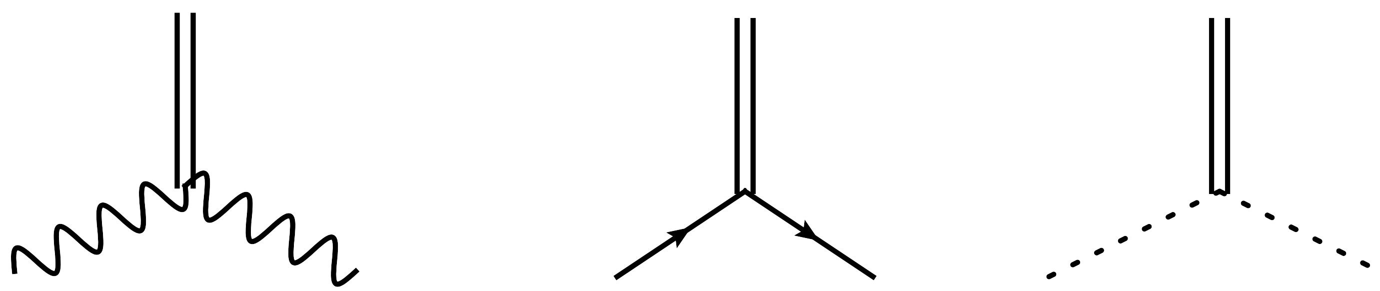
BERNHARD MISTLBERGER

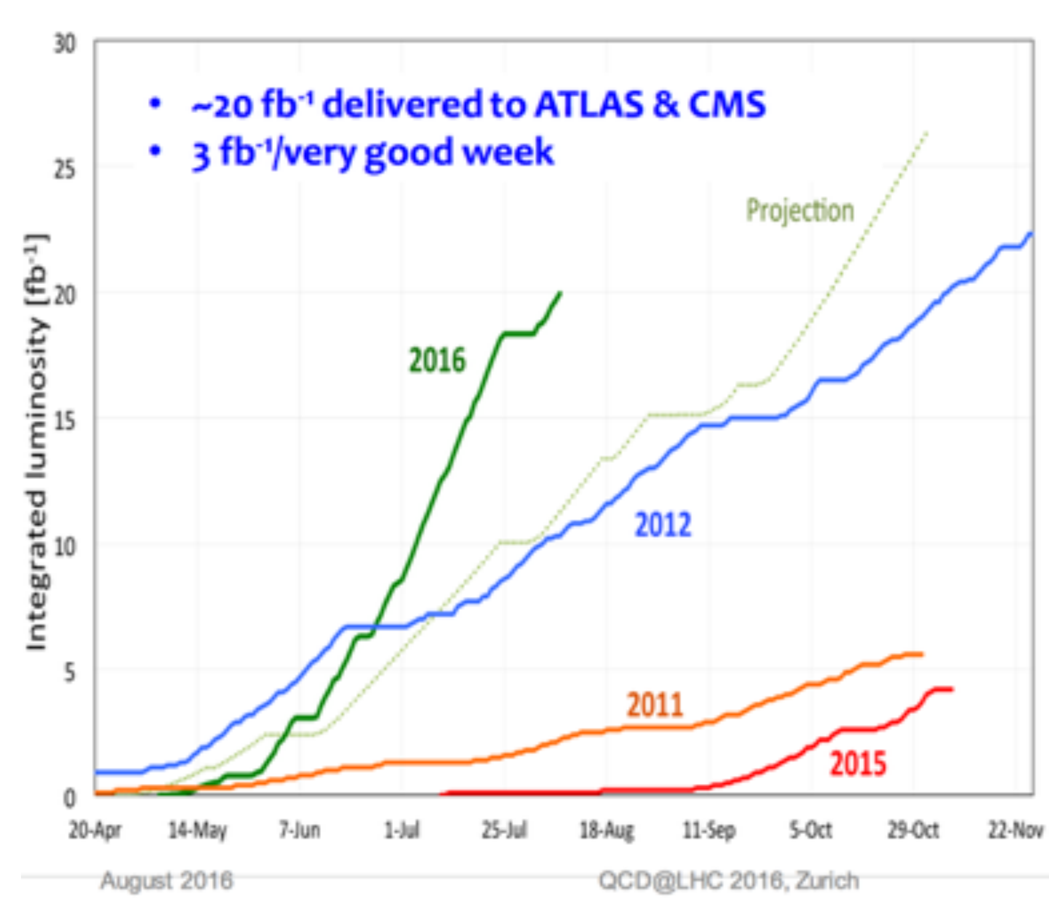
# PRECISION PREDICTIONS FOR HIGGS BOSON PHENOMENOLOGY

- 4th of July 2012: The begin of the precision physics age of Higgs boson phenomenology

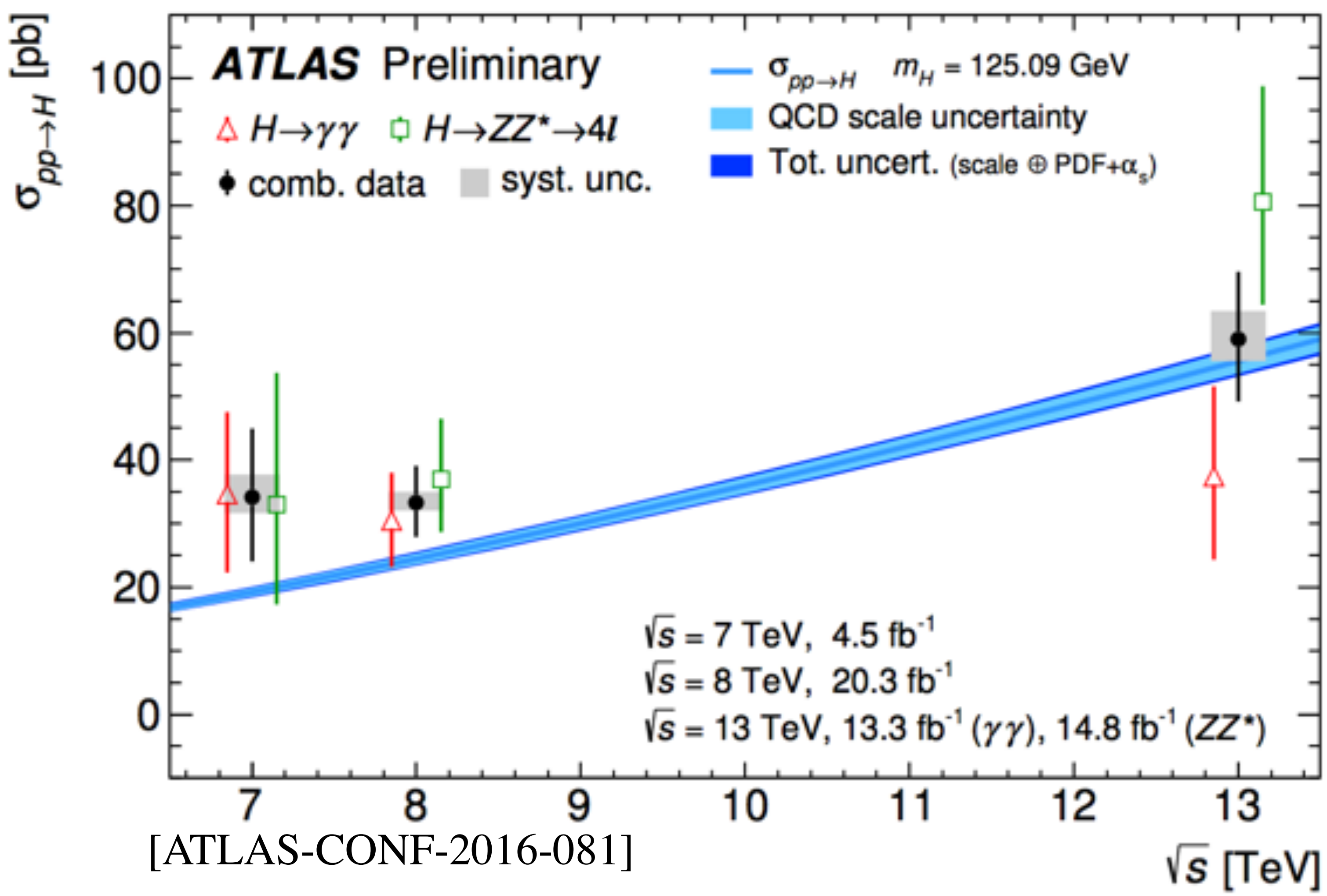
- Immediately after the discovery of the Higgs boson we started to ask questions about it’s nature:
  Couplings, spin, parity, mass, cross sections …



- 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




[ATLAS-CONF-2016-081]

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

- ATLAS: $H \to \gamma\gamma \ + \ H \to 4l$
- Cleanest channels

[2015]

| Total cross section [pb] | 7 TeV | 8 TeV | 13 TeV |
|---|---|---|---|
| $H \to \gamma\gamma$ | $35^{+13}_{-12}$ | $30.5^{+7.5}_{-7.4}$ | $40^{+31}_{-28}$ |
| $H \to ZZ^* \to 4\ell$ | $33^{+21}_{-16}$ | $37^{+9}_{-8}$ | $12^{+25}_{-16}$ |
| Combination | $34 \pm 10$ (stat.) $^{+4}_{-2}$ (syst.) | $33.3^{+5.5}_{-5.3}$ (stat.) $^{+1.7}_{-1.3}$ (syst.) | $24^{+20}_{-17}$ (stat.) $^{+7}_{-3}$ (syst.) |
| LHC-XS | $17.5 \pm 1.6$ | $22.3 \pm 2.0$ | $50.9^{+4.5}_{-4.4}$ |

