Higgs boson signal and background in MCFM

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arXiv:1105.0020, 1107.5569 [hep-ph]

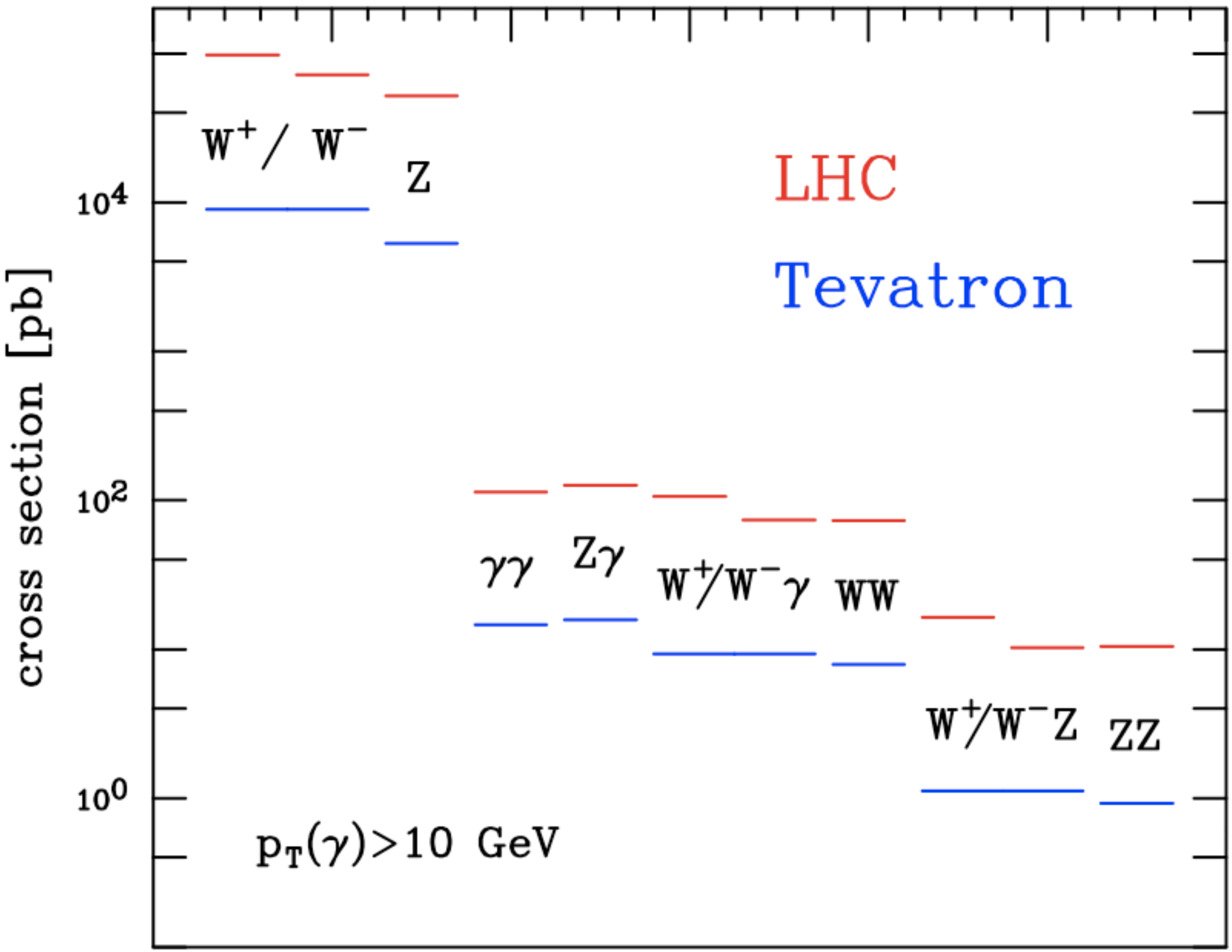
MCFM

* MCFM is a unified approach to NLO corrections, both to cross sections and differential distributions: http://mcfm.fnal.gov (v6.1, October 2011)
* Publically available code.

  J. M. Campbell, R. K. Ellis, C. Williams (main authors)
  R. Frederix, F. Maltoni, F. Tramontano, S. Willenbrock, G. Zanderighi....

* Standard Model processes for diboson pairs, vector boson+jets, heavy quarks, Higgs...
* Decays of unstable particles are included, maintaining spin correlations.
* Amplitudes (especially the one-loop contributions) calculated *ab initio* or taken from the literature.

Vector boson cross sections



Higgs cross sections

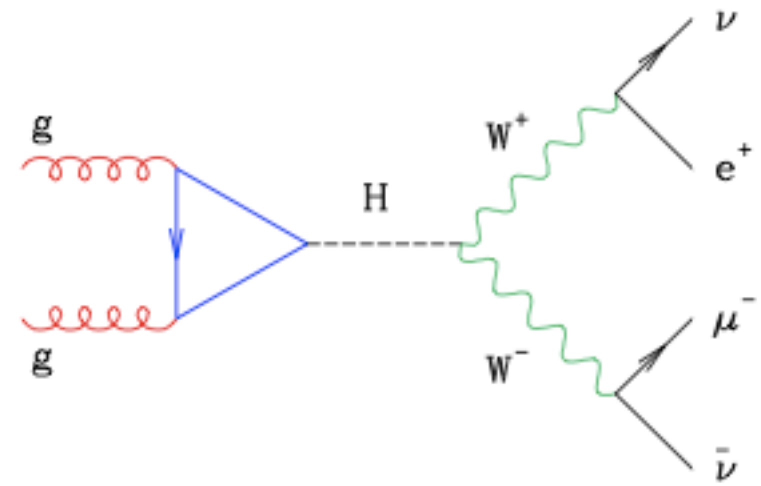
- Higgs cross sections in MCFM

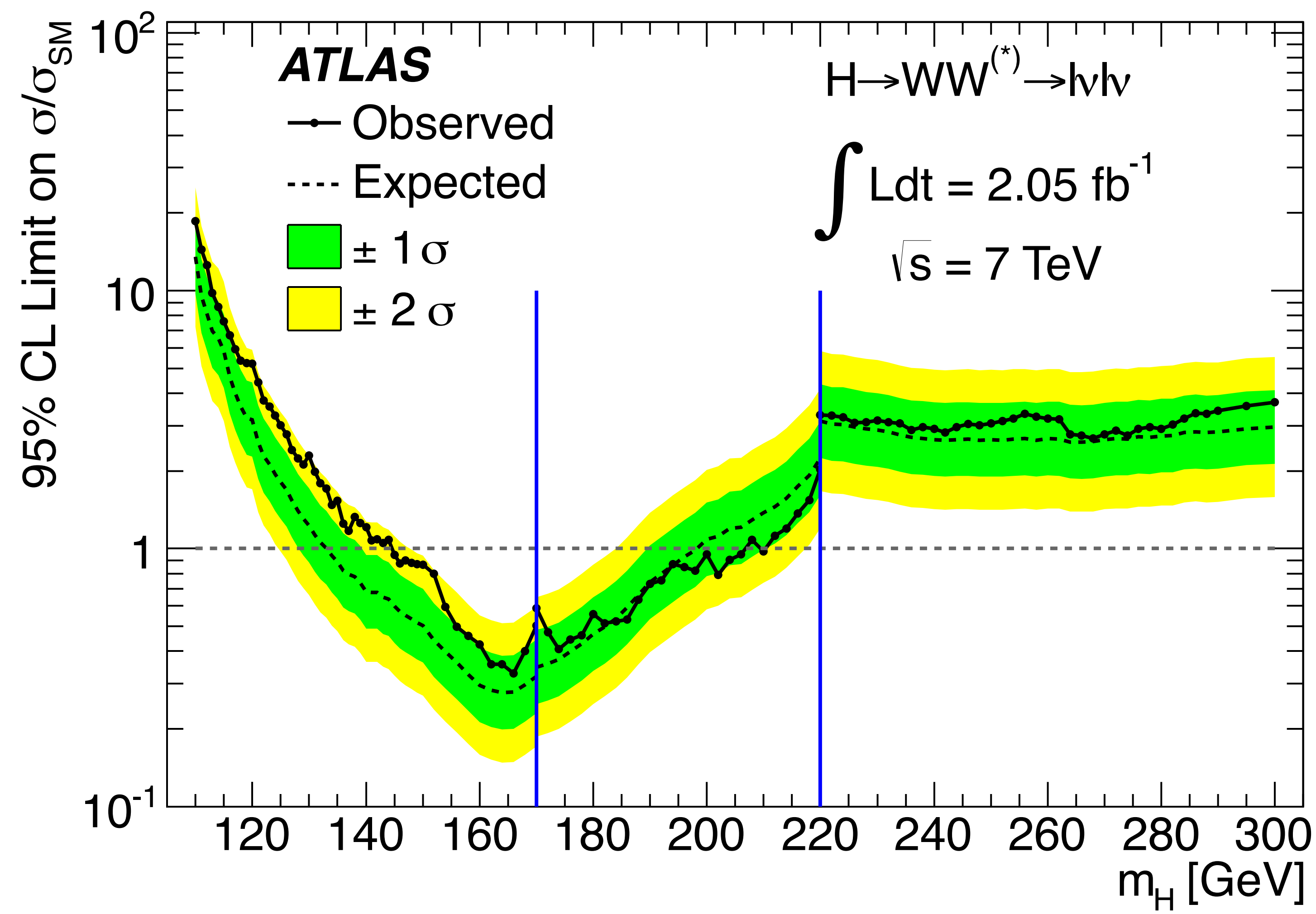
Process	Order	Comment
$pp \to H$	NLO	effective theory $m_t \to \infty$
$pp \to H + 1$ jet	NLO	effective theory $m_t \to \infty$
$pp \to H + 2$ jets	NLO	effective theory $m_t \to \infty$
$pp \to H + 2$ jets	NLO	Vector boson fusion W and Z exchange
$pp \to W^{\pm}H$	NLO	W decay to $l\nu$ included
$pp \to ZH$	NLO	Z-decay to $l\bar{l}$ included
$pp \to t\bar{t}H$	LO	top decay to $bl\nu$ included

- Many of these cross sections are known at NNLO, so MCFM is not state of the art in this regard.
- The most precise theoretical cross sections were important in the limit-setting phase, and will be important in the coupling measurement phase.
- Discovery phase?

H→WW production

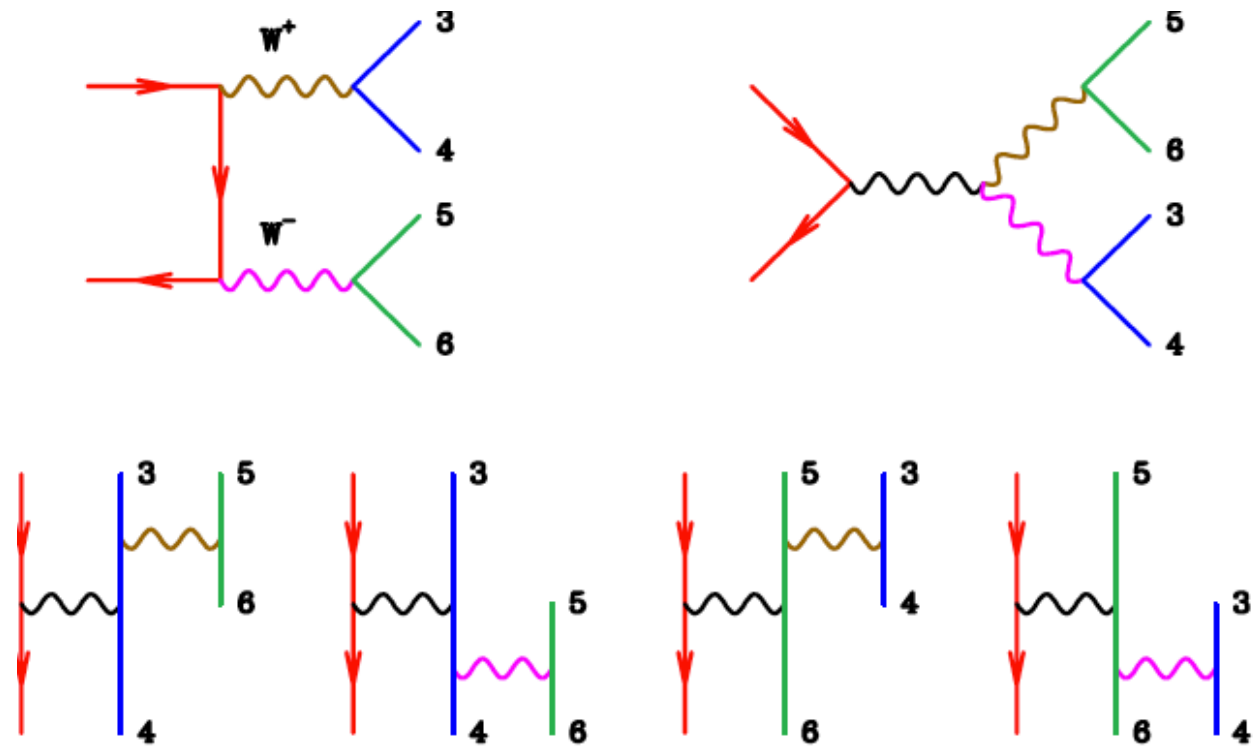
- Sensitive mode in the middle mass range $130 < m_H < 2\ M_Z$
- Background depends on the number of jets.
- Irreducible background: Standard model WW production.





