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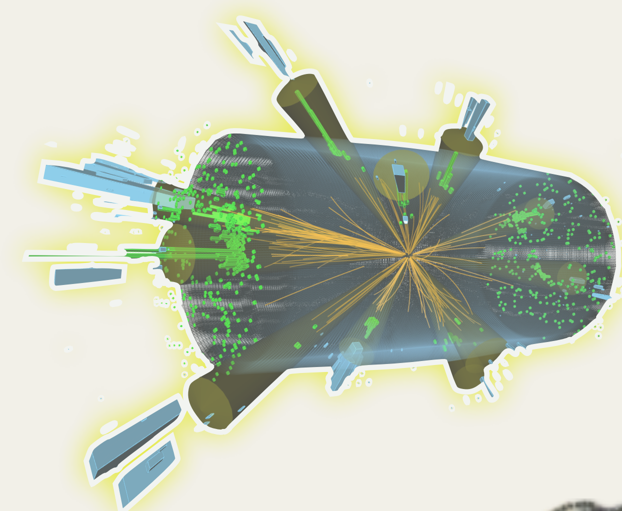
# Bounding the Higgs-boson width at the HL-LHC through interference effects

Seminar of the II. Physikalisches Institut
10 May 2019



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MCnet

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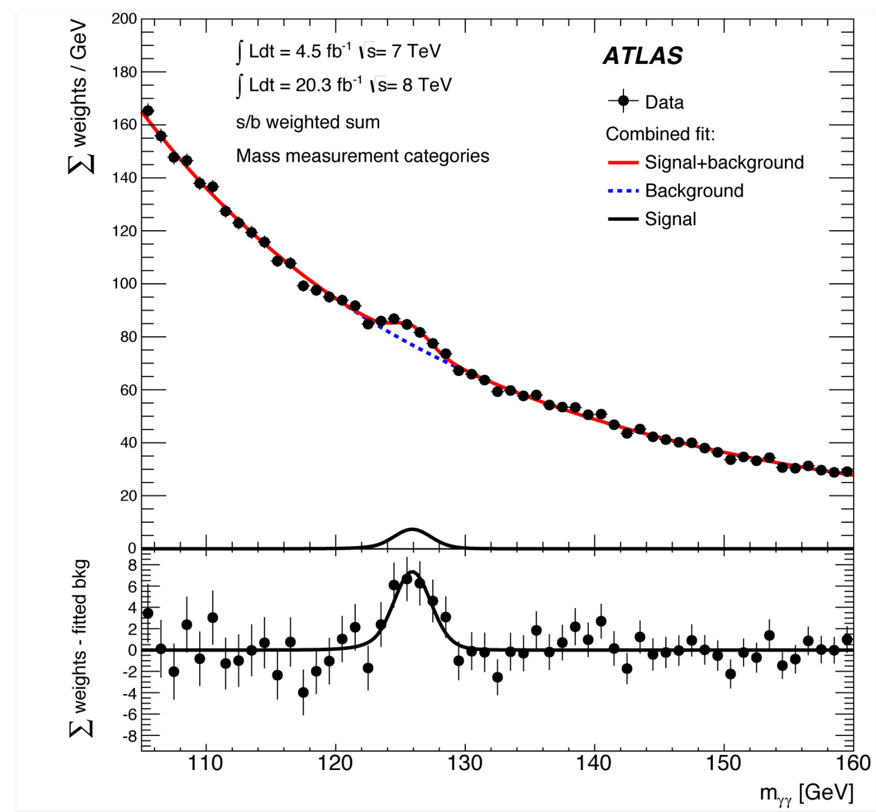
# Motivation for this study

# Motivation

- the Higgs boson $H$ might couple to unknown fields
  - (e.g. scalar $A_0$, with $H \to A_0 A_0 \to gggg$ with $2m_{A_0} < m_H$)
  - (side note: dominant invisible decay ruled out from $E_{T,\text{miss}}$ measurements) [ATLAS-CONF-2013-011]

$\rightsquigarrow$ measure $\Gamma_H > \Gamma_H^{\text{SM}} \Rightarrow$ new physics




- alas, can not measure width directly
  - $\Gamma_H^{\text{SM}} \approx 4$ MeV
  - experimental resolution: $\sigma_{\text{res}} \approx$ 1–2 GeV @ LHC

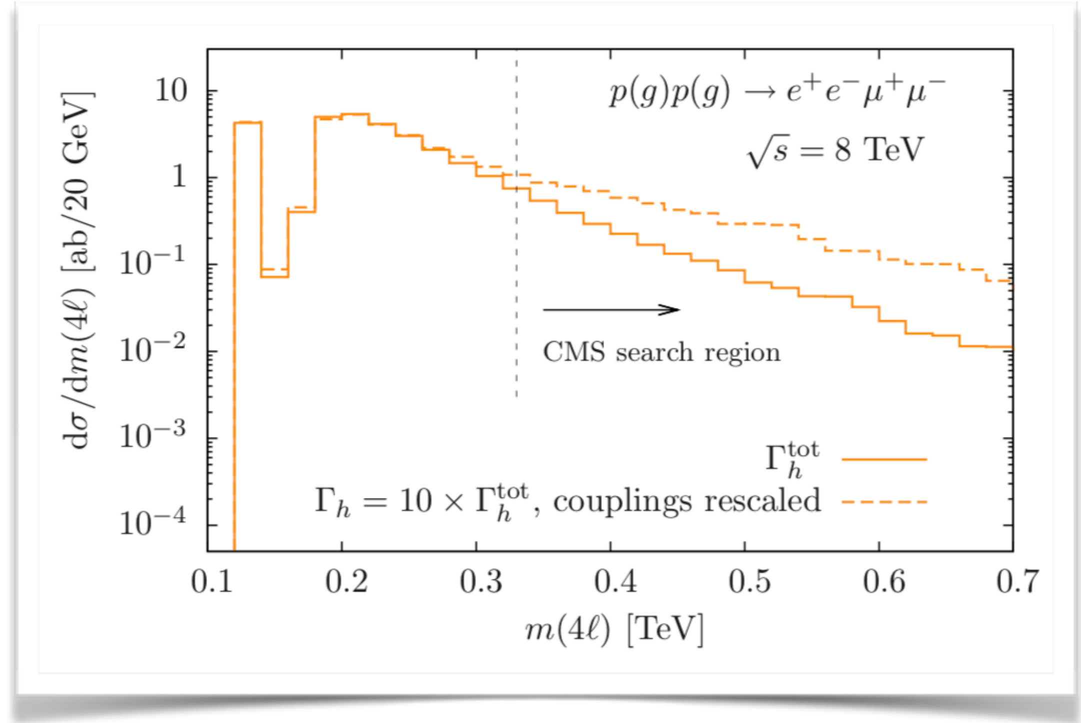
- via on-shell signal cross section $\sigma \sim g^2/\Gamma_H$?

$\rightsquigarrow$ can only extract bound if assume $g = g^{\text{SM}}$

☛ **can we break this coupling-width degeneracy?**

# Motivation: breaking the degeneracy I

[Englert Spannowsky 1405.0285]

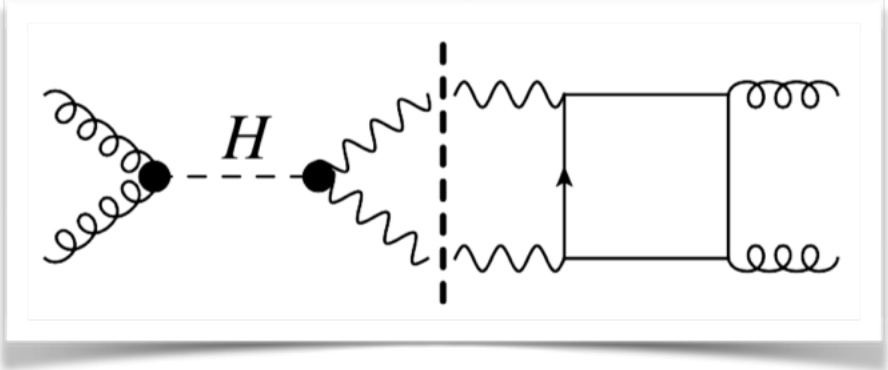



- one way: complement with off-shell measurements [Caola Melnikov 1307.4935]
  - on-shell $\sigma \sim g^2/\Gamma_H$ vs. off-shell $\sigma \sim g^2$
  - require signal strength $\mu_{\gamma\gamma} \approx 1$ (data!) $\Rightarrow$ bound on $\Gamma_H$
  - $ZZ$ channel due to relatively large off-shell $\sigma$
- expectation at HL-LHC for SM hypothesis: $\Gamma_H$ = 4±1 MeV [ATLAS 1902.00134]
- but need to assume coupling scale-independence: $g(m_{\rm H}) \approx g(\sqrt{s})$ [Englert Spannowsky 1405.0285]
  - can construct BSM models that violate this
    e.g. SU(3) scalar (“squark”) modifies $ggH$ coupling

☛ **interpretation of measurement becomes model-dependent**

# Motivation: breaking the degeneracy II

- eat the cake and have it?
  i.e. stay on-shell & break degeneracy
- take interference terms into account




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

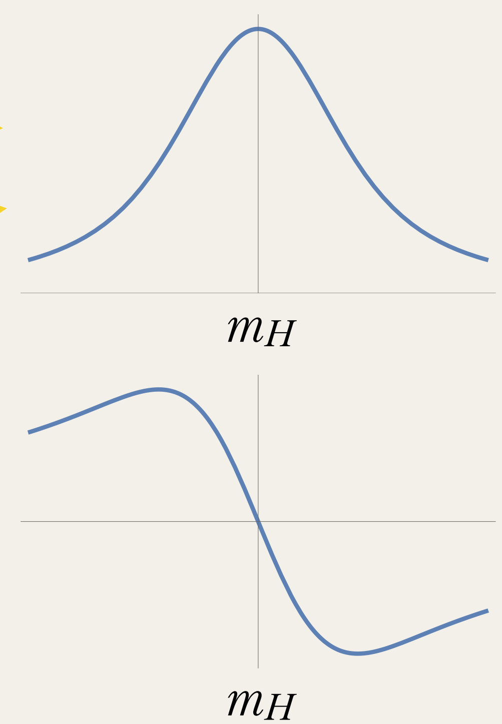
$$\hat{\sigma}_\mathrm{S} = \mathrm{Re}\{\mathcal{L}\} \frac{1}{2m_H^2} \int \mathrm{d}\Phi \, \frac{|\mathcal{A}_S|^2}{m_H \Gamma_H} \,,$$

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

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

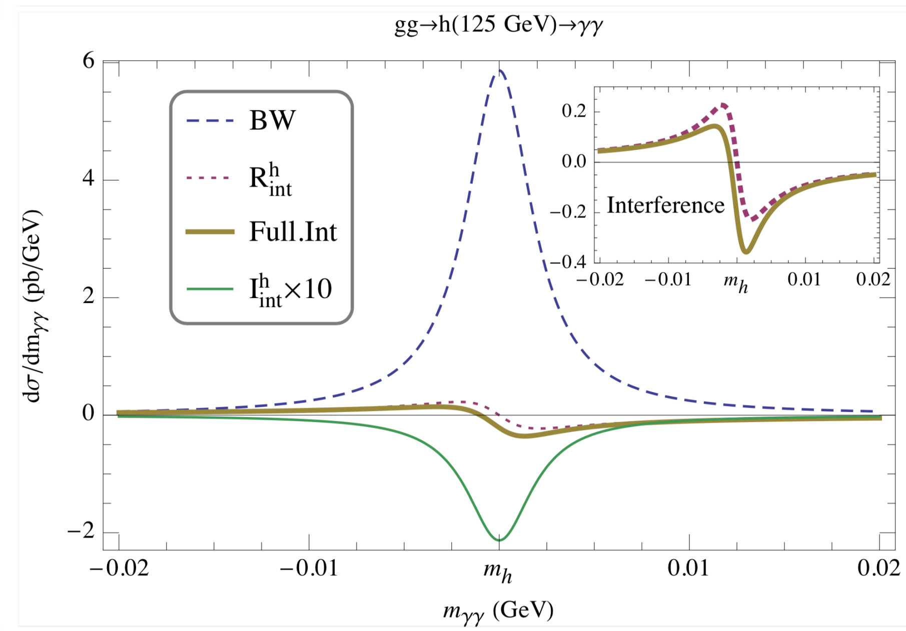
$$\mathcal{L} = \frac{1}{\pi} \frac{m_H \Gamma_H + i(m_{\gamma\gamma}^2 - m_H^2)}{(m_{\gamma\gamma}^2 - m_H^2)^2 + m_H^2 \Gamma_H^2}$$

qualitative contribution shapes after smearing:




⇝ sum gives distorted+shifted peak

# Motivation: breaking the degeneracy II




[Campbell et al. 1704.08259]

- use rate change induced by $\sigma_{\mathrm{I}}$ term
  [Campbell et al. 1704.08259]
  - $\Gamma_H \lesssim$ 8–22 $\Gamma_H^{\mathrm{SM}}$ in diphoton channel @ HL-LHC
- or use asymmetric $\sigma_{\mathrm{R}}$ term
  (rate increase below nominal mass,
  decrease above) ⇒ observable peak shift & deformation
  - use diphoton channel
    - clean experimental signature
    - larger shift effect than e.g. $ZZ$
  - estimates using fixed-order calculations for shift-based bounds exist, $\Gamma_H \lesssim$ 15 $\Gamma_H^{\mathrm{SM}}$ @ HL-LHC
    [Dixon, Li 1305.3854 (2013)]

# Motivation: questions and goals

- fixed-order ✔, but is this robust?
  - resummation corrections expected to be important
    [Cieri et al 1706.07331, Bozzi et al hep-ph/0302104]
  - realistic analysis and crystal-ball smearing for $m_{\gamma\gamma}$ seem to reduce the shift effect
    [ATL-PHYS-PUB-2016-009]

☛ calculate particle-level prediction for Higgs width bound at HL-LHC, compare showers