[ATLAS-CONF-2015-069 ]

- ATLAS: $H \to \gamma\gamma$ + $H \to 4l$
- Cleanest channels

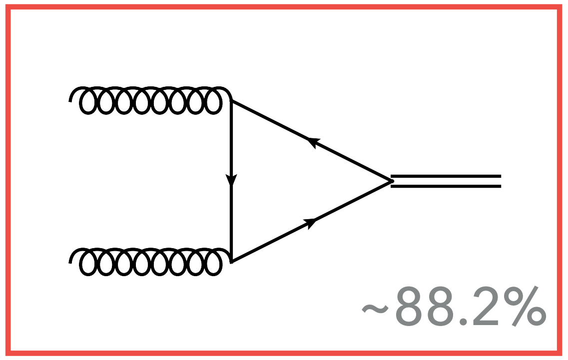
[2016]

| Decay channel | Total cross section ($pp \to H + X$) | | |
|---|---|---|---|
| | $\sqrt{s}$ =7 TeV | $\sqrt{s}$ =8 TeV | $\sqrt{s}$ =13 TeV |
| $H \to \gamma\gamma$ | $35^{+13}_{-12}$ pb | $30.5^{+7.5}_{-7.4}$ pb | $37^{+14}_{-13}$ pb |
| $H \to ZZ^* \to 4\ell$ | $33^{+21}_{-16}$ pb | $37^{+9}_{-8}$ pb | $81^{+18}_{-16}$ pb |
| Combination | $34 \pm 10$ (stat.) $^{+4}_{-2}$ (syst.) pb | $33.3^{+5.5}_{-5.3}$ (stat.) $^{+1.7}_{-1.3}$ (syst.) pb | $59.0^{+9.7}_{-9.2}$ (stat.) $^{+4.4}_{-3.5}$ (syst.) pb |
| SM predictions [7] | $19.2 \pm 0.9$ pb | $24.5 \pm 1.1$ pb | $55.5^{+2.4}_{-3.4}$ pb |

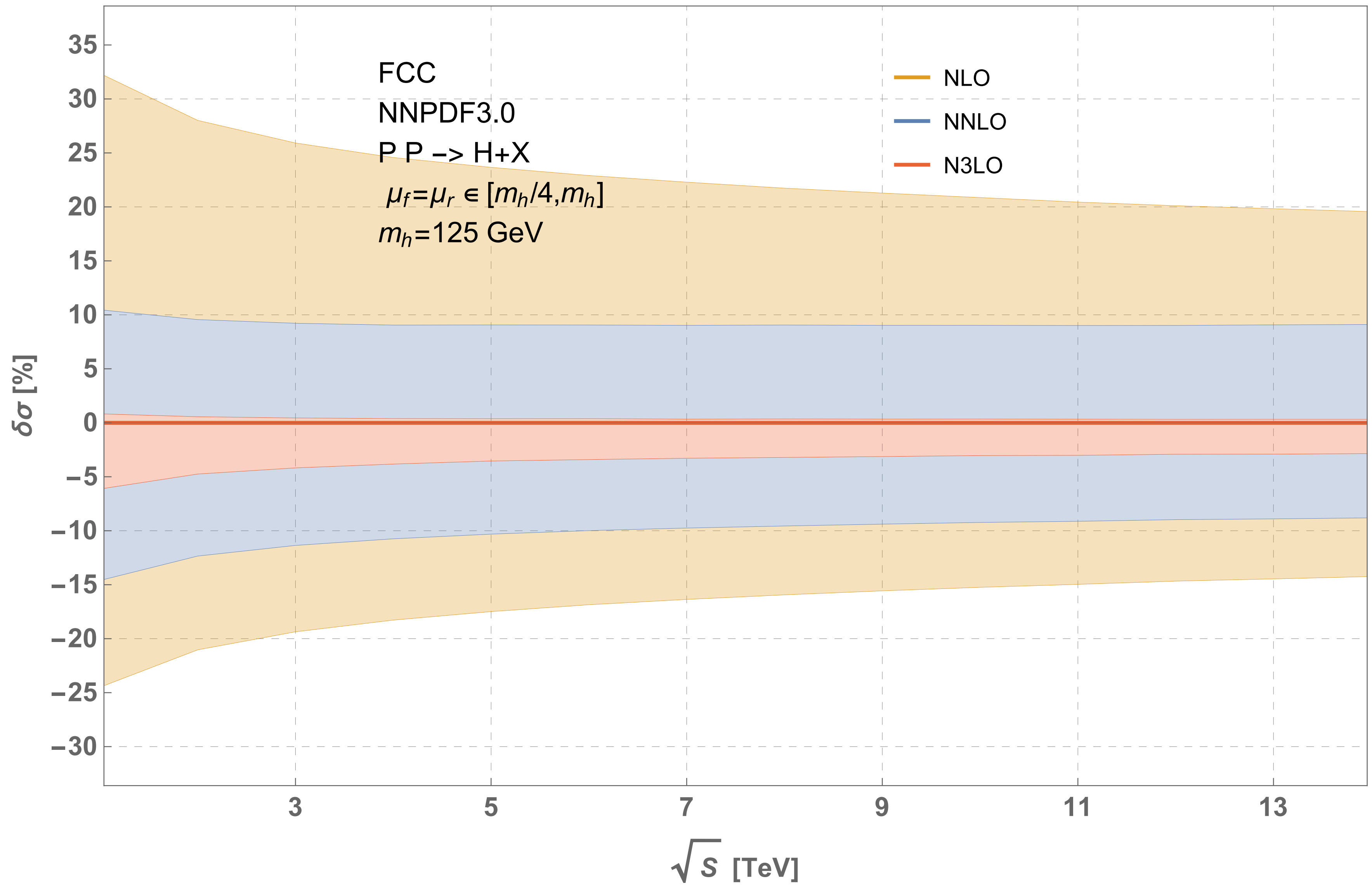
[ATLAS-CONF-2016-081]

- Currently statistical errors dominate
- $100 fb^{-1} \sim$ Factor of 3 better uncertainties!

# GLUON FUSION - INCLUSIVE CROSS SECTION




- EFT: N3LO gives small scale variation
  But: Only approximation



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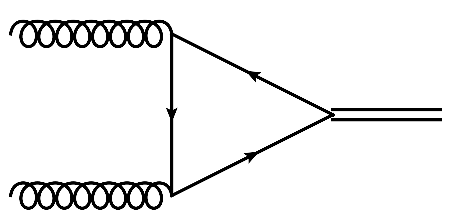


$$\boxed{\sigma = 48.58\,\mathrm{pb}^{+2.22\,\mathrm{pb}\,(+4.56\%)}_{-3.27\,\mathrm{pb}\,(-6.72\%)}\ (\text{theory}) \pm 1.56\,\mathrm{pb}\,(3.20\%)\ (\text{PDF}+\alpha_s)\,.}$$

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

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

# GLUON FUSION – INCLUSIVE CROSS SECTION

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

- Many residual uncertainties of comparable importance

| $\delta(\text{scale})$ | $\delta(\text{trunc})$ | $\delta(\text{PDF-TH})$ | $\delta(\text{EW})$ | $\delta(t,b,c)$ | $\delta(1/m_t)$ |
|---|---|---|---|---|---|
| $^{+0.10\ \mathrm{pb}}_{-1.15\ \mathrm{pb}}$ | $\pm 0.18$ pb | $\pm 0.56$ pb | $\pm 0.49$ pb | $\pm 0.40$ pb | $\pm 0.49$ pb |
| $^{+0.21\%}_{-2.37\%}$ | $\pm 0.37\%$ | $\pm 1.16\%$ | $\pm 1\%$ | $\pm 0.83\%$ | $\pm 1\%$ |

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Addressable with an adequate level of fun

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Addressable with an adequate level of fun

Little bit harder

# GLUON FUSION – ELECTROWEAK CORRECTIONS

Energy independent EWK corrections

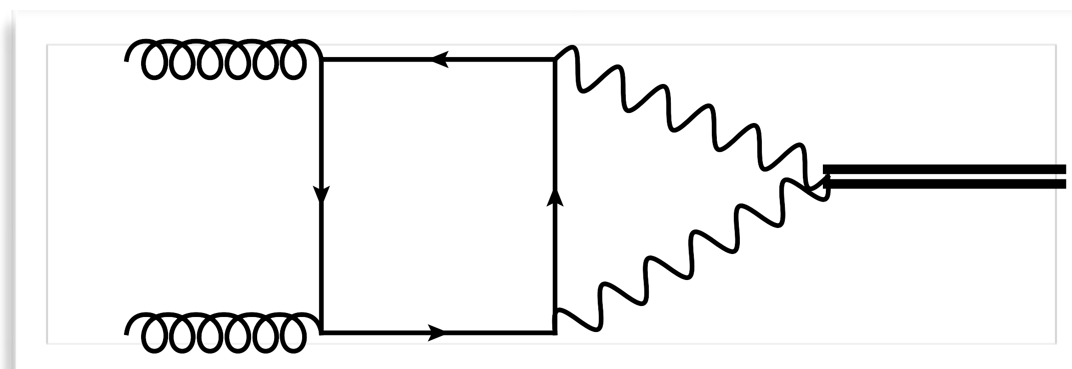
$$\sigma = \sigma_{QCD} \times (1 + \delta_{EWK})$$ + ~5 %

$\mathcal{O}(\alpha\alpha_S)$ Approximation

[Actis,Passarino,Sturm,Uccirati;Degrassi,Maltoni;
Anastasiou,Boughezal,Petriello,....]

