GEORG-AUGUST-UNIVERSITÄT
GÖTTINGEN

Institut für Theoretische Physik

Bounding the Higgs-boson width at the HL-LHC through interference effects

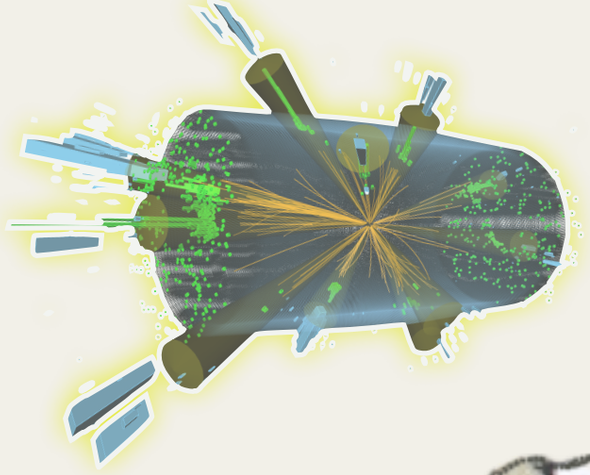
DIS 2019 in Torino

9 April 2019

WG3: Higgs and BSM Physics in Hadron Collisions

Enrico Bothmann

Lance Dixon, Stefan Höche, Silvan Kuttimalai



MCnet

SHERPA overview

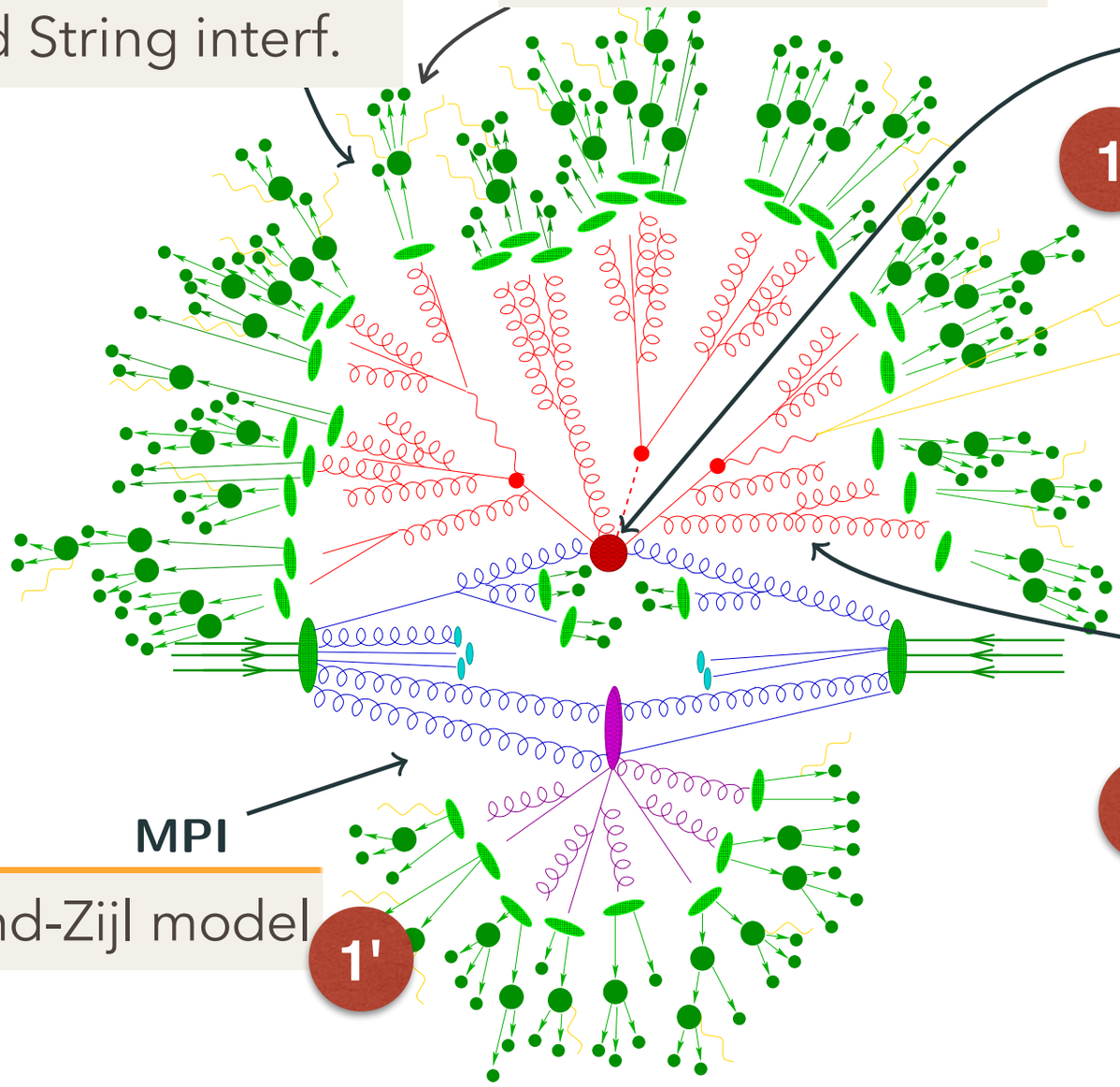
[Gleisberg et al. 0811.4622]

Hadron Decays

Phase-space or EFTs
YFS QED corrections

Hadronization 3

Cluster fragmentation
& Lund String interf.



Hard process

1 automated: LO, NLO QCD
(3.0: NLO EW, DY/DIS NNLO QCD)
tree generators (Amegic & Comix)
external loop libraries

Parton shower

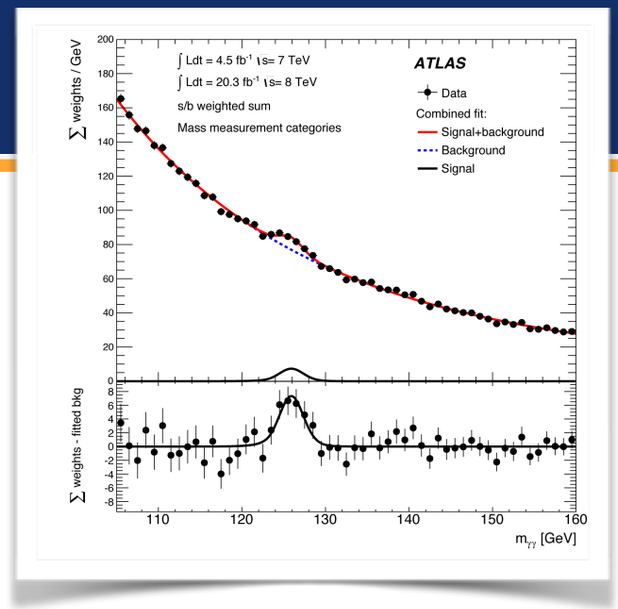
2 parton showers (CS & Dire)
QED (YFS resummation & shower)

MPI

Sjöstrand-Zijl model 1'

↝ each "MC point" gives a fully differential simulated event

Motivation



- LHC: Higgs mostly produced through gluon fusion
- H→γγ decay of high relevance due to clean final state
  - measure mass peak M_H with good accuracy
  - can not measure width directly, $\Gamma_H < O(10^{-2})$ × exp. resolution σ_{res}
- Higgs might couple to unknown states ⇝ $\Gamma_H > \Gamma_H^{SM}$
- on-shell signal cross section ~g^2/Γ_H ⇝ coupling-width degeneracy
- how to break degeneracy to measure Γ_H without assumptions on g?
  - complement with off-shell measurements (measure with precision $\Gamma_H = 4 \pm 1$ MeV, but need to assume that couplings do not vary with scale)
    [ATLAS 1902.00134]
  - stay on-shell, use interference-induced rate change (bound ~8–22 Γ_H/Γ_H^{SM})
    [Campbell et al. 1704.08259]
  - stay on-shell, use interference-induced peak shift/deformation

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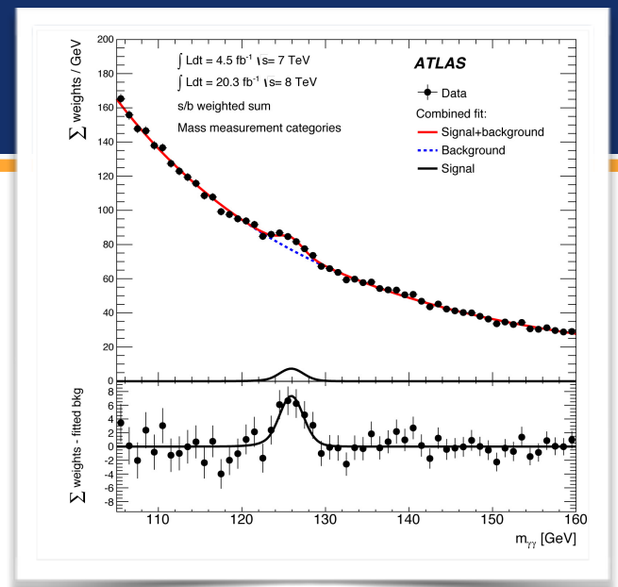
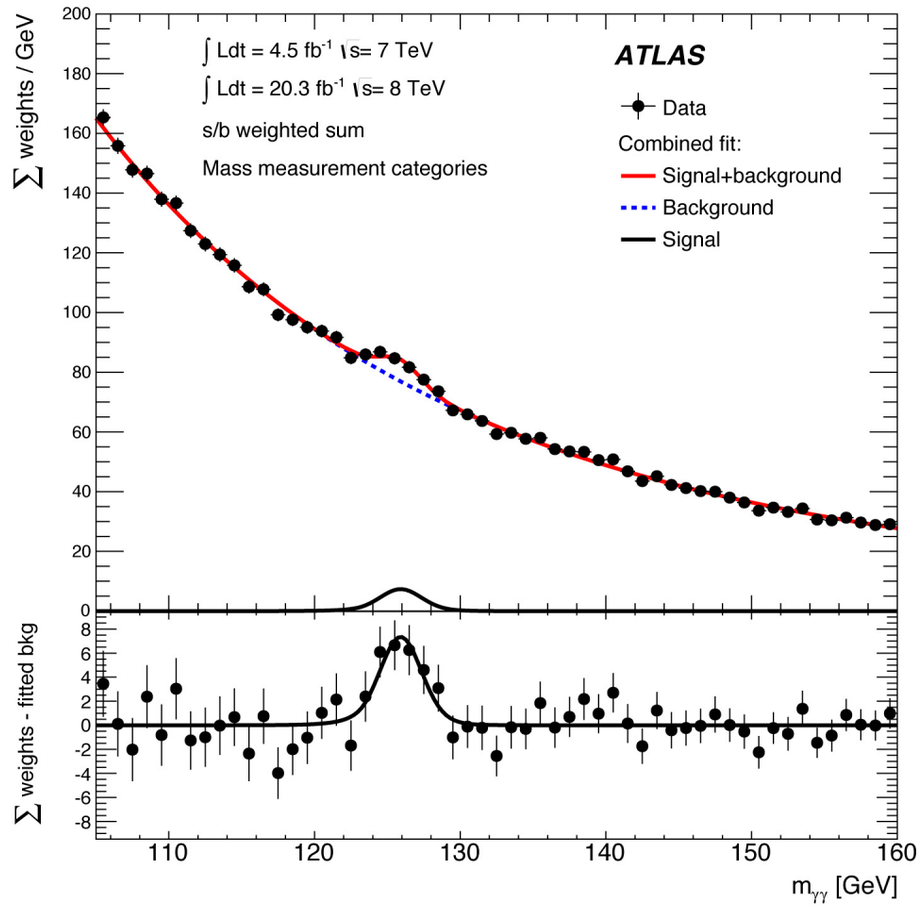


- use interference-induced peak shift/deformation
- estimates for shift-based bounds at fixed-order already exist, but are they robust?
  [Dixon, Li 1305.3854 (2013)]
- calculate particle-level prediction and use realistic analysis cuts
  - Sherpa S-MC@NLO with implementation of NLO calculation for interference terms
    [Dixon, Li 1305.3854 (2013)]
  - background 0j@NLO, ≤3j@LO CKKW-L
  - estimate (HL-)LHC reach using toy experiments
  - new: explore possibility of a direct fit to the distorted line shape

Overview: Mass shift through interference



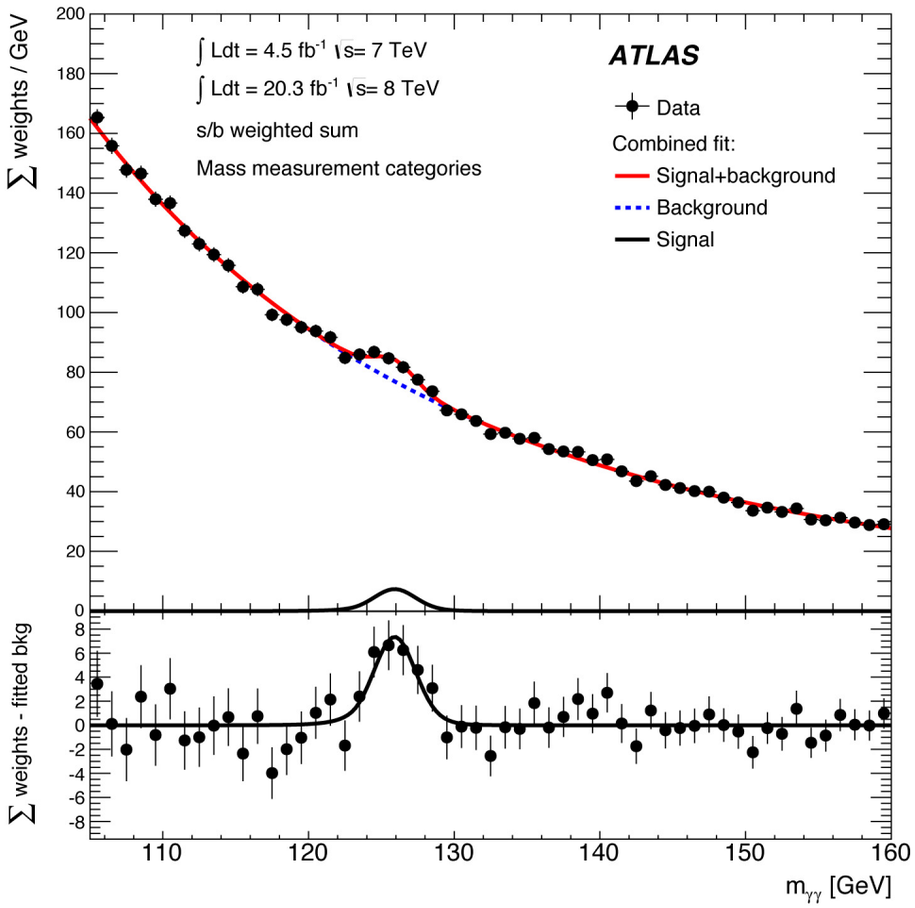
Overview: Mass shift through interference