☛ use realistic cuts and smearing

☛ bonus: find better way to extract bounds

# Theory predictions

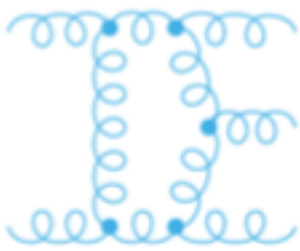
Exercise 1.1.1.1.1a: Given locality, causality, Lorentz invariance, and known physical data since 1860, show that the Lagrangian describing all observed physical processes (sans gravity) can be written:

$$
\begin{gathered}
-\frac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \frac{1}{4}g_s^2 f^{abc} f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu + \\
\frac{1}{2}ig_s^2(\bar{q}^\sigma_i \gamma^\mu q^\sigma_j) g^a_\mu + \bar{G}^a \partial^2 G^a + g_s f^{abc}\partial_\mu \bar{G}^a G^b g^c_\mu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu - \\
M^2 W^+_\mu W^-_\mu - \frac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \frac{1}{2c_w^2} M^2 Z^0_\mu Z^0_\mu - \frac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \frac{1}{2}\partial_\mu H \partial_\mu H - \\
\frac{1}{2}m_h^2 H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - M^2 \phi^+ \phi^- - \frac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \frac{1}{2c_w^2} M \phi^0 \phi^0 - \beta_h [\frac{2M^2}{g^2} + \\
\frac{2M}{g} H + \frac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-)] + \frac{2M^4}{g^2}\alpha_h - igc_w[\partial_\nu Z^0_\mu (W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - Z^0_\nu (W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu (W^+_\nu \partial_\nu W^-_\mu - \\
W^-_\nu \partial_\nu W^+_\mu)] - igs_w[\partial_\nu A_\mu (W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu (W^+_\mu \partial_\nu W^-_\mu - \\
W^-_\mu \partial_\nu W^+_\mu) + A_\mu (W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)] - \frac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \\
\frac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c_w^2 (Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + \\
g^2 s_w^2 (A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w [A_\mu Z^0_\nu (W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha[H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-] - \\
\frac{1}{8}g^2\alpha_h[H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2H^2] - \\
gMW^+_\mu W^-_\mu H - \frac{1}{2}g\frac{M}{c_w^2} Z^0_\mu Z^0_\mu H - \frac{1}{2}ig[W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - \\
W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)] + \frac{1}{2}g[W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) - W^-_\mu(H\partial_\mu\phi^+ - \\
\phi^+\partial_\mu H)] + \frac{1}{2}g\frac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) - ig\frac{s_w^2}{c_w} M Z^0_\mu (W^+_\mu\phi^- - W^-_\mu\phi^+) + \\
igs_w M A_\mu (W^+_\mu\phi^- - W^-_\mu\phi^+) - ig\frac{1-2c_w^2}{2c_w} Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) + \\
igs_w A_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \frac{1}{4}g^2 W^+_\mu W^-_\mu [H^2 + (\phi^0)^2 + 2\phi^+\phi^-] - \\
\frac{1}{4}g^2\frac{1}{c_w^2} Z^0_\mu Z^0_\mu [H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2\phi^+\phi^-] - \frac{1}{2}g^2\frac{s_w^2}{c_w} Z^0_\mu \phi^0 (W^+_\mu\phi^- + \\
W^-_\mu\phi^+) - \frac{1}{2}ig^2\frac{s_w^2}{c_w} Z^0_\mu H (W^+_\mu\phi^- - W^-_\mu\phi^+) + \frac{1}{2}g^2 s_w A_\mu \phi^0 (W^+_\mu\phi^- + \\
W^-_\mu\phi^+) + \frac{1}{2}ig^2 s_w A_\mu H (W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\frac{s_w}{c_w}(2c_w^2 - 1) Z^0_\mu A_\mu \phi^+\phi^- - \\
g^1 s_w^2 A_\mu A_\mu \phi^+\phi^- - \bar{e}^\lambda(\gamma\partial + m_e^\lambda)e^\lambda - \bar{\nu}^\lambda\gamma\partial\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial + m_u^\lambda)u^\lambda_j - \\
\bar{d}^\lambda_j(\gamma\partial + m_d^\lambda)d^\lambda_j + igs_w A_\mu[-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \frac{2}{3}(\bar{u}^\lambda_j\gamma^\mu u^\lambda_j) - \frac{1}{3}(\bar{d}^\lambda_j\gamma^\mu d^\lambda_j)] + \\
\frac{ig}{4c_w} Z^0_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s_w^2 - 1 - \gamma^5)e^\lambda) + (\bar{u}^\lambda_j\gamma^\mu(\frac{4}{3}s_w^2 - \\
1 - \gamma^5)u^\lambda_j) + (\bar{d}^\lambda_j\gamma^\mu(1 - \frac{8}{3}s_w^2 - \gamma^5)d^\lambda_j)] + \frac{ig}{2\sqrt{2}} W^+_\mu [(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)e^\lambda) + \\
(\bar{u}^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)] + \frac{ig}{2\sqrt{2}} W^-_\mu [(\bar{e}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\lambda\kappa}\gamma^\mu(1 + \\
\gamma^5)u^\lambda_j)] + \frac{ig}{2\sqrt{2}}\frac{m_e^\lambda}{M}[-\phi^+(\bar{\nu}^\lambda(1-\gamma^5)e^\lambda) + \phi^-(\bar{e}^\lambda(1+\gamma^5)\nu^\lambda)] - \\
\frac{g}{2}\frac{m_e^\lambda}{M}[H(\bar{e}^\lambda e^\lambda) + i\phi^0(\bar{e}^\lambda\gamma^5 e^\lambda)] + \frac{ig}{2M\sqrt{2}}\phi^+[-m_d^\kappa(\bar{u}^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) + \\
m_u^\lambda(\bar{u}^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j] + \frac{ig}{2M\sqrt{2}}\phi^-[m_d^\lambda(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m_u^\kappa(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1 - \\
\gamma^5)u^\kappa_j] - \frac{g}{2}\frac{m_u^\lambda}{M} H(\bar{u}^\lambda_j u^\lambda_j) - \frac{g}{2}\frac{m_d^\lambda}{M} H(\bar{d}^\lambda_j d^\lambda_j) + \frac{ig}{2}\frac{m_u^\lambda}{M}\phi^0(\bar{u}^\lambda_j\gamma^5 u^\lambda_j) - \\
\frac{ig}{2}\frac{m_d^\lambda}{M}\phi^0(\bar{d}^\lambda_j\gamma^5 d^\lambda_j) + \bar{X}^+(\partial^2 - M^2)X^+ + \bar{X}^-(\partial^2 - M^2)X^- + \bar{X}^0(\partial^2 - \\
\frac{M^2}{c_w^2})X^0 + \bar{Y}\partial^2 Y + igc_w W^+_\mu(\partial_\mu\bar{X}^0 X^- - \partial_\mu\bar{X}^+ X^0) + igs_w W^+_\mu(\partial_\mu\bar{Y}X^- - \\
\partial_\mu\bar{X}^+ Y) + igc_w W^-_\mu(\partial_\mu\bar{X}^- X^0 - \partial_\mu\bar{X}^0 X^+) + igs_w W^-_\mu(\partial_\mu\bar{X}^- Y - \\
\partial_\mu\bar{Y}X^+) + igc_w Z^0_\mu(\partial_\mu\bar{X}^+ X^+ - \partial_\mu\bar{X}^- X^-) + igs_w A_\mu(\partial_\mu\bar{X}^+ X^+ - \\
\partial_\mu\bar{X}^- X^-) - \frac{1}{2}gM[\bar{X}^+ X^+ H + \bar{X}^- X^- H + \frac{1}{c_w^2}\bar{X}^0 X^0 H] + \\
\frac{1-2c_w^2}{2c_w} igM[\bar{X}^+ X^0\phi^+ - \bar{X}^- X^0\phi^-] + \frac{1}{2c_w} igM[\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-] + \\
igMs_w[\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-] + \frac{1}{2}igM[\bar{X}^+ X^+\phi^0 - \bar{X}^- X^-\phi^0]
\end{gathered}
$$

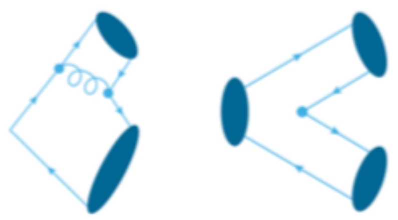
# Monte-Carlo event generation: ingredients

$$\frac{\mathrm{d}\sigma}{dX} = \sum_{ab,n} \int \mathrm{d}x_a \mathrm{d}x_b \mathrm{d}\Phi_n(\{p_i\}) f_a(x_a, \mu_F^2) f_b(x_b, \mu_F^2) \,|\, \mathcal{M}_{ab\to n}(x_a x_b s, \{p_i\}, \mu_R^2, \mu_F^2) \,|^2\, O_n(\{p_i\})$$

- perturbative
  - perturbative MEs for small $n$ (hard process)
  - semi-classical approx for large $n$: parton shower / resummation (Bremsstrahlung)

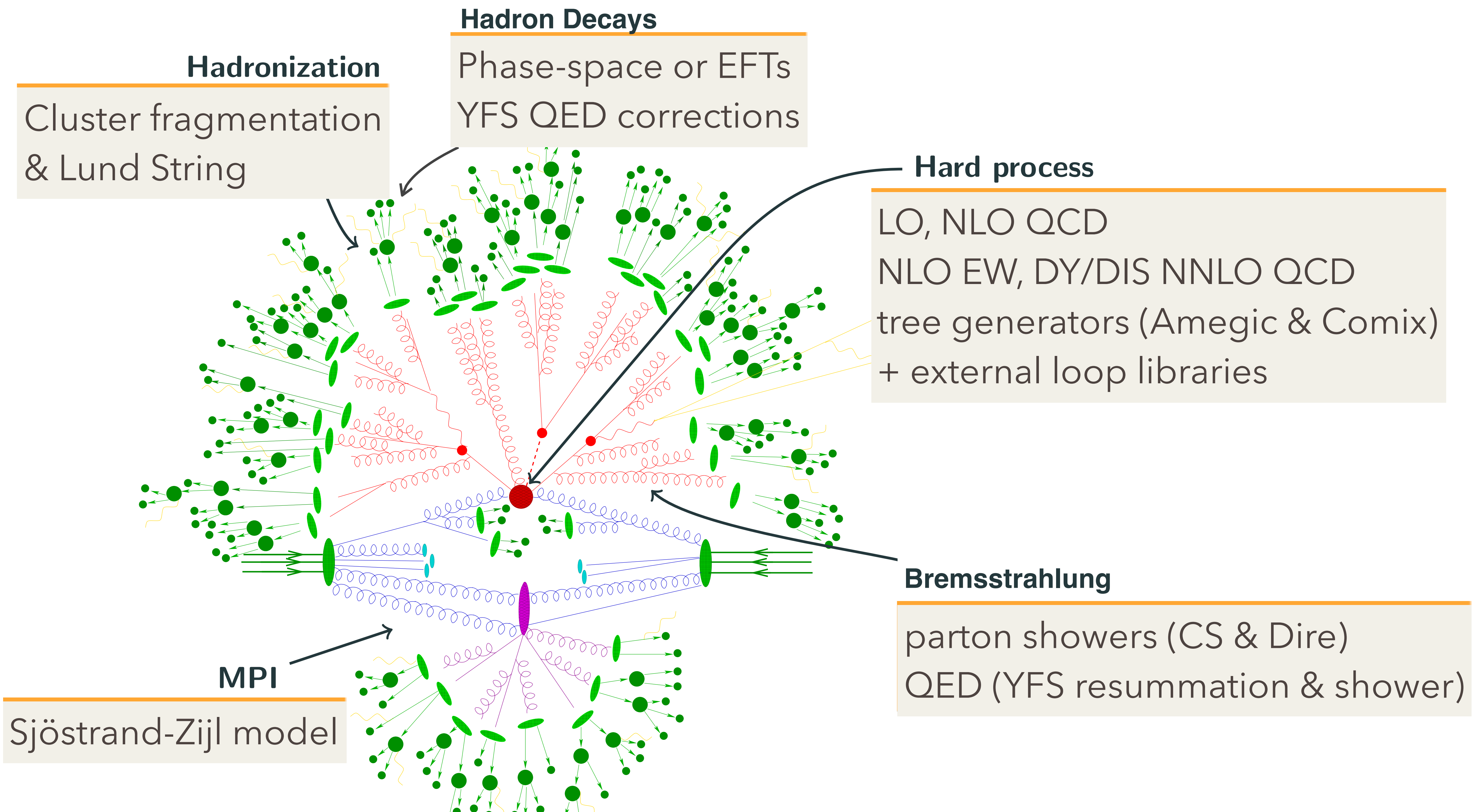


- non-perturbative
  - incoming proton structure (PDFs)
  - parton-hadron transition (hadronisation, decays)
  - remnant interactions, intrinsic $k_\mathrm{T}$ (underlying event)



- measurement function $O_n = \delta(X - \chi_n(p))$

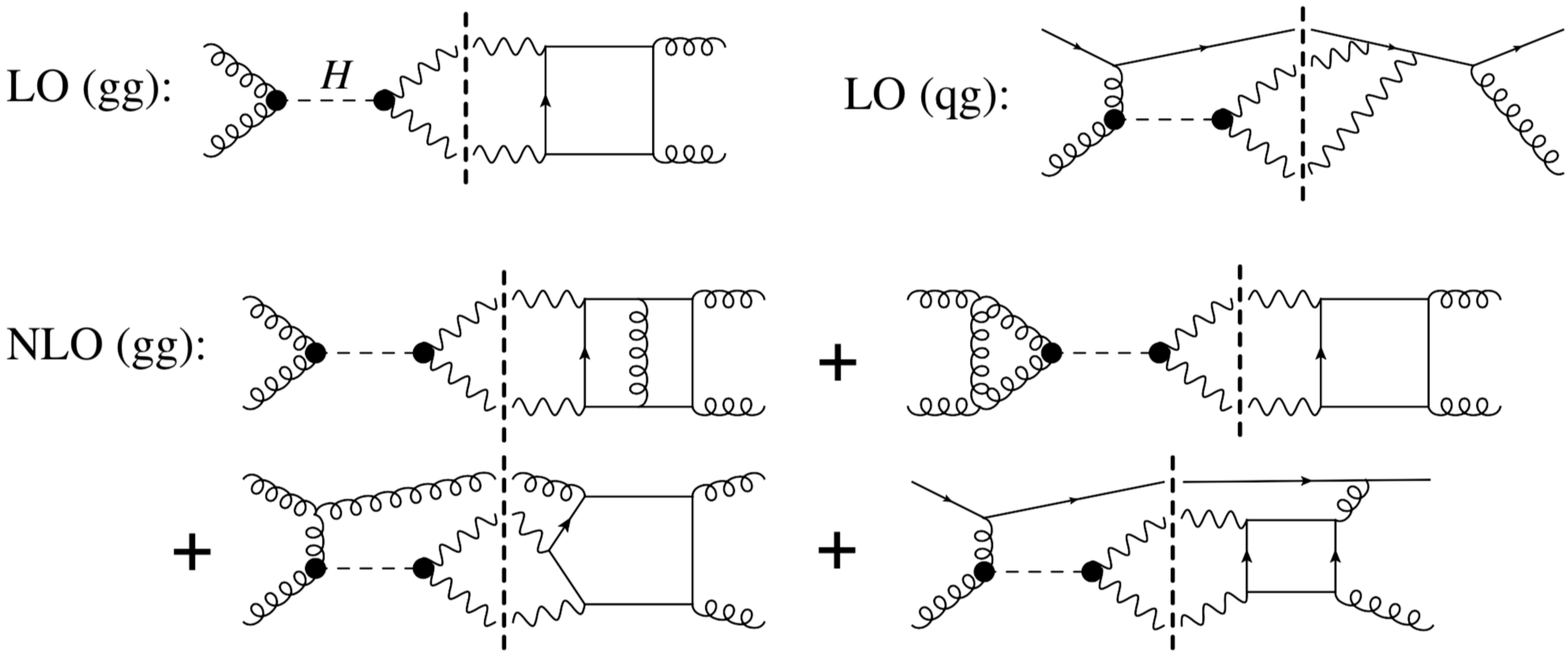
# Monte-Carlo event generation: single event




☛ each "MC point" gives a fully differential simulated event for *n* final-state particles, to which any $O_n$ can be applied