Residual Error

$\sim 1\%?$



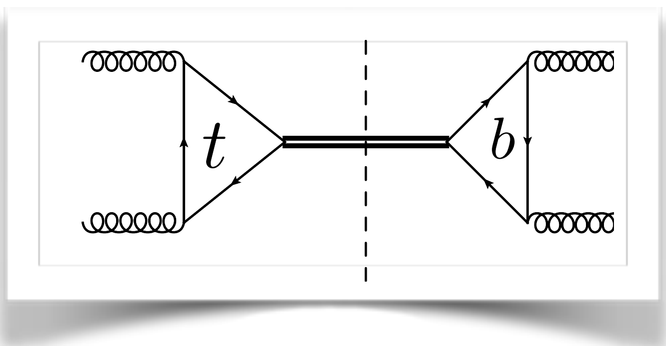
Factorisation vs. Non-Factorisation

Recently: Computation of LO through $\mathcal{O}(\epsilon^2)$ [Bonetti,Melnikov,Tancredi]

Corrections to H+J (Energy dependent) [Keung,Petriello]

Very small for inclusive Higgs production

# GLUON FUSION – MASS CORRECTIONS

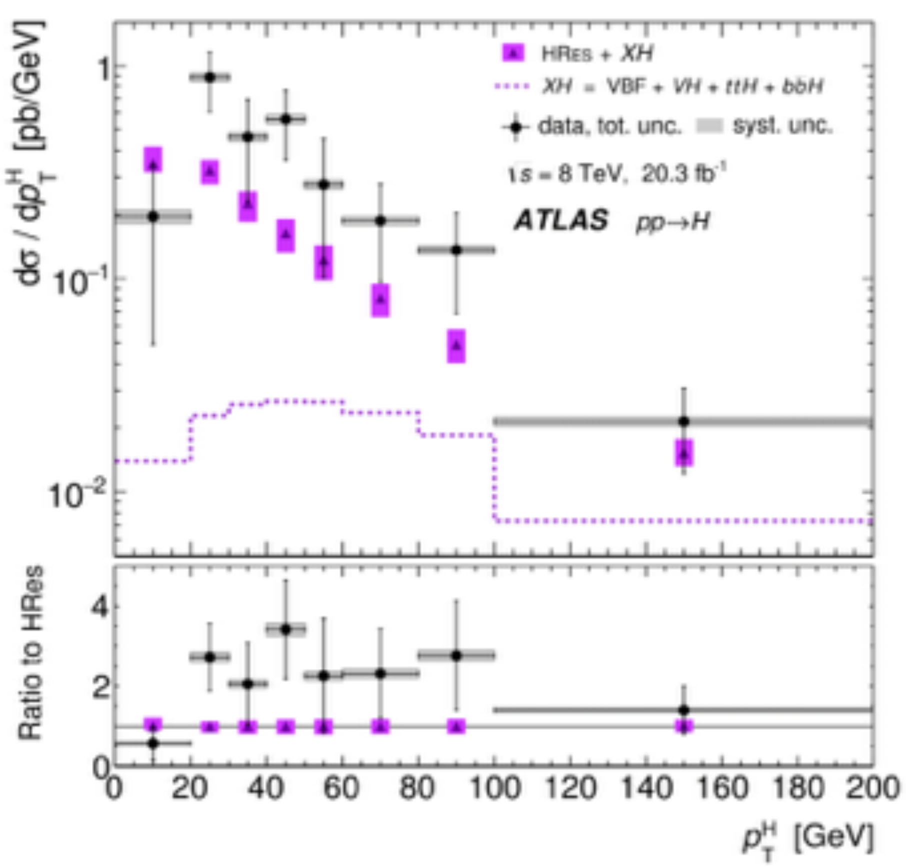



| | | |
|---|---|---|
| $\sigma^{NLO}_{eft}$ | 34.81[1] | |
| $\sigma^{NLO}_{eft;R}$ | 37.00[2] | +6.3% |
| $\sigma^{NLO}_{ex;t}$ | 36.76[1] | +5.6% |
| $\sigma^{NLO}_{ex;t+b}$ | 35.09[1] | +0.8% |
| $\sigma^{NLO}_{ex;t+b+c}$ | 34.91[1] | +0.3% |

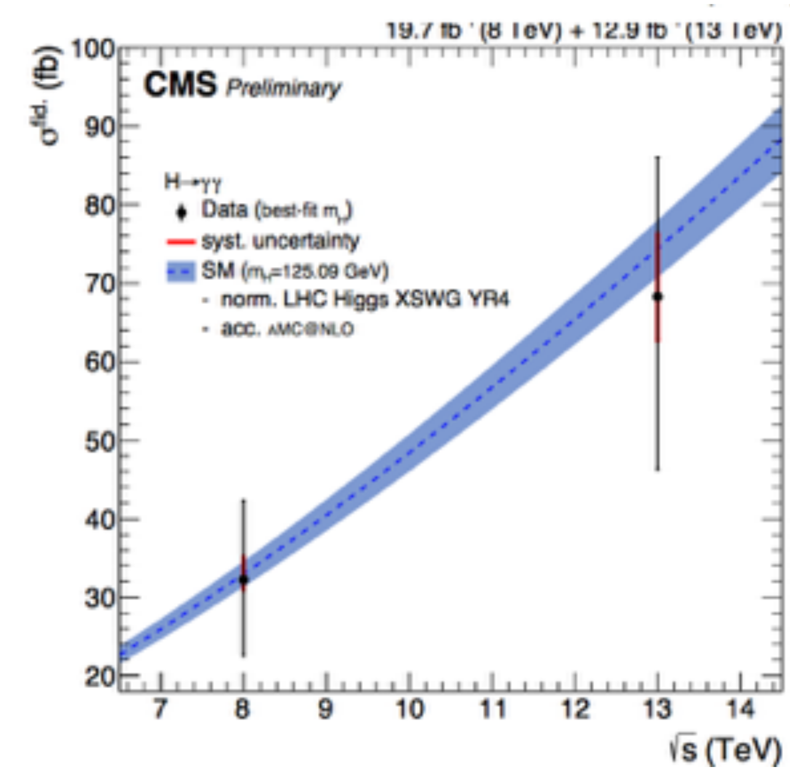
- Interference contributions with light quarks are large and negative!
- Exact mass corrections known up to NLO.
  (3-loop computation for NNLO)
- Interference effects turn positive when going to higher jet multiplicity -> Gionata's talk
- Recent progress and Real-Virtual diagrams
  [Bonciani,DelDuca,Frellesvig,Henn,Moriello,Smirnov]
  [Melnikov,Tancredi,Wever]