[Martin 1208.1533 (2012)]

observation: interference of gg→H→γγ with gg→quark loop→γγ

⇒ smeared Higgs mass peak in $m_{\gamma\gamma}$ shifts:

$$\Delta M_H = -150\,\mathrm{MeV} \quad (\mathrm{LO})$$



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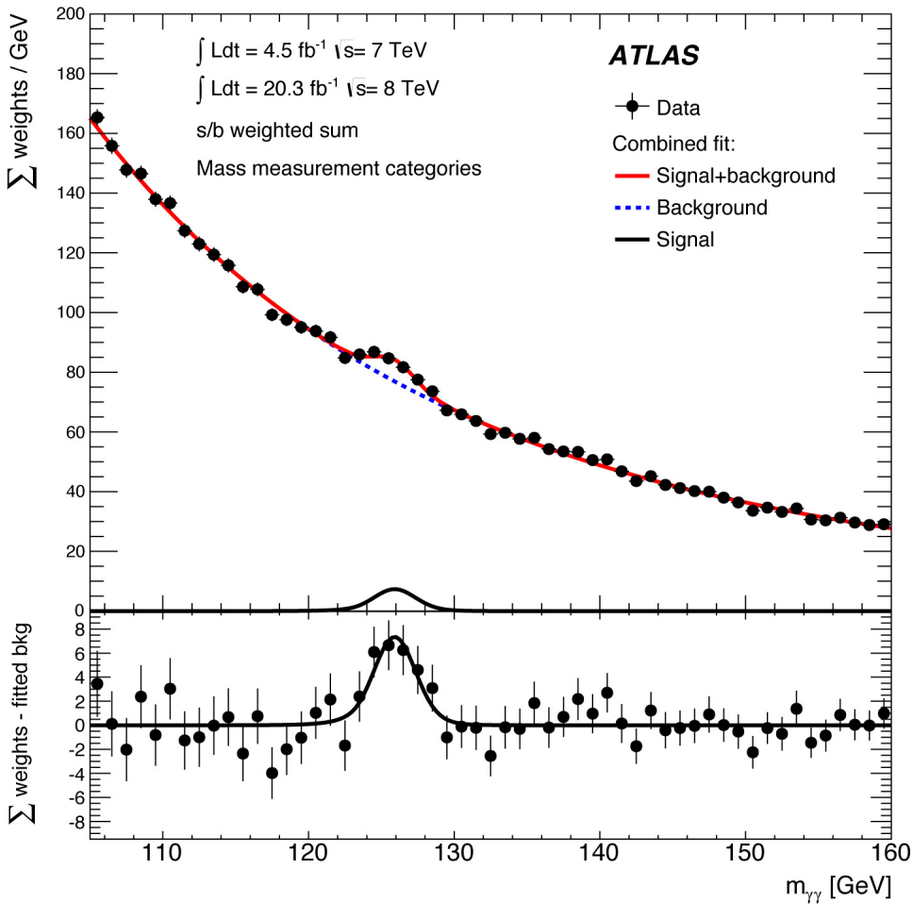
$$\sim 30 \times \Gamma_{\text{H}}^{\text{SM}} \quad (4\,\text{MeV})$$

$$\sim 0.1 \times \sigma_{\text{res}} \quad (1.7\,\text{GeV})$$

$$\sim 2.5 \times m_H^{\gamma\gamma}\ \text{uncert.} \quad (0.4\,\text{GeV at } 36\,\text{fb}^{-1}\ 13\,\text{TeV})$$

[ATLAS 1806.00242]



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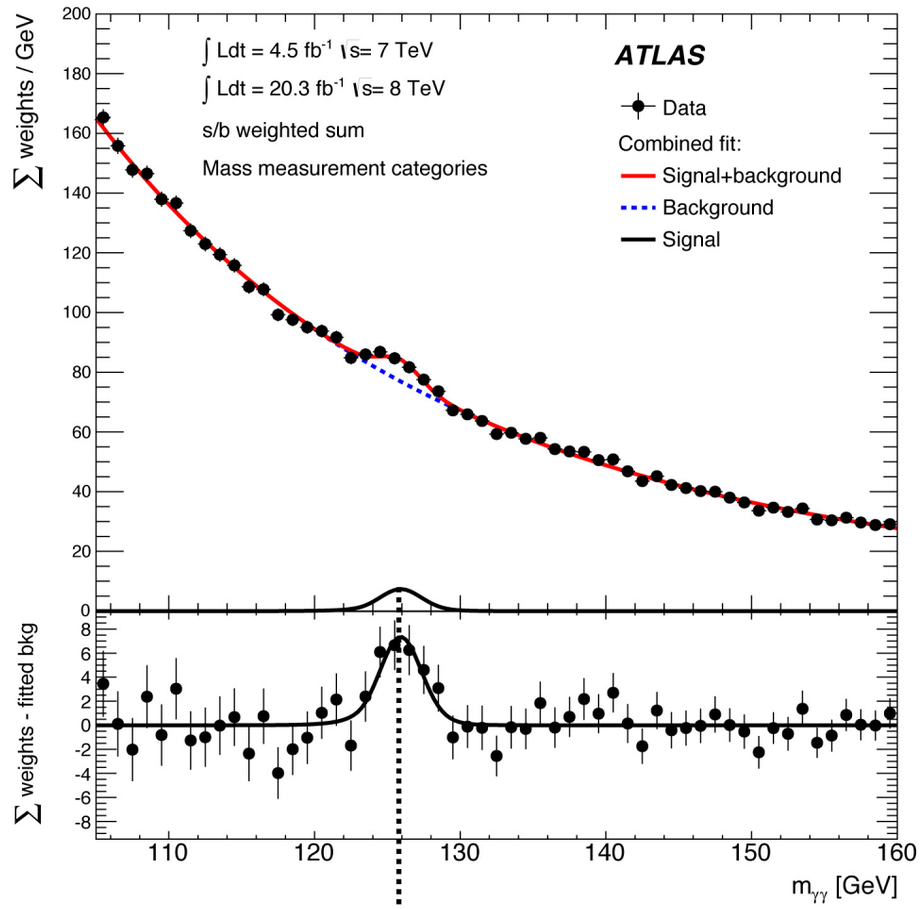

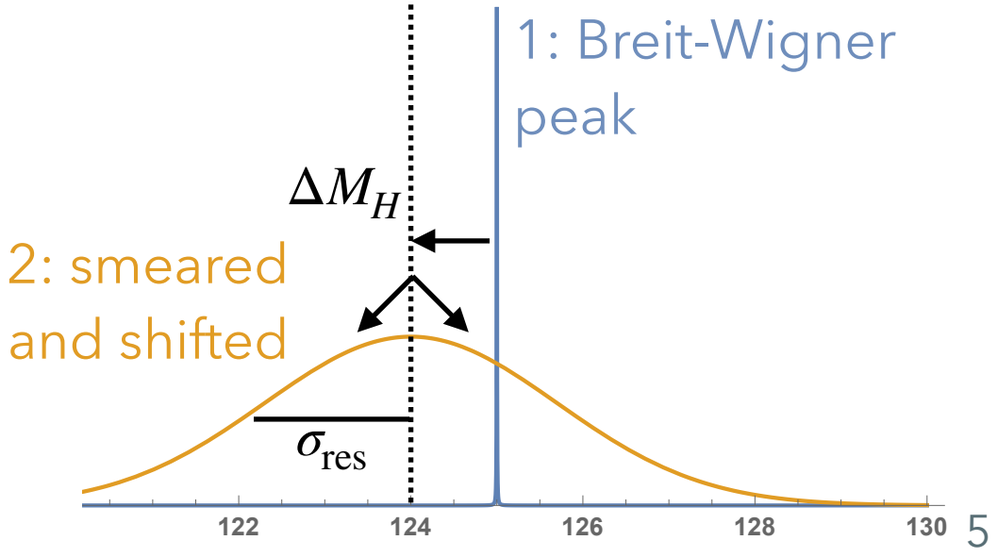

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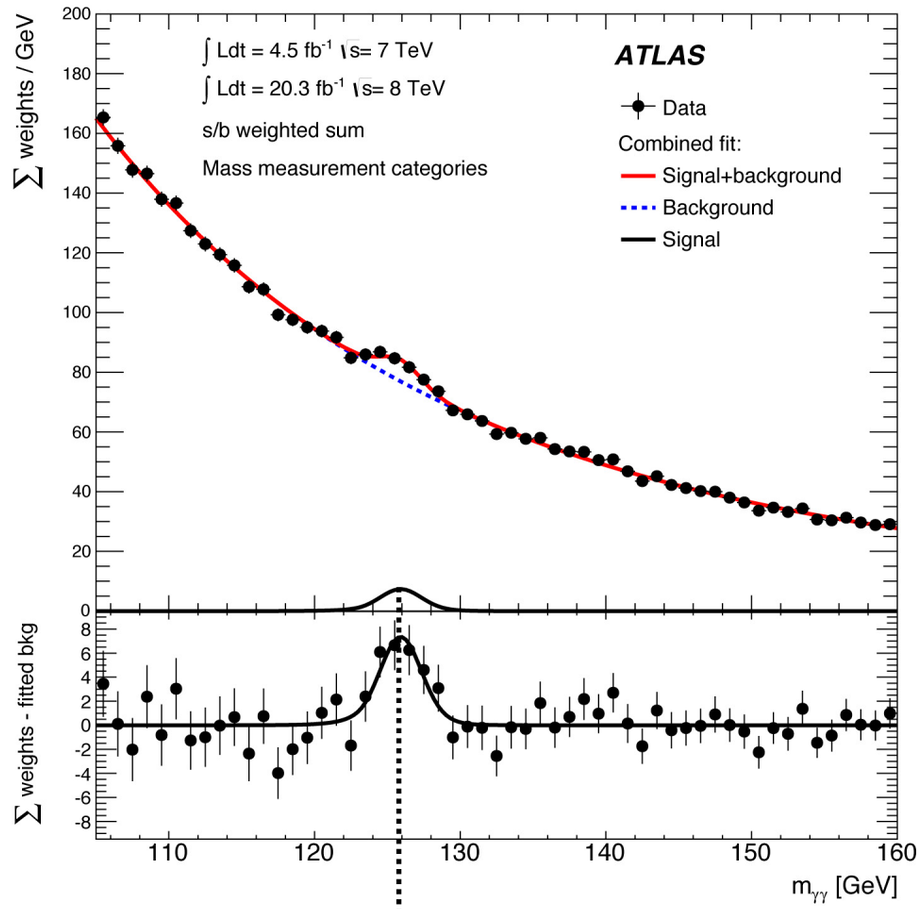
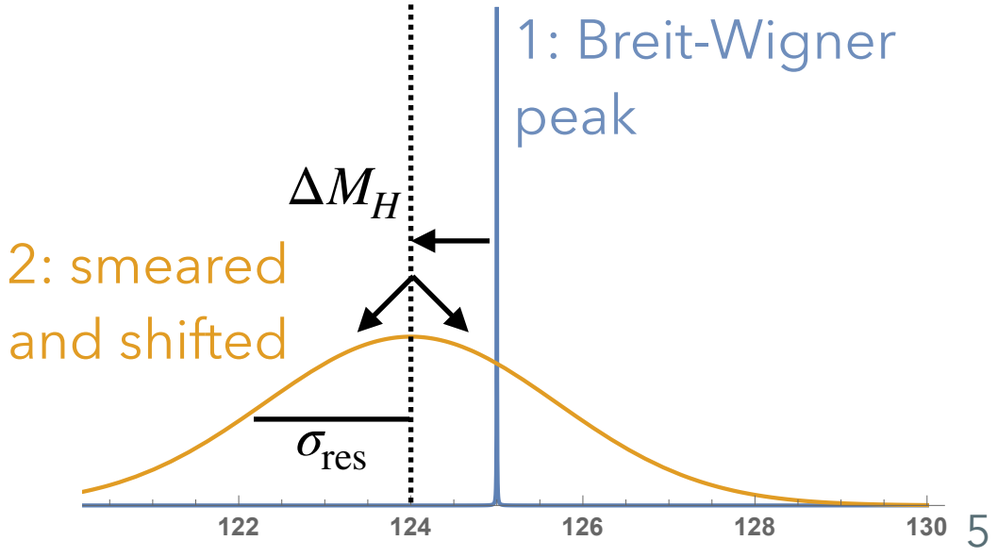
[Dixon, Li 1305.3854 (2013)]

$$\Delta M_H = -70\,\text{MeV} \quad \text{(NLO)}$$

(reduced due to large signal K factor)

observation: fixing signal event yield gives Γ_{H} bound independent from further assumptions on couplings and/or decay modes

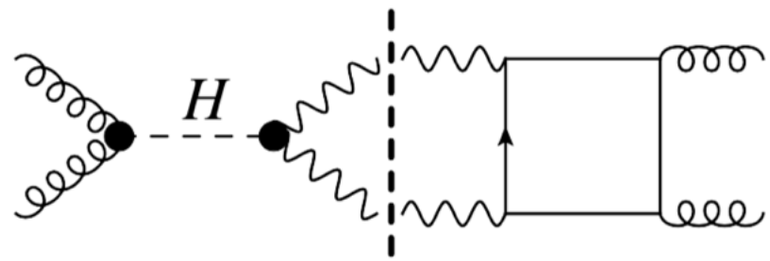




Why is the peak shifting?

[Martin 1208.1533 (2012)]

$$\mathscr{M} = \frac{1}{m^2 - m_H^2 + i\, m_H \Gamma_H} \frac{\mathscr{A}_S}{\sqrt{\pi}} + \frac{\mathscr{A}_B}{\sqrt{\pi}}$$



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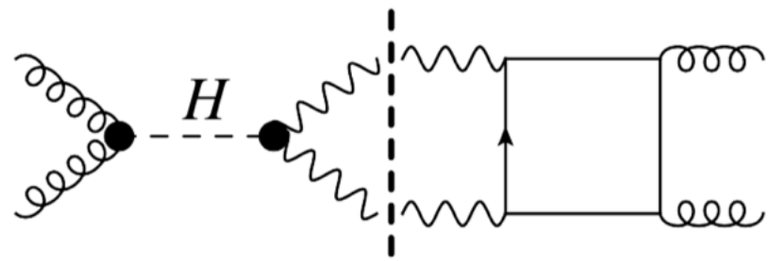

$$\hat{\sigma}_{\mathrm{S}} = \mathrm{Re}\{\mathscr{L}\} \frac{1}{2m_H^2} \int \mathrm{d}\Phi \frac{|\mathscr{A}_S|^2}{m_H \Gamma_H} ,$$

$$\hat{\sigma}_{\mathrm{I}} = \mathrm{Re}\{\mathscr{L}\} \frac{1}{2m_H^2} \int \mathrm{d}\Phi\, 2\, \mathrm{Im}\left\{\mathscr{A}_S \mathscr{A}_B^*\right\} ,$$

$$\hat{\sigma}_{\mathrm{R}} = \mathrm{Im}\{\mathscr{L}\} \frac{1}{2m_H^2} \int \mathrm{d}\Phi\, 2\, \mathrm{Re}\left\{\mathscr{A}_S \mathscr{A}_B^*\right\} .$$

$$\mathscr{L} = \frac{1}{\pi} \frac{m_H \Gamma_H + i(m_{\gamma\gamma}^2 - m_H^2)}{(m_{\gamma\gamma}^2 - m_H^2)^2 + m_H^2 \Gamma_H^2}$$

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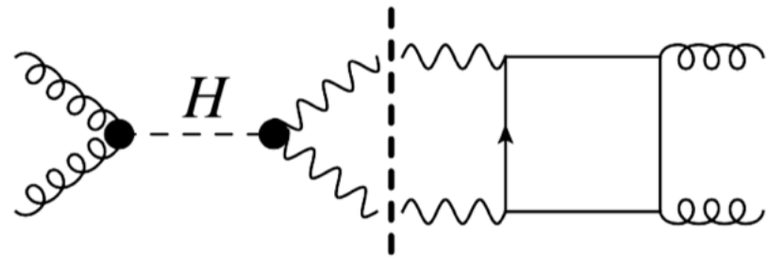

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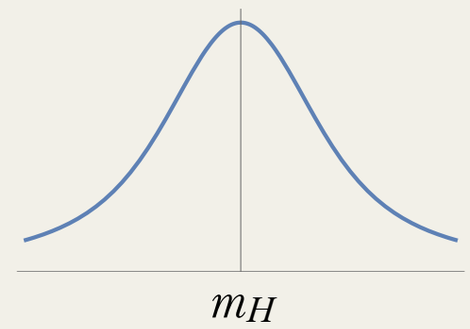
qualitative contribution shapes after smearing:



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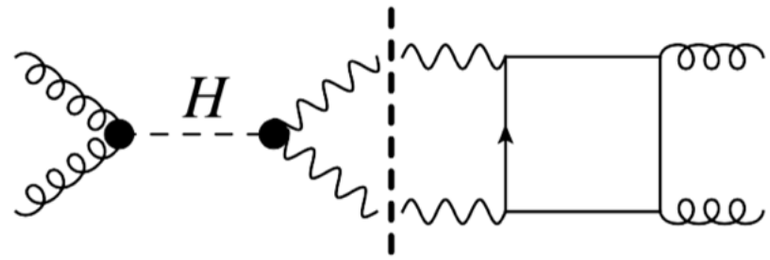

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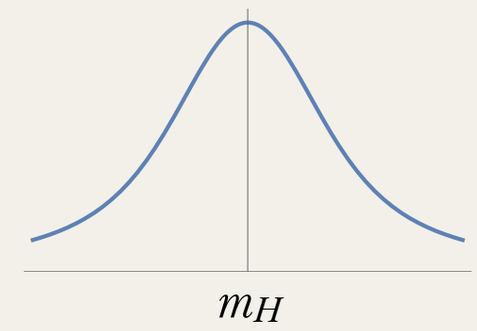

⇝ sum gives distorted+shifted peak

Why should we care?