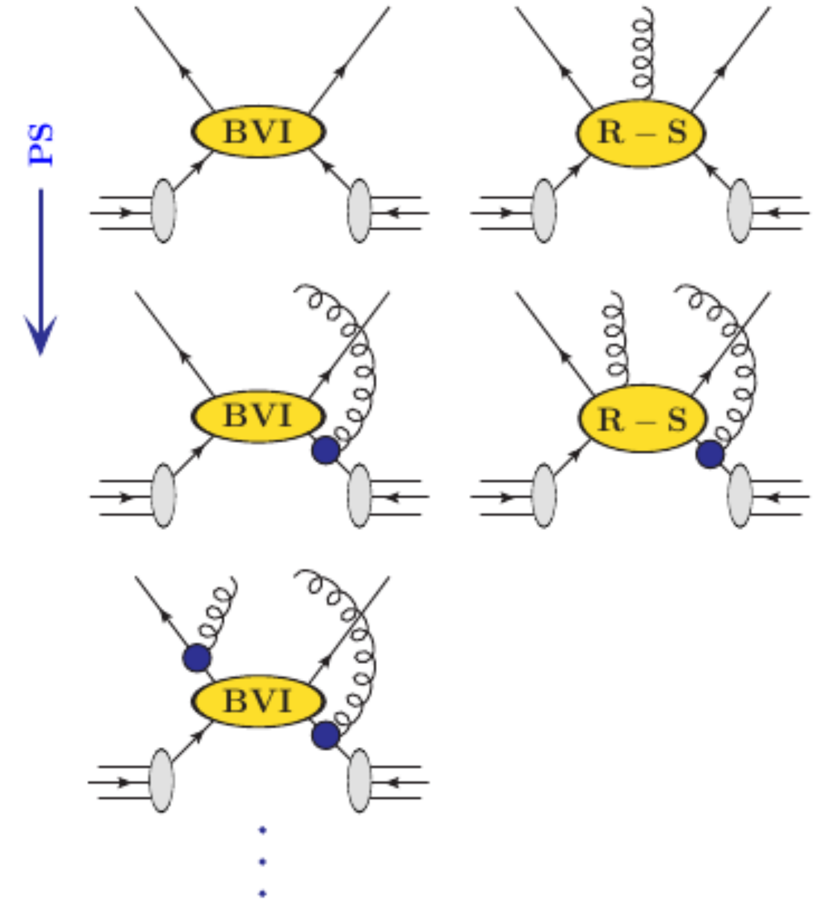
# Interference contributions

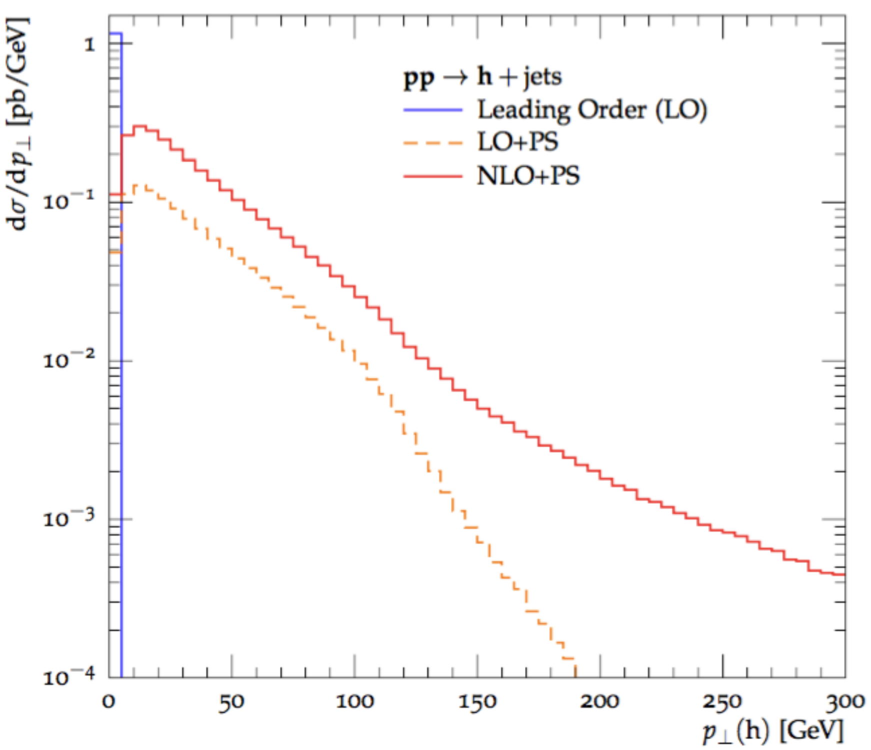
[Dixon 1305.3854]



# Signal & Interference simulation

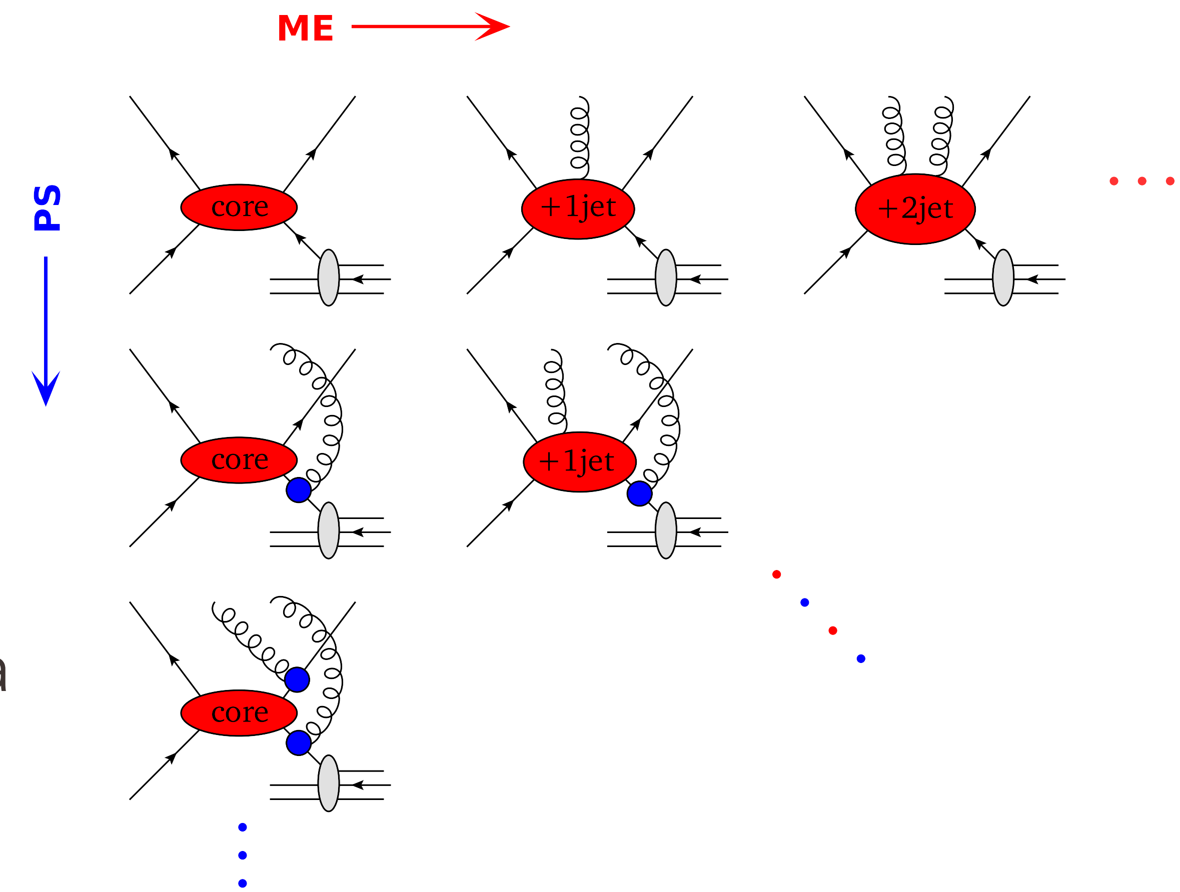
- SHERPA provides an implementation of NLO interference terms from [Dixon, Li 1305.3854 (2013)]
- METS scale setter, core: $\mu_F = \mu_R = m_{\gamma\gamma}$
- within our framework, we can thus use MC@NLO to combine NLO terms with PS
  - MC@NLO combines NLO ME and PS, while retaining
    [Frixione, Webber JHEP06(2002)029]
    [Höche et al JHEP09(2012)049]
    - NLO accuracy in expansion of $\alpha_S$
    - full logarithmic accuracy of PS resummation
- matching uncertainties formally higher-order, but can be enhanced by large $K$ factors (for which $gg \to H$ is infamous!)

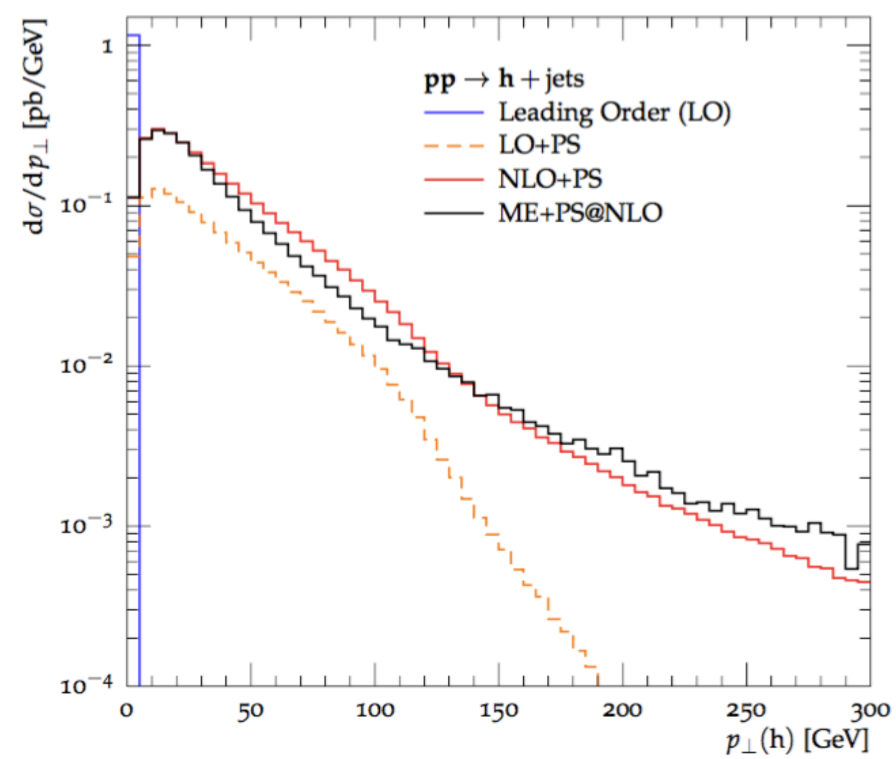


# Background simulation

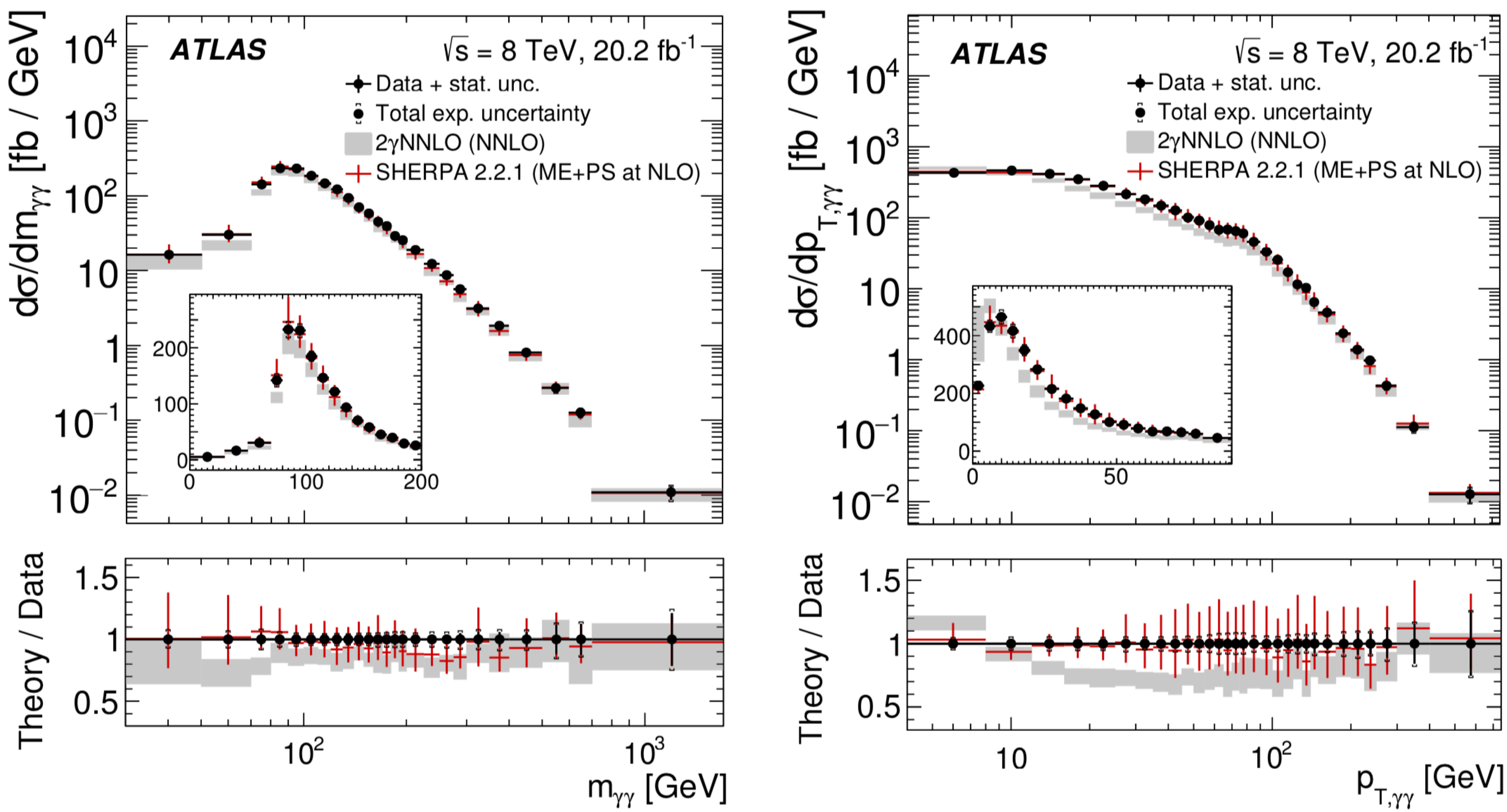
- use generic internal ME generators + OpenLoops for the virtual
- METS scale setter, core: $\mu_F = \mu_R = m_{\gamma\gamma}$
- MEPS@(N)LO combines matched (N)LO ME for several multiplicies into a single event sample, here:
  - 2 → 2 @ NLO; 2 → 3,4,5 @ LO
  - i.e. first few (hard) emissions by ME (improvement over shower radiation pattern)
  - double-counting removed by slicing the phase space into PS (soft/collinear) and ME (hard) regions