# GLUON FUSION – INCLUSIVE/EXCLUSIVE CROSS SECTION

- 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



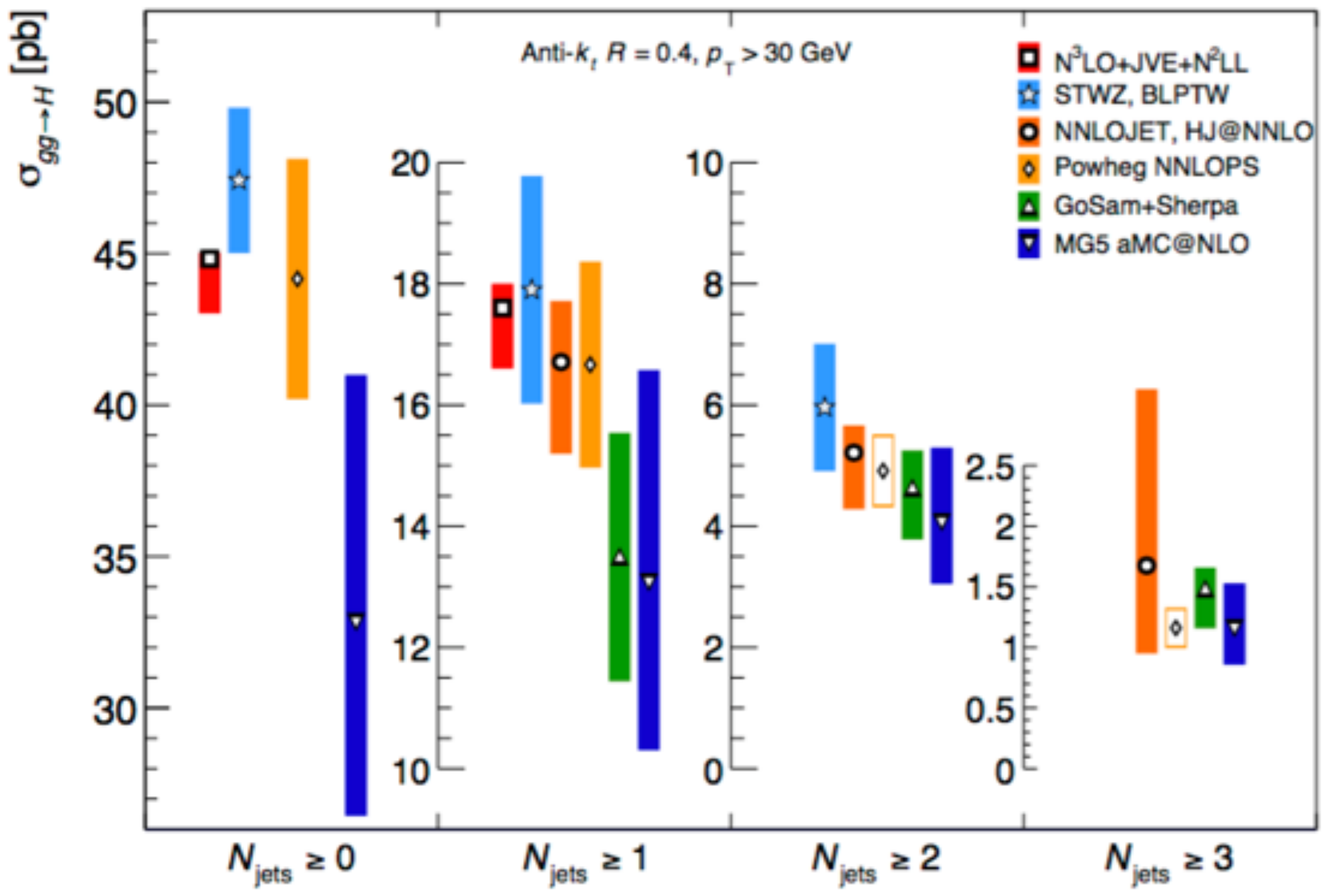

$$H \to \gamma\gamma$$




**CMS**

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

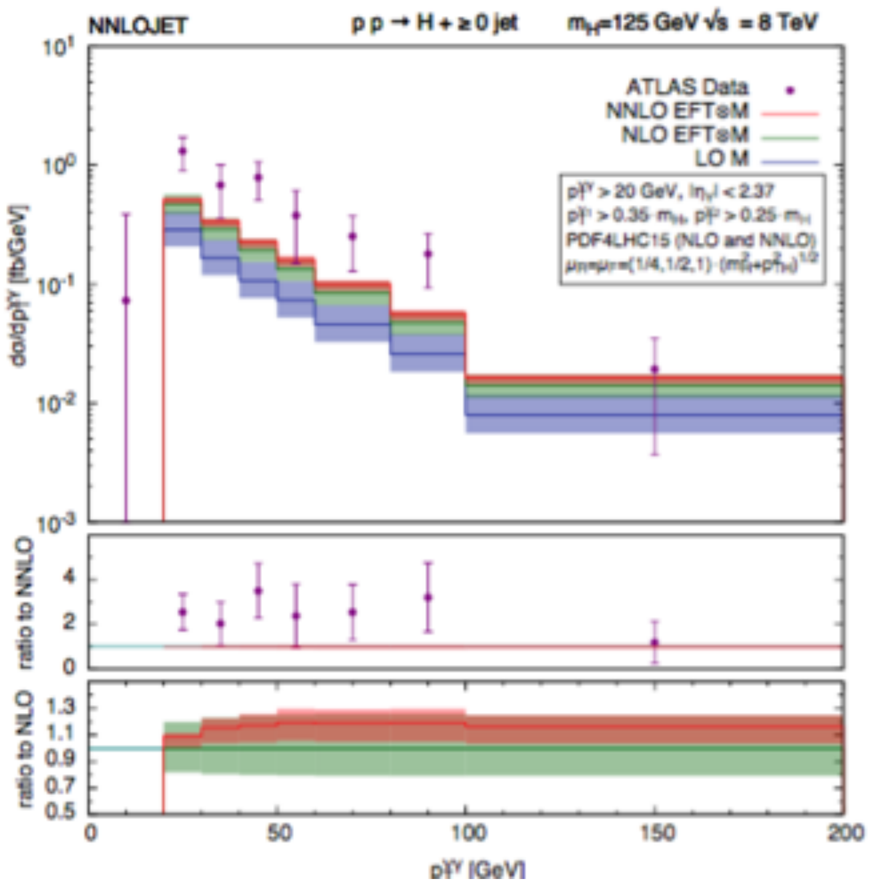
# GLUON FUSION – INCLUSIVE JET BINS



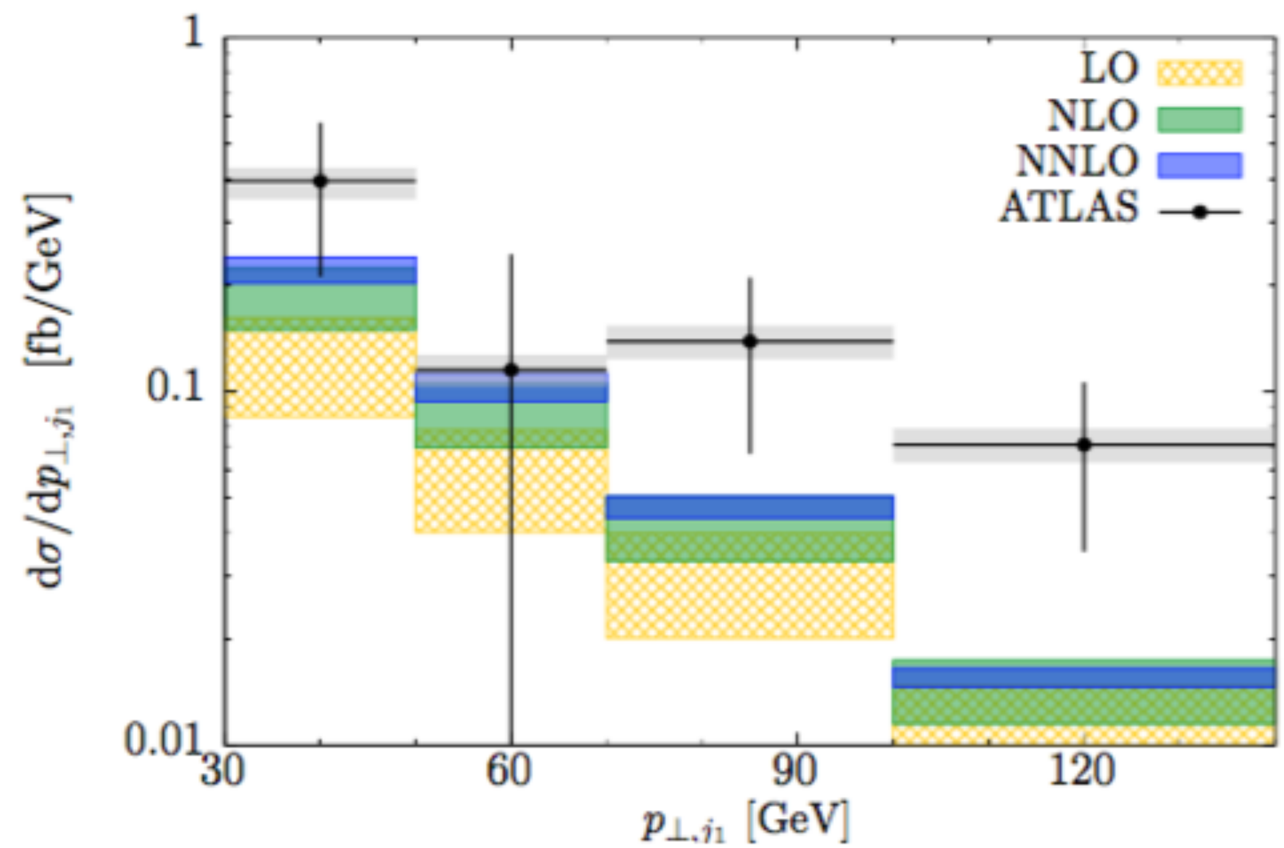

- Still **very** large statistics in one jet bin
- Some observables dependent on higher Jet multiplicity (VBF)

# GLUON FUSION – LEADING JET PT

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

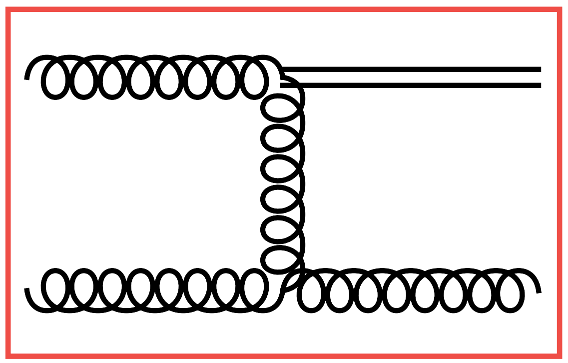



[Caola,Melnikov,Schulze]