[Dixon, Li 1305.3854 (2013)]

- BSM: factors c_g, c_γ for **Hgg**, **Hγγ** couplings (SM: 1)
- let c_g, c_γ, Γ_H vary, but keep measured signal yield fixed: $\mu_{\gamma\gamma} \approx 1$

BSM parametrisation = SM × signal yield

$$\frac{(c_g c_\gamma)^2 \sigma_S}{m_H \Gamma_H} + c_g c_\gamma \sigma_I = \left(\frac{\sigma_S}{m_H \Gamma_H^{\mathrm{SM}}} + \sigma_I \right) \mu_{\gamma\gamma}$$

- σ_I very small, can be neglected for $\Gamma_H \lesssim 100\ \Gamma_H^{\mathrm{SM}}$

$$\Rightarrow c_g c_\gamma = \sqrt{\mu_{\gamma\gamma} \frac{\Gamma_H}{\Gamma_H^{\mathrm{SM}}}} \quad \text{and with} \quad \Delta m_H \sim c_g c_\gamma \quad \rightarrow \quad \Delta m_H \sim \sqrt{\mu_{\gamma\gamma} \frac{\Gamma_H}{\Gamma_H^{\mathrm{SM}}}}$$

⇒ bound on Γ_H independent from further assumptions on couplings and/or decay modes

A reference value for m_H

we need a comparison value to extract $\Delta m_H = m_H^{\text{shifted}} - m_H^{\text{actual}}$

- ɣɣj has smaller relative magnitude of interference
- … and opposite sign of interference for qg- and gg-initiated channels ⇒ cancellation

⇝ $p_{T,H}$ cut dependent mass shift

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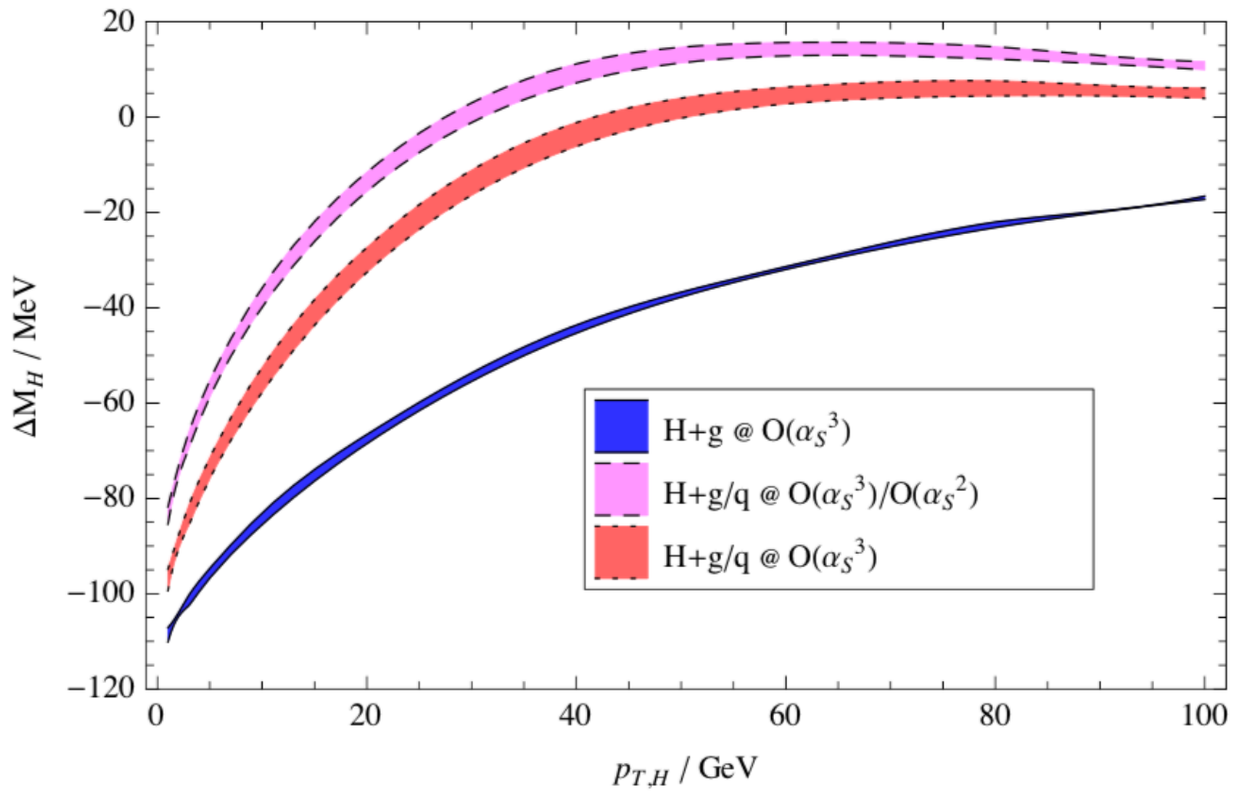

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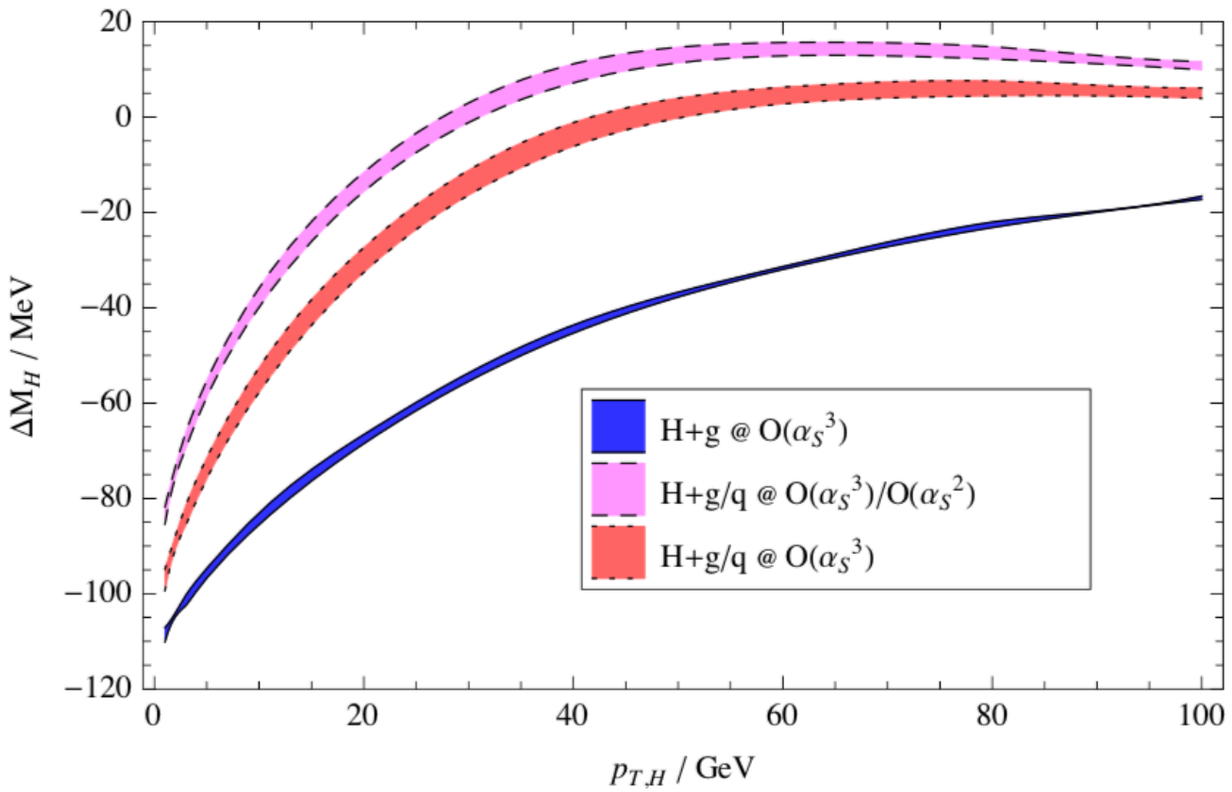

- extract shift within **gg→H→γγ(j)** channel by comparing large p_T bin and low p_T bin

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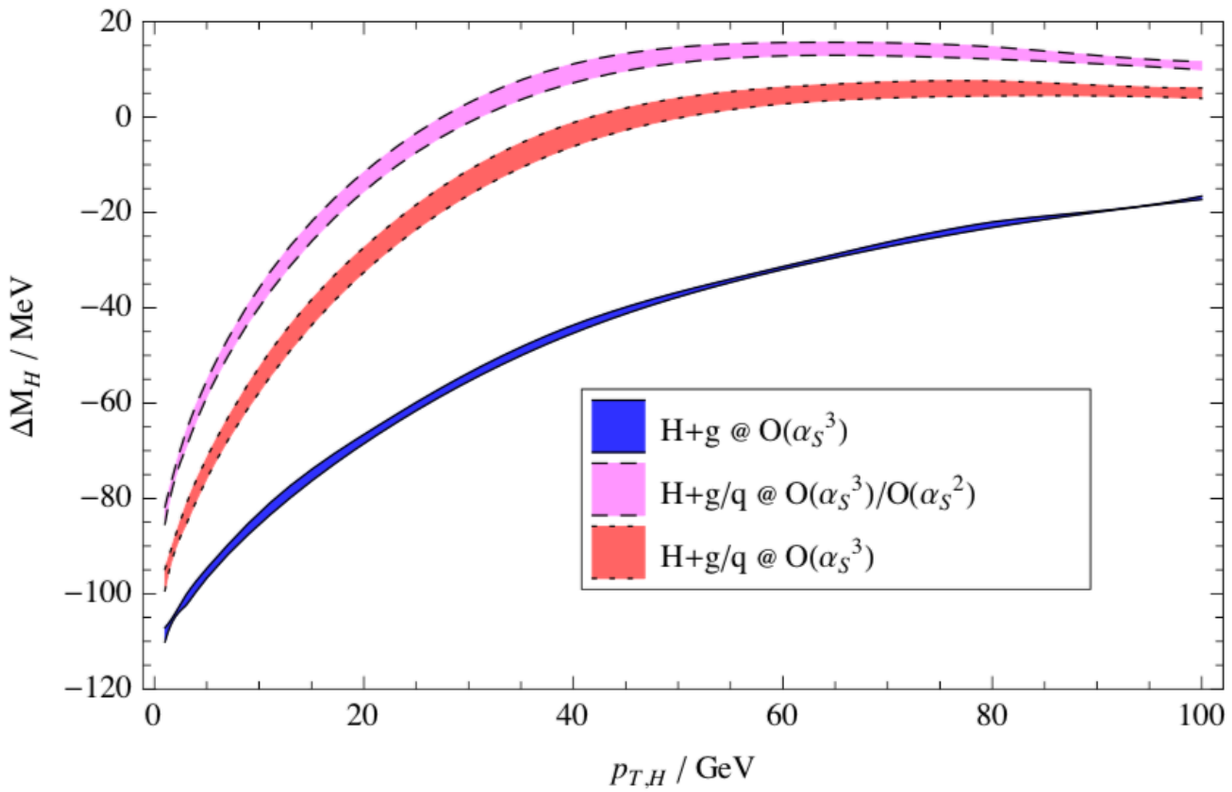

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- projection to HL-LHC (3 ab^{-1}): 95 % CL limit for $\Gamma_H \leq 15\ \Gamma_H^{SM}$

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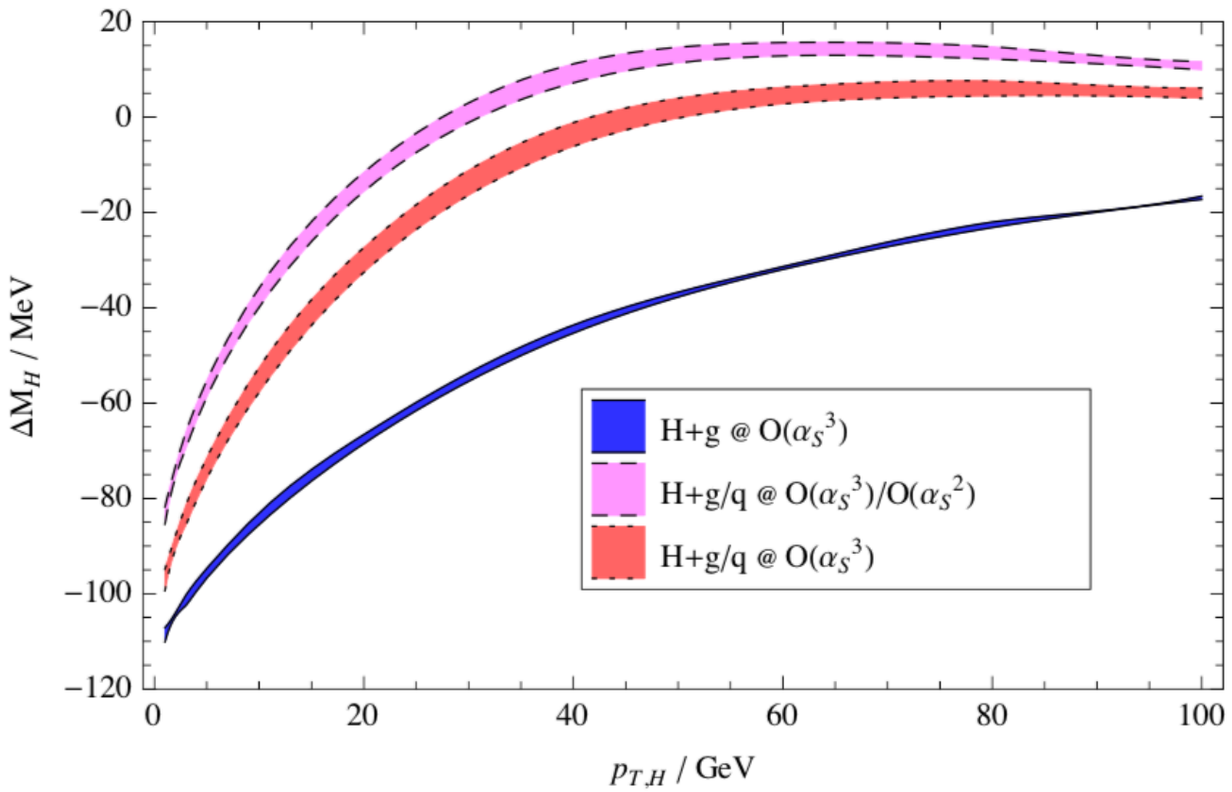

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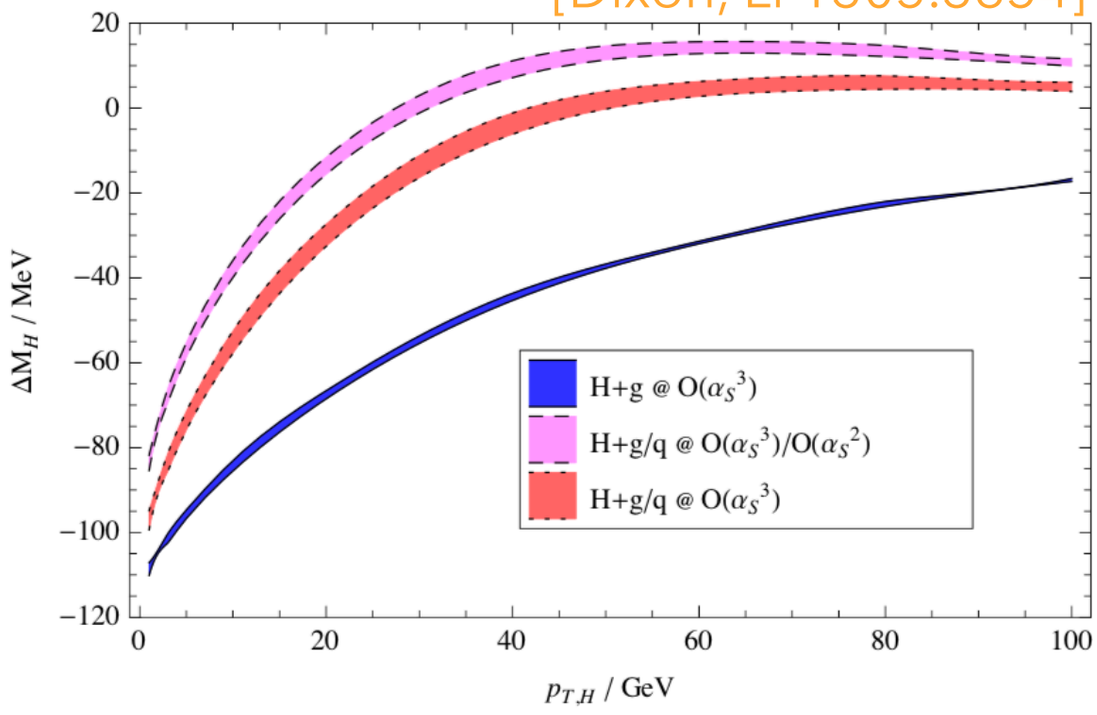
- but fixed-order unreliable for low p_T ⇝ how stable when including resummation (& hadronisation?) effects

p_T extraction for fixed-order & resummed

[Dixon, Li 1305.3854]