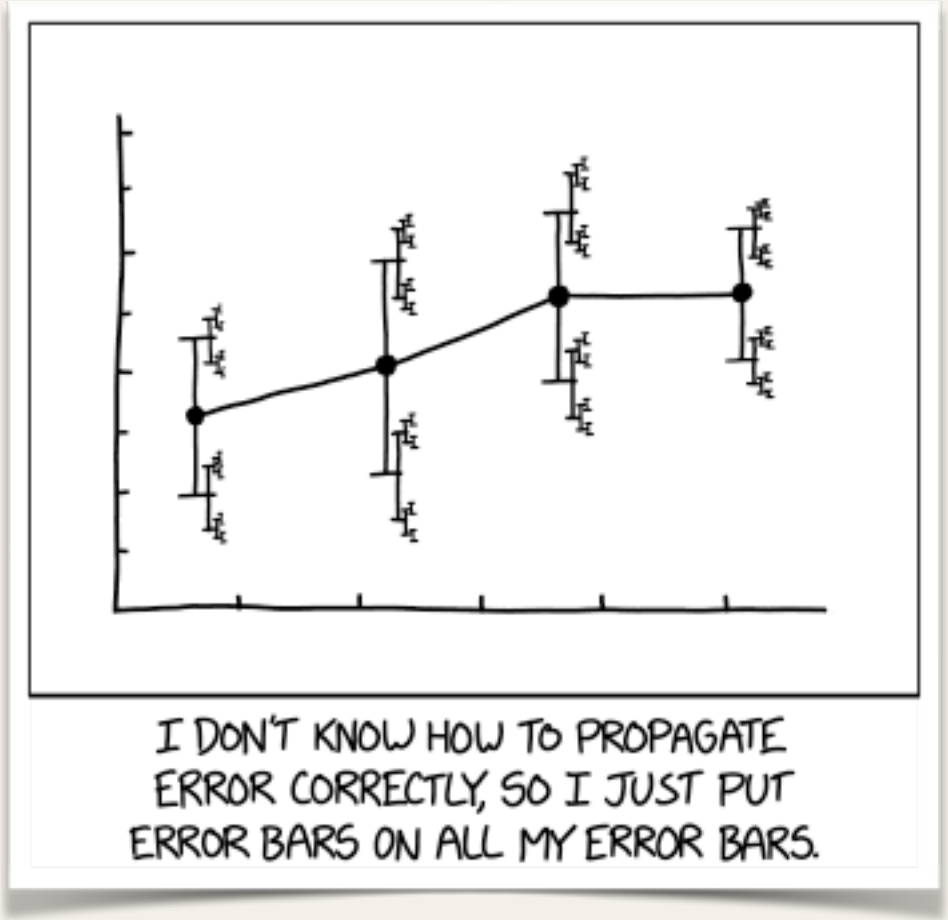
# Background simulation

[ATLAS 1704.03839]




⤳ simulated data seems to give realistic background description

# Strategies for extracting bounds on the width



# Mass shift through interference

[Martin 1208.1533 (2012)]

observation: interference of $gg \to H \to \gamma\gamma$ with QCD $gg \to$ e.g. quark loop $\to \gamma\gamma$
$\Rightarrow$ smeared Higgs mass peak in $m_{\gamma\gamma}$ shifts:

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

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

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

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

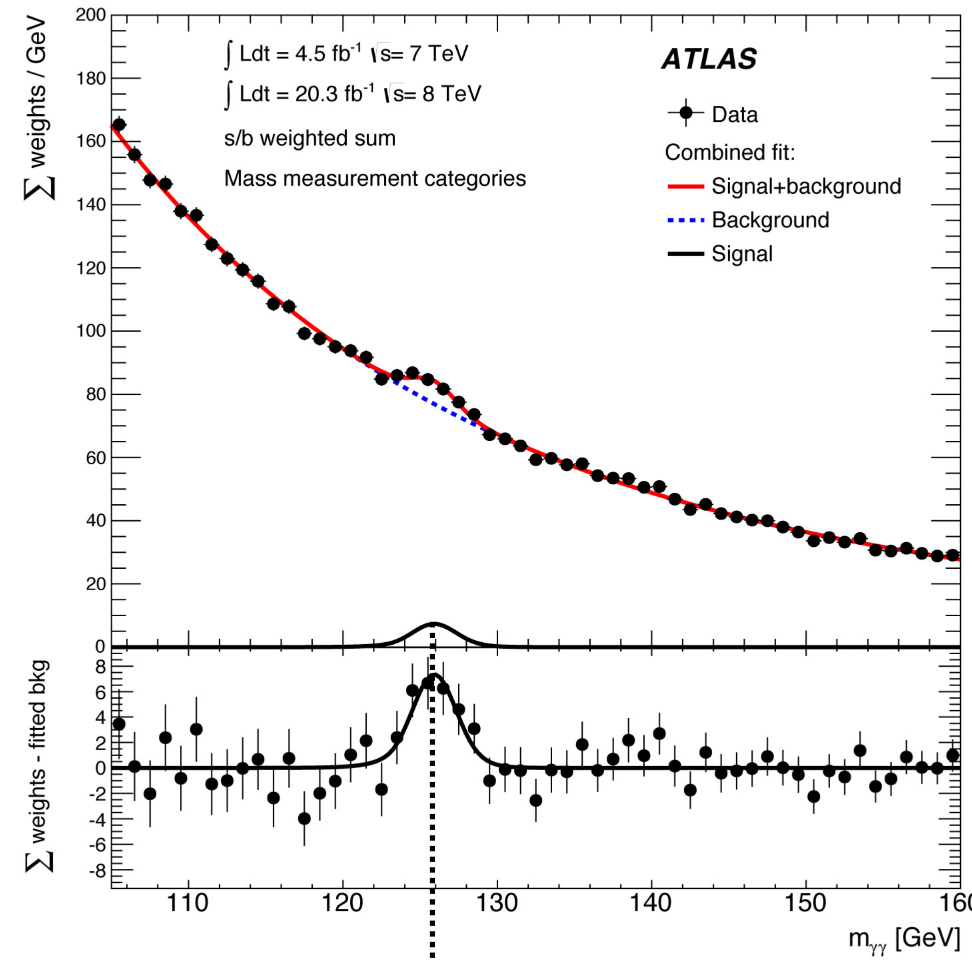
[ATLAS 1806.00242]

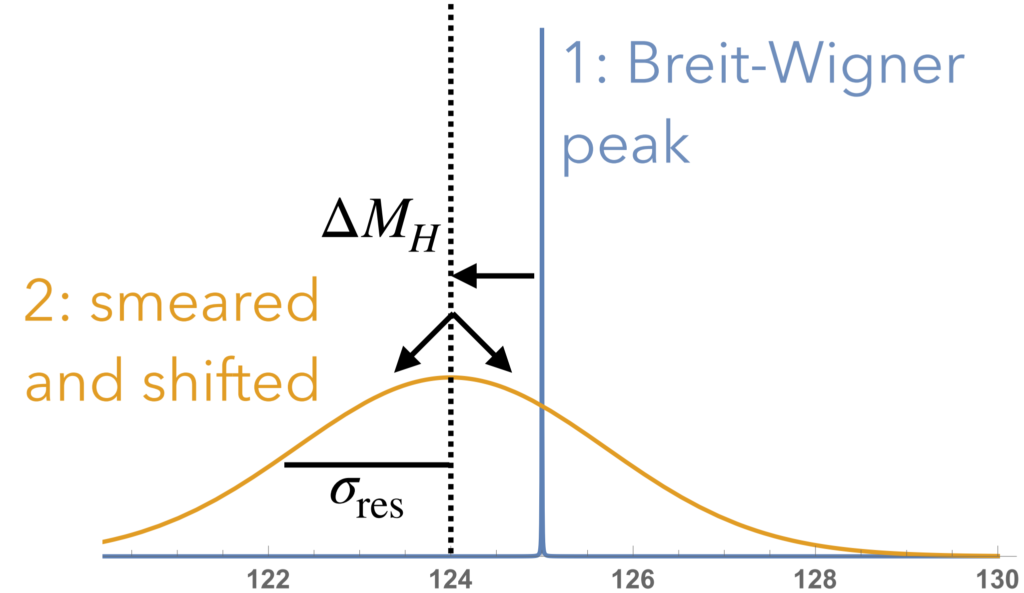
[Dixon, Li 1305.3854 (2013)]

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

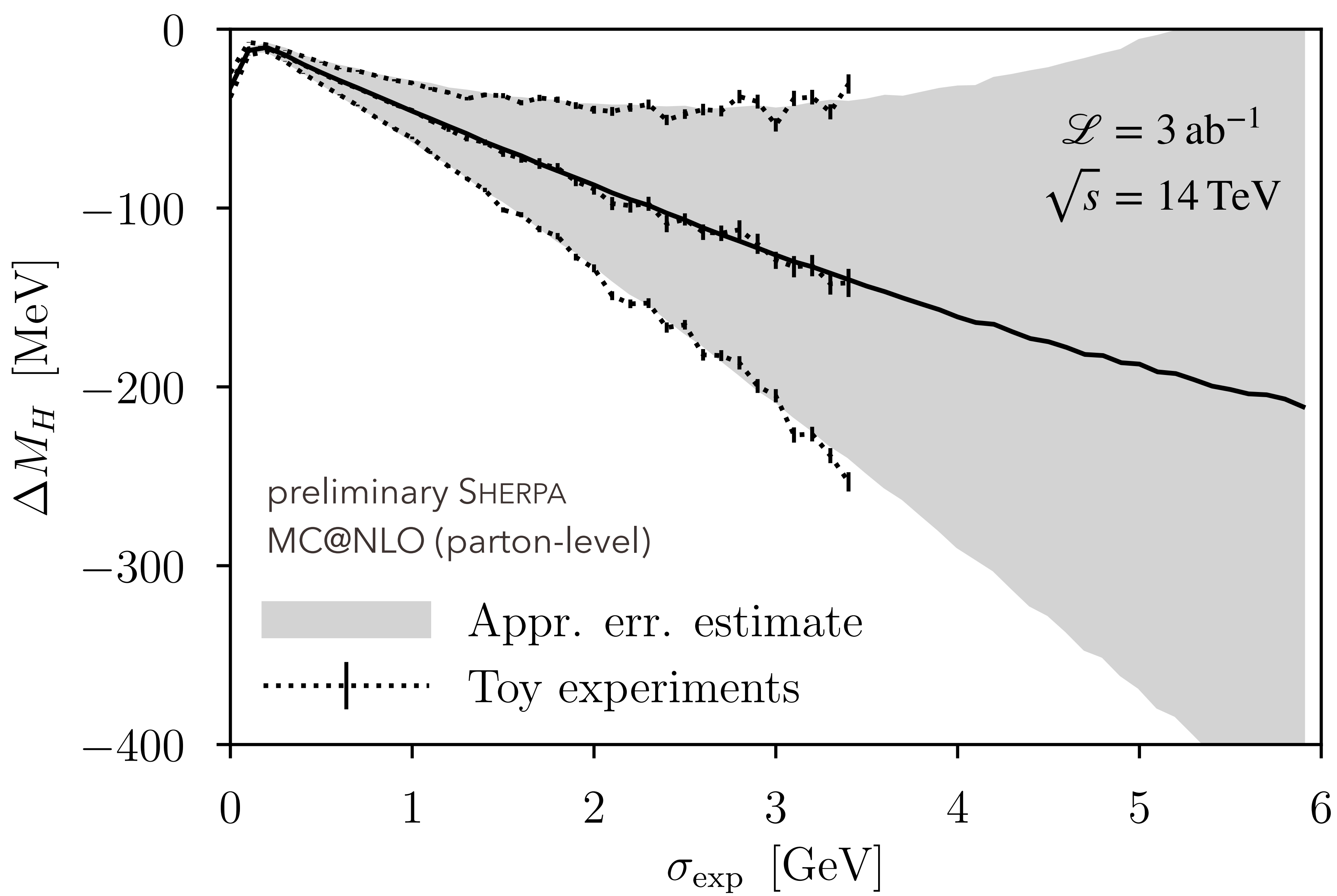
(reduced due to large signal K factor)

observation: fixing signal event yield gives $\Gamma_H$ bound independent from further assumptions on couplings and/or decay modes



# Mass shift grows with experimental resolution




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

# Extract width from mass shift

[Dixon, Li 1305.3854 (2013)]

- BSM: scaling factors $c_g$, $c_\gamma$ for $Hgg$, $H\gamma\gamma$ couplings
- let $c_g$, $c_\gamma$, $\Gamma_H$ vary, but keep measured signal yield fixed: $\mu_{\gamma\gamma} \approx 1$

BSM parametrisation = SM × signal yield

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

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

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

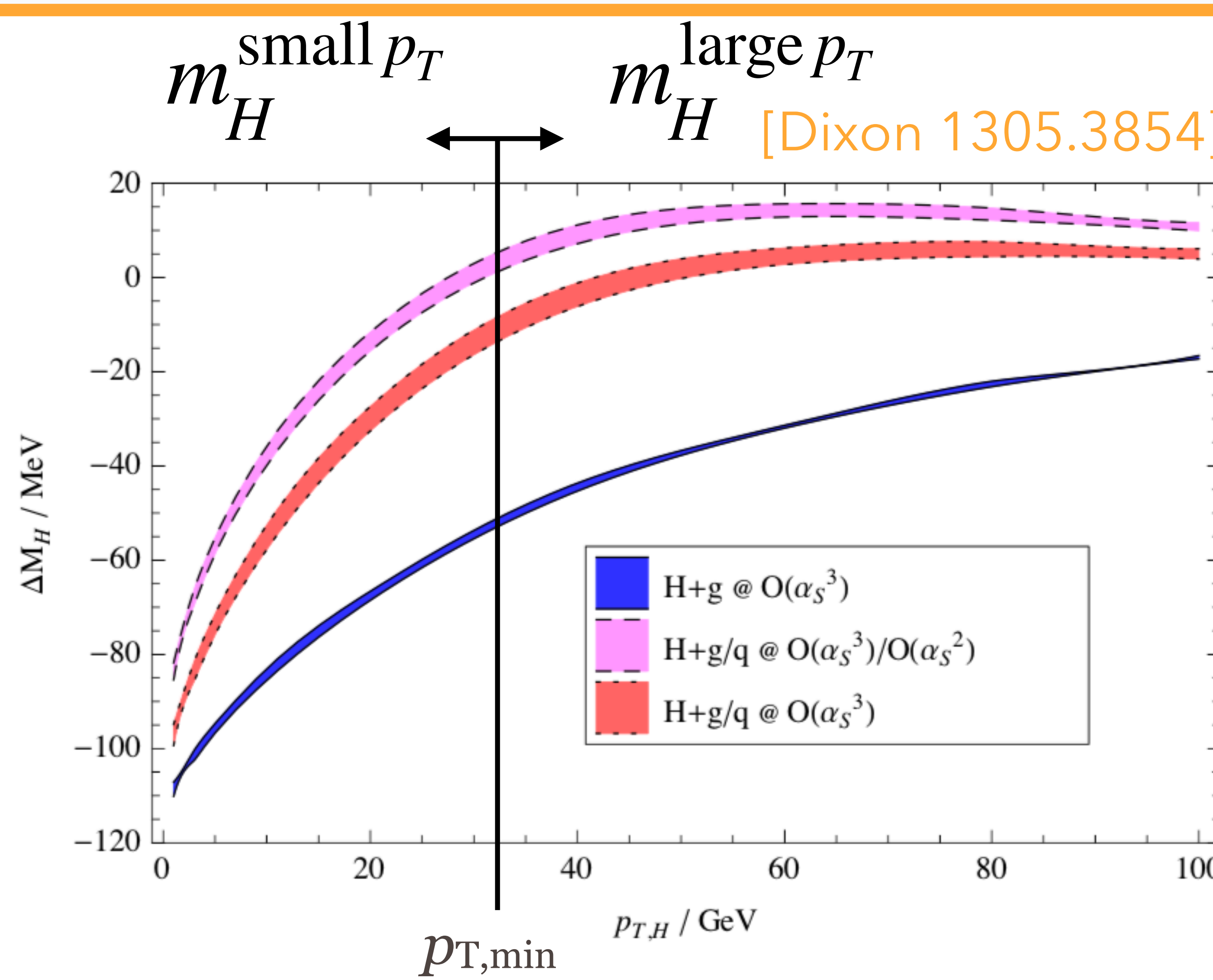
⇒ bound on $\Gamma_{\mathrm{H}}$ independent from further assumptions on couplings and/or decay modes