WW production in MCFM

- Includes both doubly resonant and singly resonant diagrams with Z/γ*.
- Full NLO-Virtual corrections from DKS, (hep-ph/9803250)
- Includes gg fermion loop contributions, that are formally higher order, using compact analytic formulae.



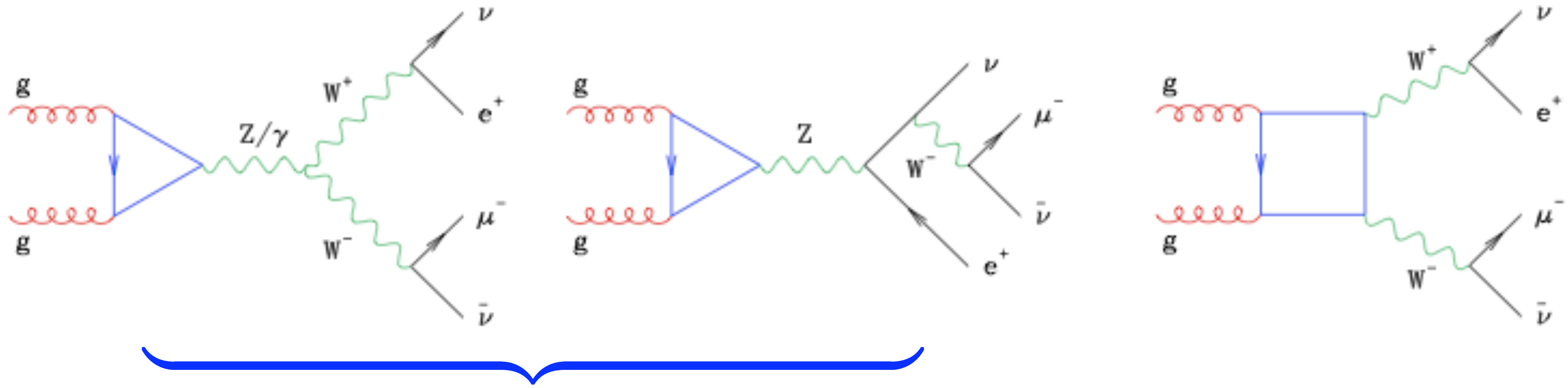
Cut dependent

	$\sqrt{s} = 7$ TeV		$\sqrt{s} = 8$ TeV	
	MSTW2008	CT10	MSTW2008	CT10
LO(fb)	377	371	460	453
NLO (including gg) (fb)	501	490	624	613
gg fraction %	2.03	1.97	2.24	2.17

Total cross section for $pp \to W^+W^- \to \nu_e e^+ \mu^- \bar{\nu}_\mu$ at $\sqrt{s} = 7$ and 8 TeV with no cuts

$gg \to WW$

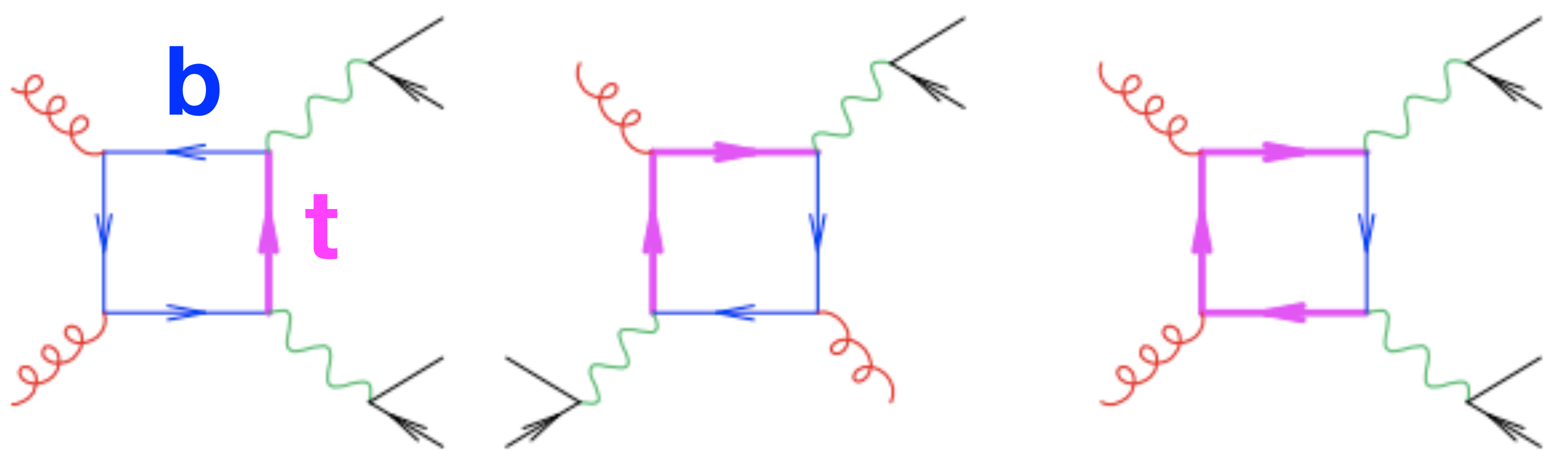
Dicus, Kao, Repko (87); van der Bij, Glover (89); Binoth et al. (05)



no net contribution
(Landau-Yang,Furry and EW gauge inv.)

straightforward for
massless quark loops

- Contribution of 3rd generation? Diagrams with 1,2 and 3 top quarks.



- We obtain analytic results for $m_t \neq 0$, $m_b = 0$.

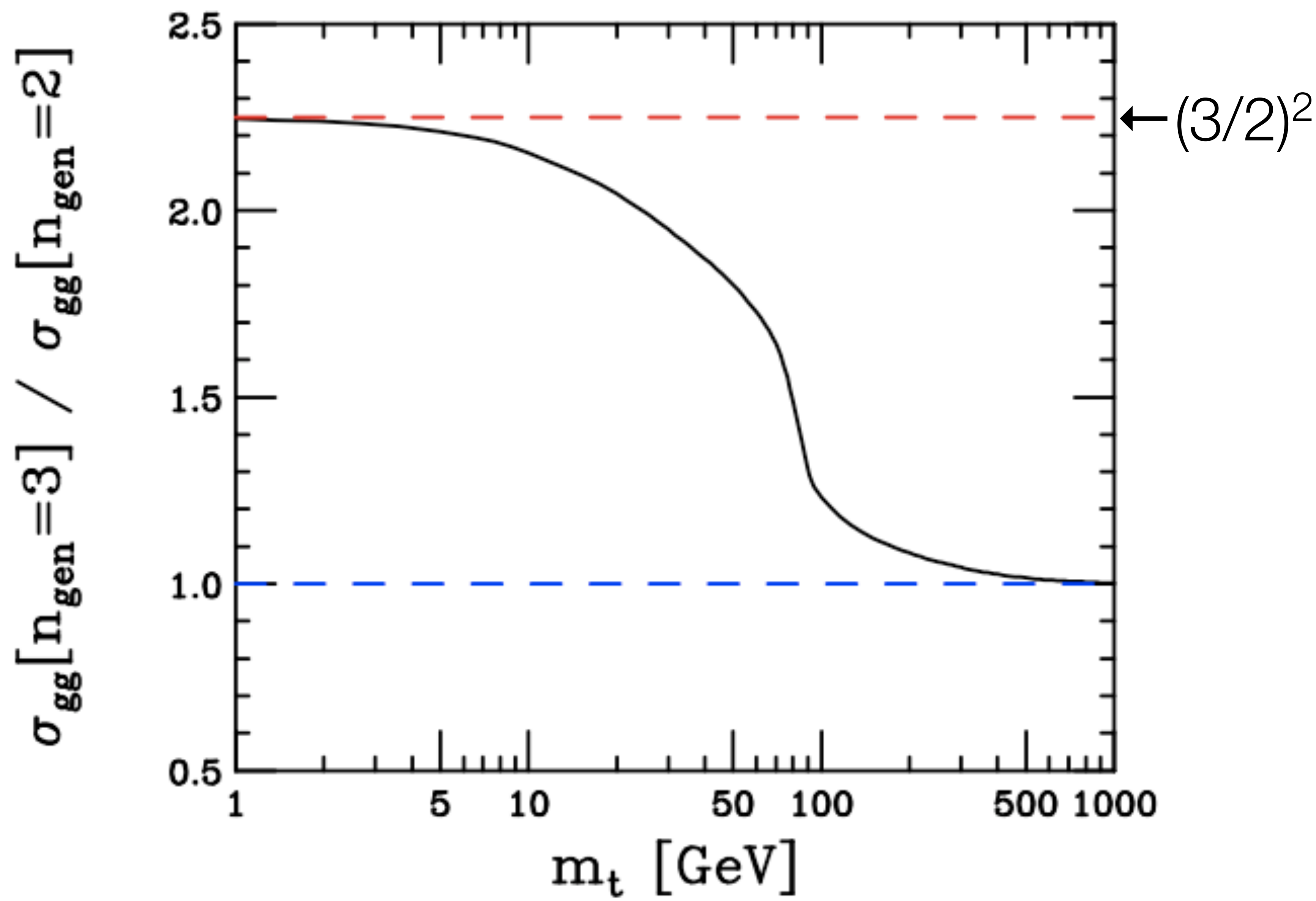
Analytic calculation

* Use unitarity cuts to determine coefficients of basis integrals in general expansion:

$$\mathcal{A}_{\text{massive}} = \sum_{i=1}^{6} d_i D^{(i)} + \sum_{i=1}^{12} c_i C^{(i)} + \sum_{i=1}^{6} b_i B^{(i)} + \mathcal{R}$$

* Many simplifications:
  * all but one bubble coefficient can be obtained from massless result.
  * rational term is not amenable to 4-dim. cut techniques, but is identical to the massless case.
* Result is not compact enough to write down, but short enough to be evaluated efficiently.

Impact of the 3rd generation

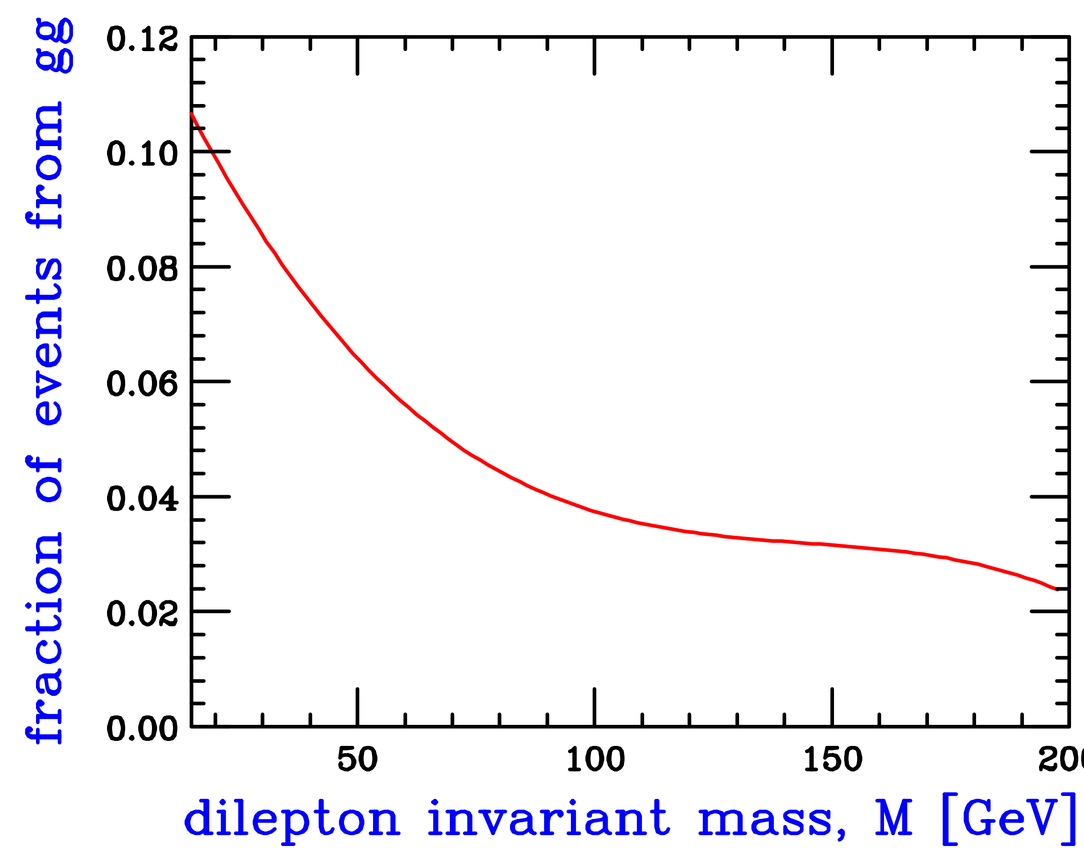


- Transition from massless result for 3 generations to that for 2 generations.
- 10% deviation from 2 generation result for actual top mass.