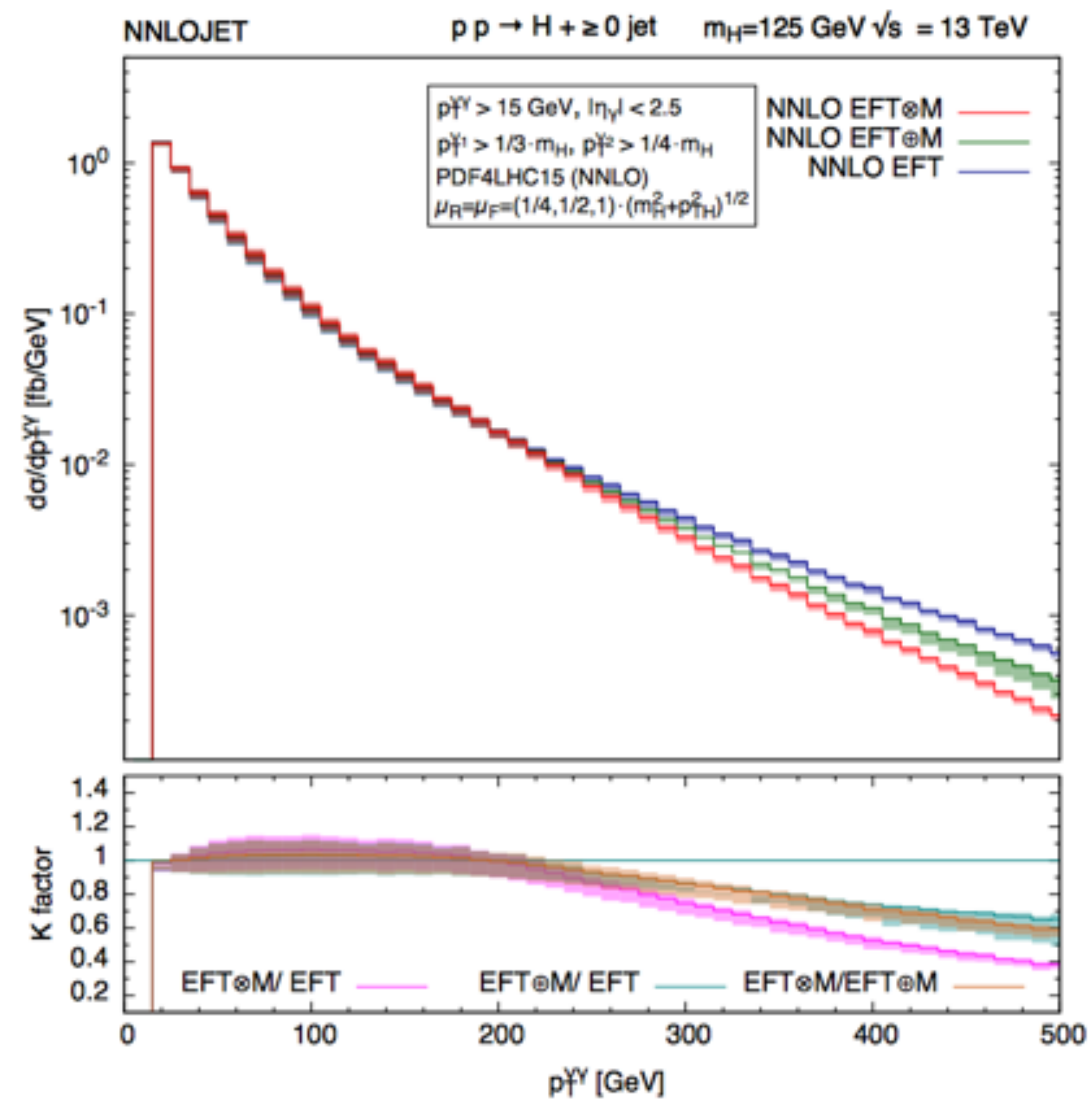



- Still largely uncertainty dominated
- Worries: Systematics ~ NNLO scale!
- Impact of PDFs on differential predictions? (DY)
- Hopefully many more pheno studies to come

# GLUON FUSION – HIGGS + JET AND MASSES



- NNLO EFT for small pT
- pT=400 GeV: 50 % uncertainty due to masses at LO
- full NLO H+J ?
- EFT works well for pT< ~200 GeV



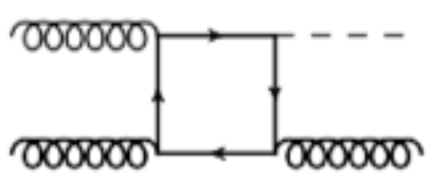

[Chen,Cruz-Martinez,Gehrmann,Glover,Jaquier]

# GLUON FUSION - HIGGS + JET AND MASSES

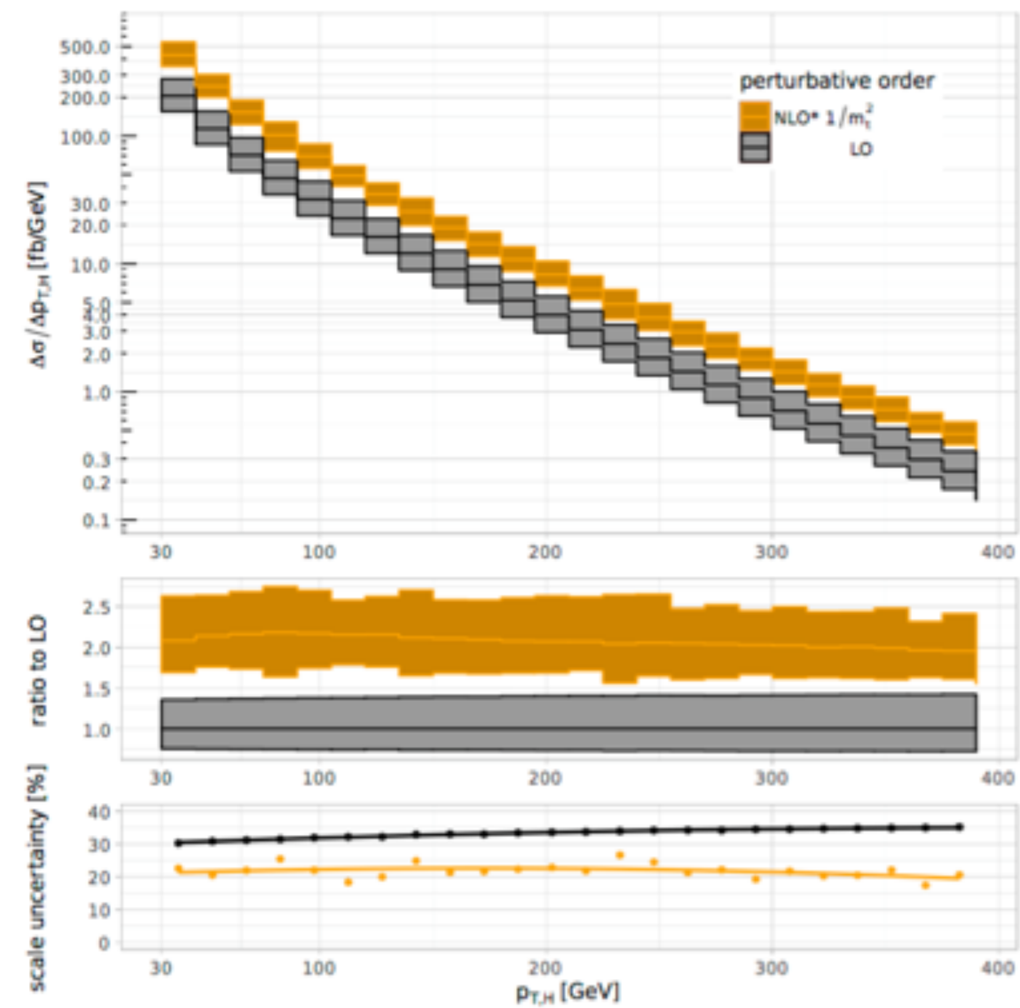
- Different behaviour

$$\sigma_{EFT} \sim \frac{1}{p_t^2} \text{ vs. } \sigma_{full} \sim \frac{1}{p_t^4}$$

- Start to probe the dynamics in the loop



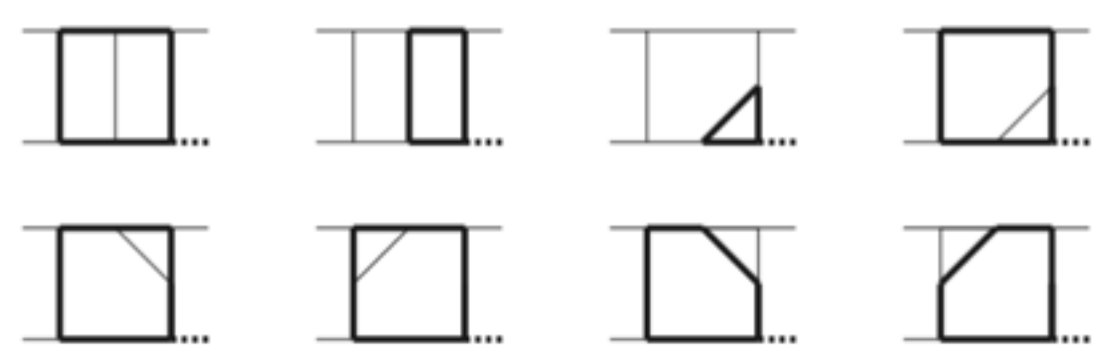
- Full calculation: Very difficult.
  Many master integrals of many scales, elliptic functions etc.