# A reference value for $m_H$

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

- $\gamma\gamma$+$j$ has smaller relative magnitude of interference
- … and opposite sign of interference for $qg$- and $gg$-initiated channels ⇒ cancellation

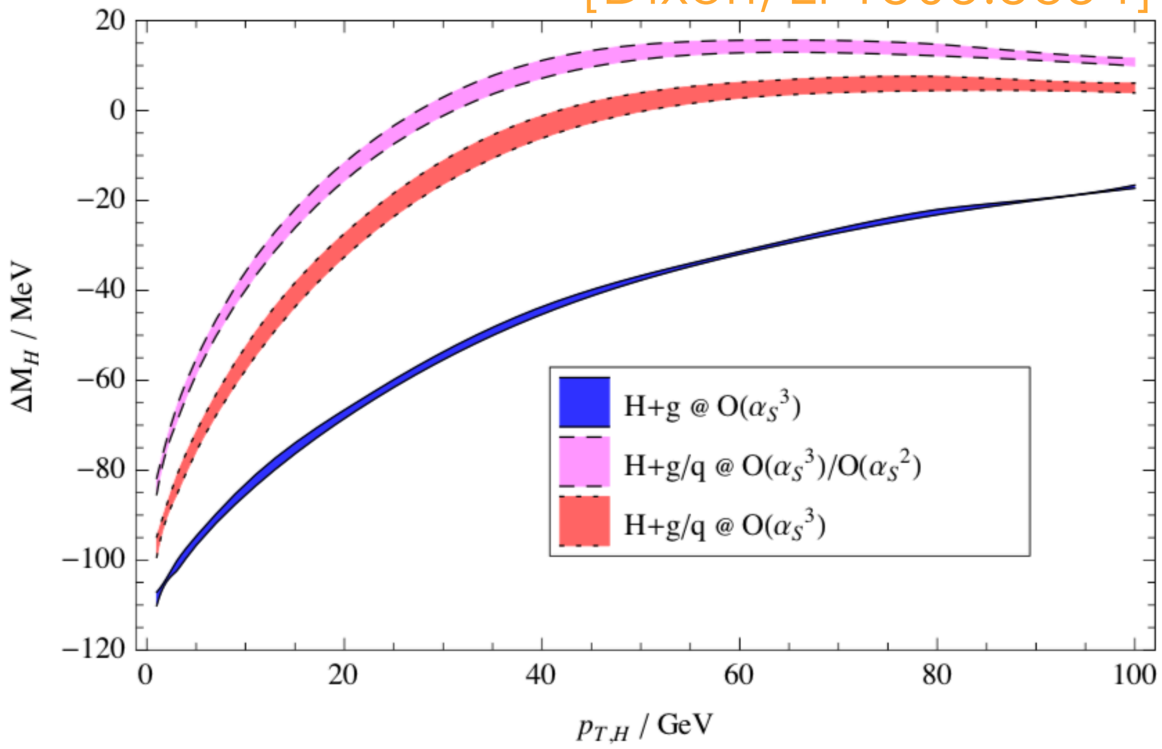
⤳ $p_{T,H}$ cut dependent mass shift



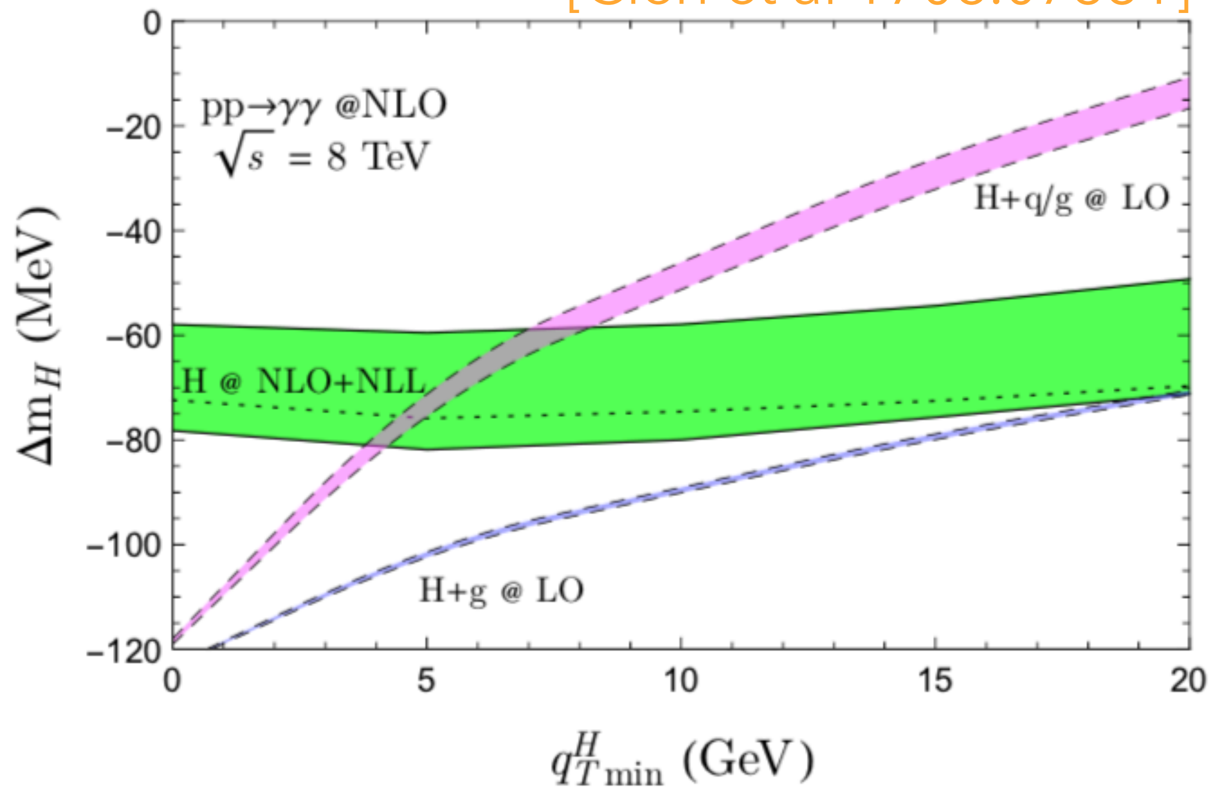

- extract shift within $gg \to H \to \gamma\gamma(j)$ channel by comparing large $p_T$ bin and low $p_T$ bin
- projection to HL-LHC (3 ab$^{-1}$): 95 % CL limit for $\Gamma_H \leq 15\ \Gamma_H^{SM}$
- requires precise knowledge of the $p_{T,H}$ spectrum
  - but fixed-order unreliable for low $p_T$
    ⤳ how stable when including resummation (& hadronisation?) effects

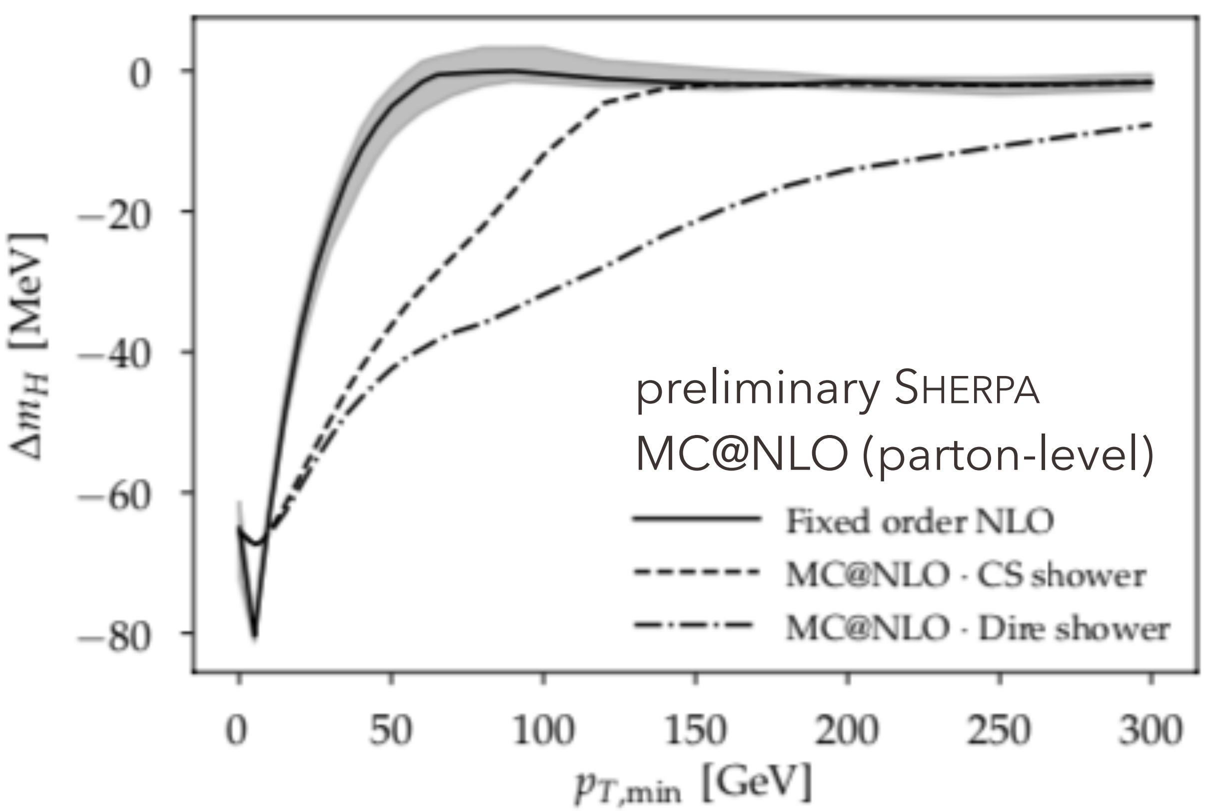
# $p_T$ extraction for fixed-order & resummed

[Dixon, Li 1305.3854]




[Cieri et al 1706.07331]




- 100 ≲ $p_{T,\mathrm{min}}$ ≲ 150 plagued by sizable theory uncertainties
- need NLO for γγ+$j$ interference terms to get get better precision;
- can include some higher-order terms to reduce this effect …

# An alternative approach …

- can we just go back to the $m_{\gamma\gamma}$ distribution and fit something that includes the shape distortion?
  - no need to define reference mass
  - conceptually simpler
    "just an invariant mass distribution fit"
  - distribution described at NLO, smaller theoretical errors
- convolution of Lorentzian (signal profile) with Gaussian (exp. resolution) described by Faddeeva function:

$$w(z) = e^{-z^2}\mathrm{erfc}(-iz)$$

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

- calculate line profile that enters the fit:

$$\mathcal{F} = \alpha \left[ \mathrm{Re}\{\mathcal{S}\} + \beta \sqrt{\frac{\Gamma_H}{\Gamma_H^{\mathrm{SM}}}}\, \mathrm{Im}\{\mathcal{S}\} \right]$$

  - in terms of the shape function

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

  - using $c_{g\gamma} = \sqrt{\frac{\Gamma_H}{\Gamma_H^{\mathrm{SM}}}}$

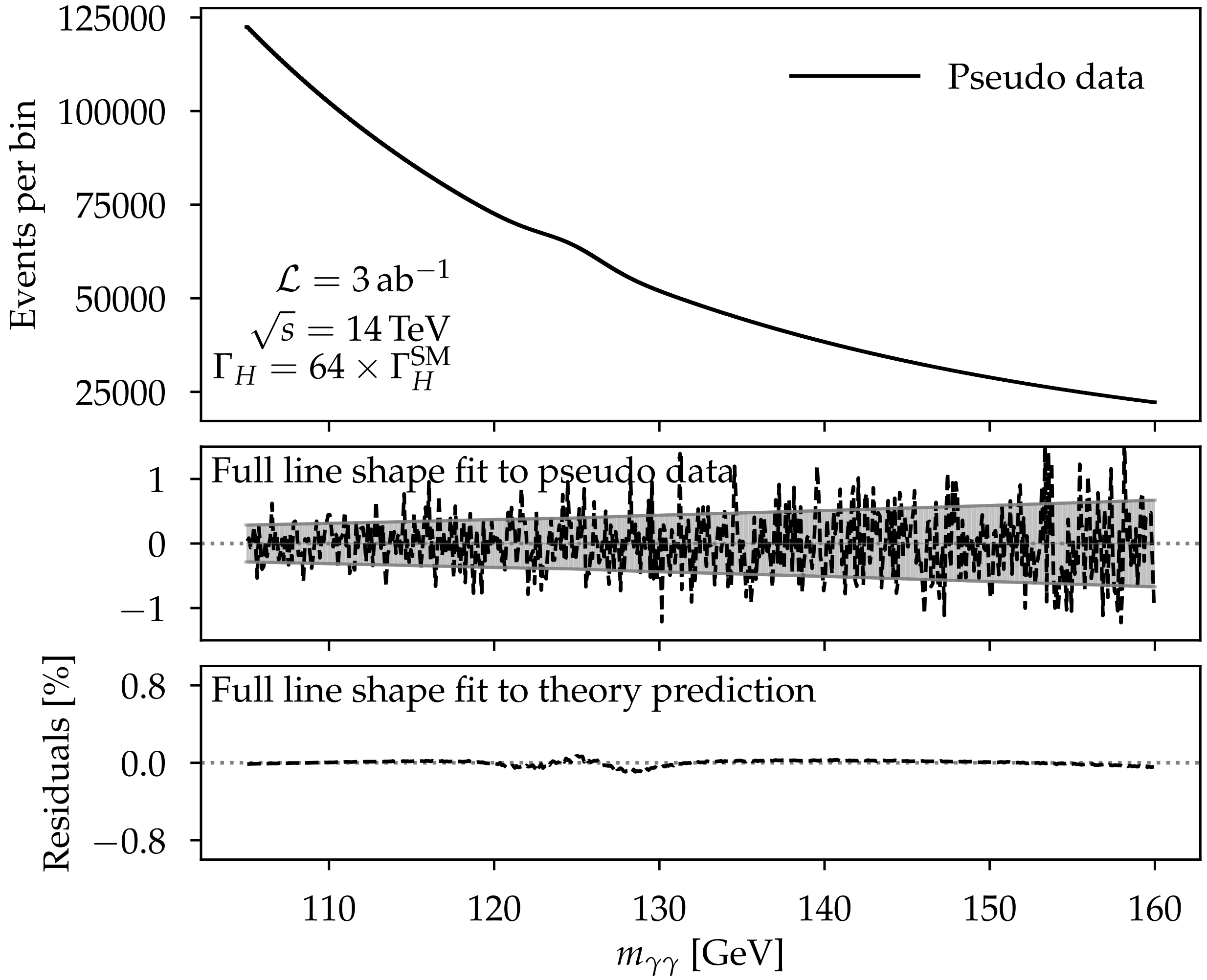
- $\alpha$ is a fit parameter, $\beta$ is determined by relative cross section normalisations (this is where our theory predictions enter)