Full NLO results for WW production

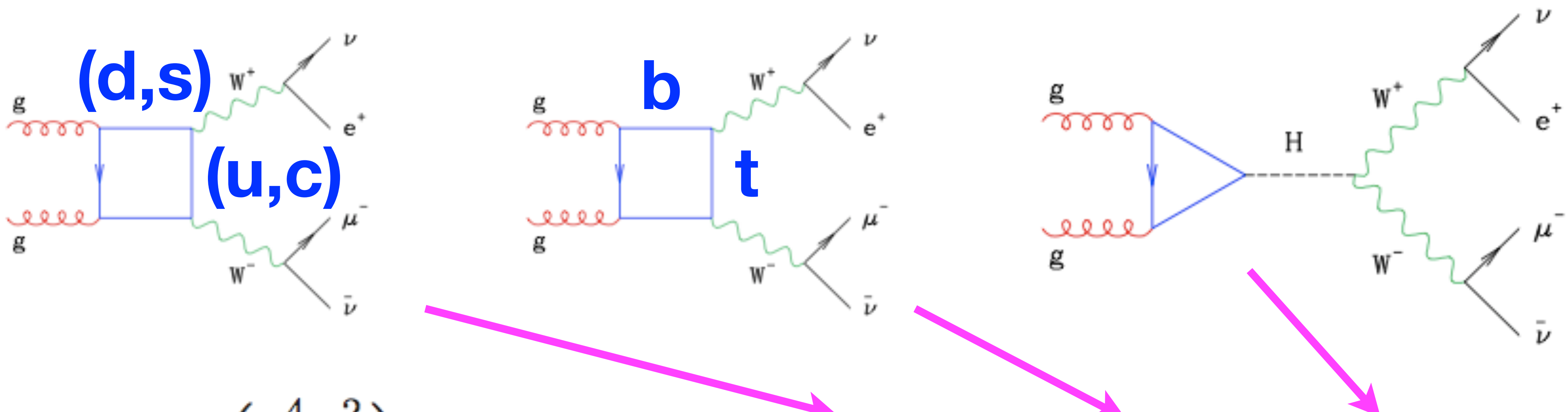
$\sqrt{s}$ [TeV] and cuts	$\sigma^{LO}(e^+\mu^-\nu_e\overline{\nu}_\mu)$ [fb]	$\sigma^{NLO}(e^+\mu^-\nu_e\overline{\nu}_\mu)$ [fb]	K-factor	% gg
7 (Basic)	144	249	1.73	3.05
7 (Higgs)	7.14	15.19	2.13	6.85
14 (Basic)	296	566	1.91	4.73
14 (Higgs)	13.7	34.7	2.53	10.09

* Impact of gluon-gluon contribution enhanced by the Higgs search cuts (e.g. M(ll)<50 GeV).



Reassessment

- Signal and background all have the same external particles → should compute all, including interference.



$$\mathcal{A}_{\rm full} = \delta^{a_1 a_2}\left(\frac{g_w^4 g_s^2}{16\pi^2}\right)\mathcal{P}_W(s_{34})\mathcal{P}_W(s_{56})\ \left[2\,\mathcal{A}_{\rm massless} + \mathcal{A}_{\rm massive} + \mathcal{A}_{\rm Higgs}\right]$$

- Is the interference important? At least need to check it's not a bigger effect than quoted NNLO uncertainty.

Dittmaier et al. (11) - LHC Higgs cross section WG

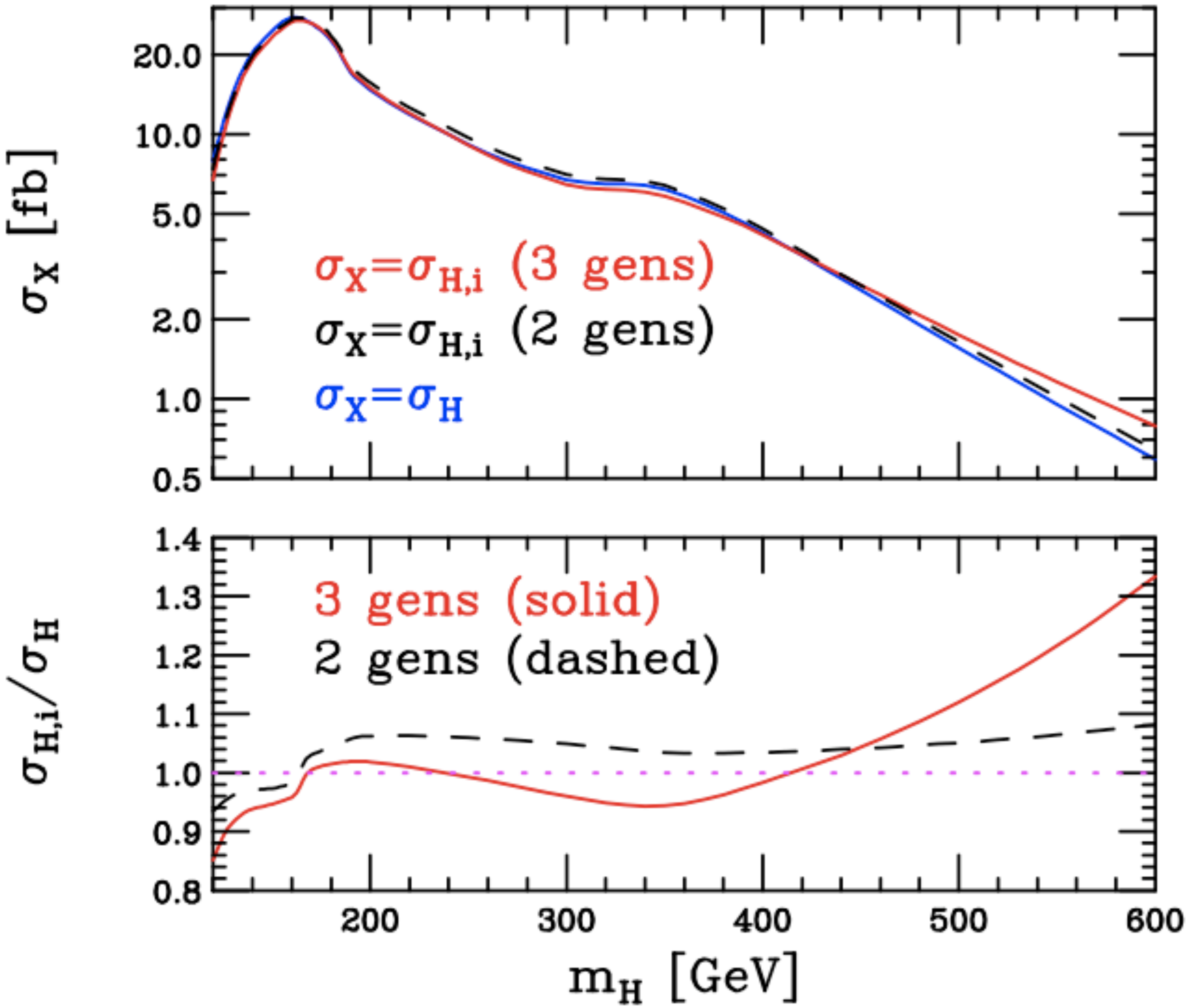
- How do we define signal and background?

Notation

$$\mathcal{A}_{\rm full} = \delta^{a_1 a_2}\left(\frac{g_w^4 g_s^2}{16\pi^2}\right)\mathcal{P}_W(s_{34})\mathcal{P}_W(s_{56})\ [\underbrace{2\,\mathcal{A}_{\rm massless} + \mathcal{A}_{\rm massive}}_{\mathcal{A}_{\rm box}} + \mathcal{A}_{\rm Higgs}]$$

- Background only: $\sigma_B \longrightarrow |\mathcal{A}_{\rm box}|^2$
- Signal only: $\sigma_H \longrightarrow |\mathcal{A}_{\rm Higgs}|^2$
- The above is the conventional approach.
- Include effect of interference: $\sigma_i \longrightarrow 2{\rm Re}\left(\mathcal{A}_{\rm Higgs}\mathcal{A}^*_{\rm box}\right)$
- Cross section in the presence of the Higgs, i.e. including also the interference: $\sigma_{H,i} \;=\; \sigma_H + \sigma_i$
- Compare results for σ_H and $\sigma_{H,i}$.

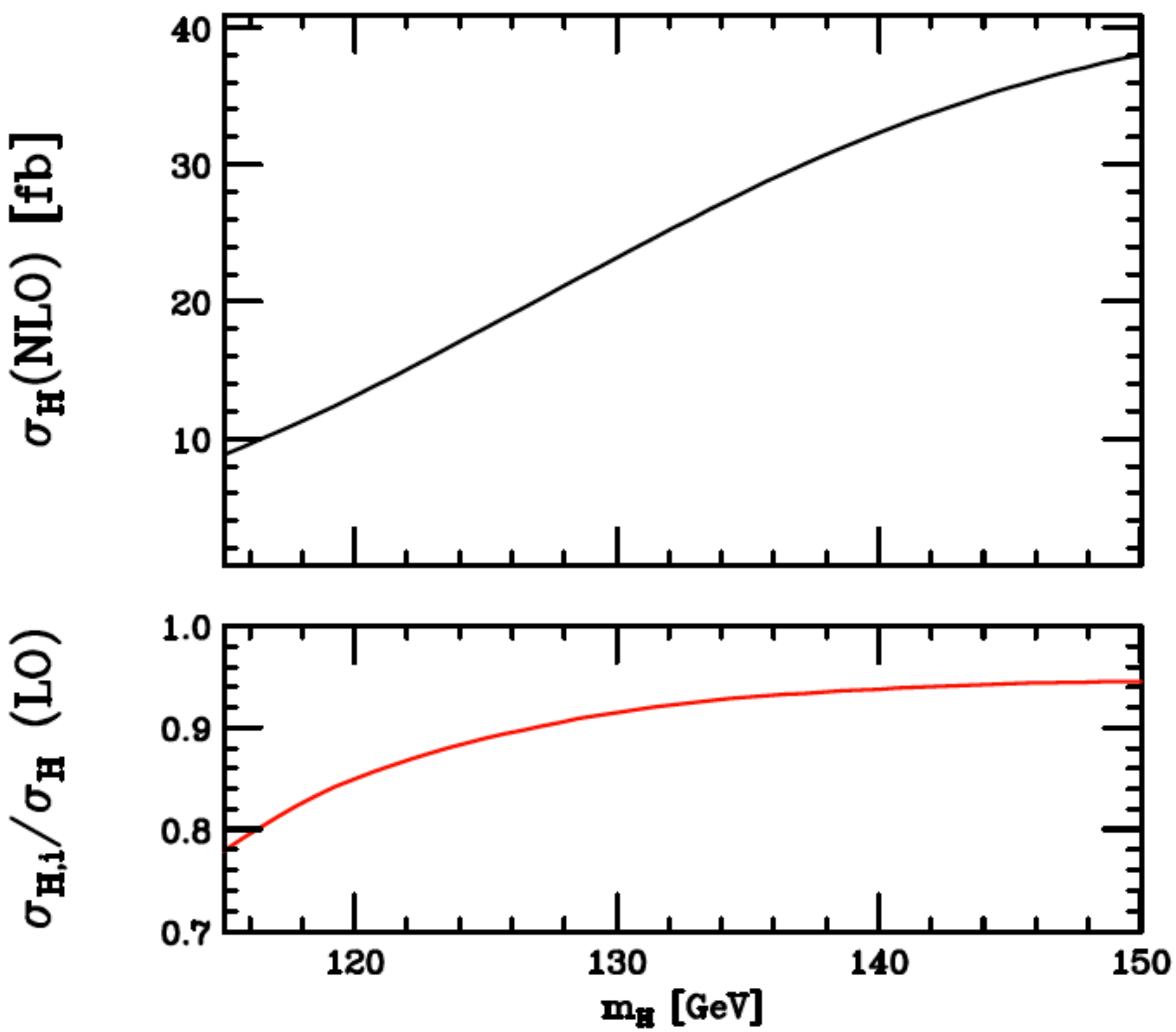
LHC results



* Significant difference, 3rd gen. contribution important.