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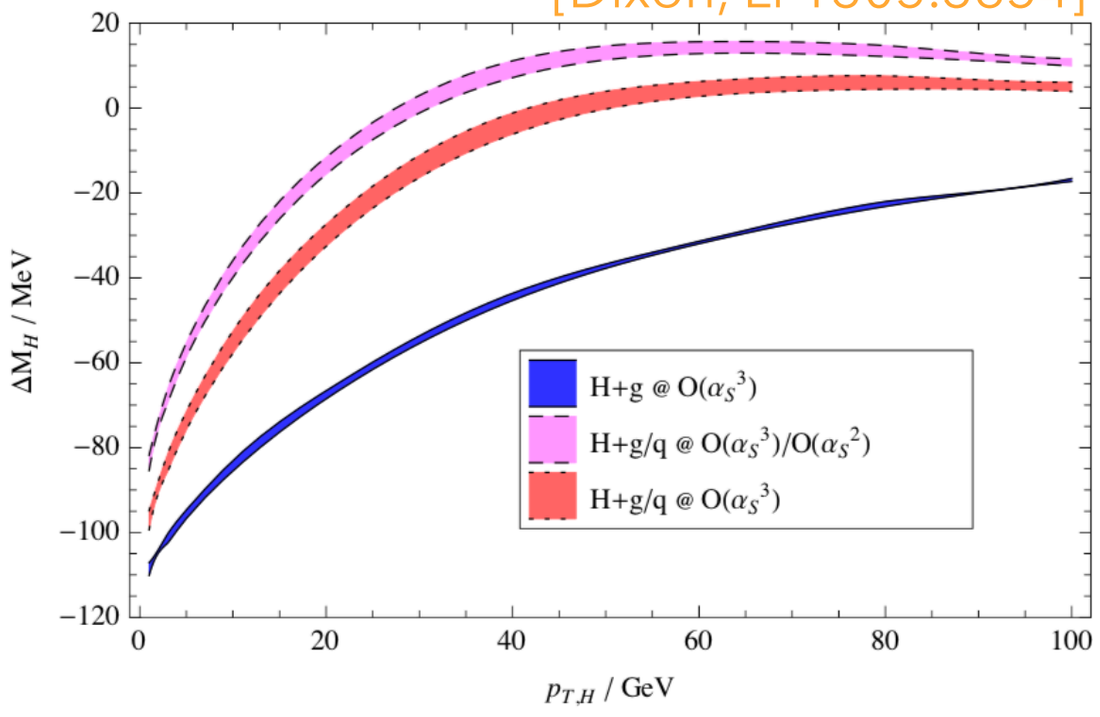
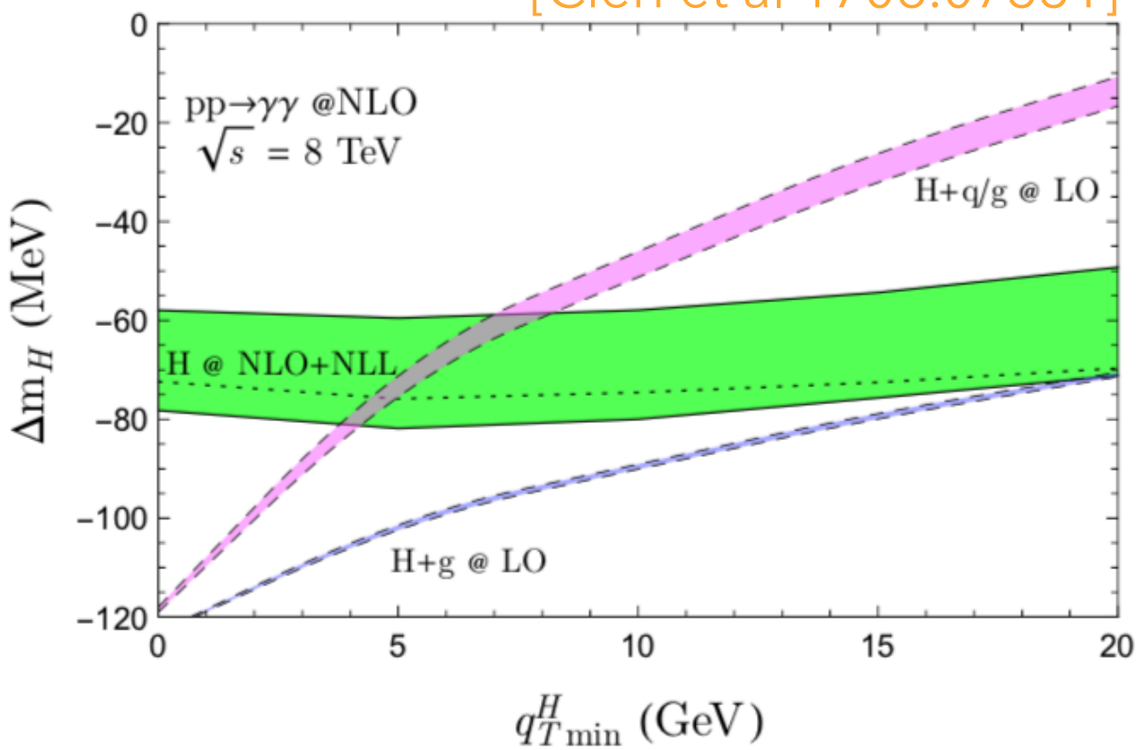


[Cieri et al 1706.07331]



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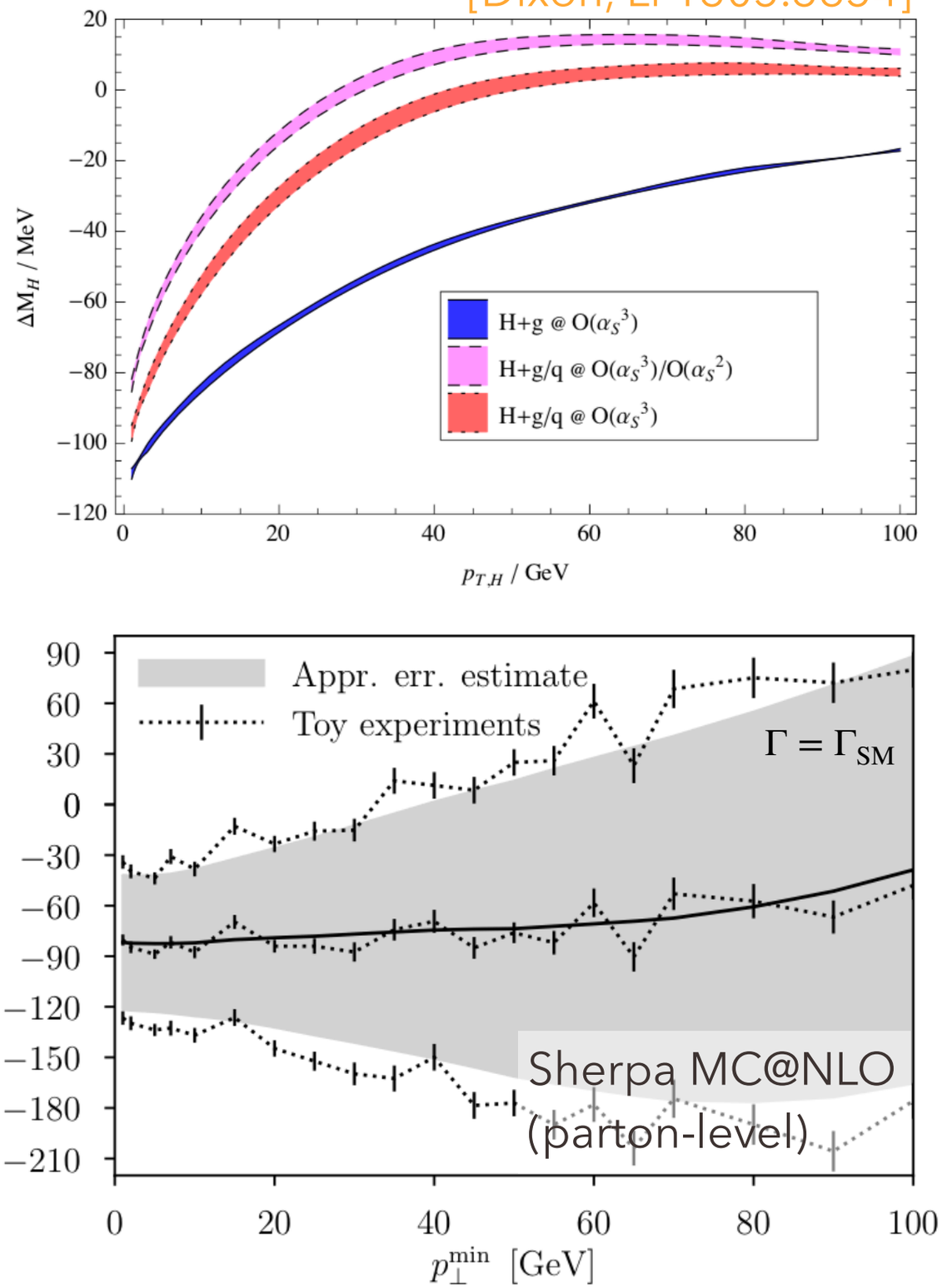

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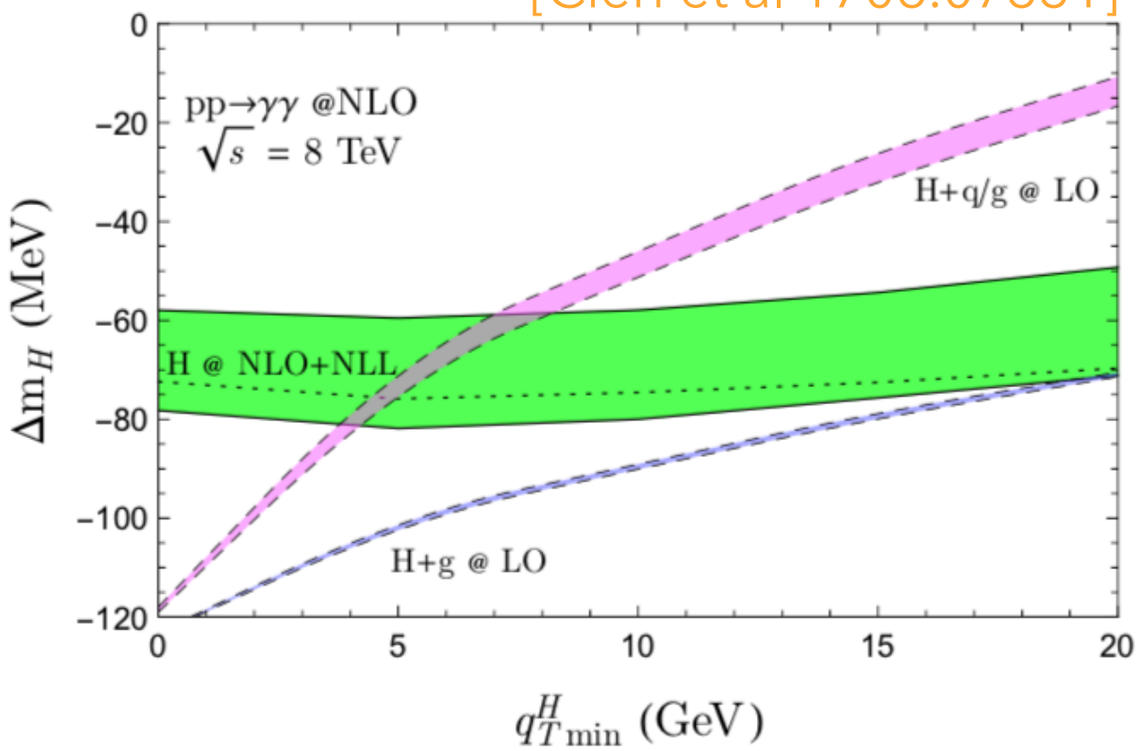

Sherpa MC@NLO
(parton-level)

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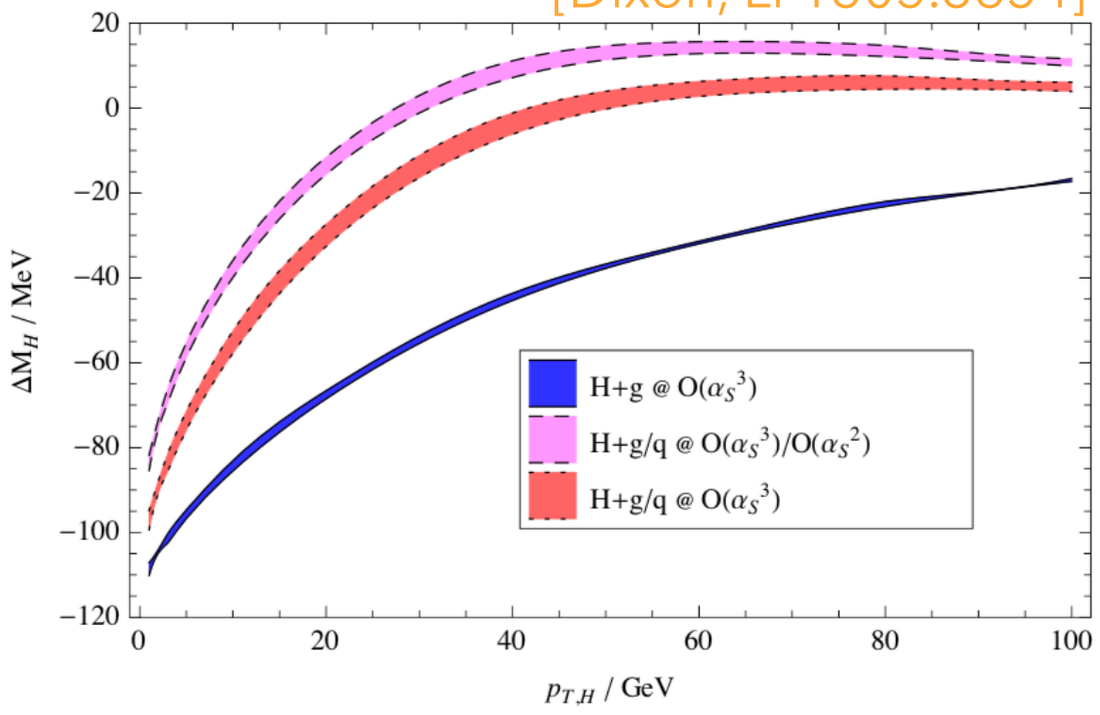

