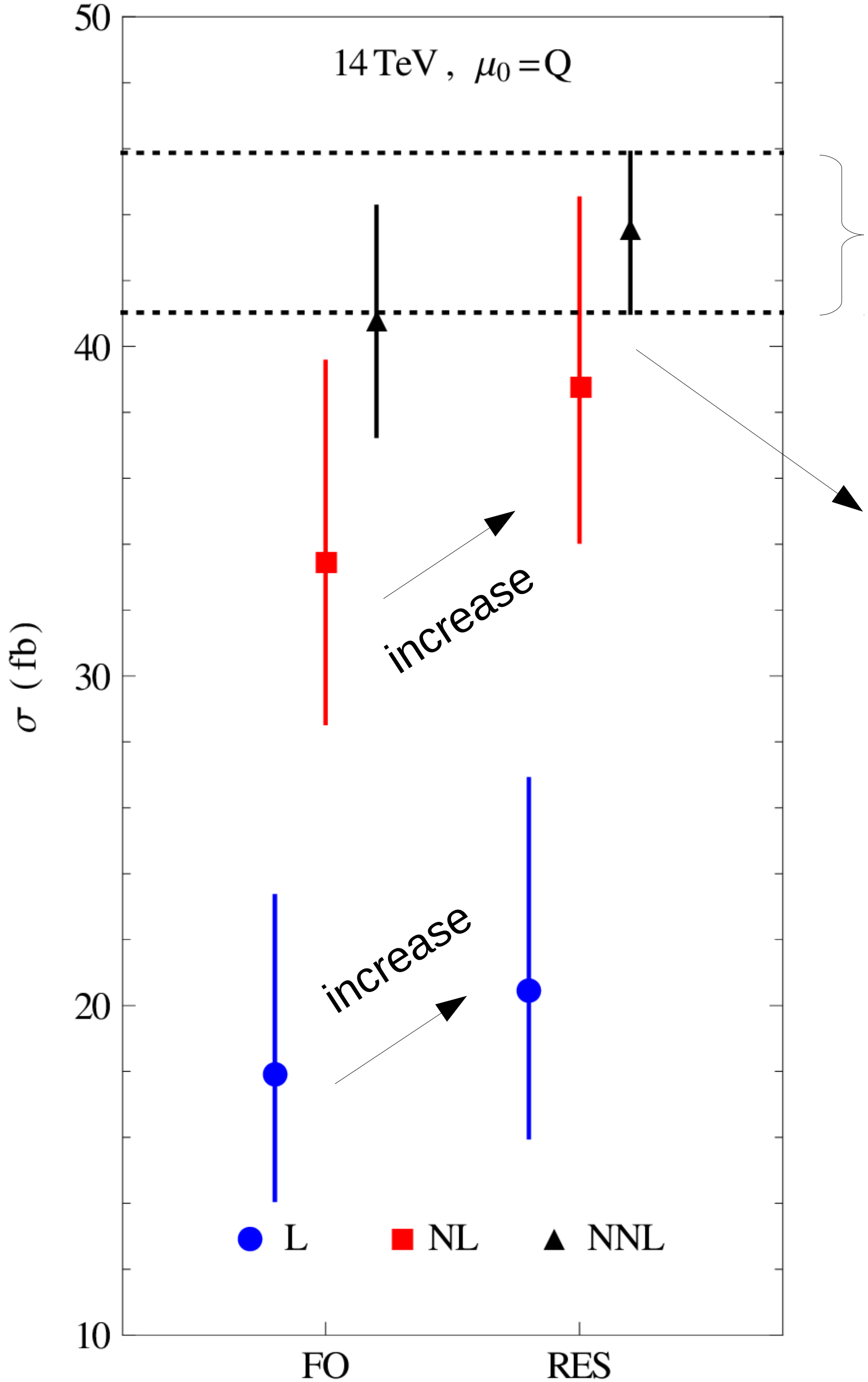


Increase in total XS:

- 8.9% at 8TeV
- 6.8% at 14TeV
- 3.8% at 100TeV

- NNLL always larger than NNLO, ratio is almost linear in Q
- Ratio increases for larger invariant masses → Closer to partonic threshold
- Larger collider energies → Smaller resummation effects (further from threshold)

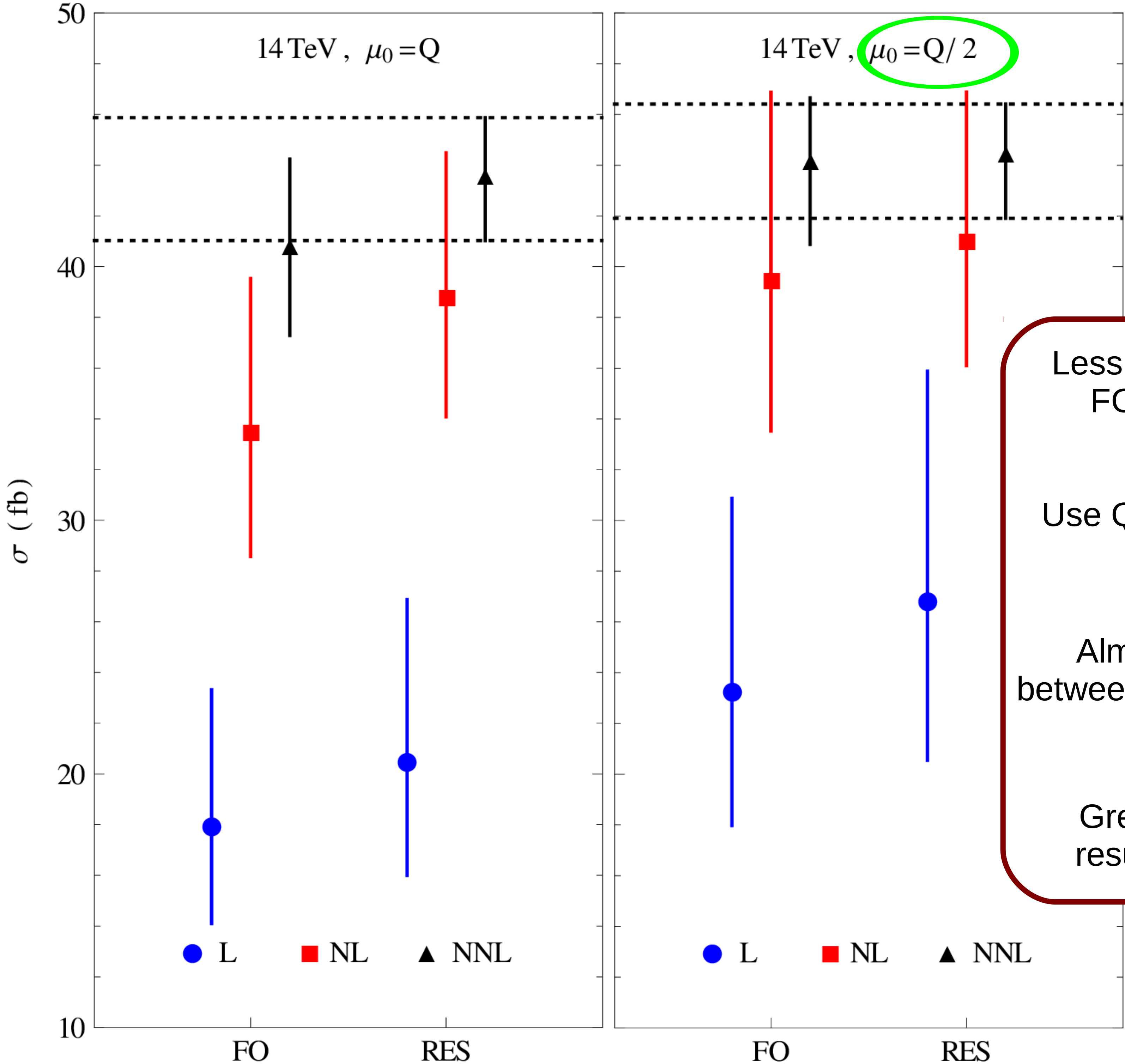
- **Total cross section**



Scale unc.
reduction at NNLL
(From ±8.5% to ±5.5%)