Interference in the 115<m_H<150 GeV (no m_T cut).

- Blow-up of low Higgs mass region.
- Shows correction to be applied to low mass cross section to account for interference with background process



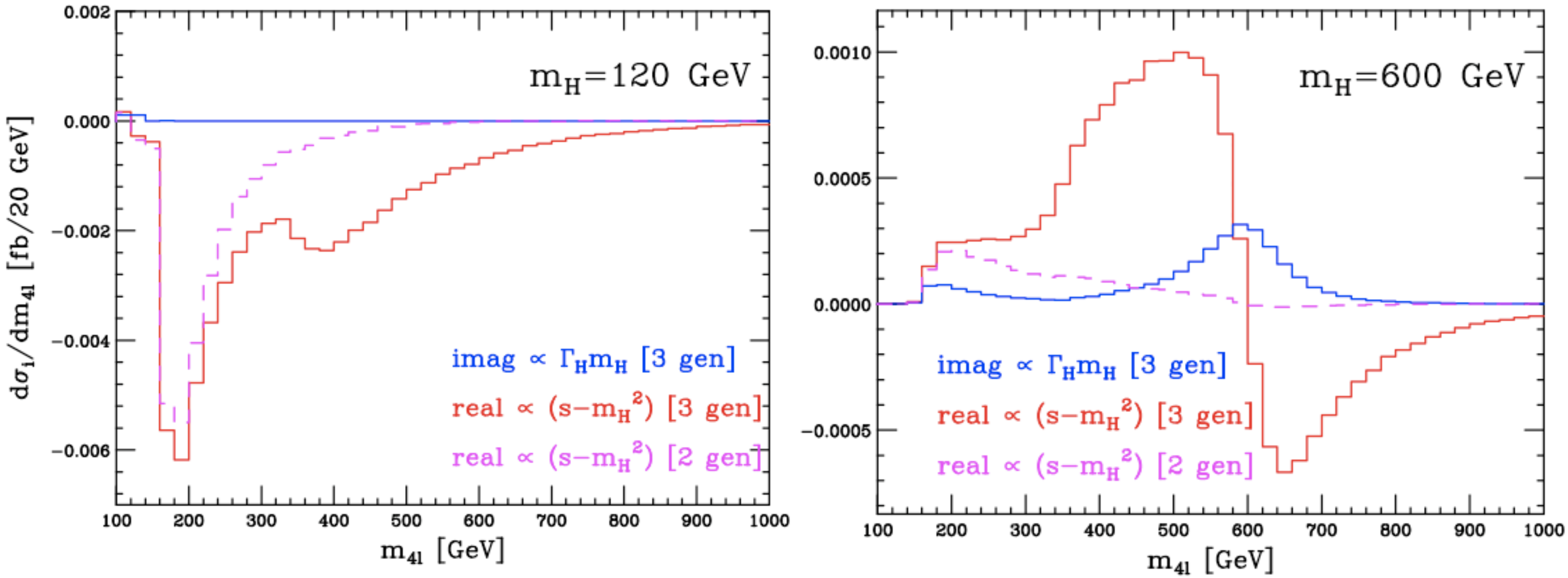
Analyzing the interference

- Separate interference by Re and Im parts of propagator:

$$\delta\sigma_i = \frac{(\hat{s}-m_H^2)}{(\hat{s}-m_H^2)^2+m_H^2\Gamma_H^2}\,\mathfrak{Re}\left\{2\widetilde{A}_{\rm Higgs}\mathcal{A}^*_{\rm box}\right\} + \frac{m_H\Gamma_H}{(\hat{s}-m_H^2)^2+m_H^2\Gamma_H^2}\,\mathfrak{Im}\left\{2\widetilde{A}_{\rm Higgs}\mathcal{A}^*_{\rm box}\right\}$$

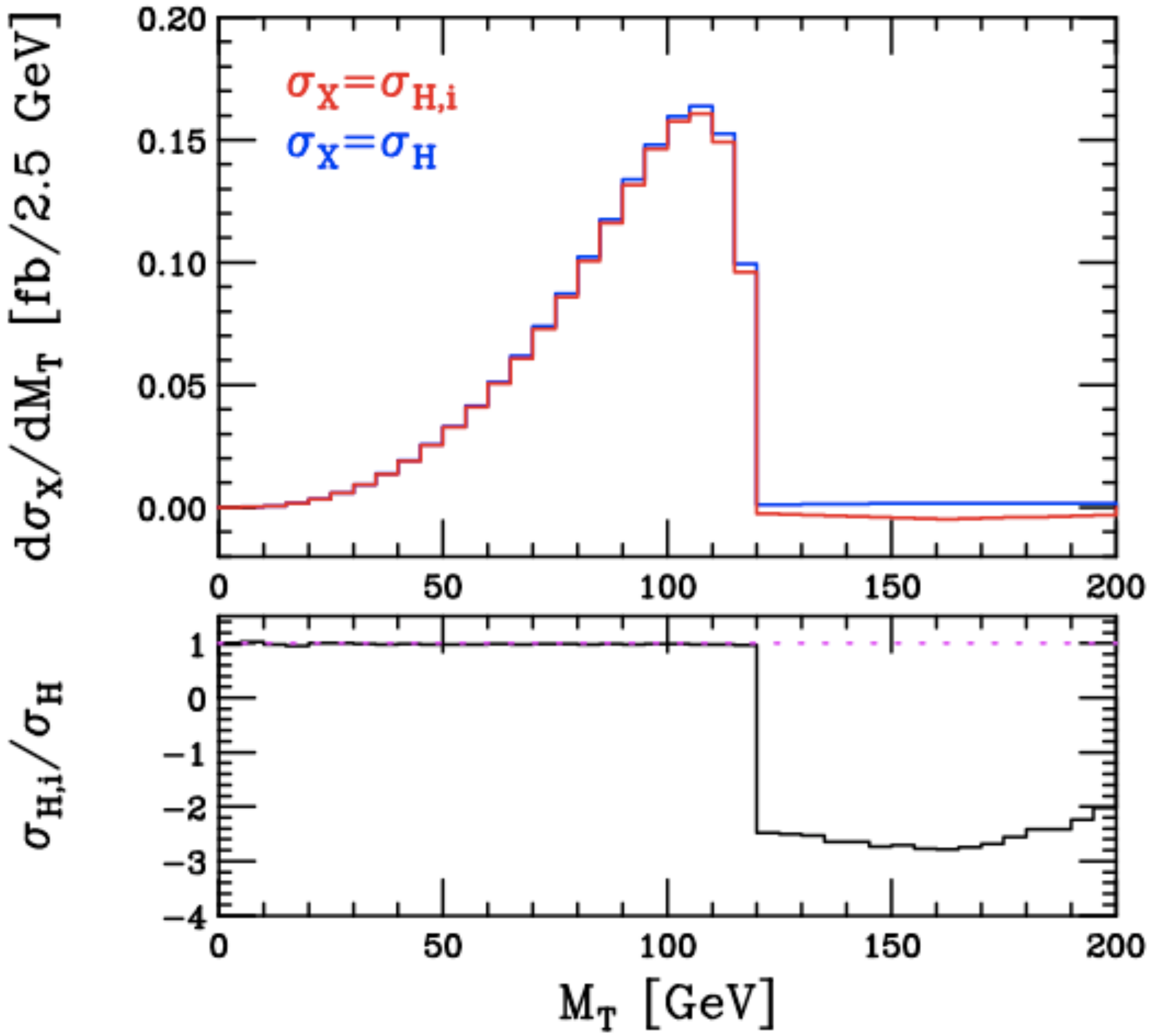
- For a small Higgs width (i.e. light Higgs) the second term is negligible.
- If the full *s*-dependence of the first term can be represented by the factor from the propagator, it should vanish on integration (odd about the Higgs mass).
  - this is the case for a similar study of interference in the $H\to\gamma\gamma$ channel, no big effects there. Dixon, Siu (03)
  - *s*-dependence more complicated here because the box diagrams favour large invariant masses (W pairs).

Visualizing the interference



* For light masses, the real term is solely responsible for the interference.
* A combination for high Higgs masses (i.e. widths).
* Long destructive tail required by unitarity. van der Bij, Glover (89)

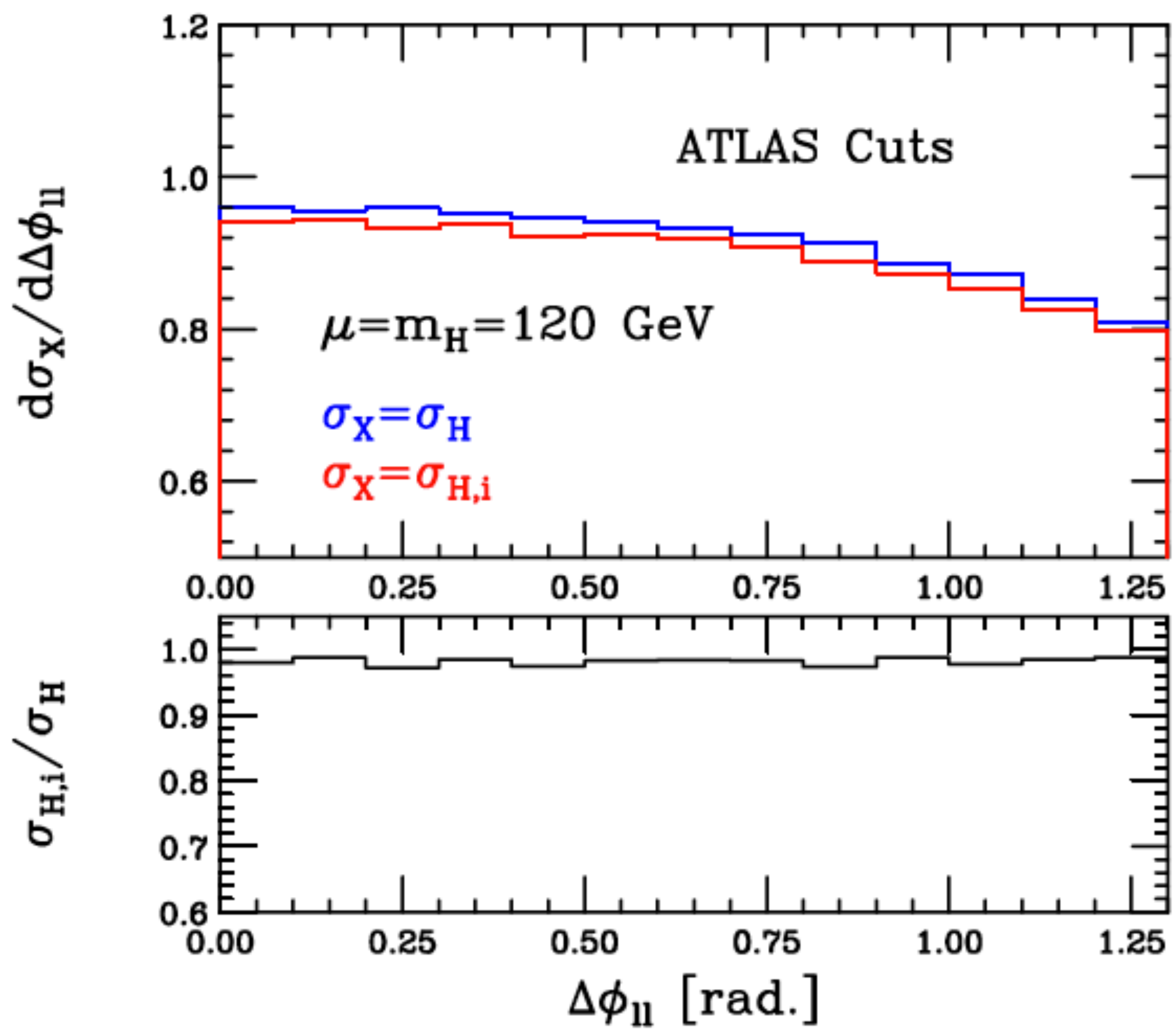
Interference vs. transverse mass



- Require $M_T < M_H$ (transverse mass less than putative Higgs mass).
- Negative value of interference for $M_T > M_H$, reflection of role of Higgs in taming high energy behaviour.
- Thanks to the miracle of Quantum mechanics, perform cut and increase "signal" and decrease background!