[Neumann,Williams]

- Planar Results:

[Bonciani,DelDuca,Frellesvig,Henn,Moriello,Smirnov]

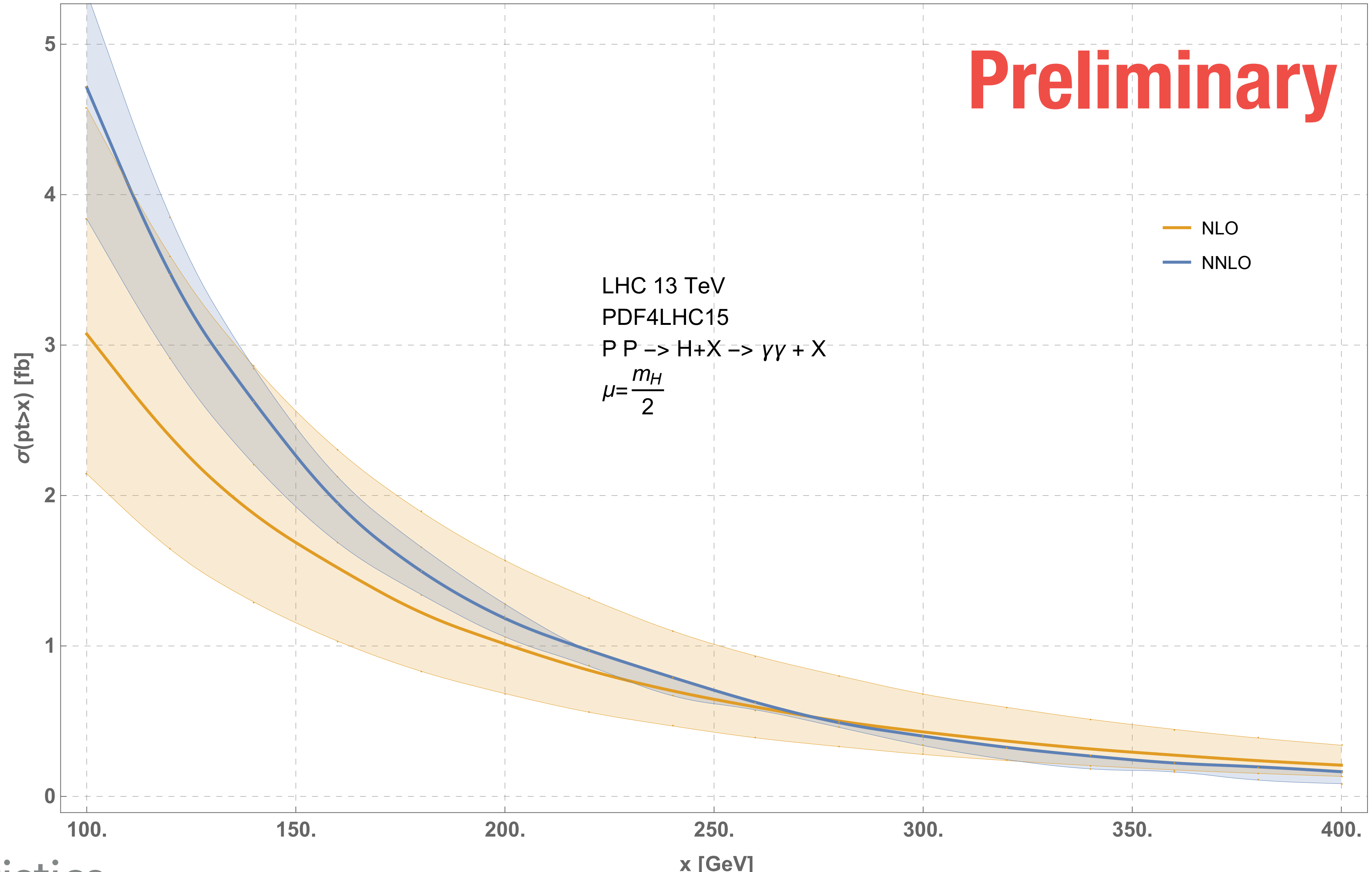


- Bottom quarks! Impact for low pT.

  [Melnikov,Tancredi,Wever]

# GLUON FUSION - HIGGS + MASSES

- What is the actual experimental sensitivity?




- Cumulative cross section: Observable with most statistics At 300 fb^1: 1 fb ~ 300 events ~ 6 % uncertainty.

- Sensitivity of selection cuts on mass effects Extrapolation uncertainty.

$$\sigma_{h\to 4l}(pt >\sim 50GeV) = 1\text{fb}$$

[Higgs +3 Jets and masses -> Gionata]

# PRECISION FOR HIGGS DIFFERENTIAL

- Successful treatment of double real radiation
- Applied to colored final state
- Big success for H+J
- Higgs +JJ:
  Complicated amplitudes
  Interesting for VBF
  [Papadopoulos,Tomasini,Wever]

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

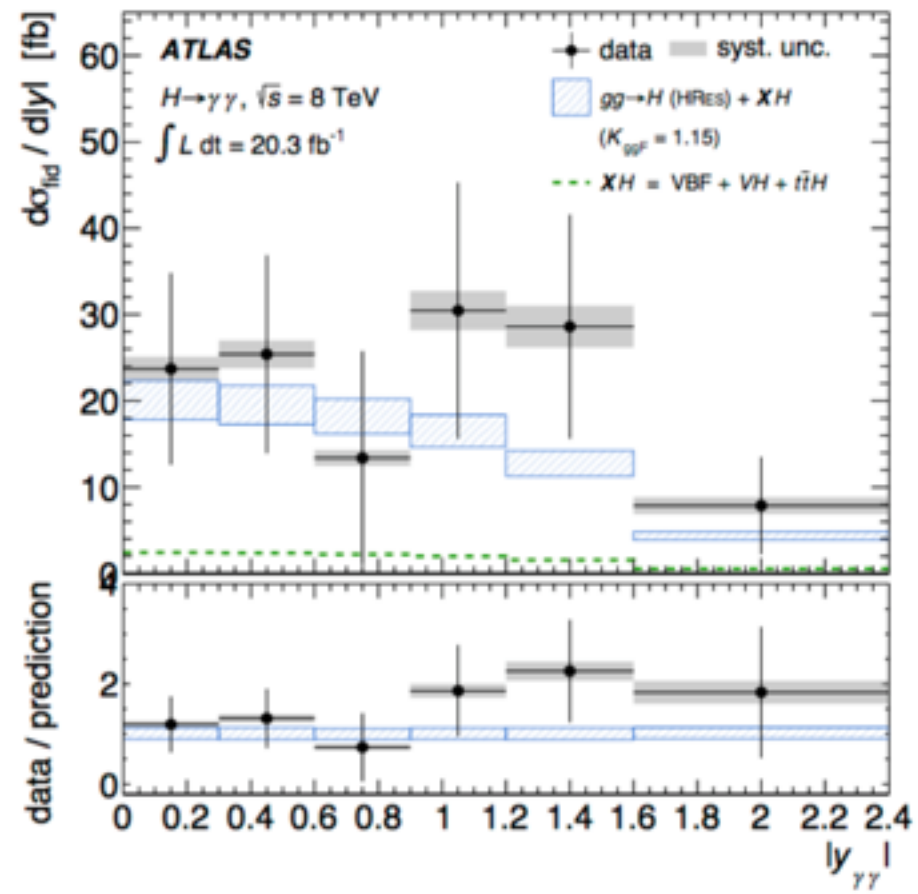
[Chen,Gehrmann,Glover,Jaquier]

[Boughezal,Caola,Melnikov,Petriello,Schulze]

[Chen,Gehrmann,Glover,Jaquier]

# PRECISION FOR HIGGS DIFFERENTIAL

- Missing for N3LO H+0 Jets
- Precision predictions for fiducial volumes
- Jet-Veto cross sections (H->WW)




**Ideally: Compute**

**fully differential N3LO corrections**

- Complications: Integration over three unresolved parton phase space, subtraction, stability, speed

**But let's start with a bit of differential**

work with Babis Anastasiou, Falko Dulat, Simone Lionetti, Andrea Pelloni, Caterina Specchia

# GENERAL IDEA – HIGGS DIFFERENTIAL

Master-Formula for differential cross section

$$\frac{d\sigma}{d\mathcal{O}} \sim \int d^d p_h dx dy f(x) f(y) \frac{\partial \hat{\sigma}}{\partial p_h} \mathcal{J}_{\mathcal{O}}(p_h)$$