Large overlap between
NLL and NNLL

- **Total cross section**



Less differences between FO and RES for Q/2

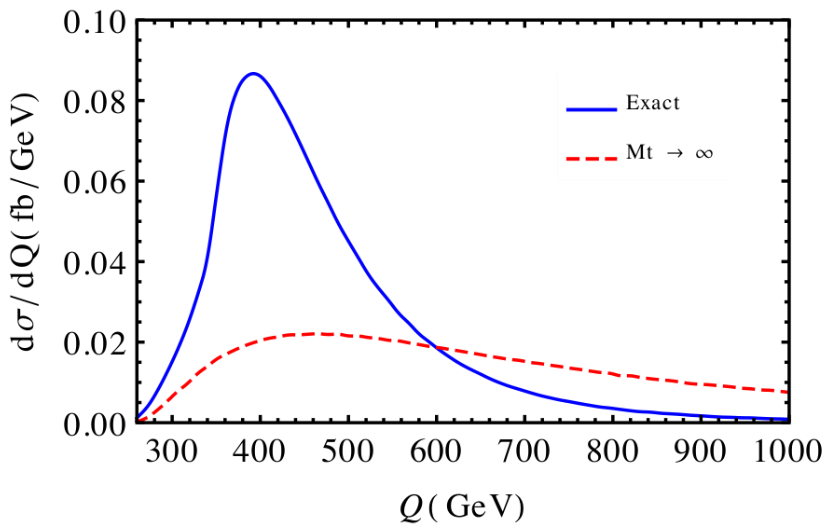
Use Q/2 for FO predictions

Almost no difference between Q and Q/2 at NNLL

Great stability of the resummed NNLL XS

Top mass effects

- **Is the EFT calculation reliable?**



- Worse than in the single Higgs case (larger inv. mass)
- Not reliable for distributions
- Underestimation of the total XS at LO of O(20%)

- **Should be more reliable to compute the QCD corrections**
  - Corrections are dominated by initial state soft radiation, not sensitive to the vertex structure
  - Usual procedure: compute the corrections in the EFT and normalize by the exact LO

- **First step: validate it at NLO**

Exact NLO not available → Current estimations: finite top mass effects of O(10%)

Conclusions

- We performed the NNLL threshold resummation for the Higgs pair production cross section in the EFT
- We consistently matched the results with the NNLO calculation
- Resummed contributions result in an increase of the total XS
- Effects are more sizable for the central scale Q, less for Q/2
- Further reduction of the scale uncertainty w.r.t. NNLO
- NNLL+NNLO results almost independent of the central scale choice
- For fixed order calculations, central scale Q/2 seems the best choice

Numerical results for the LHC

$\mu_0 = Q$	NNLL (fb)	scale unc. (%)	PDF unc. (%)	PDF+α_S unc. (%)
7 TeV	7.61	$+5.6 - 6.0$	± 3.3	± 4.3
8 TeV	11.0	$+5.5 - 6.0$	± 3.0	± 4.0
13 TeV	37.3	$+5.1 - 6.1$	± 2.1	± 3.1
14 TeV	44.2	$+5.2 - 6.1$	± 2.0	± 3.0
100 TeV	1712	$+5.2 - 6.2$	± 1.7	± 2.6
$\mu_0 = Q/2$	NNLL (fb)	scale unc. (%)	PDF unc. (%)	PDF+α_S unc. (%)
7 TeV	7.72	$+4.0 - 5.7$	± 3.4	± 4.4
8 TeV	11.2	$+4.1 - 5.7$	± 3.1	± 4.0
13 TeV	38.0	$+4.3 - 6.0$	± 2.1	± 3.1
14 TeV	45.1	$+4.4 - 6.0$	± 2.1	± 3.0
100 TeV	1749	$+5.1 - 6.6$	± 1.7	± 2.7

- Calculated using the new PDF4LHC prescription
- We used the PDF4LHC15_nnlo_mc sets (100 MC replicas).