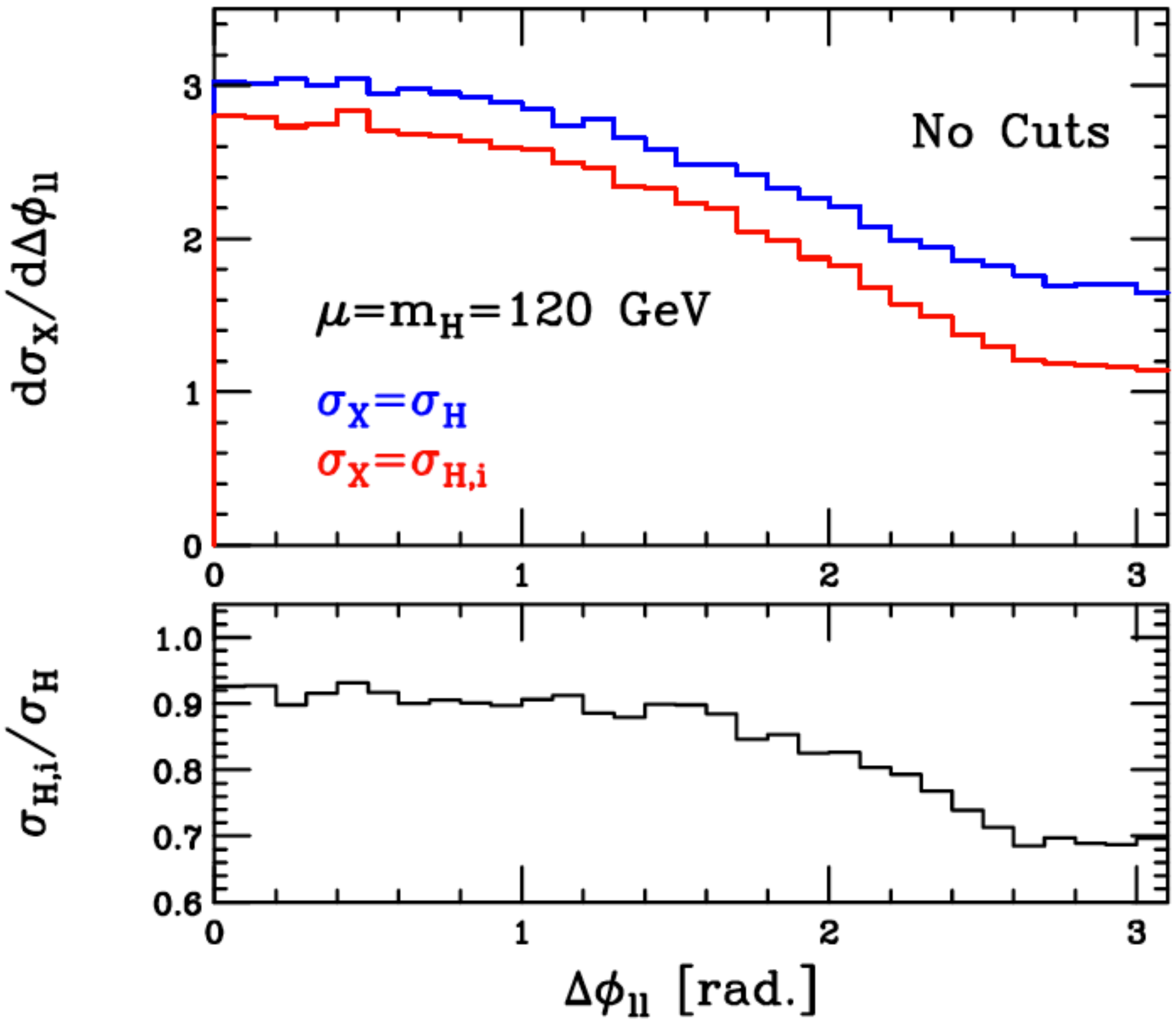
Effect of interference on Δϕ distribution.

- Cut-based analyses impose an upper limit on M_T this reduces the effect of the interference.
- ATLAS cuts include $0.75 M_H < M_T < M_H$



Effect of interference on Δϕ distribution.

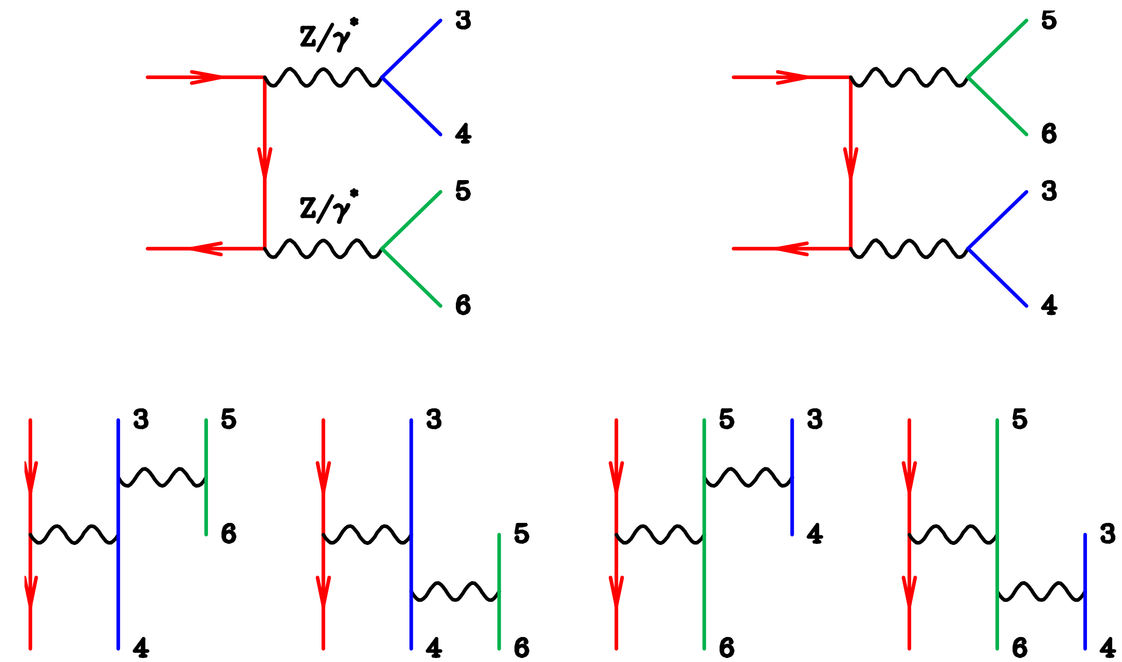
- Other analysis methods may not impose this cut.
- Without the M_T cut the shapes of distributions can change.

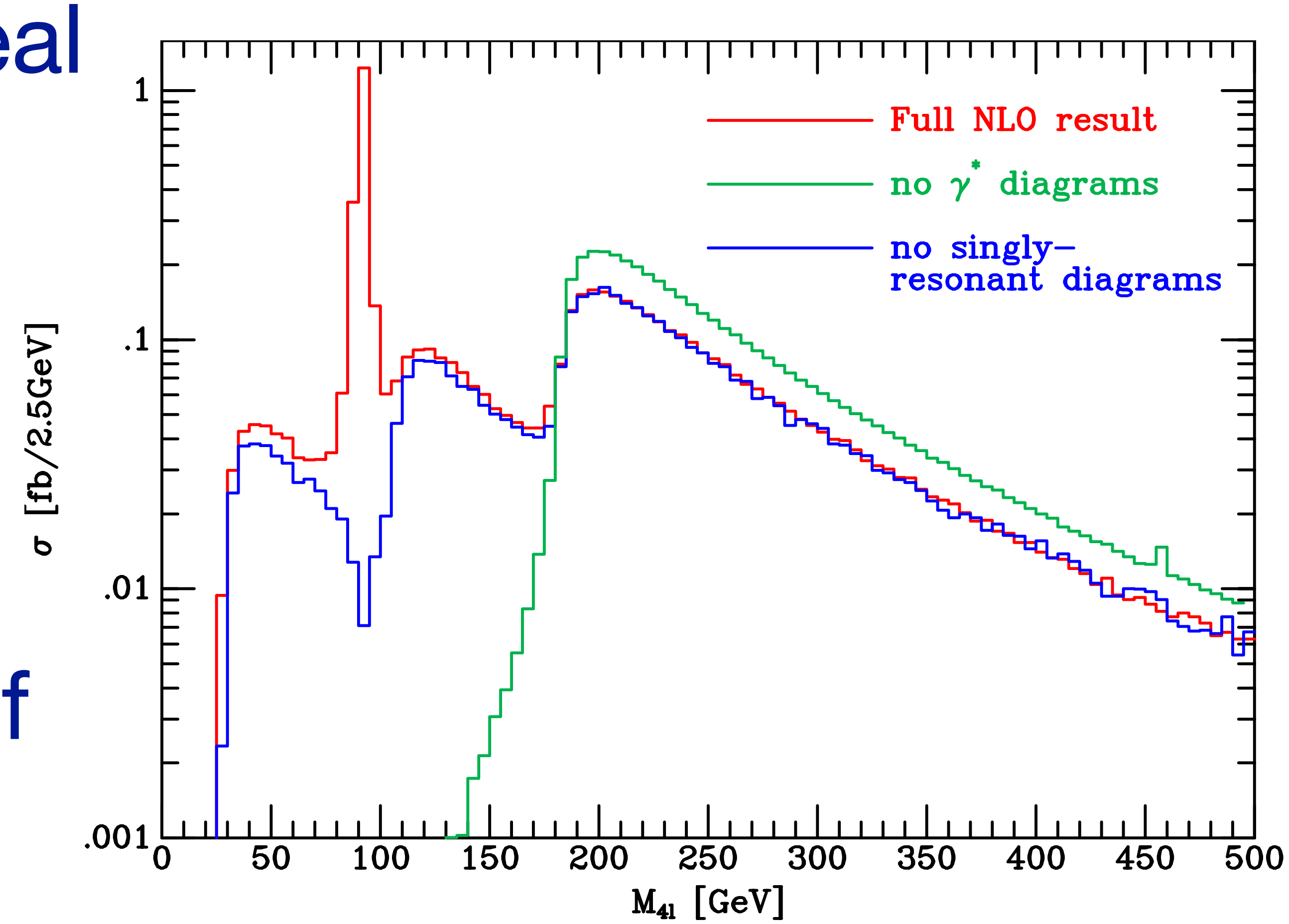


$H \to ZZ^* \to e^-e^+e^-e^+$, $e^-e^+\mu^-\mu^+$, $\mu^-\mu^+\mu^-\mu^+$

Backgrounds to H -> ZZ-> $l^+ l^- l^+ l^-$

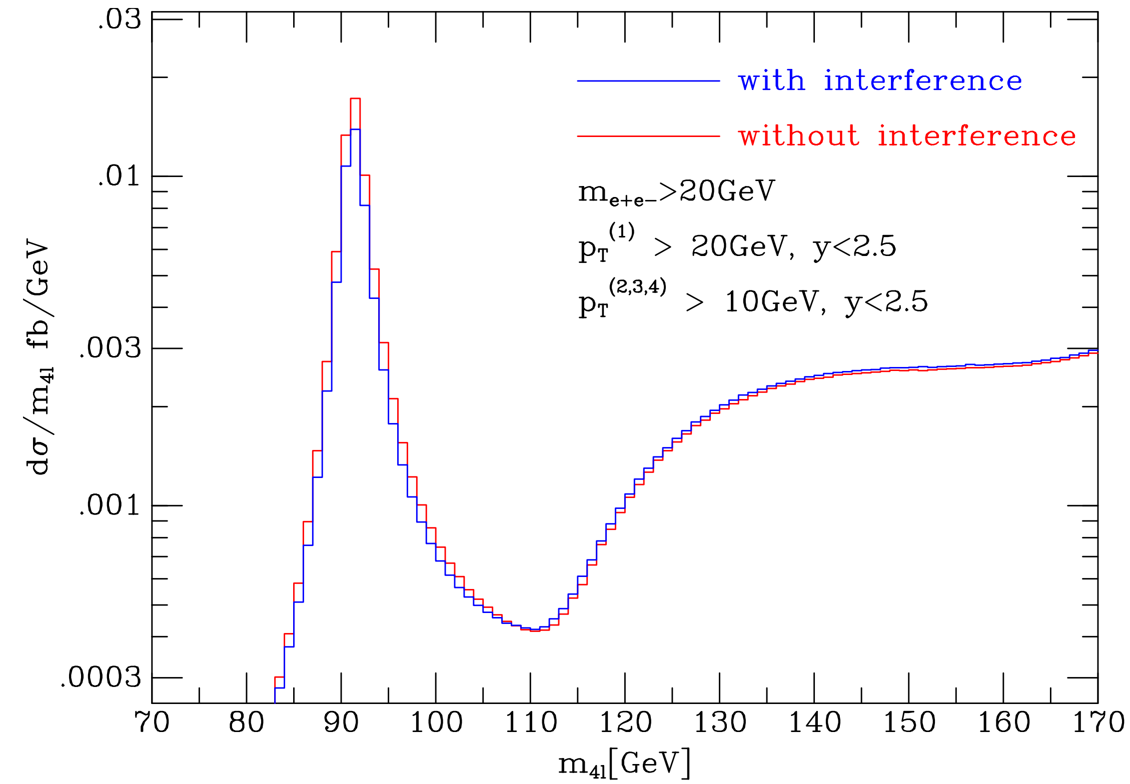
- Irreducible background from SM (Z/γ^*) boson process.
- MCFM v6.1 contains both the doubly and singly resonant processes processes + virtual and real QCD corrections.
- $M_{4l} > 2\,M_Z$, t-channel exchange diagrams dominate.
- $M_{4l} < 120$GeV, influence of singly resonant diagrams.