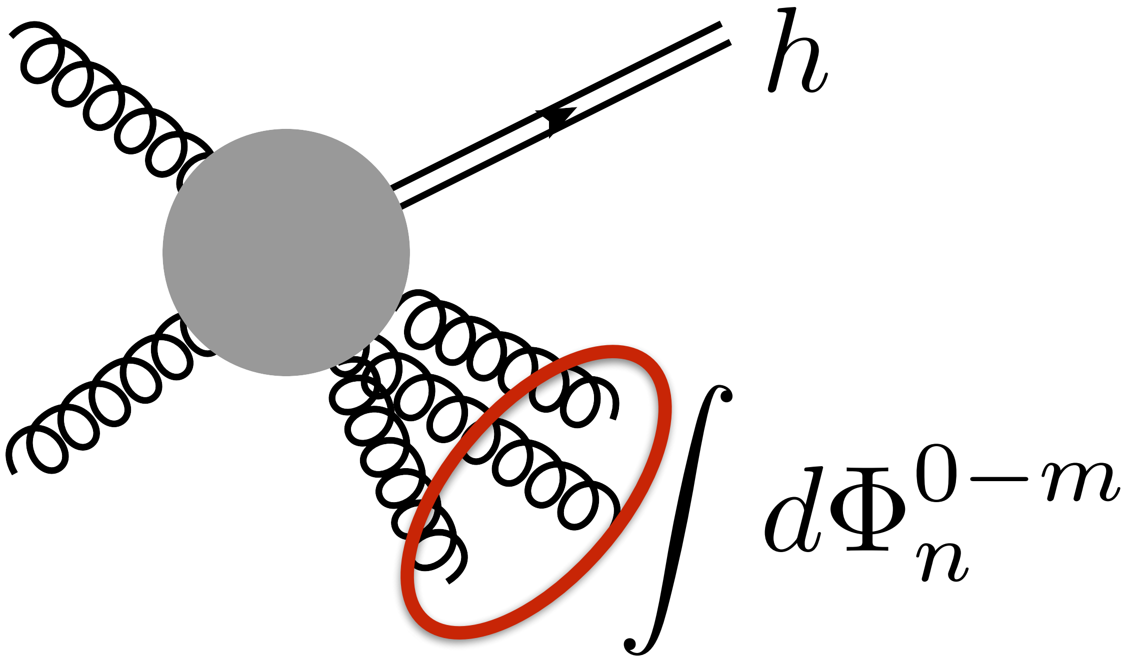
Measurement Function

Observable depending on Higgs momentum

For Example

$$\mathcal{J}_{\mathcal{O}}(p_h) = \theta(p_T < 50GeV)$$

# PHASE – SPACE FACTORISATION



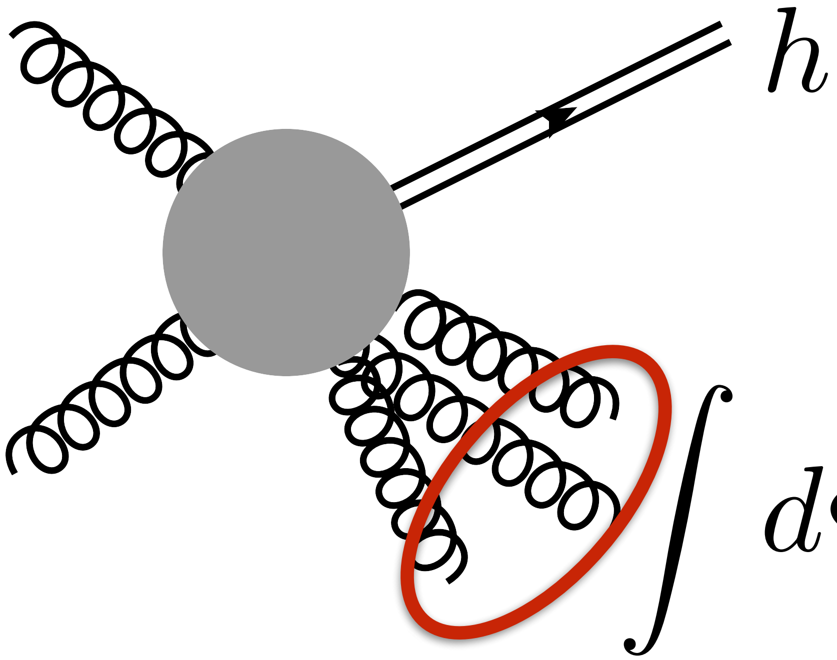

Integrate only radiation

Higgs properties:

3 Variable Problem

| | |
|---|---|
| $Y$ | Rapidity |
| $p_T$ | Transverse Momentum |
| $m_h$ | Mass / Virtuality |
| $\phi$ | Azimuthal Angle trivial! |

# PHASE – SPACE FACTORISATION




$$\int d\Phi_n^{0-m}$$

**Parametrize:**

$$(m_h^2, p_T, Y) \to (z, x, \lambda)$$

**More convenient for computation**

$$\int d\Phi_n \sim \int_0^1 d\lambda dx \left(\lambda(1-\lambda)\right)^{\frac{d}{2}-1} (1-x)^{\frac{d}{2}-2} (1-x\bar{z}\lambda)^{-\frac{d}{2}} \times \int d\Phi_n^{0-m}$$

**Phase-space singularities at the boundaries**

# INTEGRATE RADIATION

- Perform analytic integration over real radiation: Reverse Unitarity
- Reduce to phase space master integrals
- Compute master integrals via direct integration or differential equations

$$d\vec{M} = A(z, x, \lambda, \epsilon)\vec{M}$$

**Three variables for differential equations** $(z, x, \lambda)$

**Alphabet**

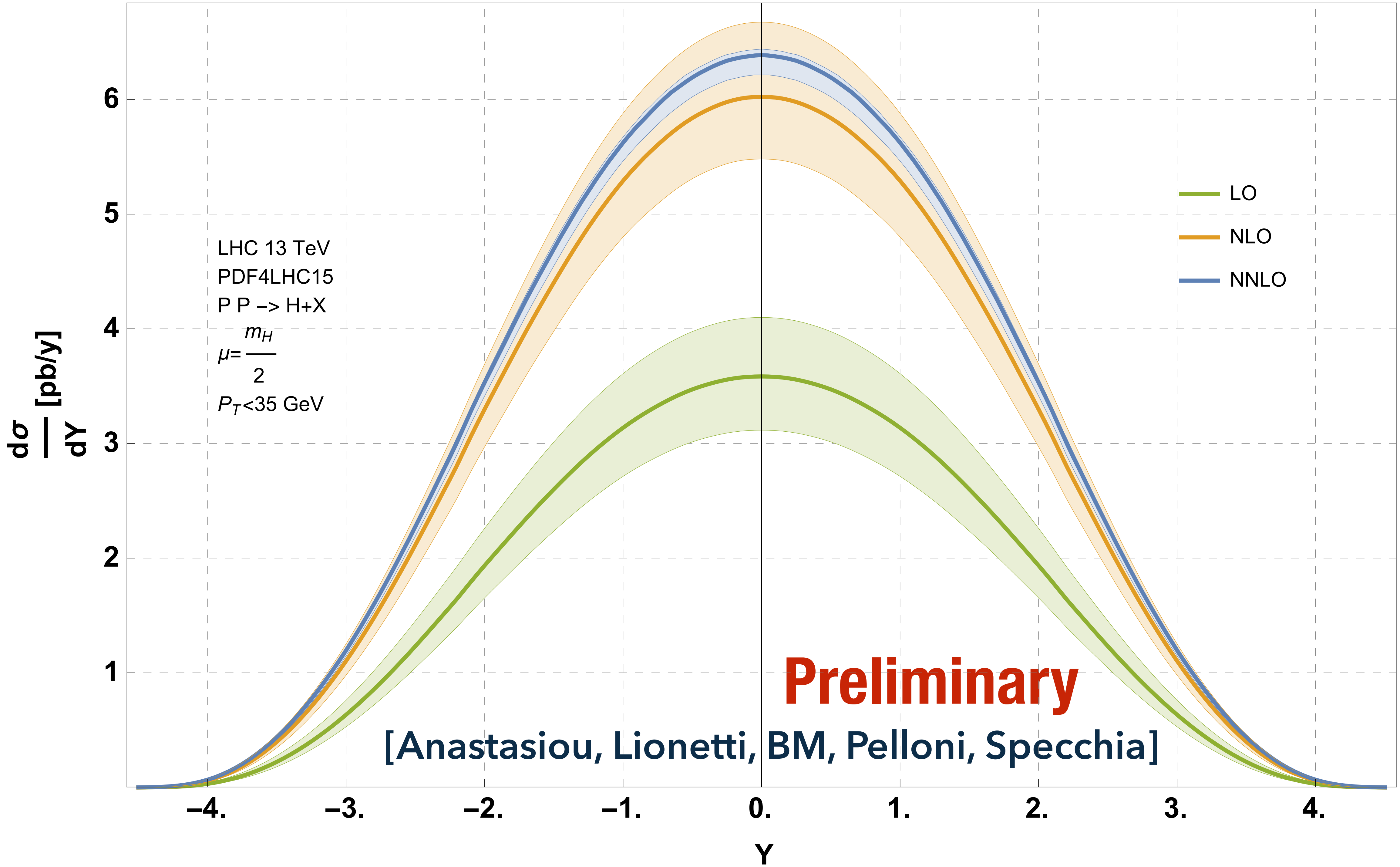
$$\{1-\bar{z}, \bar{z}, 1-x\bar{z}, 1-\lambda x\bar{z}, \lambda^2(-(x-1))x\bar{z}^2-\bar{z}+1, \lambda^2 x\bar{z}^2+\bar{z}(-2\lambda x+x-1)+1,$$

$$\lambda^2x^2\bar{z}\left(-4\lambda+\lambda^2\bar{z}+4\right)-2\lambda x(\lambda(\bar{z}-2)+2)+1, 2\lambda^2x^2\bar{z}-\sqrt{\lambda^2x^2\bar{z}\left(-4\lambda+\lambda^2\bar{z}+4\right)-2\lambda x(\lambda(\bar{z}-2)+2)+1}- \ldots$$