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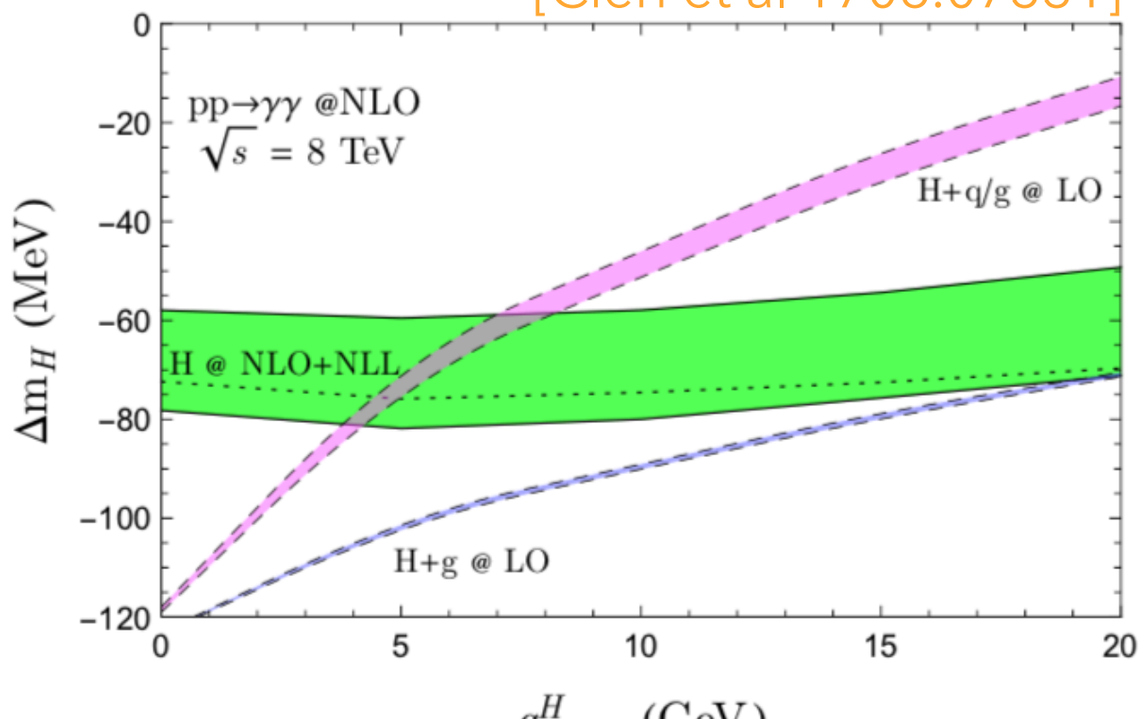

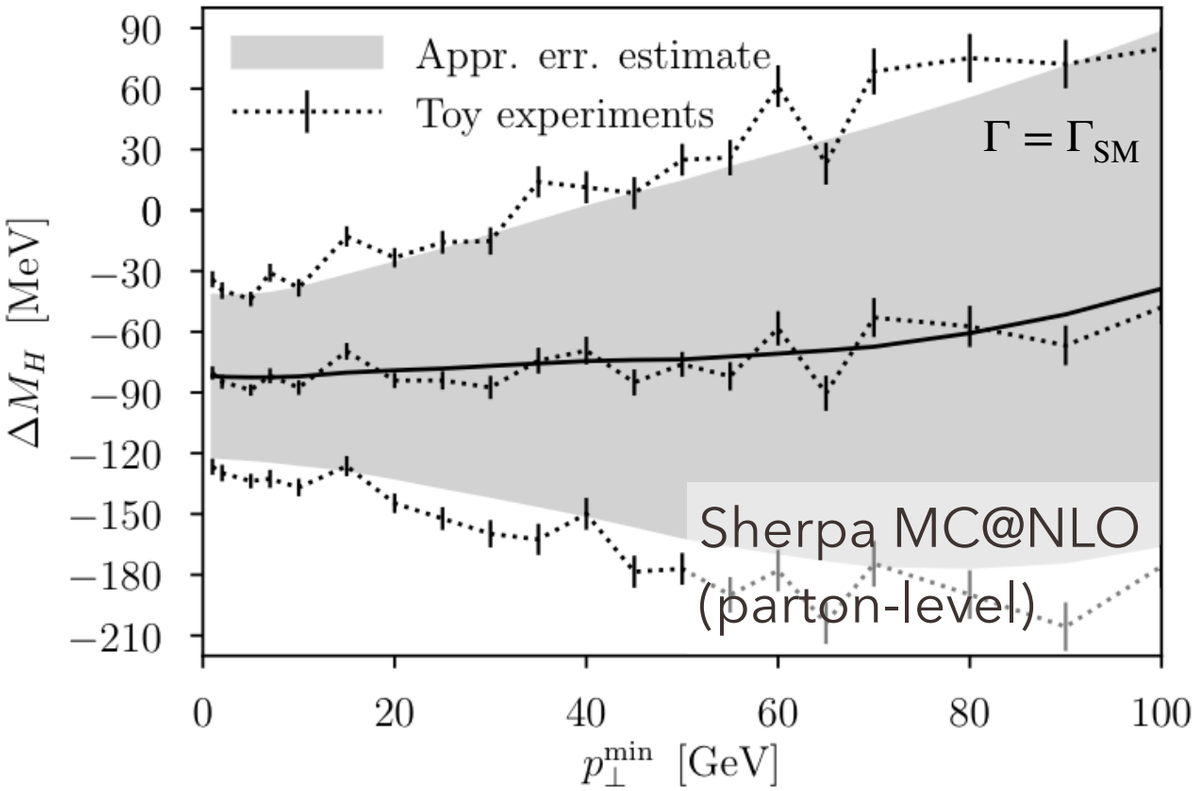

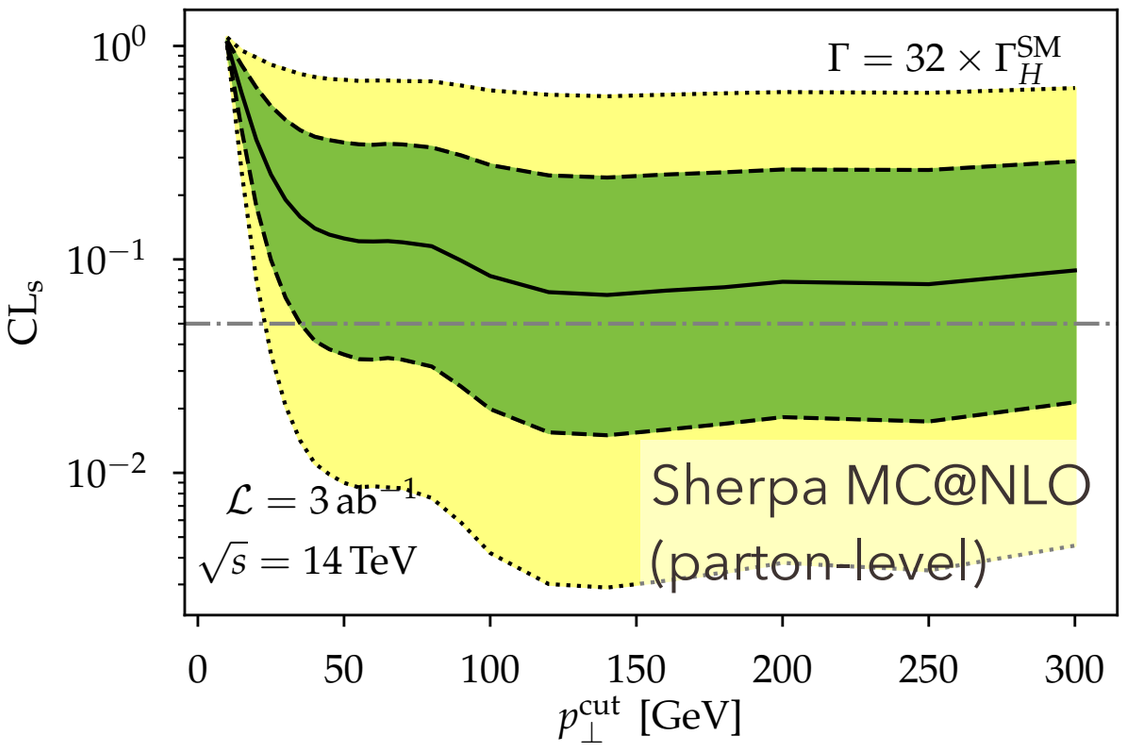

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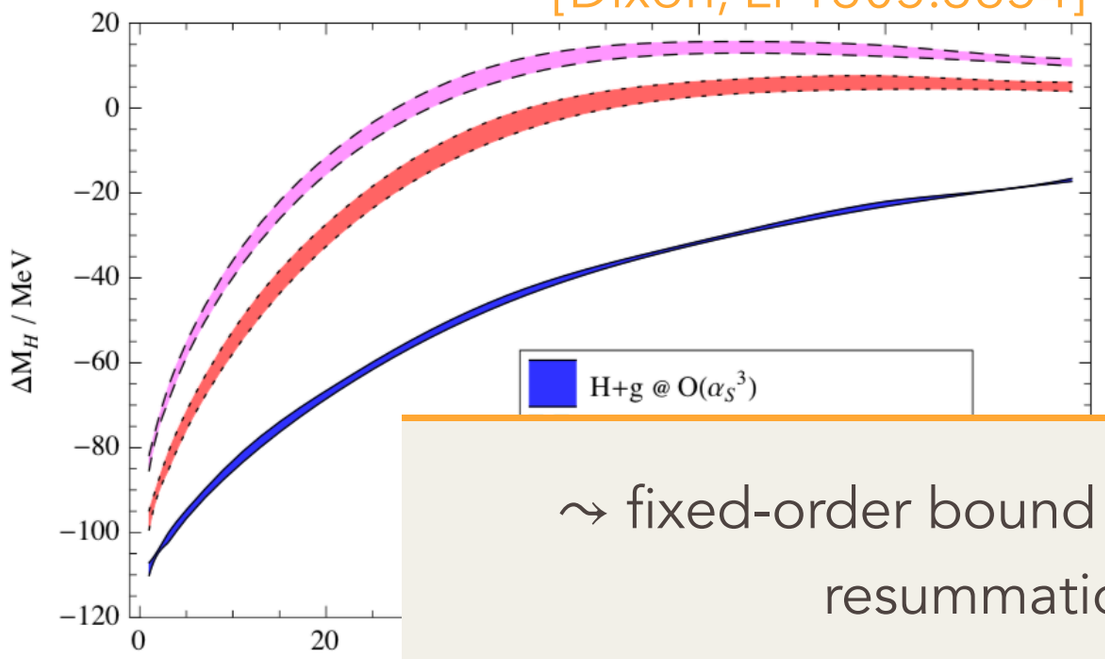
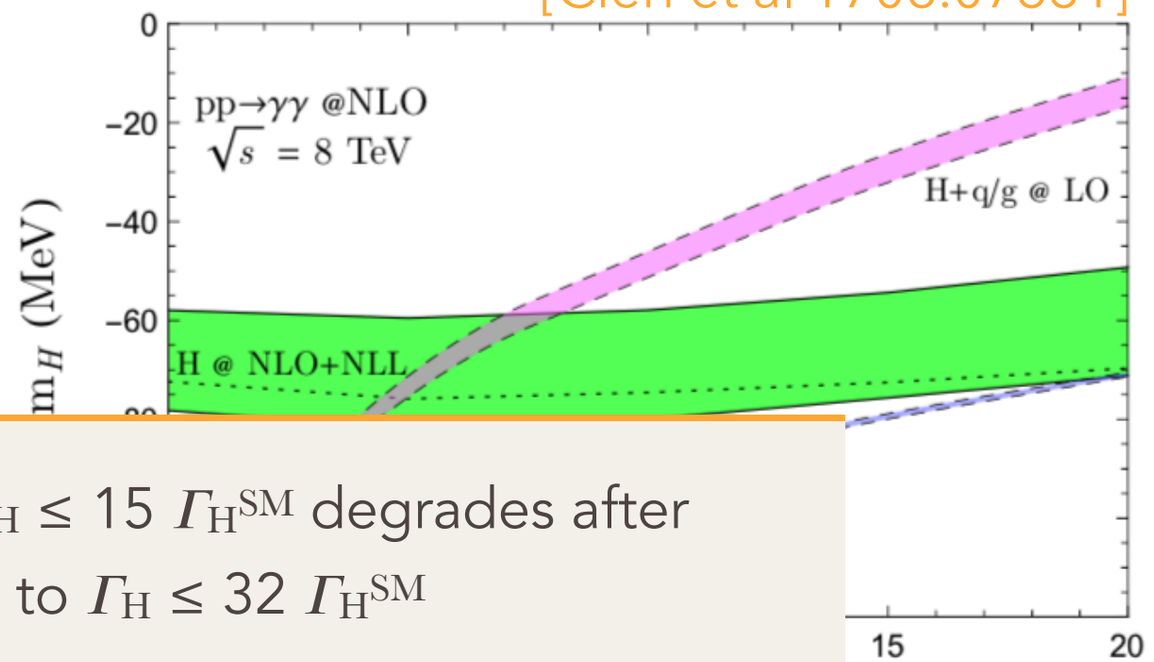
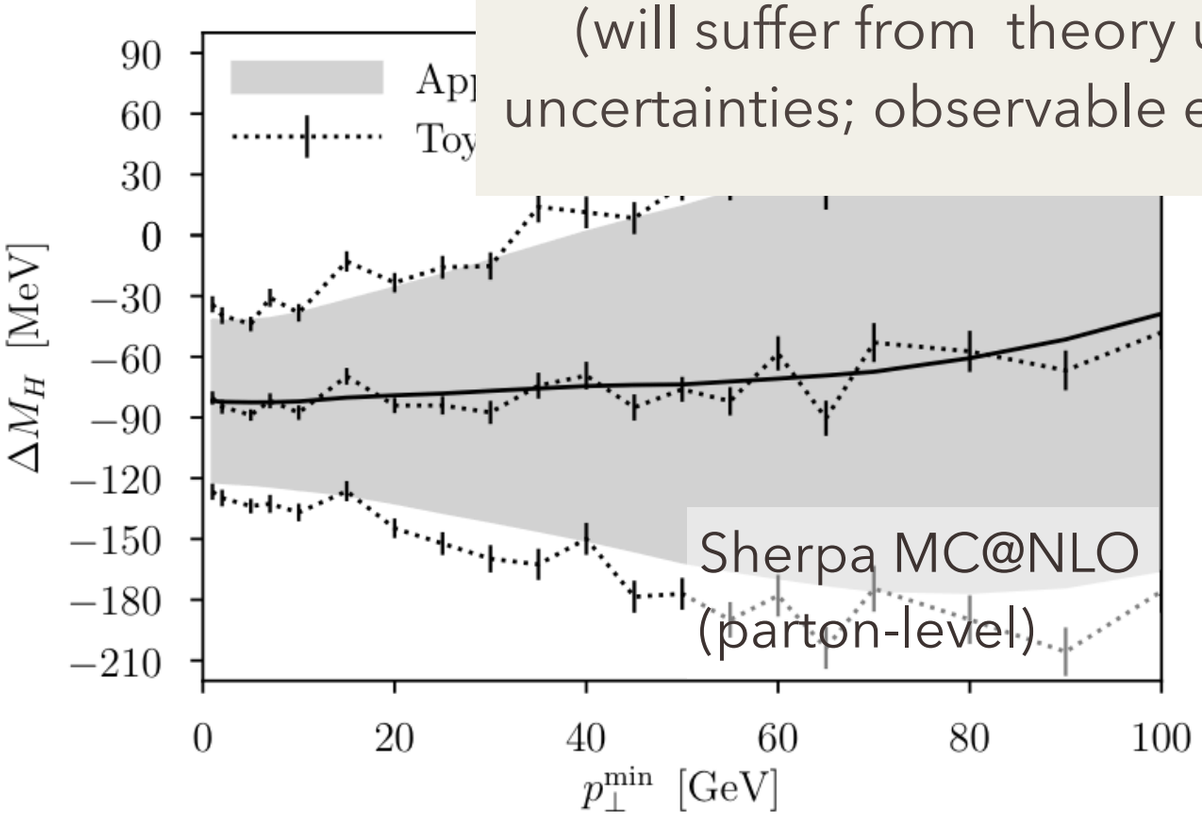


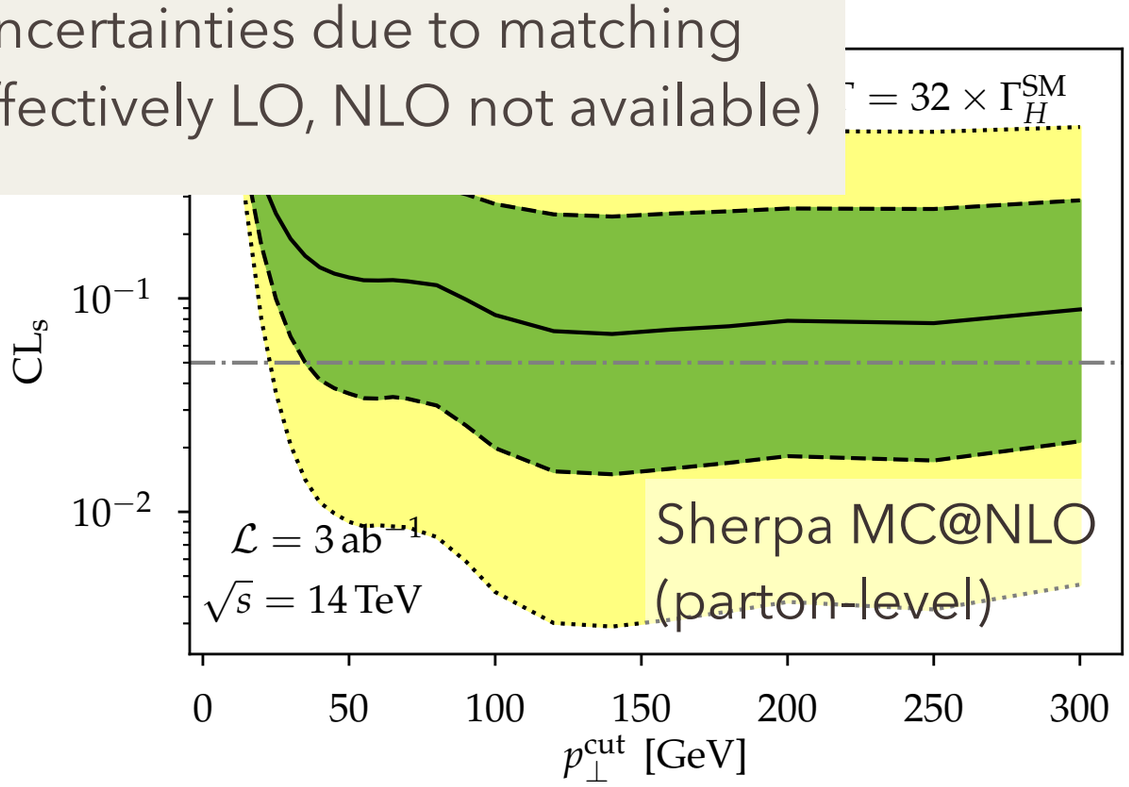
[Cieri et al 1706.07331]



↝ fixed-order bound $\Gamma_H \leq 15\ \Gamma_H^{SM}$ degrades after resummation to $\Gamma_H \leq 32\ \Gamma_H^{SM}$

(will suffer from theory uncertainties due to matching uncertainties; observable effectively LO, NLO not available)





Go back to the $m_{\gamma\gamma}$ distribution?