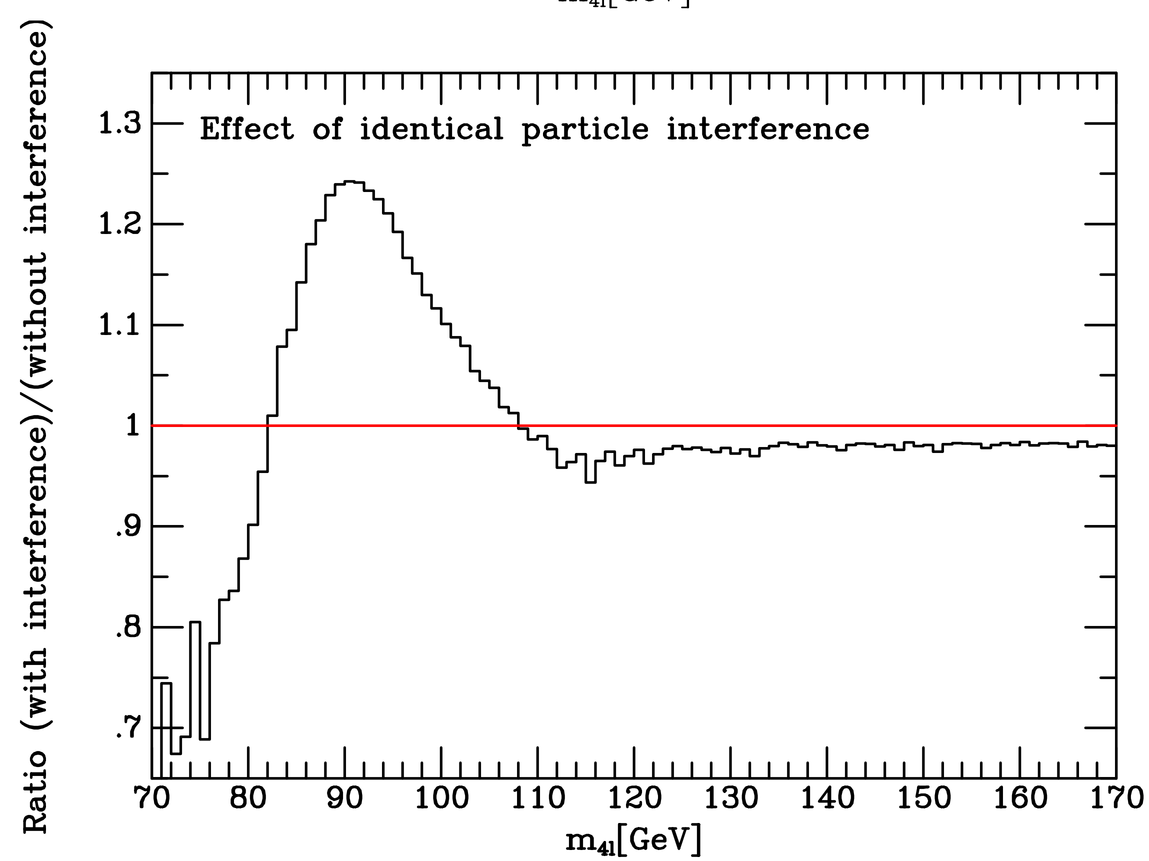




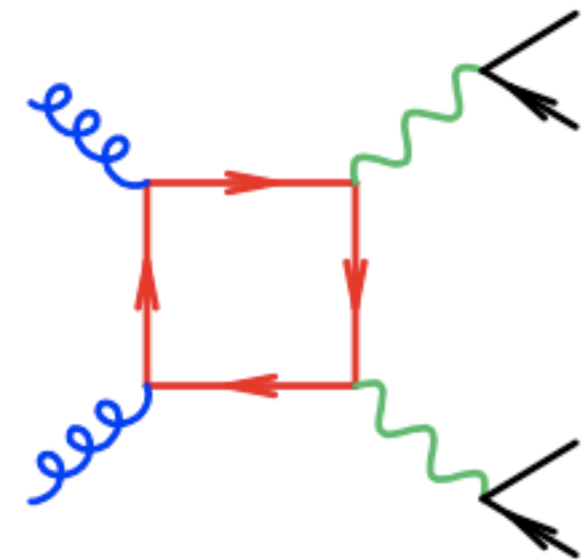
Identical particle interference, e.g. $\mu^-\mu^+\mu^-\mu^+$

- Effect of identical leptons in the final state,
- pp → $e^-e^+e^-e^+$, $\mu^-\mu^+\mu^-\mu^+$
- Identical particle interference decreases cross section in the region M_{4l}>110GeV
- In this region the effect is smallish < 5%, (cf. Melia et al, arXiv:1107.5051).





gg → ZZ contributions

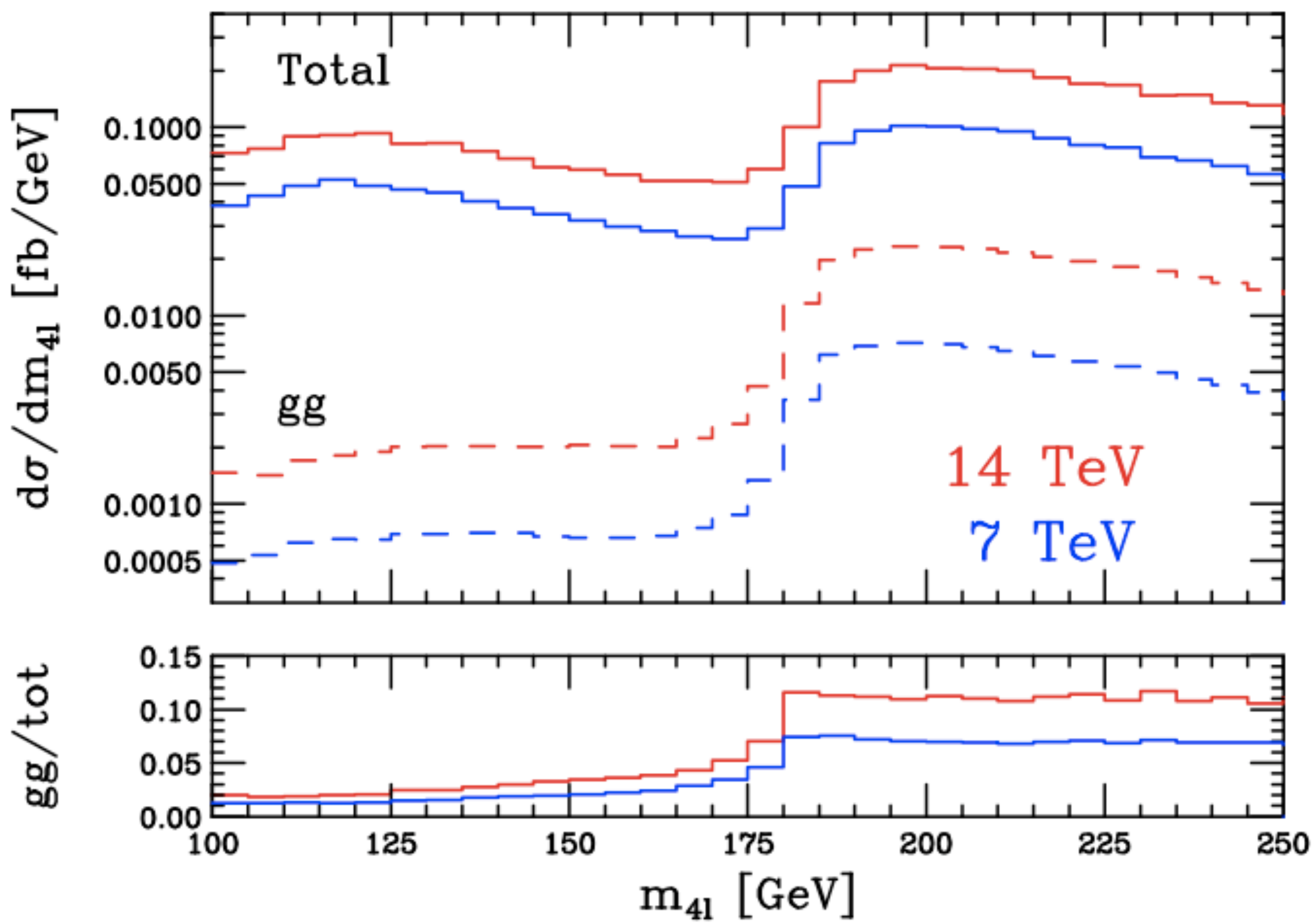


- Historically, computed with varying degrees of sophistication (on-shell, including decays, off-shell).

  Dicus, Kao, Repko (87); van der Bij, Glover (89); Matsuura et al. (91,94); Binoth et al. (08)

- For massless quarks circulating in the loop, again obtain compact analytic results by recycling (instead of numerical approaches previously).
- Analytic results ameliorate numerical stability issues.
- Contribution of the top quark loop is suppressed by a factor $(\text{top mass})^4$ and therefore neglected.
  - top gives a 1% difference in the gg contribution.