- fit $\mathcal{F}$ to the input data (here: our pseudo data)

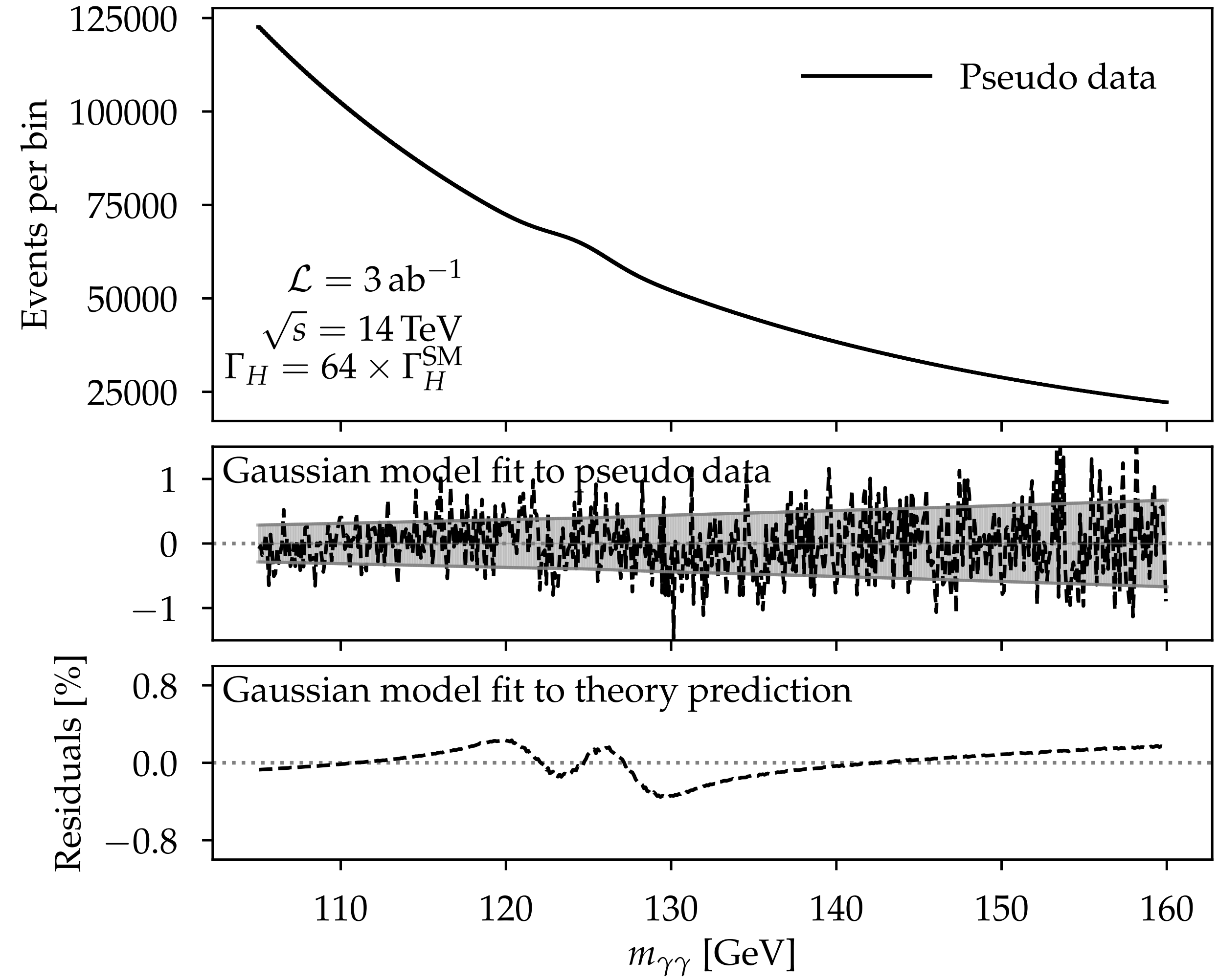
# GOF comparison for Faddeeva vs. Gaussian

preliminary SHERPA MC@NLO (parton-level)

Faddeeva fit




Gauss fit




$\rightsquigarrow$ Residuals reduced by factor > 4 by using Faddeeva function

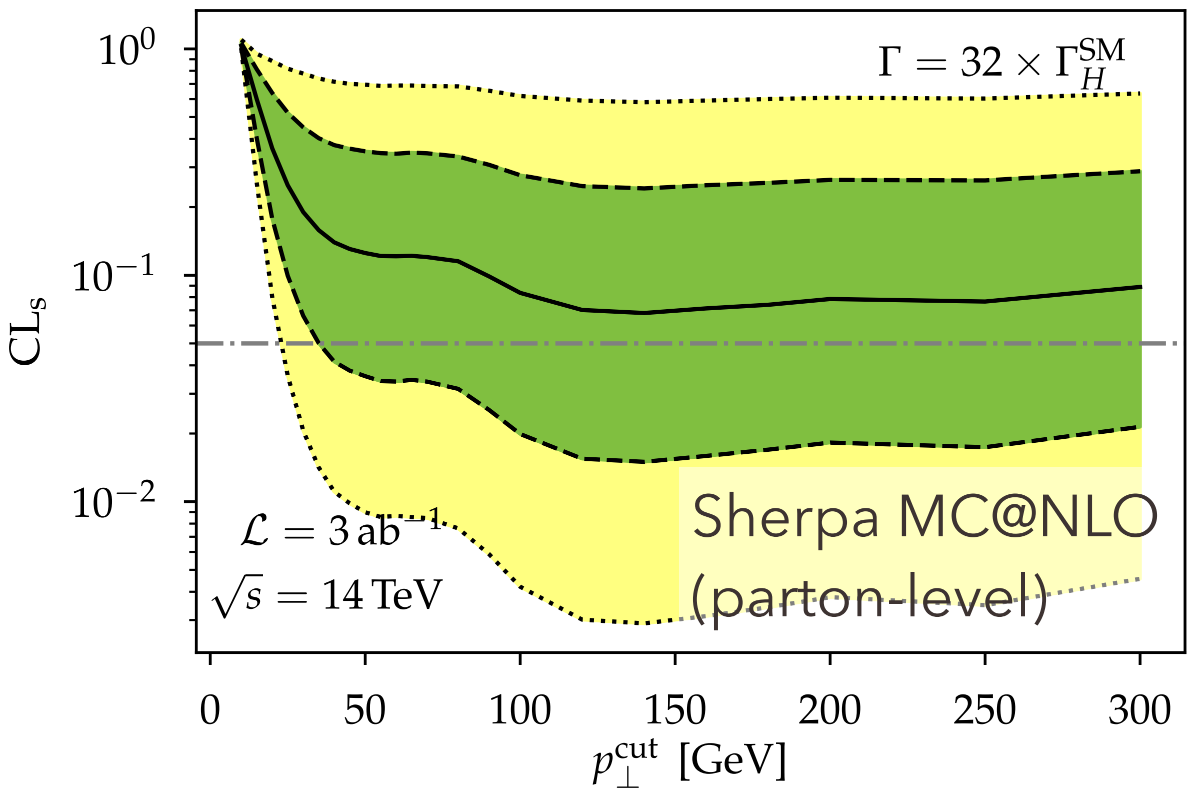
# Results

# Input parameters & Analysis

- CT10NLO and corresponding strong coupling
- EW parameters calculated from $\alpha_{\mathrm{QED}}(0) = 1/137$ and W, Z, H masses using tree-level relations
- RIVET analysis modelled after ATLAS-CONF-2017-046
  - at least two γ with $E_{\mathrm{T},\gamma} > 25$ GeV and $|\eta_\gamma| \leq 2.37$
  - $p_{\mathrm{T},\gamma 1} / m_{\gamma\gamma} > 0.35$ and $p_{\mathrm{T},\gamma 2} / m_{\gamma\gamma} > 0.25$
  - photon isolation (mimick calorimeter isolation criterion)
    - take scalar sum of $p_{\mathrm{T}}$ of all QCD particles in a cone of radius $R = 0.2$ around any photon
    - reject photon if the ratio of this sum and the $p_{\mathrm{T},\gamma}$ exceeds 6,5 %
  - experimental resolution $\sigma_{\mathrm{res}} = 1.87$ GeV
  - $m_{\gamma\gamma}$ bin size: 0.1 GeV

# $p_{T,\min}$ for the $p_T$-based analysis

preliminary SHERPA MC@NLO (parton-level)



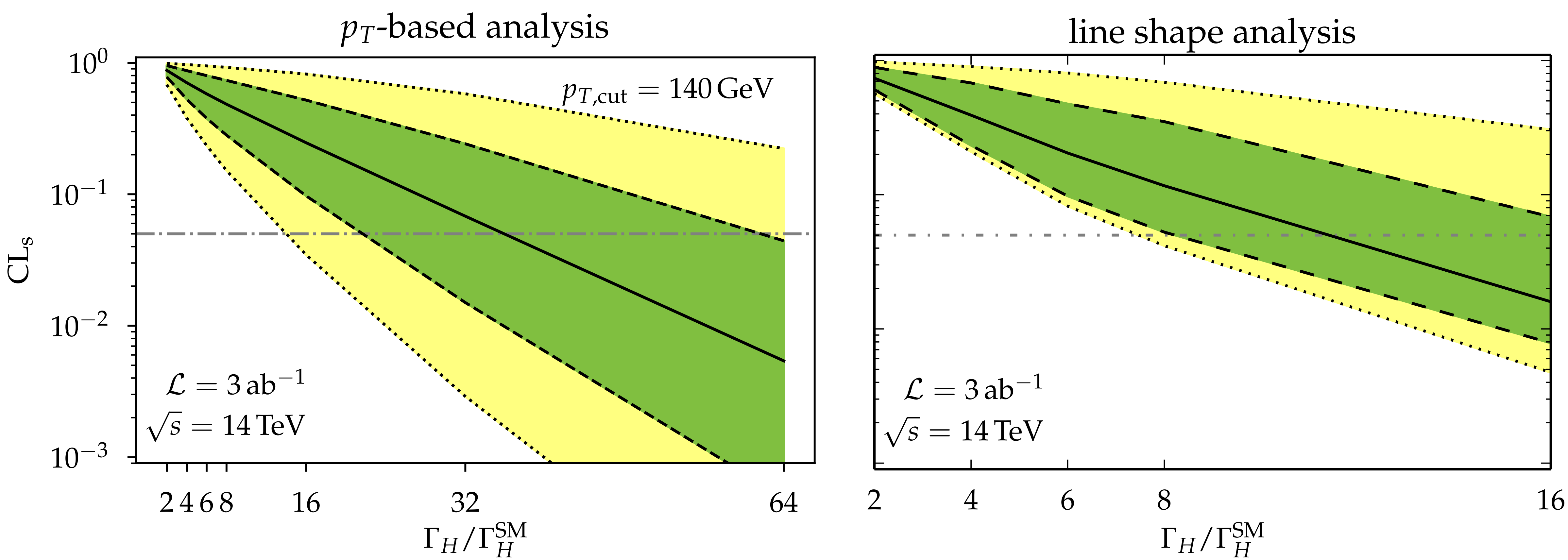

remember …

- $100 \lesssim p_{T,\min} \lesssim 150$ plagued by sizable theory uncertainties
- need NLO for $\gamma\gamma+j$ interference terms to get get better precision;
- can include some higher-order terms to reduce this effect …

☛ bad news: fixed-order bound $\Gamma_H \leq 15\ \Gamma_H{}^{SM}$ degrades after resummation to $\Gamma_H \lesssim 32+x\ \Gamma_H{}^{SM}$

# Results for both methods

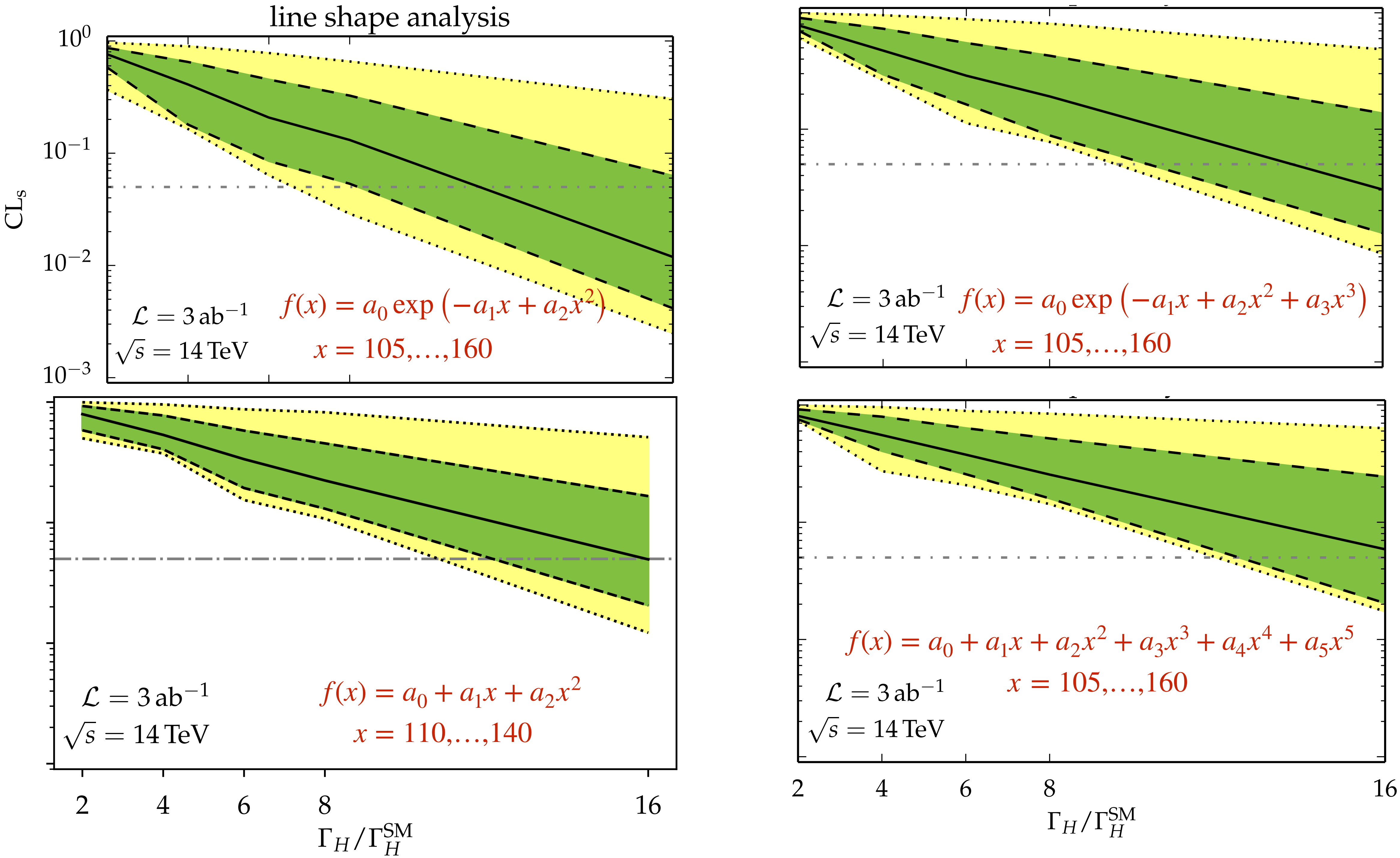
preliminary SHERPA MC@NLO (parton-level)