# CURRENT STATUS

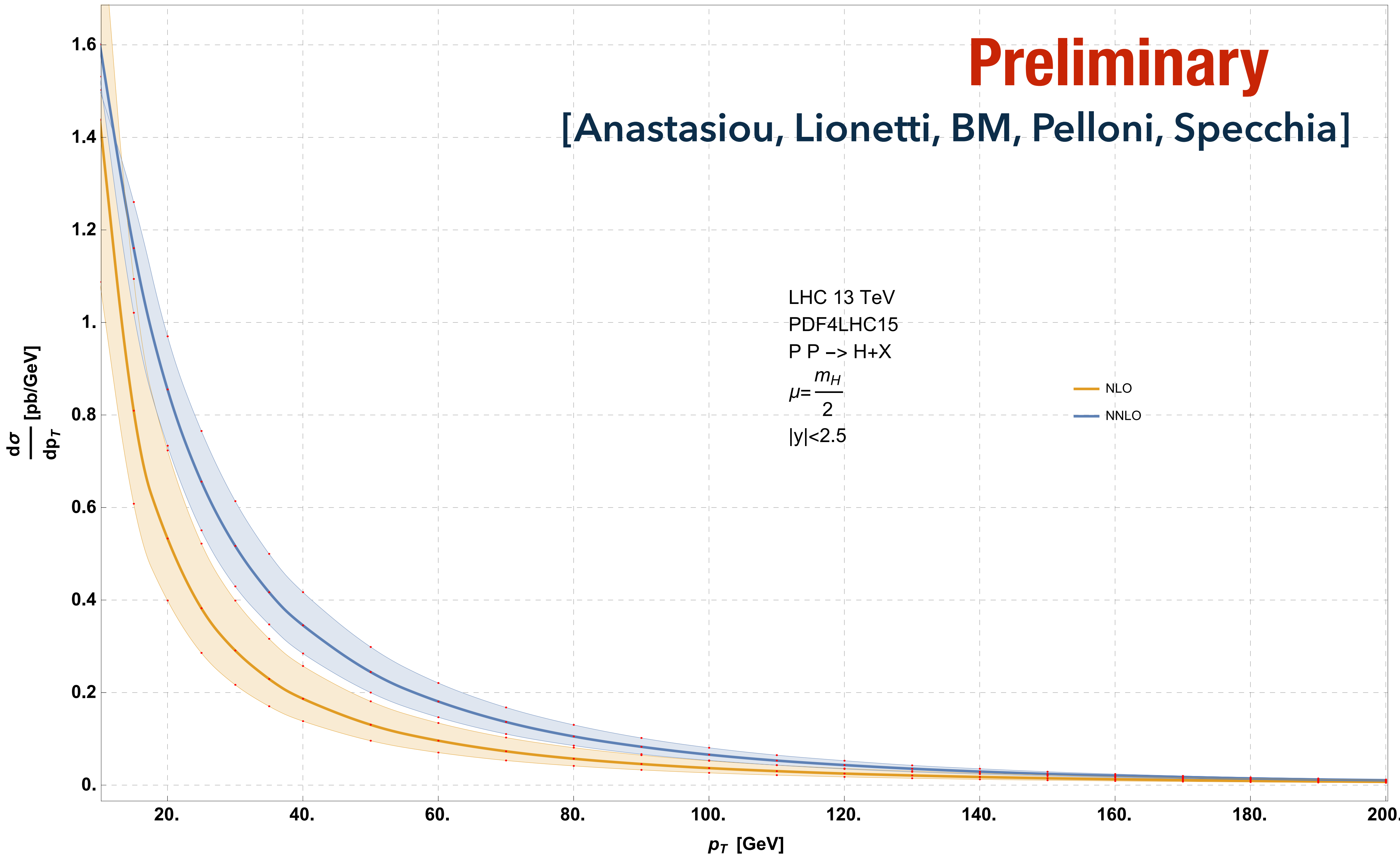
- Analytically computed all partonic cross sections for all channels at NNLO
- Subtraction of singularities and numerical integration work
- Computed $\mathcal{O}(\epsilon)$ cross section coefficient required for N3LO computation
- Numerical implementations

# NNLO RAPIDITY DISTRIBUTION



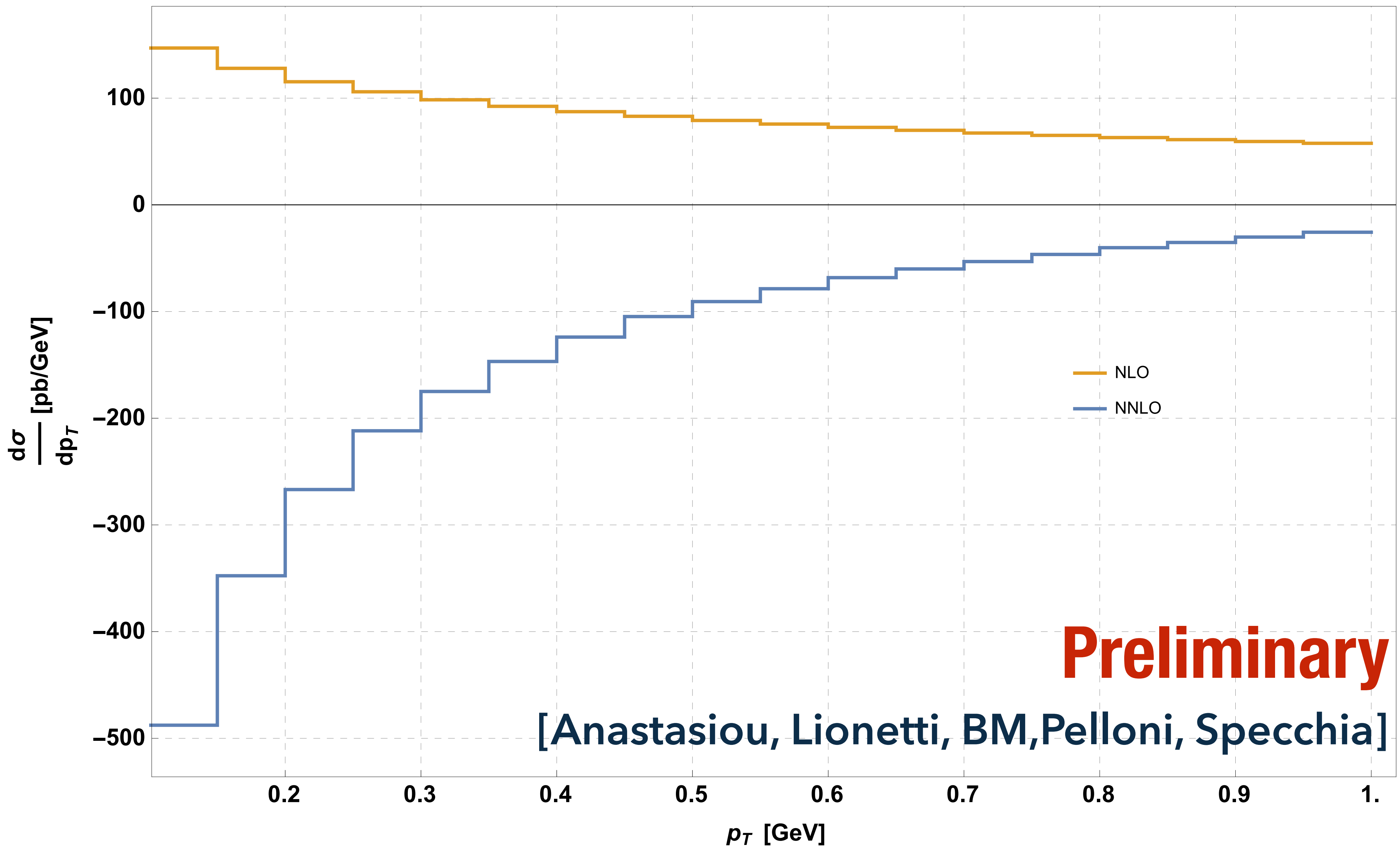

pT< 35 GeV

# NNLO PT DISTRIBUTION




## |Y|< 2.5

# NNLO PT DISTRIBUTION




## 0.1 GeV < pT < 1 GeV

# CONCLUSIONS

- QCD precision predictions for Higgs boson physics are inseparably intertwined with the success of Higgs boson phenomenology at the LHC
- Progress towards precision measurement
- Few select observables deserve our absolute best
- Number of non-negligible effects increases as we strife for higher precision
- Demand for new methods and ideas:
  Progress towards differential N3LO