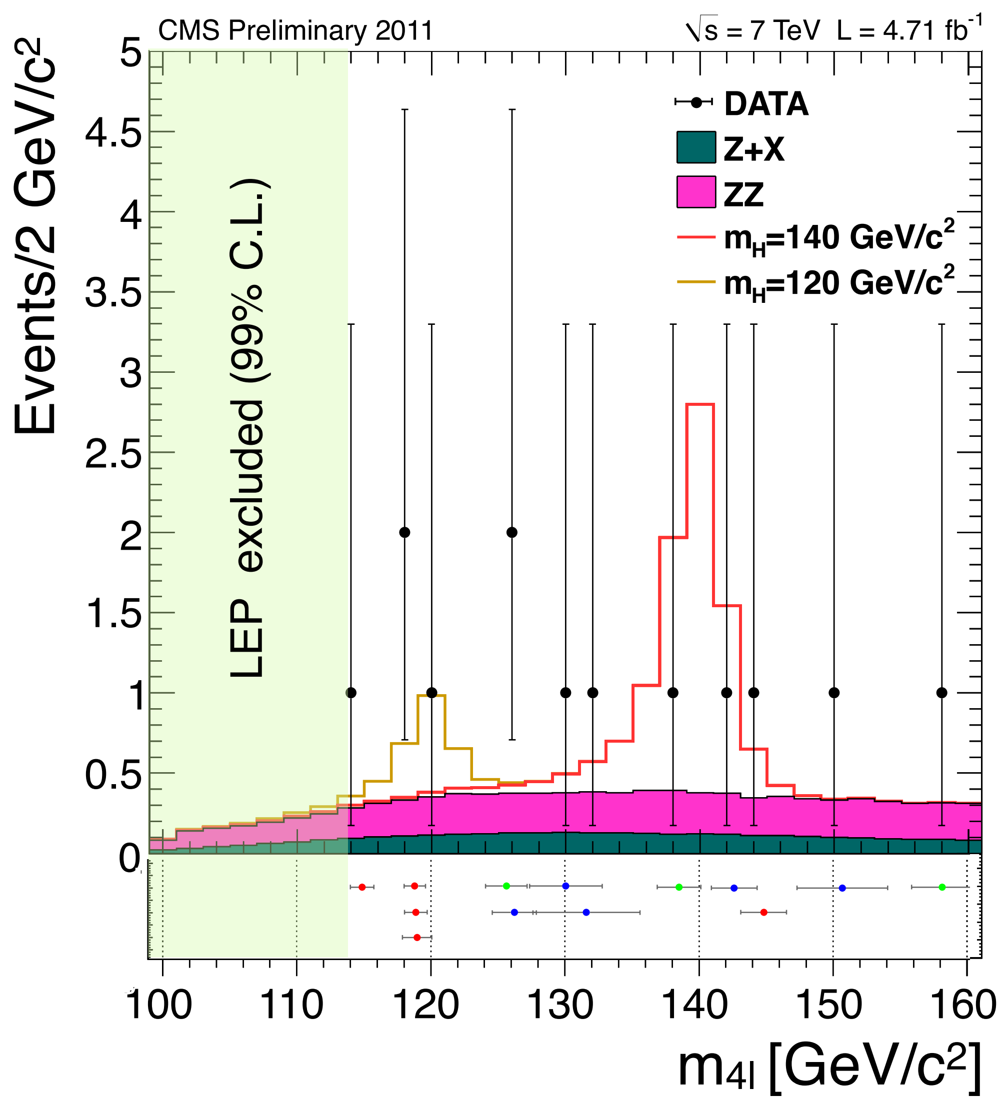
Importance of gg → ZZ



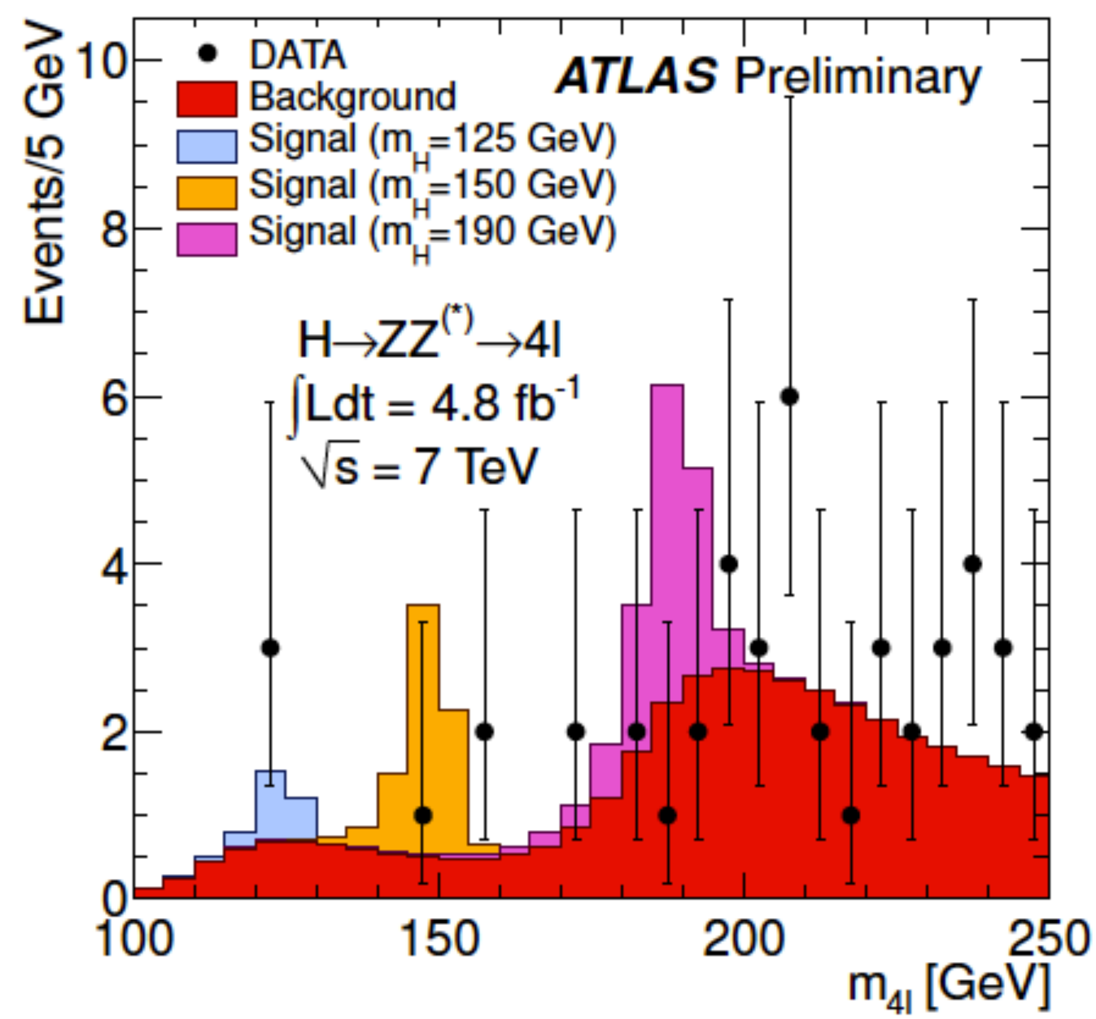
- Contribution rather small (~ few %) well below threshold, but significant above (5-10%).
- Interference with Higgs channel also expected to be small, because of the mass resolution of this channel.

Comparing CMS and ATLAS

CMS PAS-11-025

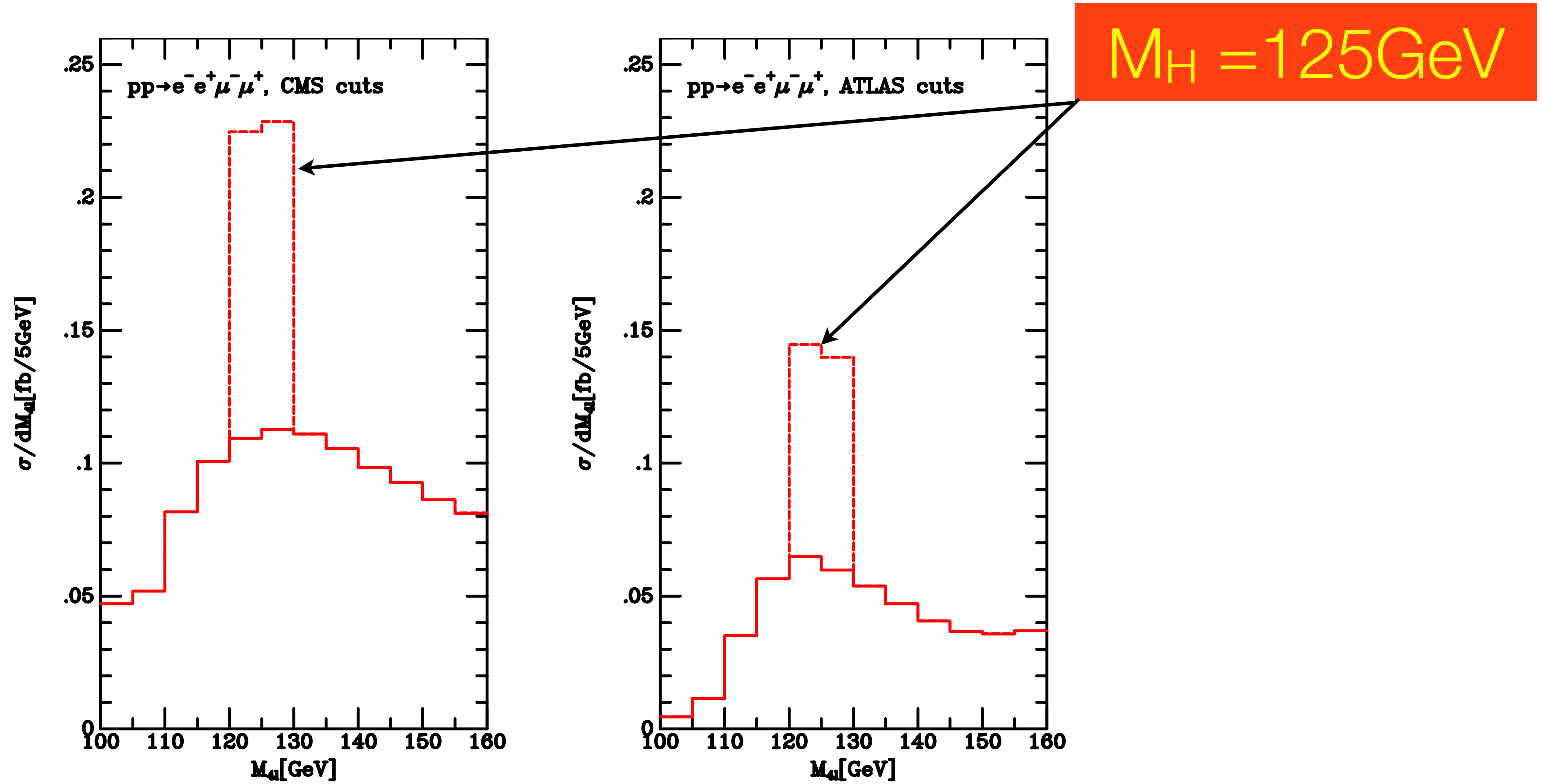


ATLAS CONF-2011-162



- It would be good to see CMS data with tighter cuts and ATLAS data with looser cuts.
- It would be good to see lower mass values of m_{4l}.

December 2011 analyses



- Signal and irreducible ZZ background for CMS PAS-11-025 and ATLAS CONF-2011-162 cuts. (Additional Z+jets background not included.)
- S/√B substantially the same for both experiments, although ATLAS cuts harder.

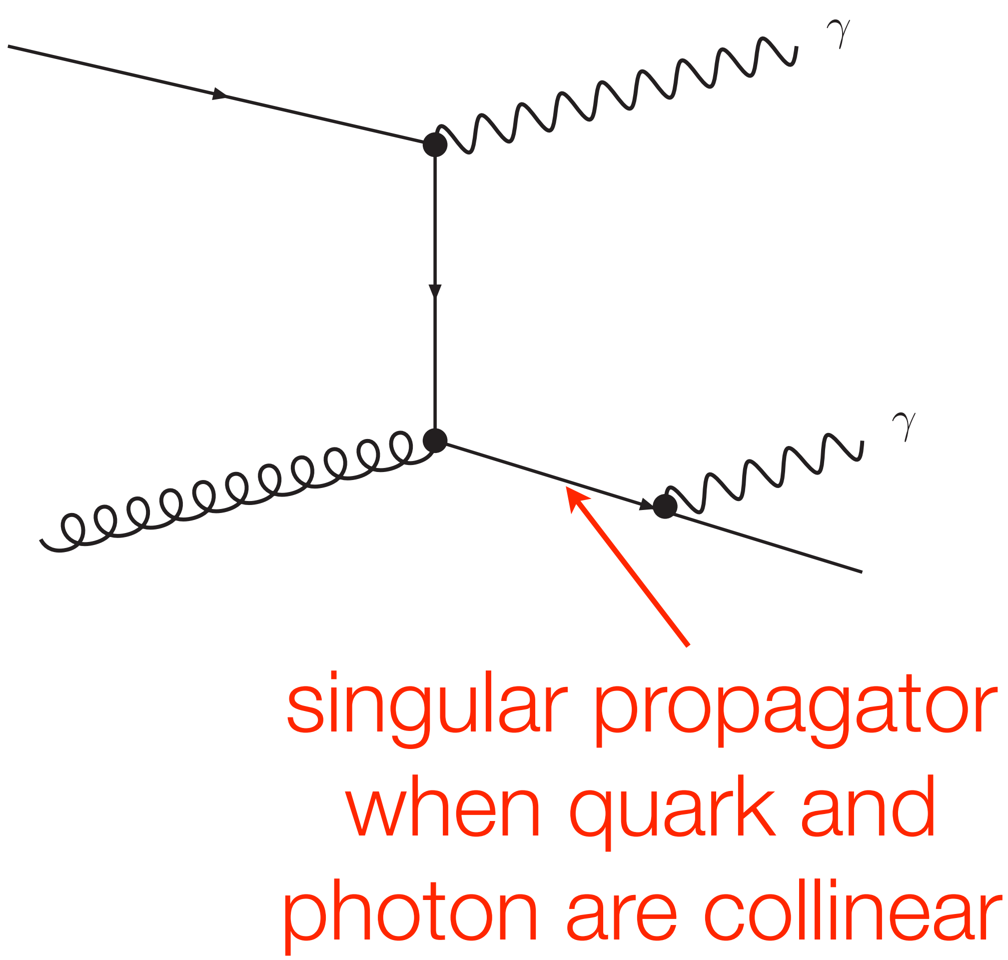
$H \to \gamma\gamma$ process

One stop shopping for photons in MCFM v6.1

* $pp \to \gamma\gamma$
  * including fragmentation contributions and $gg \to \gamma\gamma$ at NNLO
* $pp \to \gamma$+jet
  * including fragmentation contributions
* $pp \to W\gamma$
  * including photon radiation from decay products of W (electromagnetic gauge invariance!)
* $pp \to Z\gamma$
  * including photon radiation from decay products of Z.