- can we just go back to the $m_{\gamma\gamma}$ distribution and fit something that includes the shape distortion? ⇝ all data in fiducial region
- convolution of Lorentzian with Gaussian
  ⇒ Faddeeva function: $w(z) = e^{-z^2}\mathrm{erfc}(-iz)$

$$\mathcal{S} = \frac{w(z_-) - w(z_+)}{2\sqrt{2\pi}\,\sigma} \quad \text{with} \quad z_\mp = \frac{m_{\gamma\gamma} \mp M_H}{\sqrt{2}\,\sigma}, \quad M_H = \sqrt{m_H^2 - i\,m_H\Gamma_H}$$

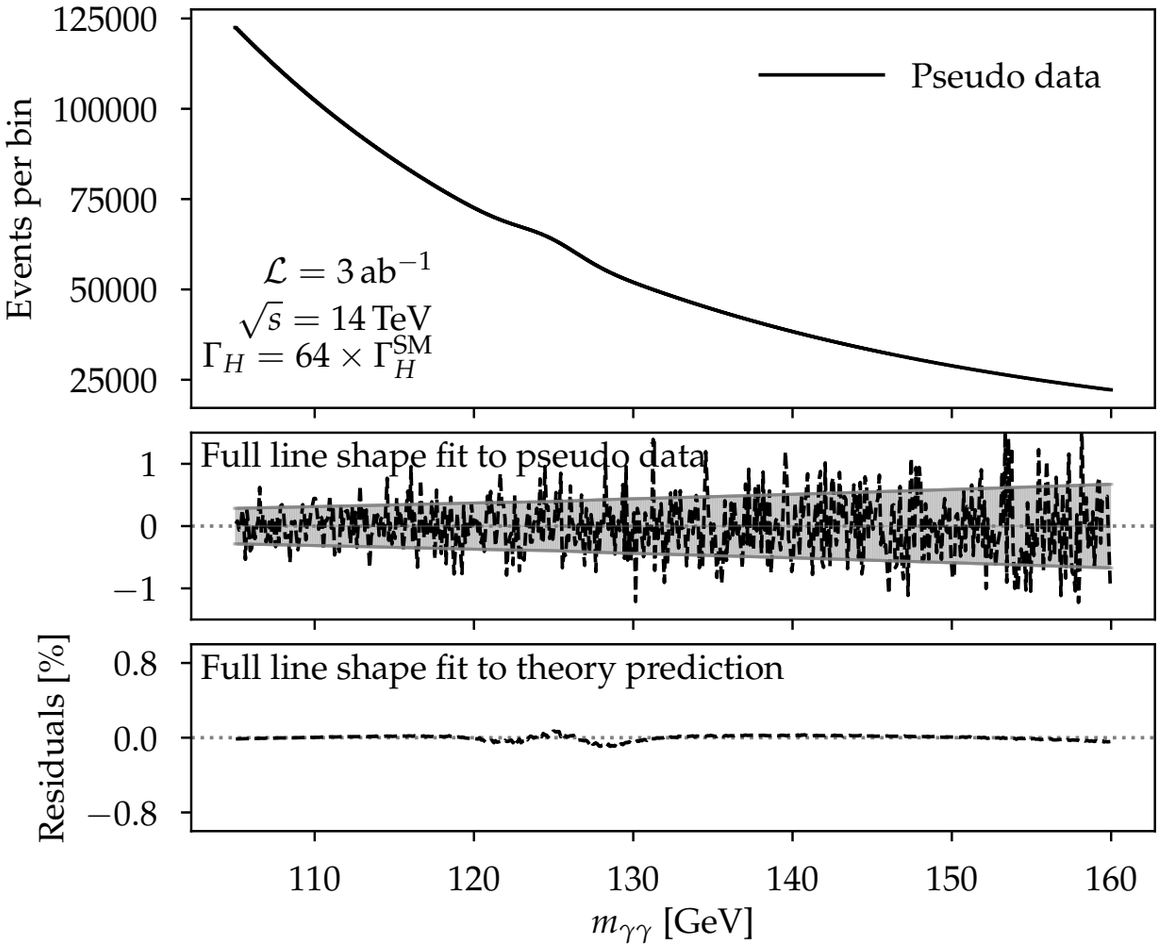
$$\mathcal{F} = N\left[\frac{\mathrm{Re}\{\mathcal{S}\}}{\mathrm{Re}\{\mathcal{N}\}} + N_{RS}\,\frac{\mathrm{Im}\{\mathcal{S}\}}{\mathrm{Im}\{\mathcal{N}\}}\right] \quad \text{where} \quad N_{RS} = \sigma_R\left(\sigma_S\,c_{g\gamma}\,\frac{\Gamma_{H,\mathrm{SM}}}{\Gamma_H} + \sigma_I\right)^{-1}$$

- sole theoretical input: σ_R, σ_S, σ_I
- fit to (MC) data

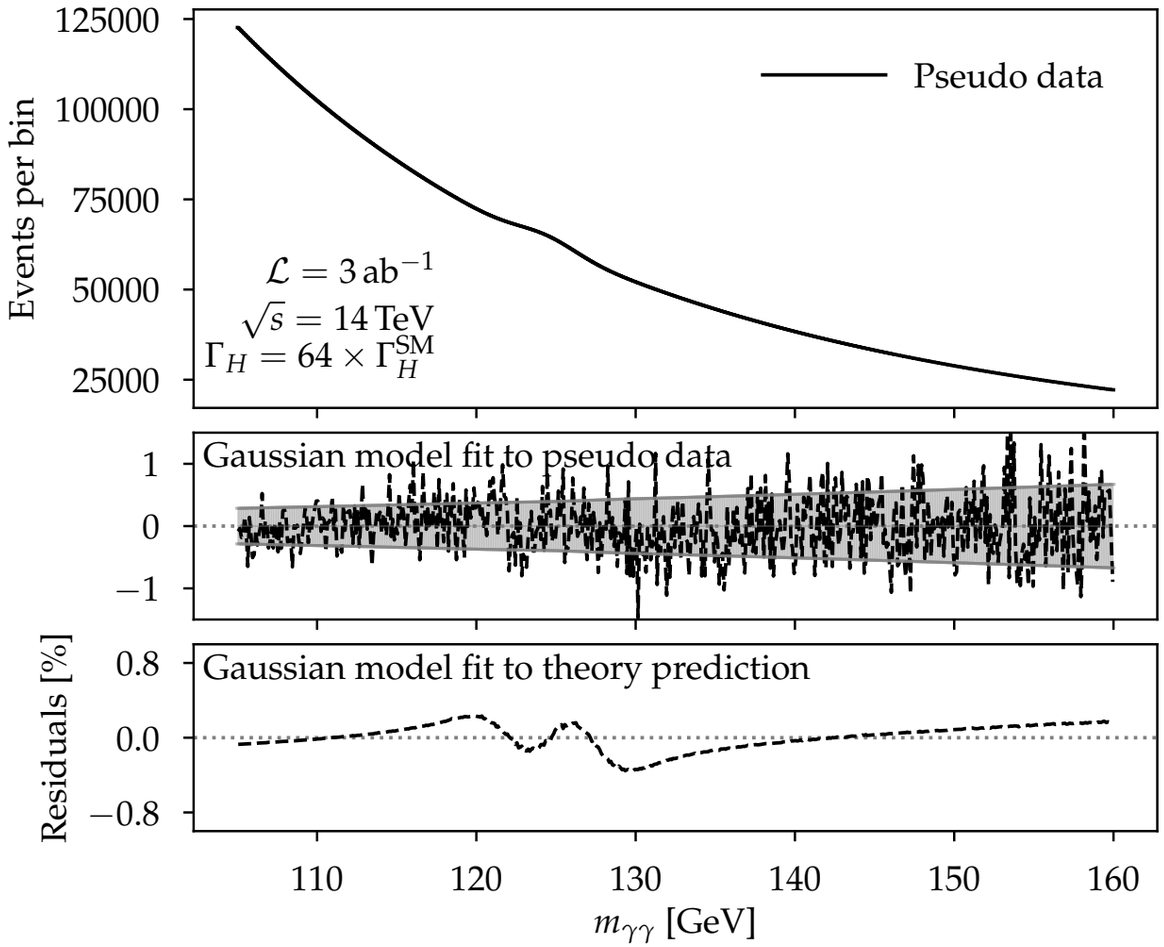
GOF comparison for Faddeeva vs. Gaussian

preliminary Sherpa MC@NLO (parton-level)

Faddeeva fit



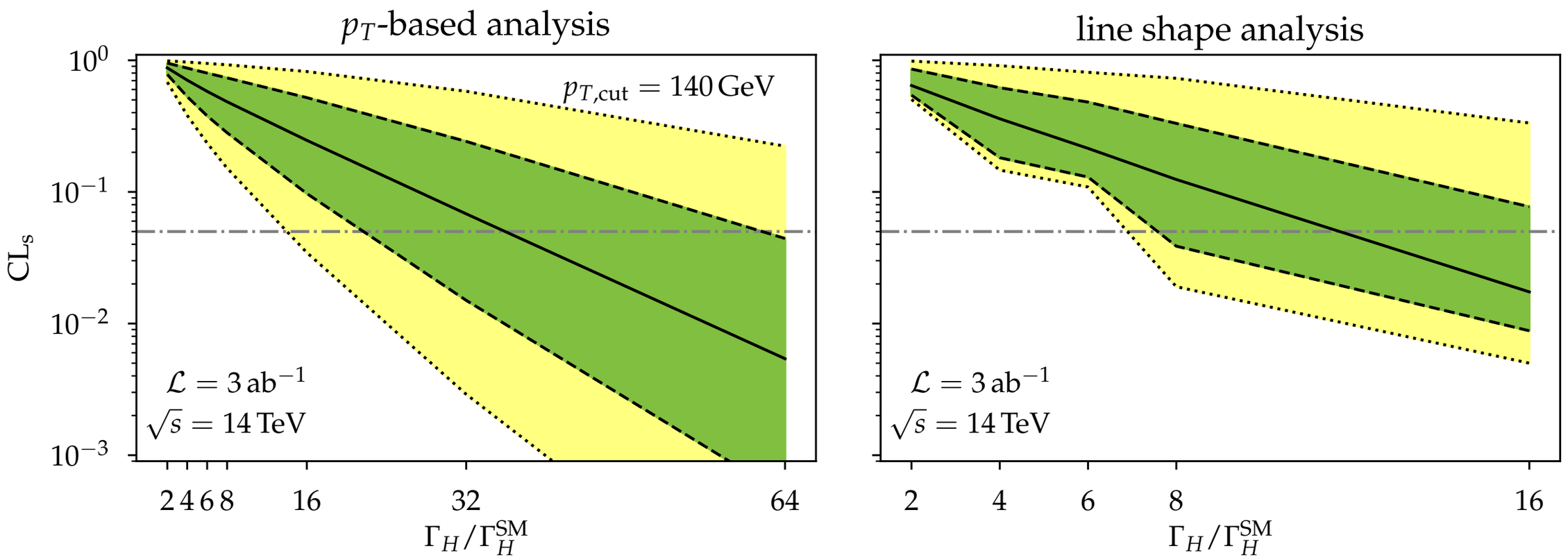
Gauss fit



⇝ Residuals reduced by factor > 4 by using Faddeeva function

Results for both methods

preliminary Sherpa MC@NLO (parton-level)