⤳ HL-LHC bound using $p_{T,\mathrm{min}}$ cut method: $\Gamma_H \lesssim 36\ \Gamma_H^{\mathrm{SM}}$

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

# Line shape method: dependence of BG fit




- ☛ study dependence on BG fit model+window
- ☛ within 1$\sigma$ uncertainty band

# Conclusions

- study interference-induced Higgs peak shift at particle-level
- extract the shift / fit distorted line shape ⇒ model-independent bound on $\Gamma_H$
- HL-LHC bounds (preliminary)
  - e.g. by comparing shift in high-/low $p_{\mathrm{T},H}$
    - fixed-order bound $\Gamma_H \leq 15\ \Gamma_H^{\mathrm{SM}}$ degrades after resummation to $\Gamma_H \lesssim 36\ \Gamma_H^{\mathrm{SM}}$
  - or by directly fitting distorted line shape in $m_{\gamma\gamma}$
    - somewhat optimistic to get $\Gamma_H \leq 12\text{–}24\ \Gamma_H^{\mathrm{SM}}$
  - based on our simple study it appears that distorted peak fit more powerful
- TODO:
  - use Crystal-Ball function for $m_{\gamma\gamma}$ smearing instead of Gaussian
    - might lower the shift effect [ATL-PHYS-PUB-2016-009]
    - does not exactly give Faddeeva function!
  - re-add event categories (?)
  - do shower comparisons for $\mathrm{CL_S}$ plots

MCnet

**opportunity for PhD students**
Marie Skłodowska-Curie Early Stage Researcher
3–6 months project in any MCnet ITN node:

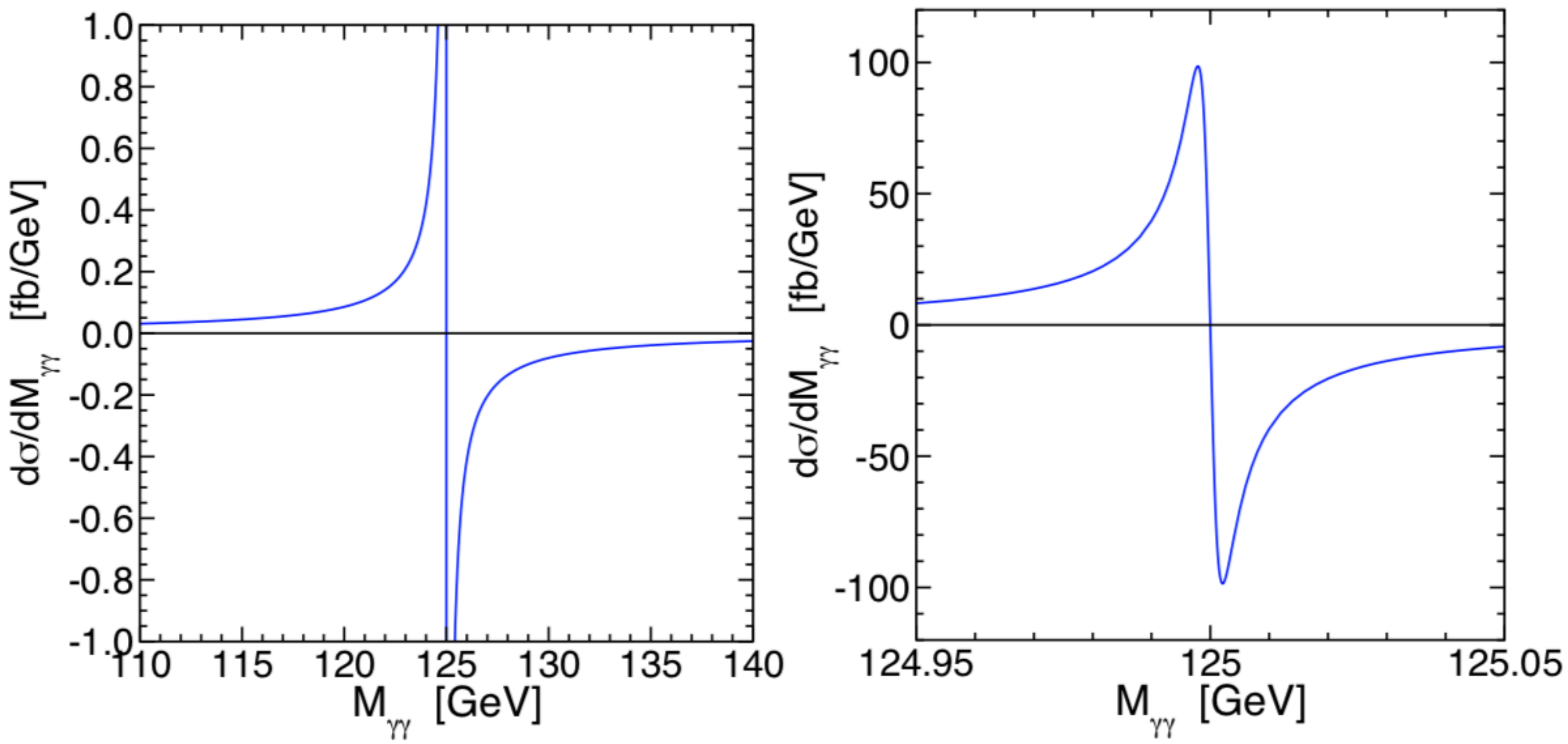
- Durham
- Glasgow
- Göttingen
- Karlsruhe
- Louvain
- Lund
- Manchester
- University College London

☛ montecarlonet.org

# Back-up

# The real interference before/after smearing

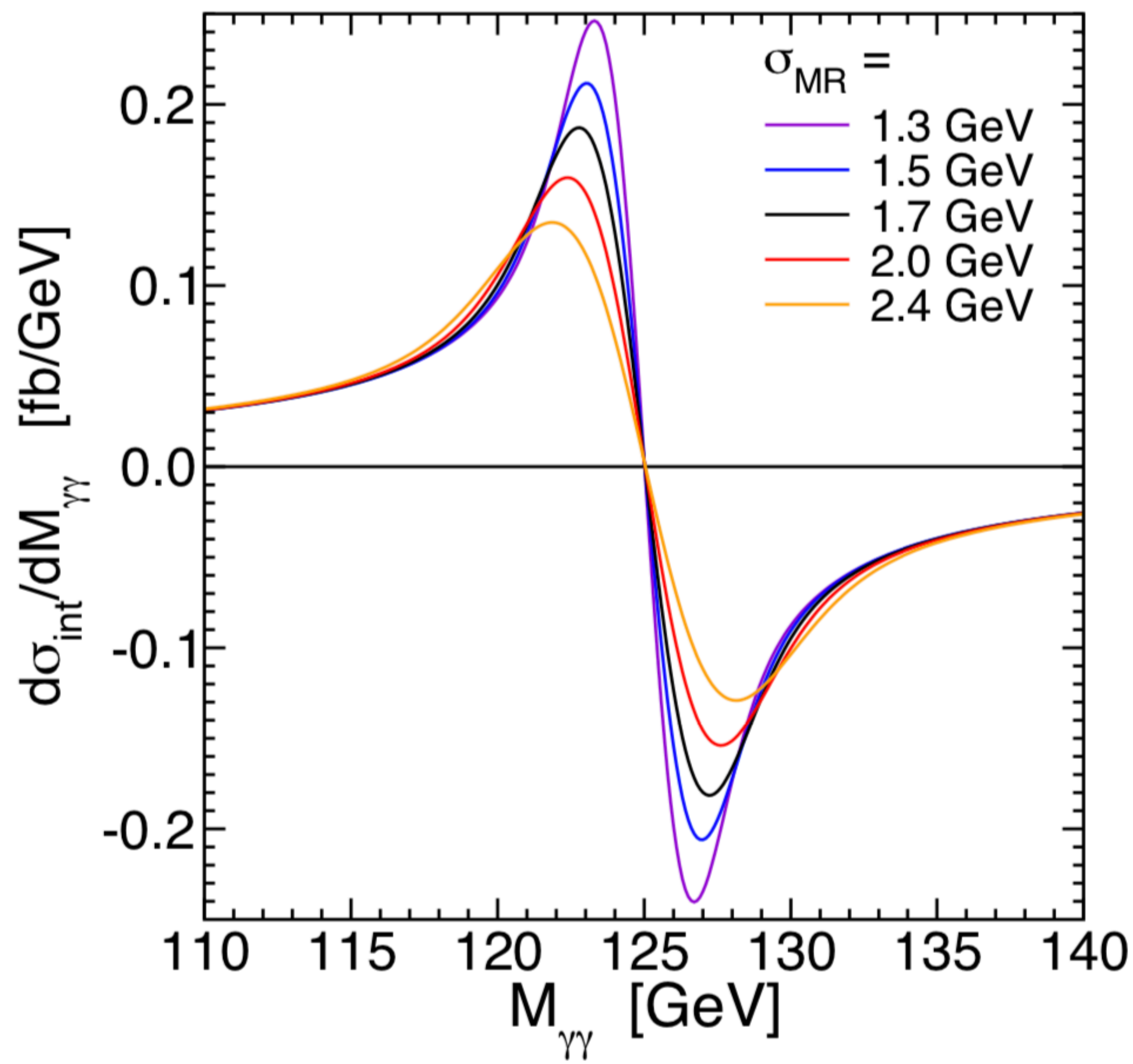
[Martin 1208.1533 (2012)]




maximum and minimum near $M_{\gamma\gamma} = M_H \pm \Gamma_H/2$

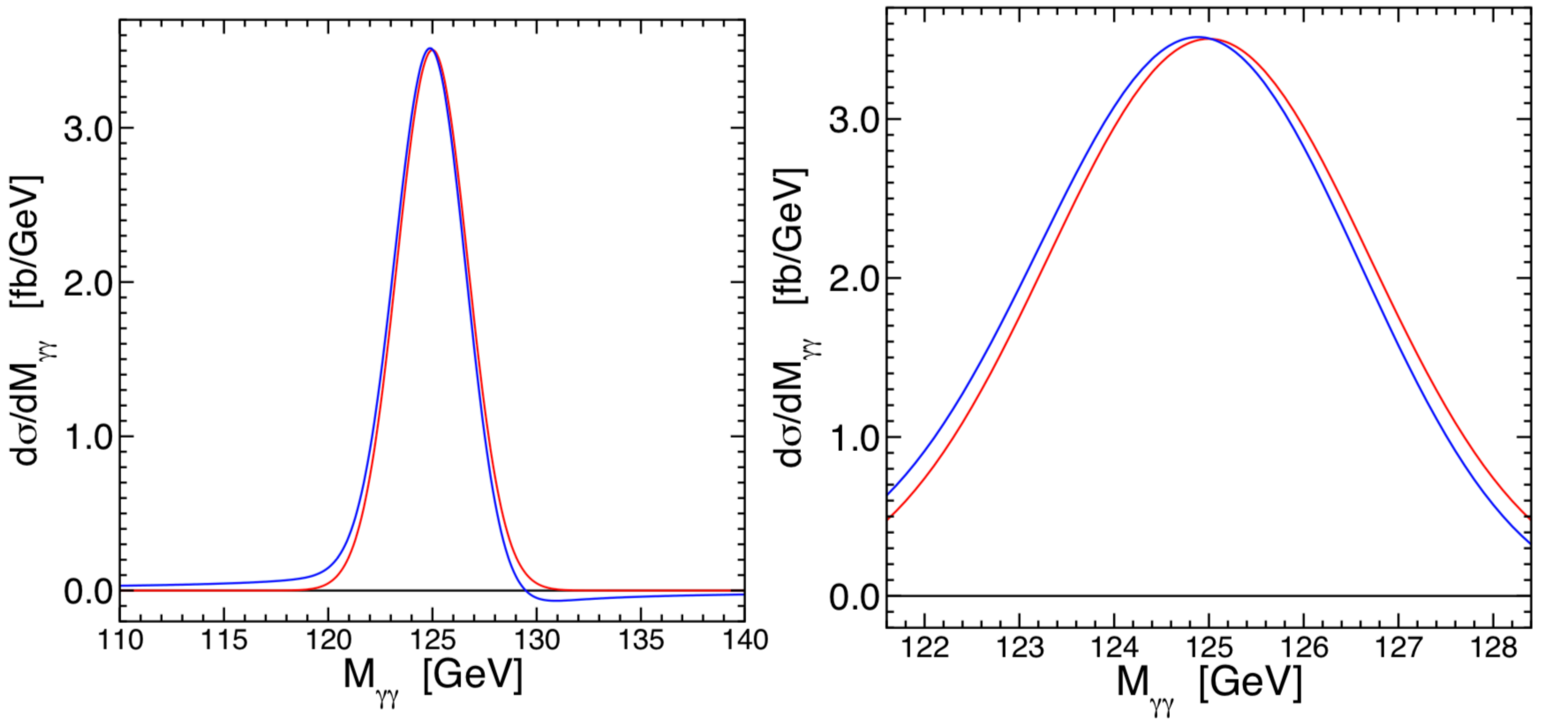
# The real interference after smearing

[Martin 1208.1533 (2012)]

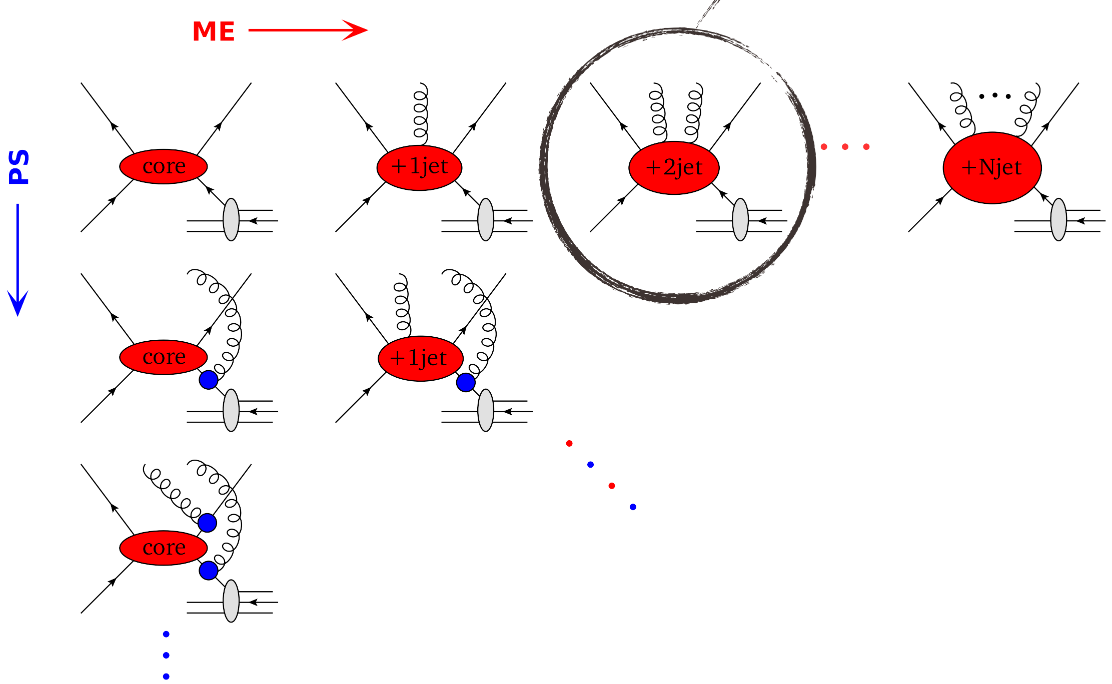


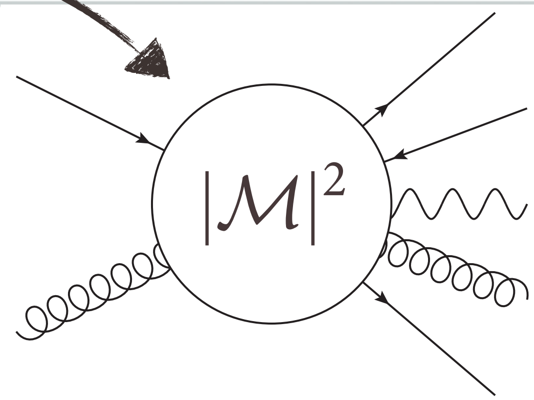
# The signal w/wo real interference

[Martin 1208.1533 (2012)]

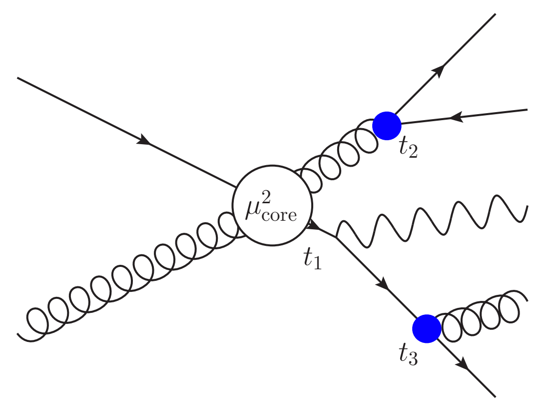


# Multi-jet merging



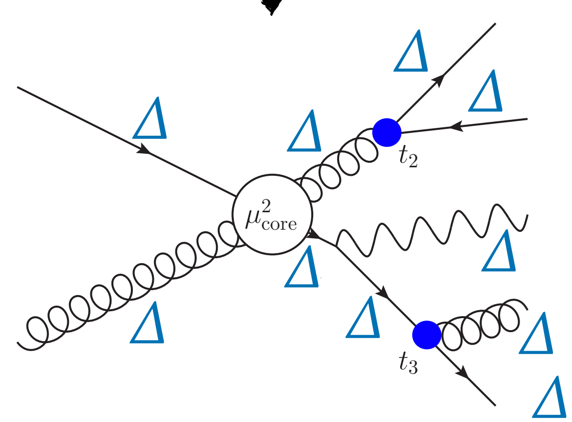

re-interpretation as parton-shower history




re-evaluation of $\alpha_S$ and PDFs at intermediate splitting scales $t_i$

take modified dependences into account in reweighting

introduce $\mu_{\rm merge}$




Sudakov rejection to make matrix elements exclusive down to $\mu_{\rm merge}$

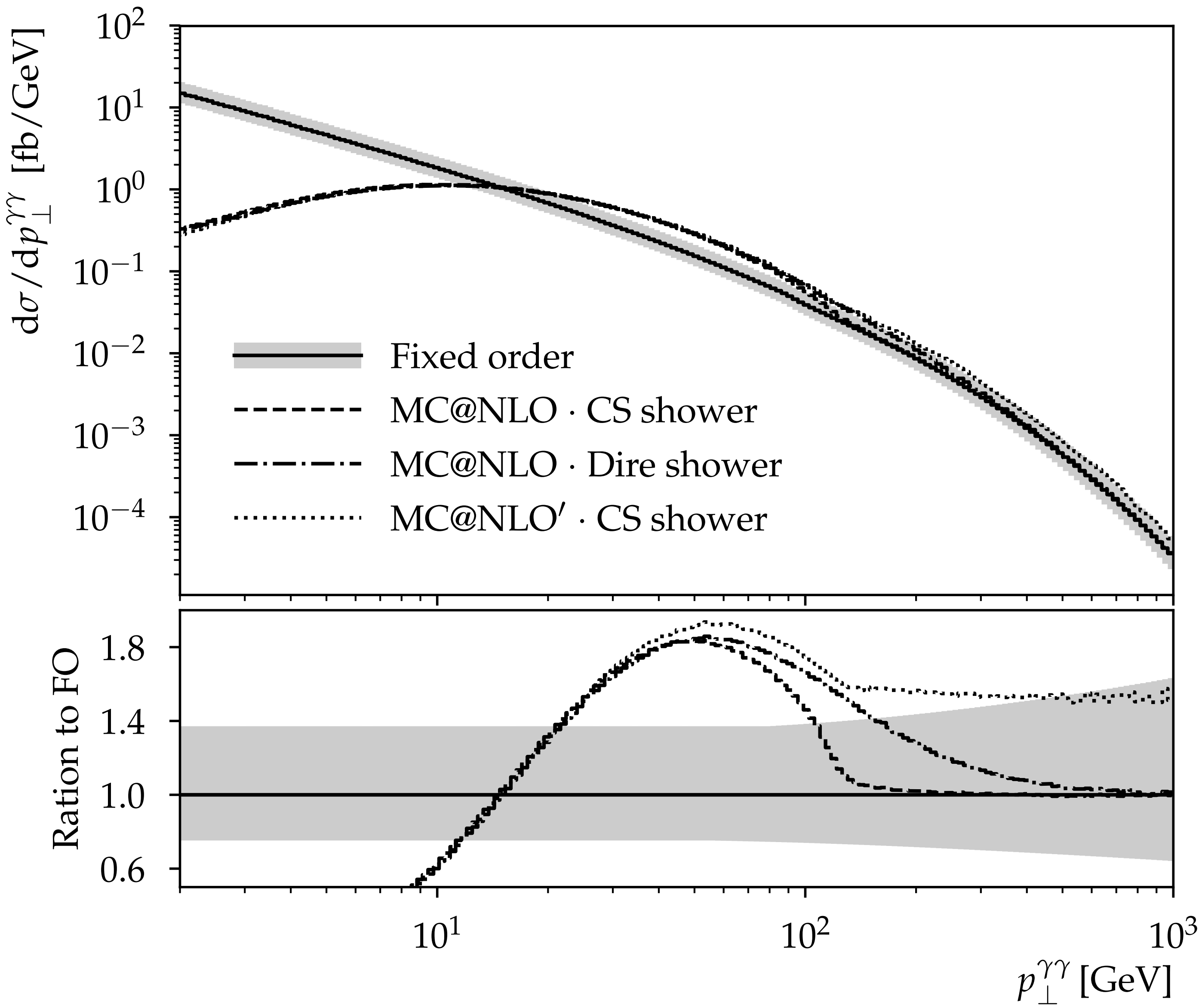
finally add genuine parton-shower emissions below $\mu_{\rm merge}$

# NLO „fudge" factor for real-emission events

ratio of the Sudakov form factor between the timelike and the spacelike region

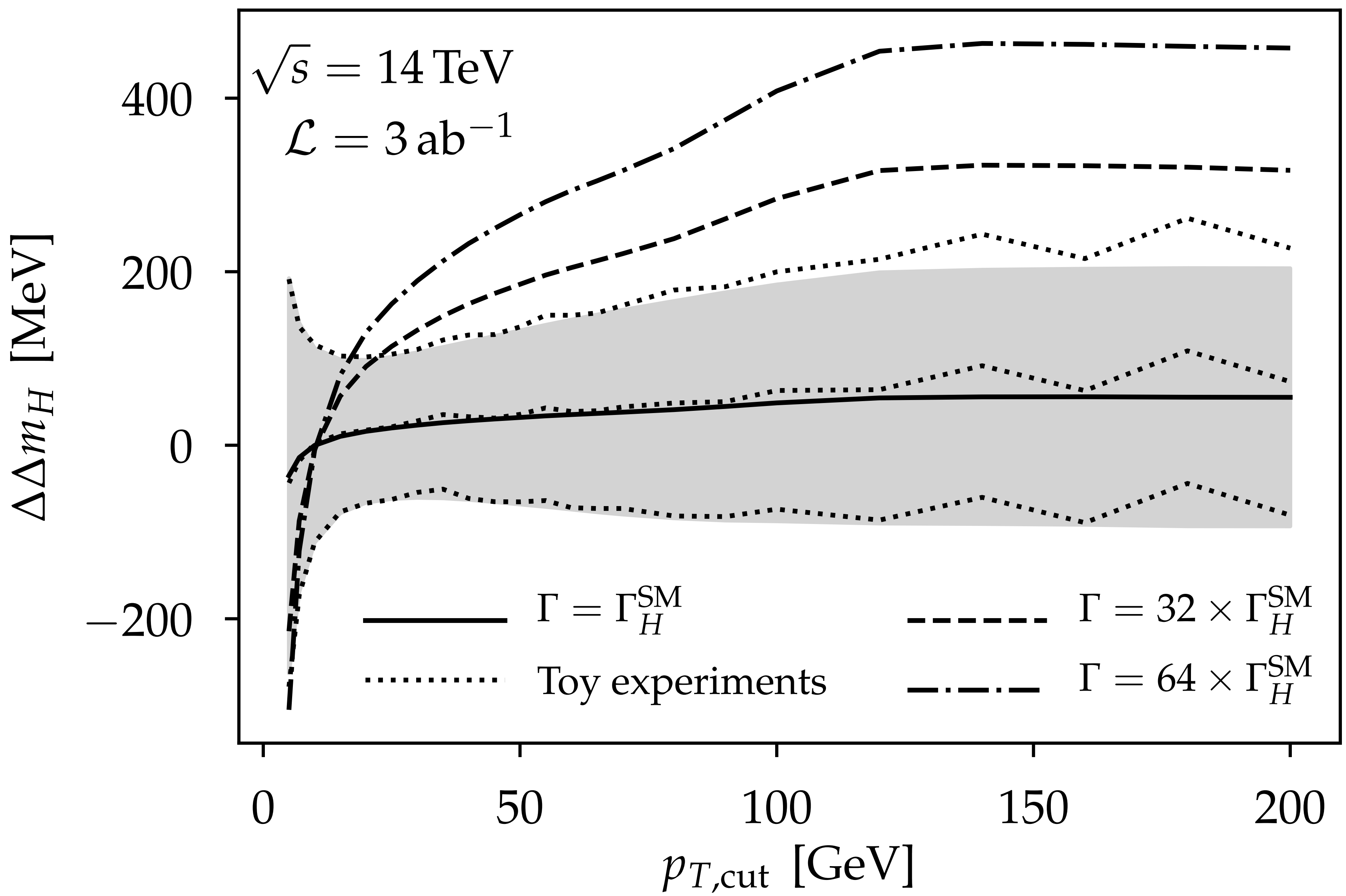
$$\left|\frac{\Gamma_a(Q^2)}{\Gamma_a(-Q^2)}\right|^2 = 1 + \frac{\alpha_s(Q^2)}{2\pi} C_a \pi^2 + \mathcal{O}(\alpha_s^2)$$

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

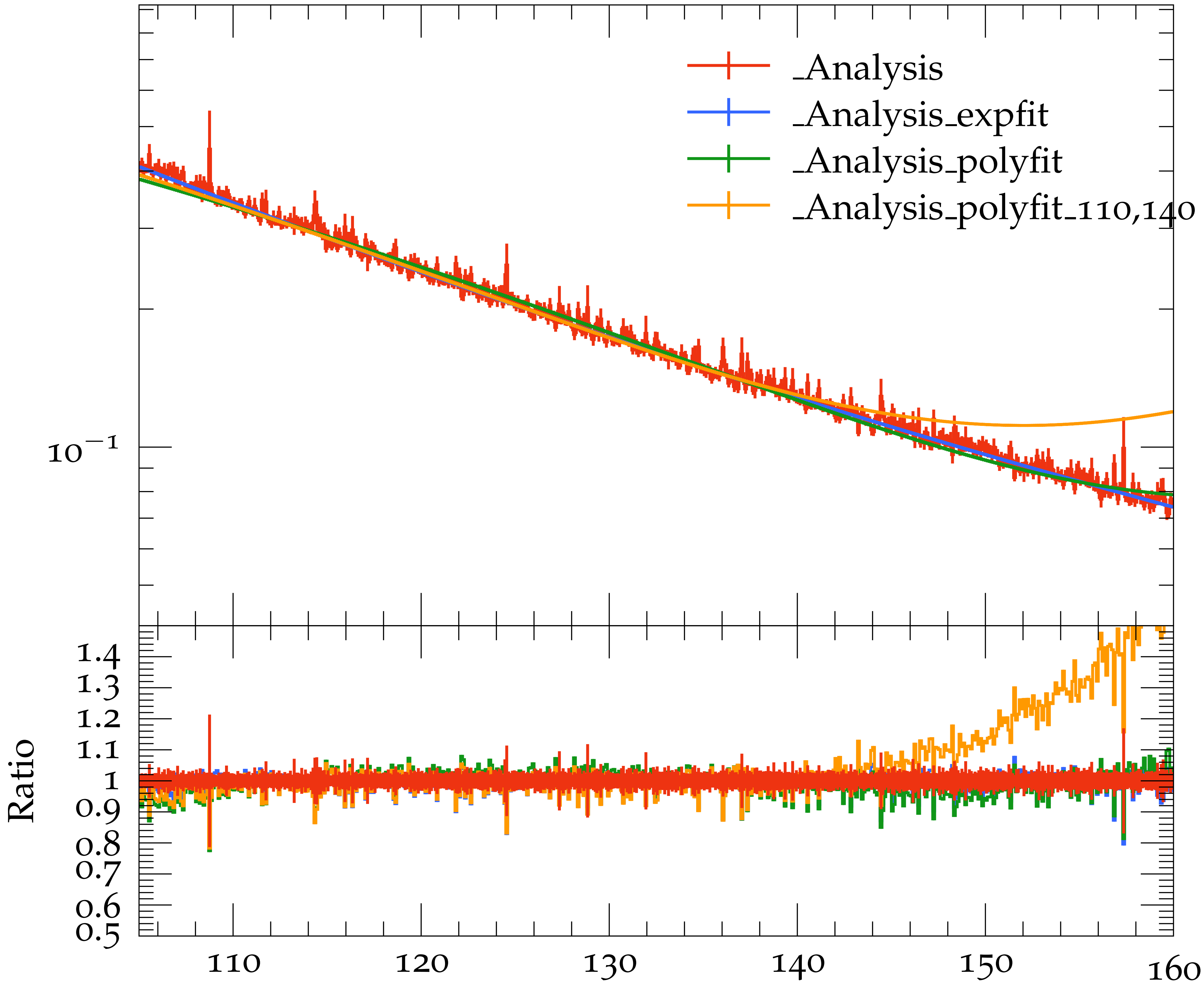



include universal higher-order corrections in all components of the NLO calculation and subtracted the overlap

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



# Background fit



# Fit procedure

1. generate fit results for each pseudo data set using LL fit (followed by a preparatory fit with the Least Squares method)
   ⇒ MC sample of results to be expected from an eventual fit to data

2. sample that distribution and calculate $CL_S$ distribution
   ⇒ Brazilian plot

- Gauß fit (for $p_T$-based method):
  - main result of fit: $\Delta M_H$ distribution
  - fitted quantities: $m_H$, $\Gamma_H$, total normalisation, background hypothesis params
  - parameters held fixed: $\sigma_{res}$
- Faddeeva fit
  - main result of fit: $\Gamma_H$ distribution
  - fitted quantities: same as in Gauß fit (but different functional form)
  - parameters held fixed: $\sigma_{res}$, relative normalisation $\beta$