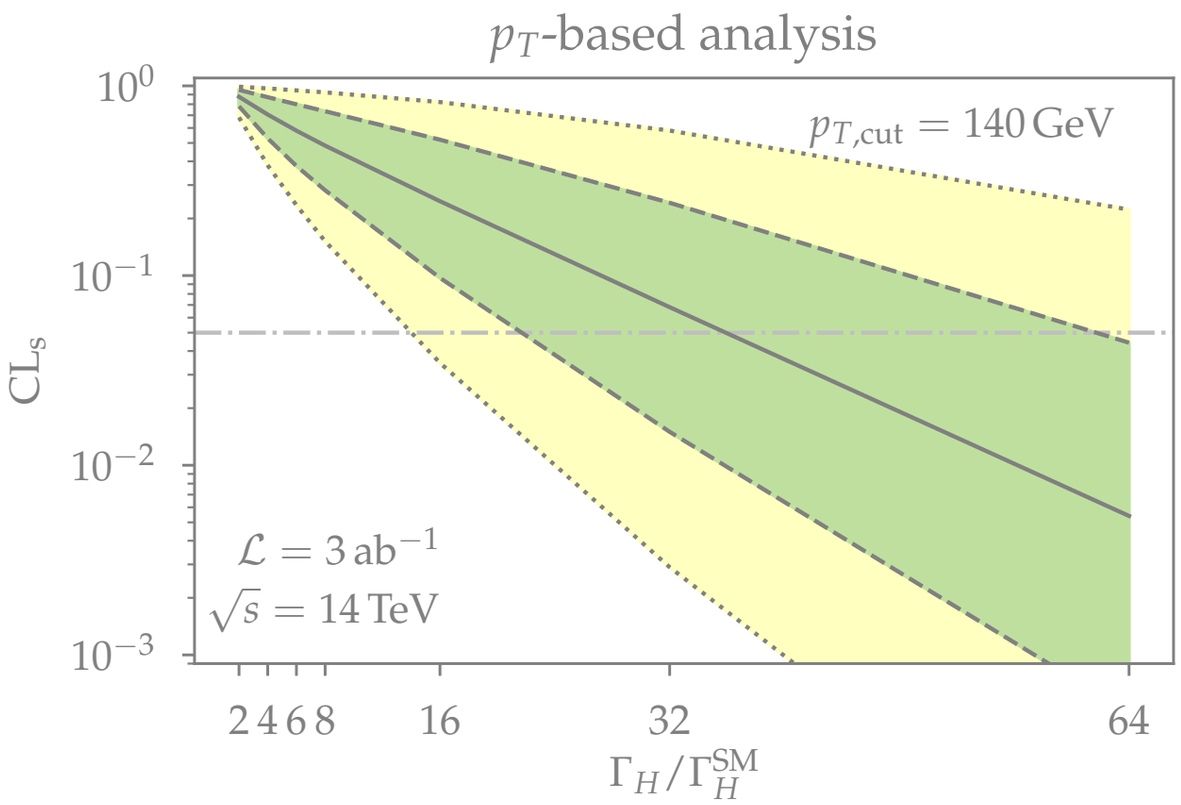


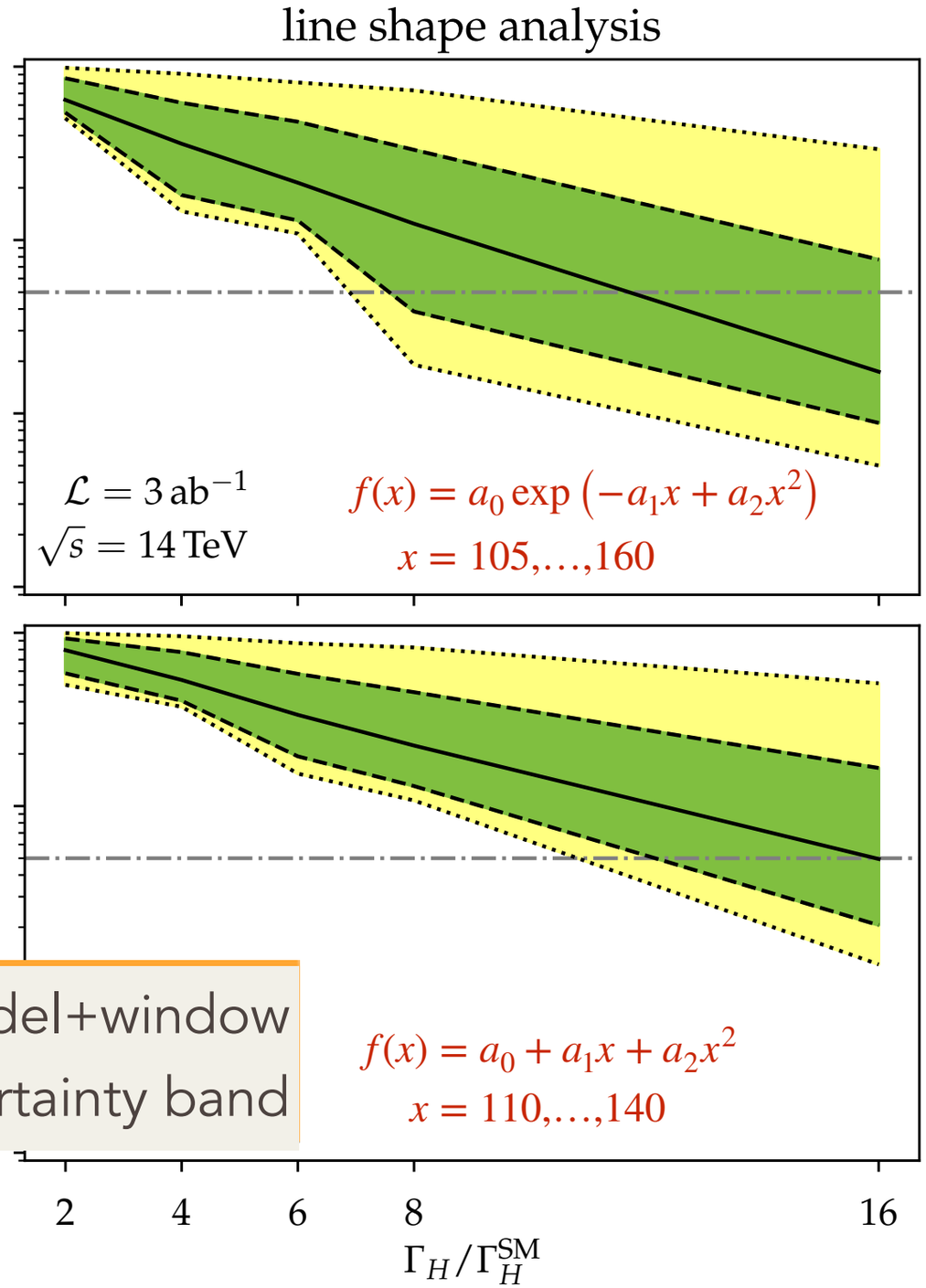
↝ HL-LHC bound using p_T cut method: $\Gamma_H \lesssim 32\ \Gamma_H^{\text{SM}}$

↝ HL-LHC bound using direct-fit method: $\Gamma_H \lesssim 12\ \Gamma_H^{\text{SM}}$

Line shape method: dependence of BG fit

preliminary Sherpa MC@NLO (parton-level)





↝ dependence on BG fit model+window within 1σ uncertainty band

Conclusions

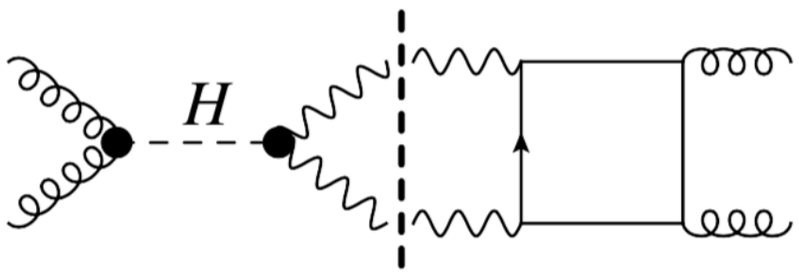
- interference-induced Higgs peak shift
- extract the shift ⇒ model-independent bound on Γ_H
- HL-LHC bounds (preliminary)
  - e.g. by comparing shift in high-/low H p_T
    - fixed-order bound $\Gamma_H \leq 15\ \Gamma_H^{SM}$ degrades after resummation to $\Gamma_H \leq 32\ \Gamma_H^{SM}$
  - or by directly fitting distorted peak in $m_{\gamma\gamma}$
    - optimistic to get $\Gamma_H \leq 12\ \Gamma_H^{SM}$
- TODO:
  - use Crystal-Ball function for signal fits instead of Gaussian

Back-up

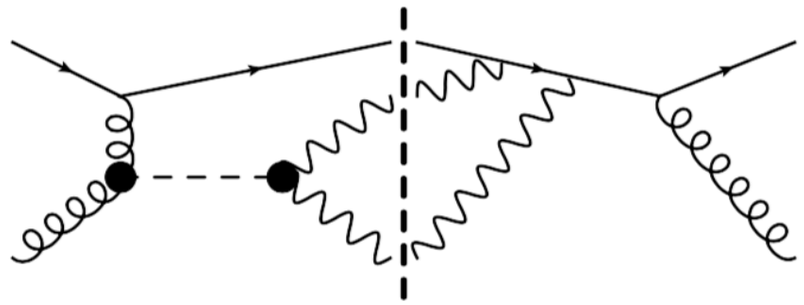
Interference contributions

[Dixon 1305.3854]

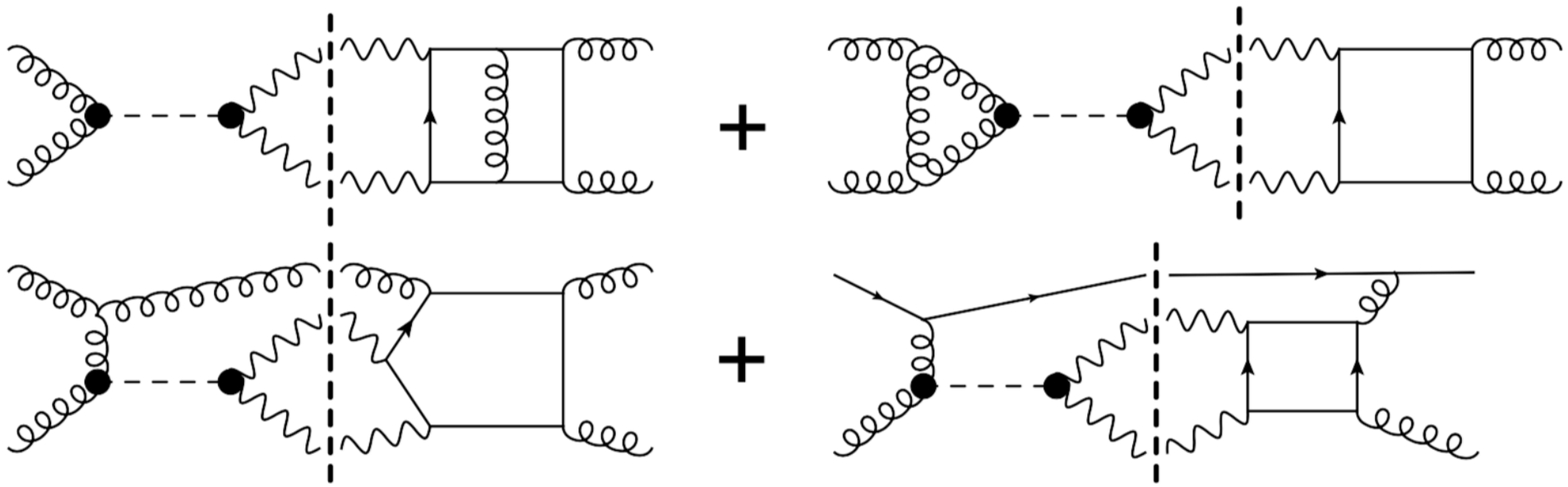
LO (gg):



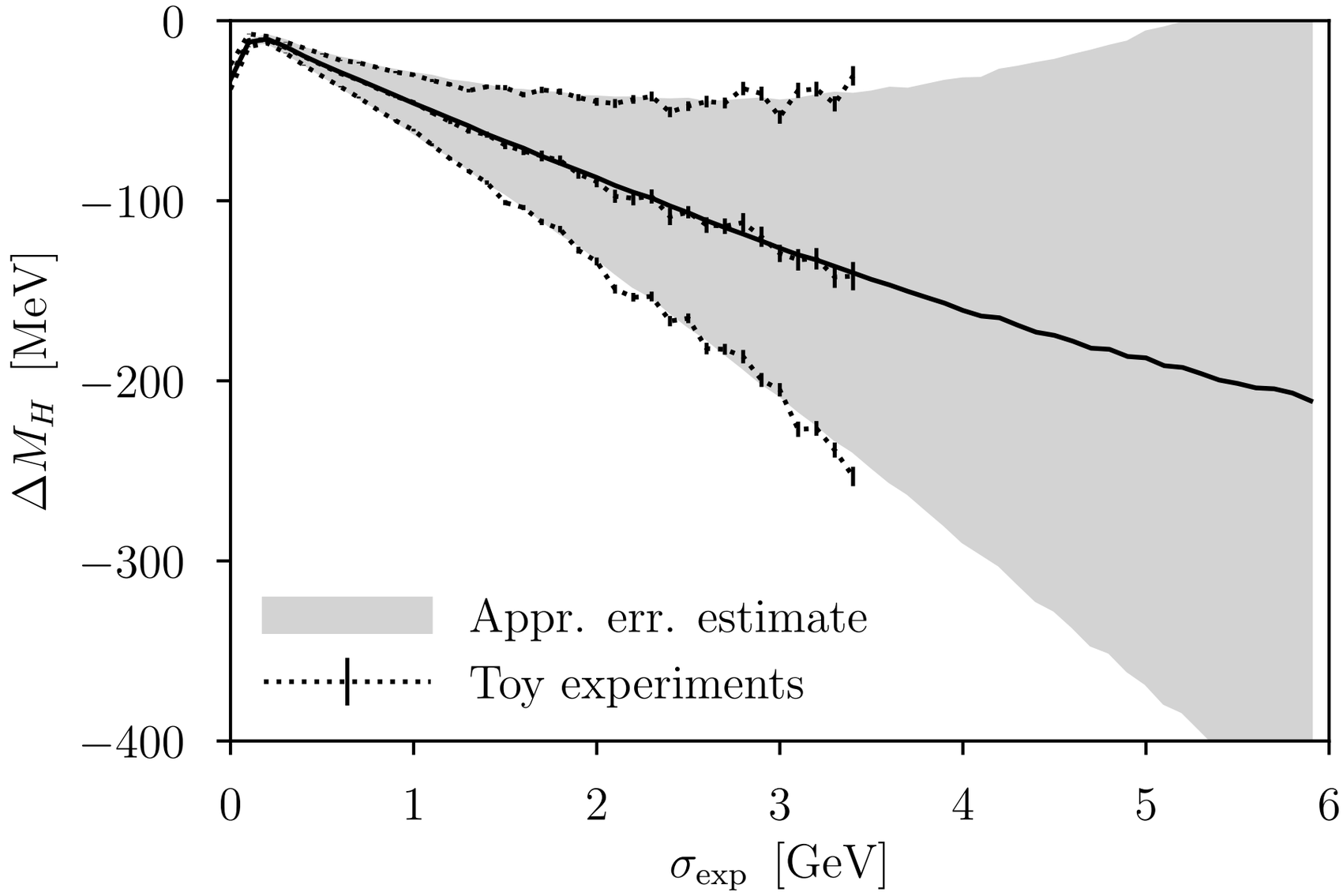
LO (qg):



NLO (gg):

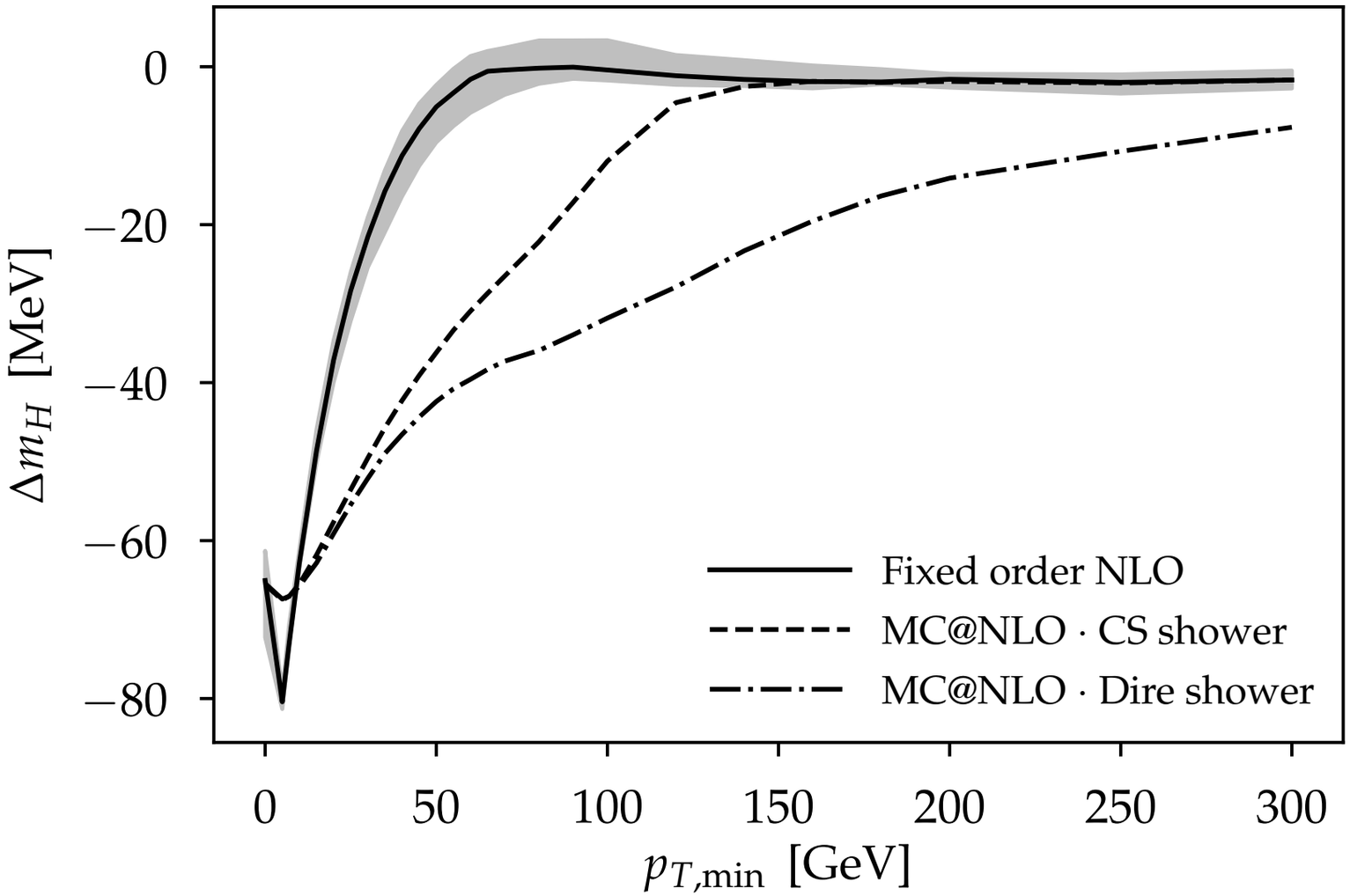


Reducing the experimental resolution



↝ larger exp. uncert. gives larger shift, but at some point fitting the washed out peak comes with large uncertainties itself

Matching uncertainties

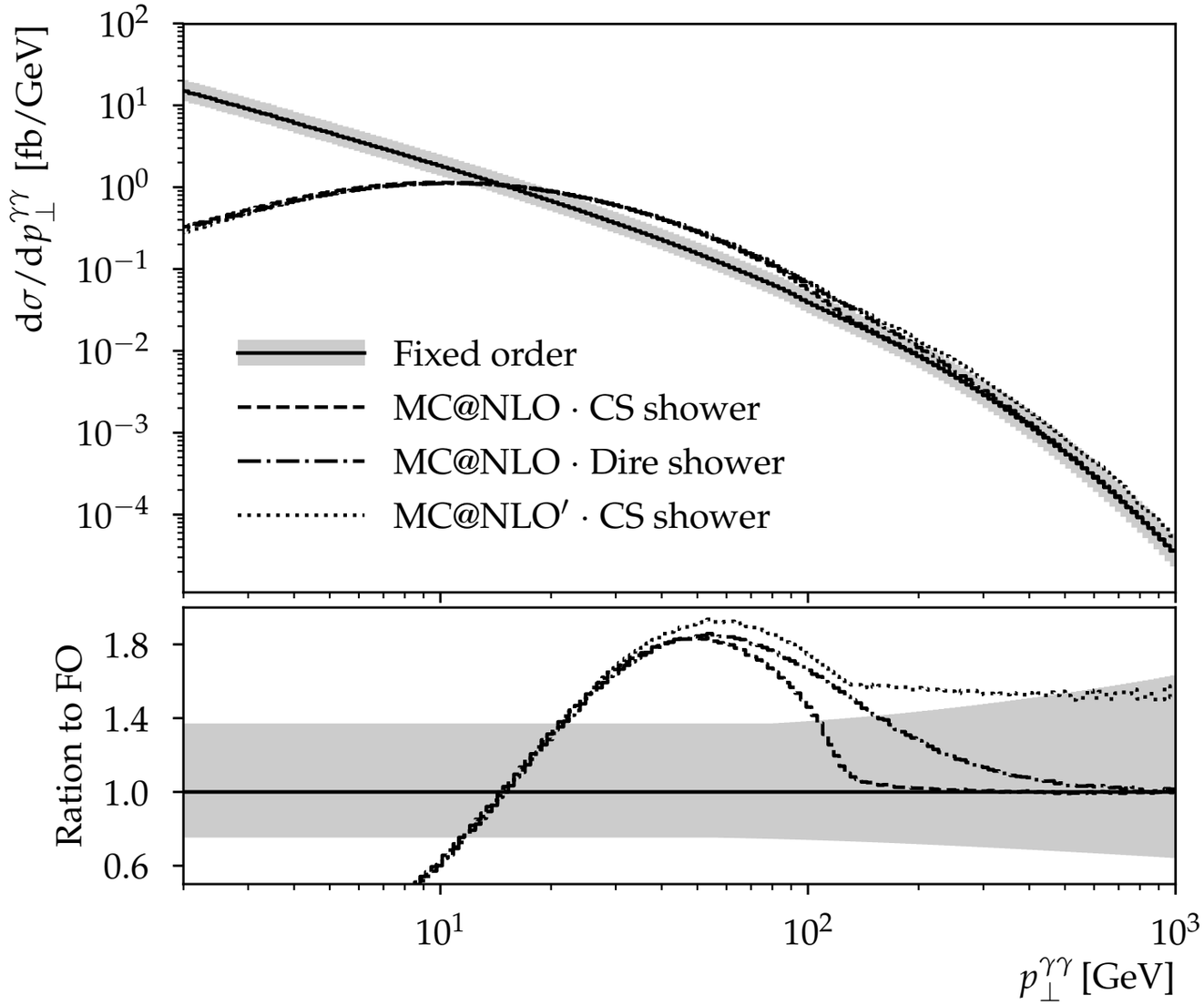


↝ large matching uncertainties, can be traced back to the large radiative corrections to the signal at NLO

NLO „fudge" factor for real-emission events

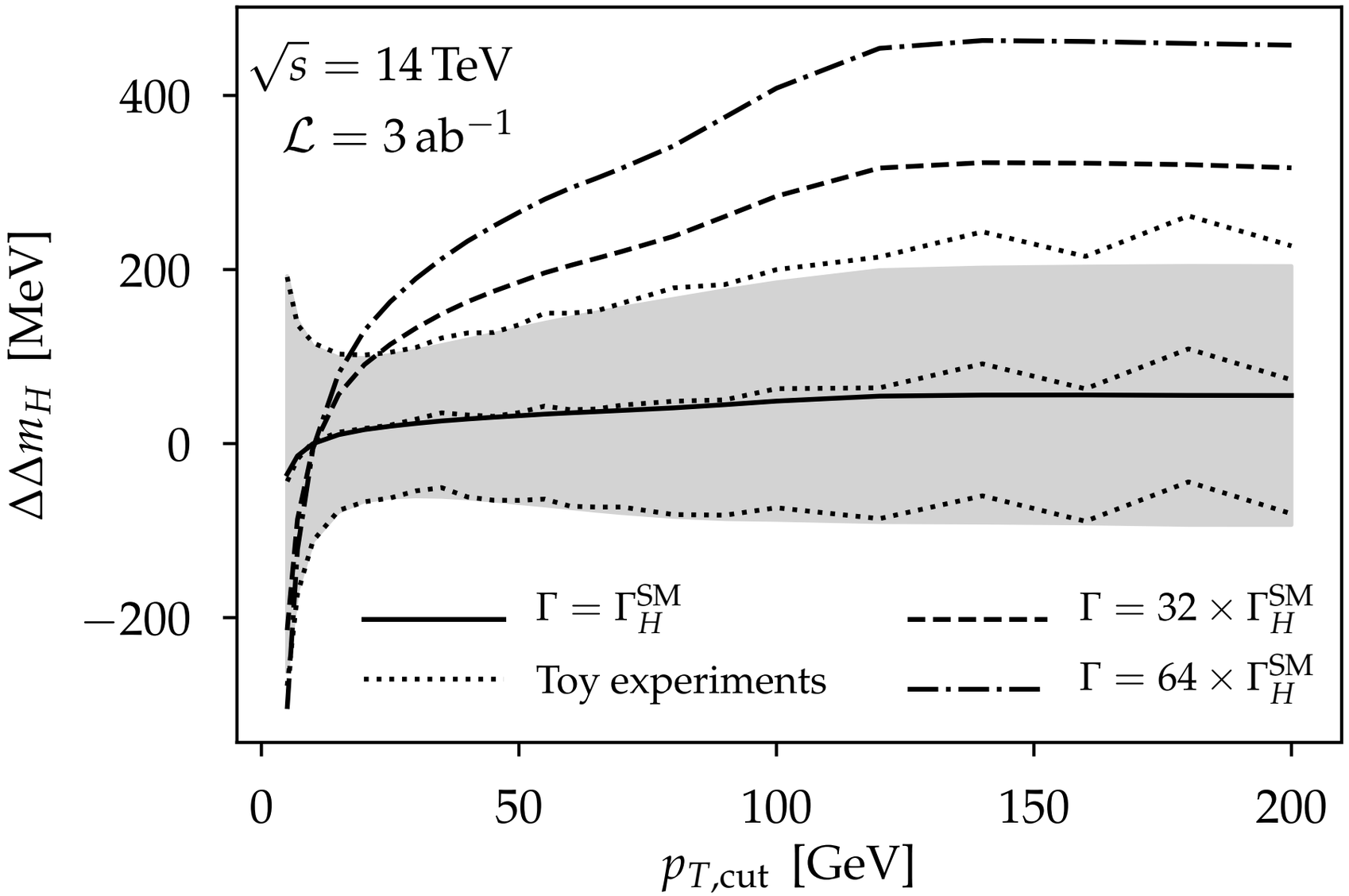
$$\left|\frac{\Gamma_a(Q^2)}{\Gamma_a(-Q^2)}\right|^2 = 1 + \frac{\alpha_s(Q^2)}{2\pi} C_a \pi^2 + \mathcal{O}(\alpha_s^2)$$

[Magnea, Sterman Phys. Rev. D42, 4222 (1990)]



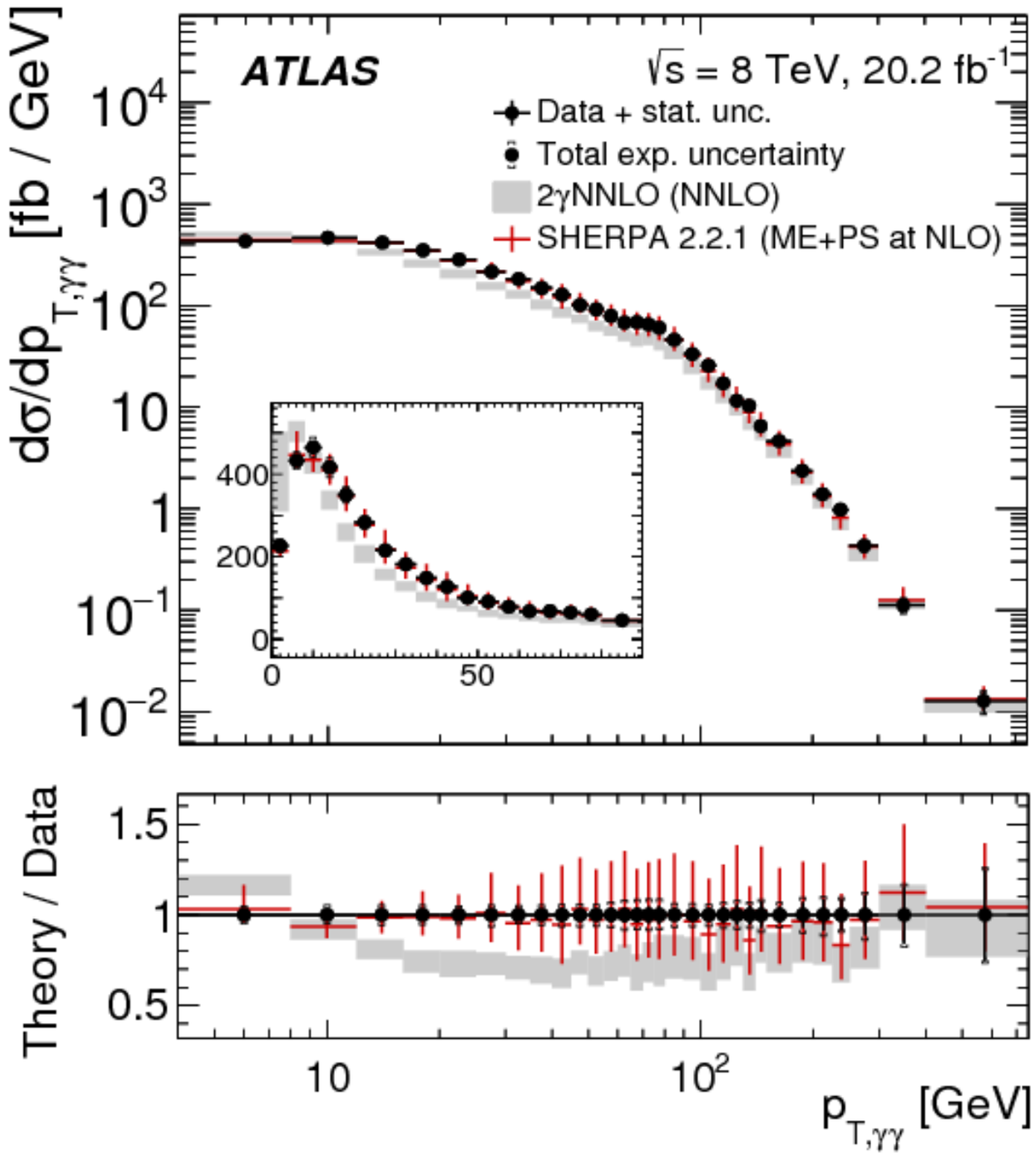
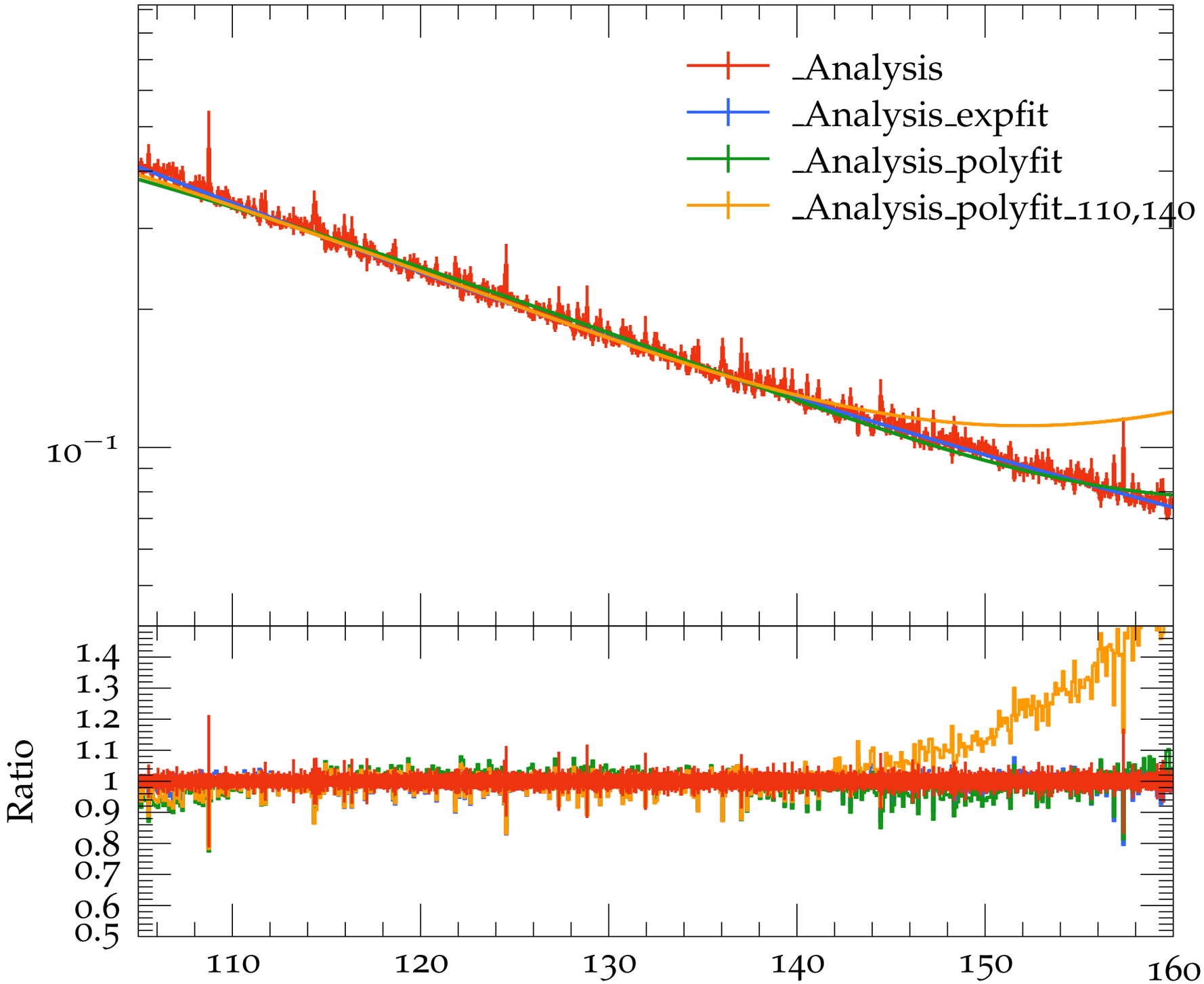
include universal higher-order corrections in all components of the NLO calculation and subtracted the overlap

Difference of mass shift above vs. below $p_{T,cut}$



Background prediction

[ATLAS 1704.03839]



Background fit