Dealing with photons

- In the presence of QCD radiation (i.e. beyond LO) cross sections with photons develop additional singularities.



- Experimentalists impose isolation cuts on the photons

$$\sum_{\in R_0} E_T(\mathrm{had}) < \epsilon_h \, p_T^\gamma \qquad \text{or} \qquad \sum_{\in R_0} E_T(\mathrm{had}) < E_T^{\mathrm{max}}$$

- But isolated photon cross sections are not infrared safe

Smooth cone solution

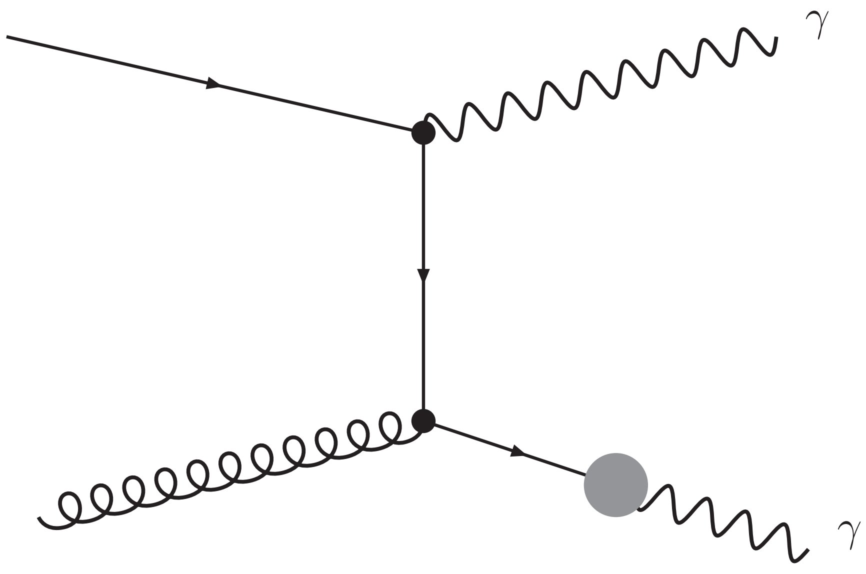
- Allow soft partons, but remove
  collinear configurations, Frixione, hep-ph/9801442

$$\sum_{R_{j\gamma} \in R_0} E_T(\text{had}) < \epsilon_h p_T^\gamma \left(\frac{1 - \cos R_{j\gamma}}{1 - \cos R_0} \right)$$

- Parton required to be softer as it gets closer to photon.
- No contribution exactly at the collinear singularity.
- This is simple to apply to a theoretical calculation and results in a well-defined cross section.
- Cannot be (exactly) implemented experimentally due to finite detector resolution.

Photon fragmentation

* The analogous quantity to pdfs is the photon fragmentation function.
* Non-perturbative input required, but perturbative evolution.

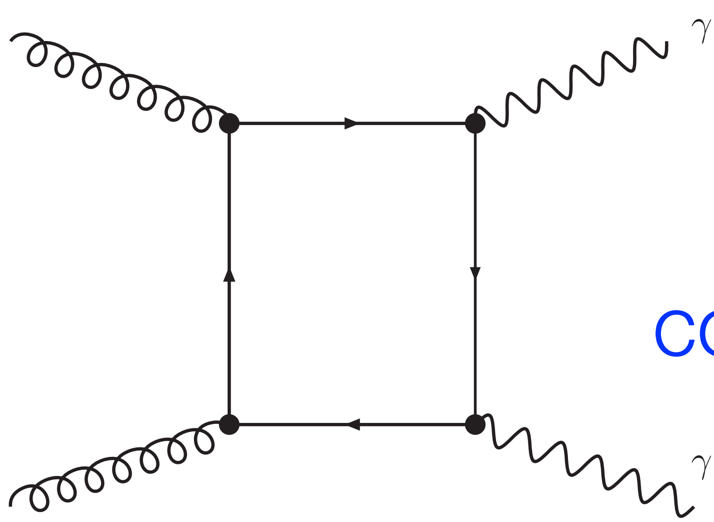


* Using conventional isolation, only the sum of the direct and fragmentation contributions is meaningful.
* After isolation, the finite contribution from the fragmentation contribution is typically small.
* Fragmentation functions defined order-by-order; here we neglect contributions beyond LO.

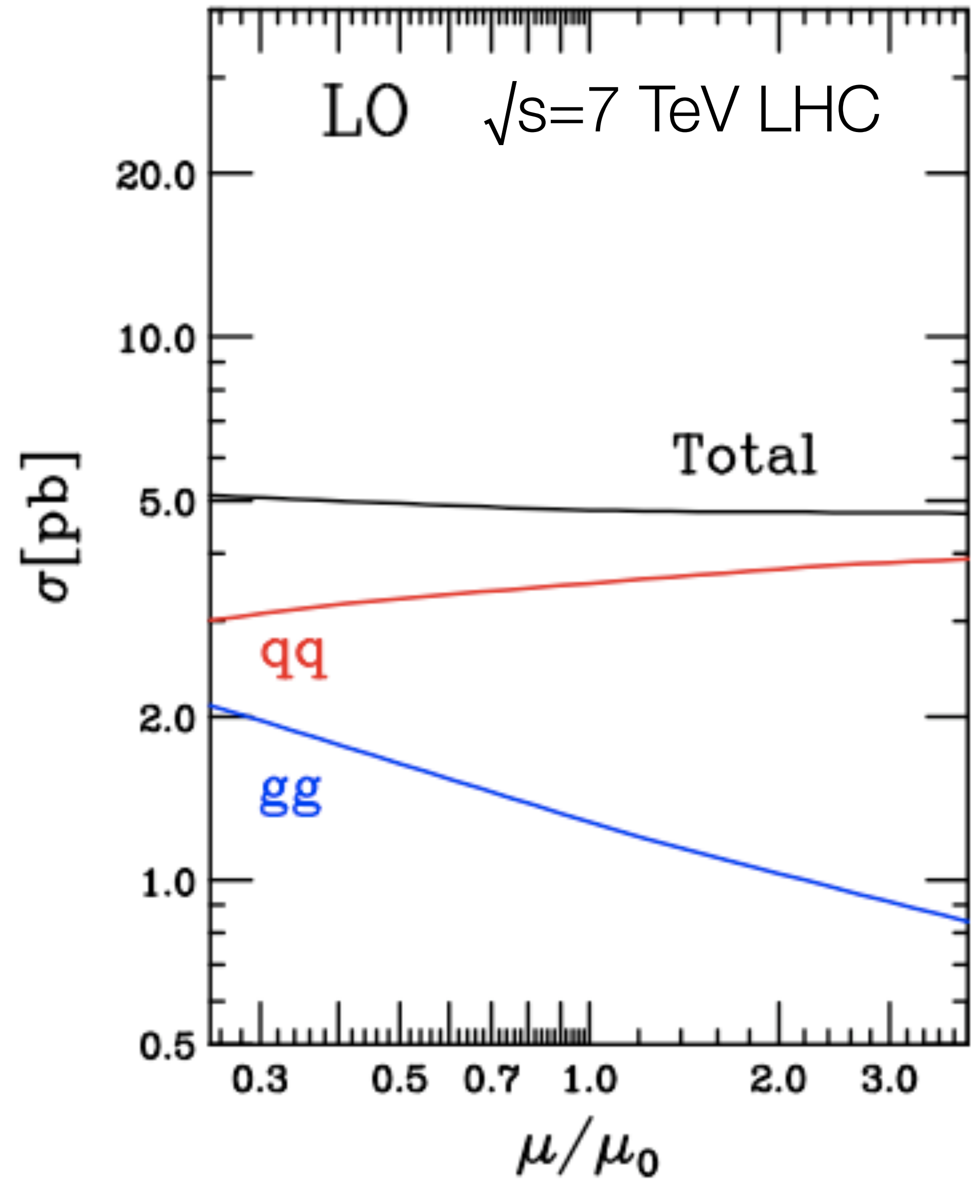
Diphoton production

- NLO corrections straightforward to compute.
- At NNLO, can obtain significant contribution from diagrams with two initial-state gluons (primarily LHC).

Ametller et al. (85); Dicus and Willenbrock (88)

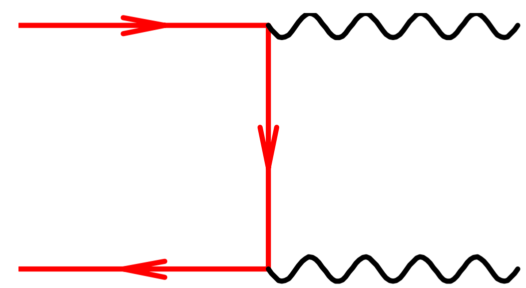


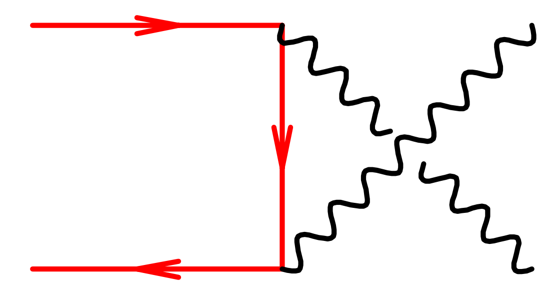
finite contribution



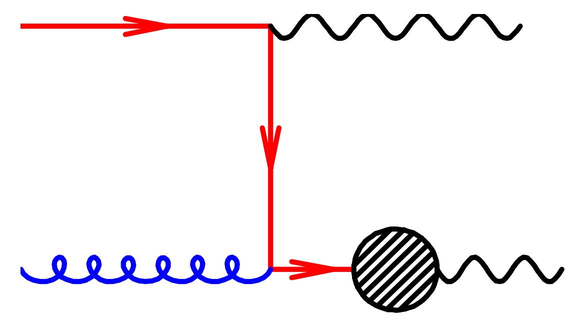
Treatment of pp→γγ in MCFM

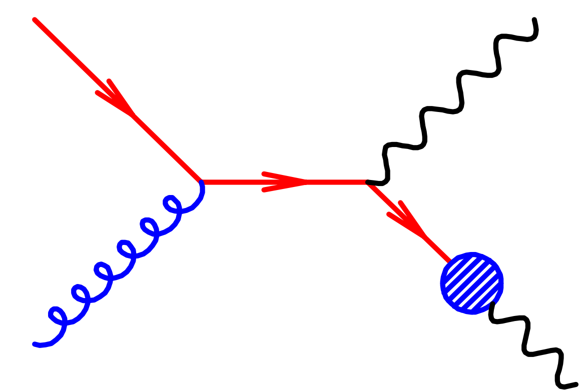
* MCFM includes a full NLO calculation.



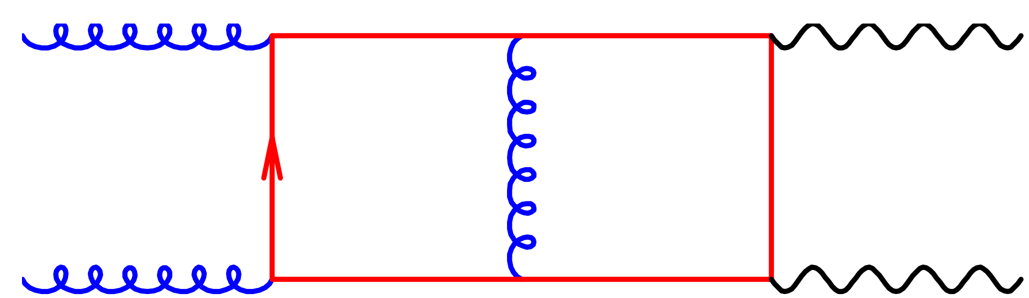


* Fragmentation contributions are included.





* MCFM includes gg contributions calculated at NNLO using two loop amplitudes of Bern et al., (hep-ph/0702003)



MCFM combines functionality of Diphox,Jetphox and gamma2MC

Glue-glue at higher order

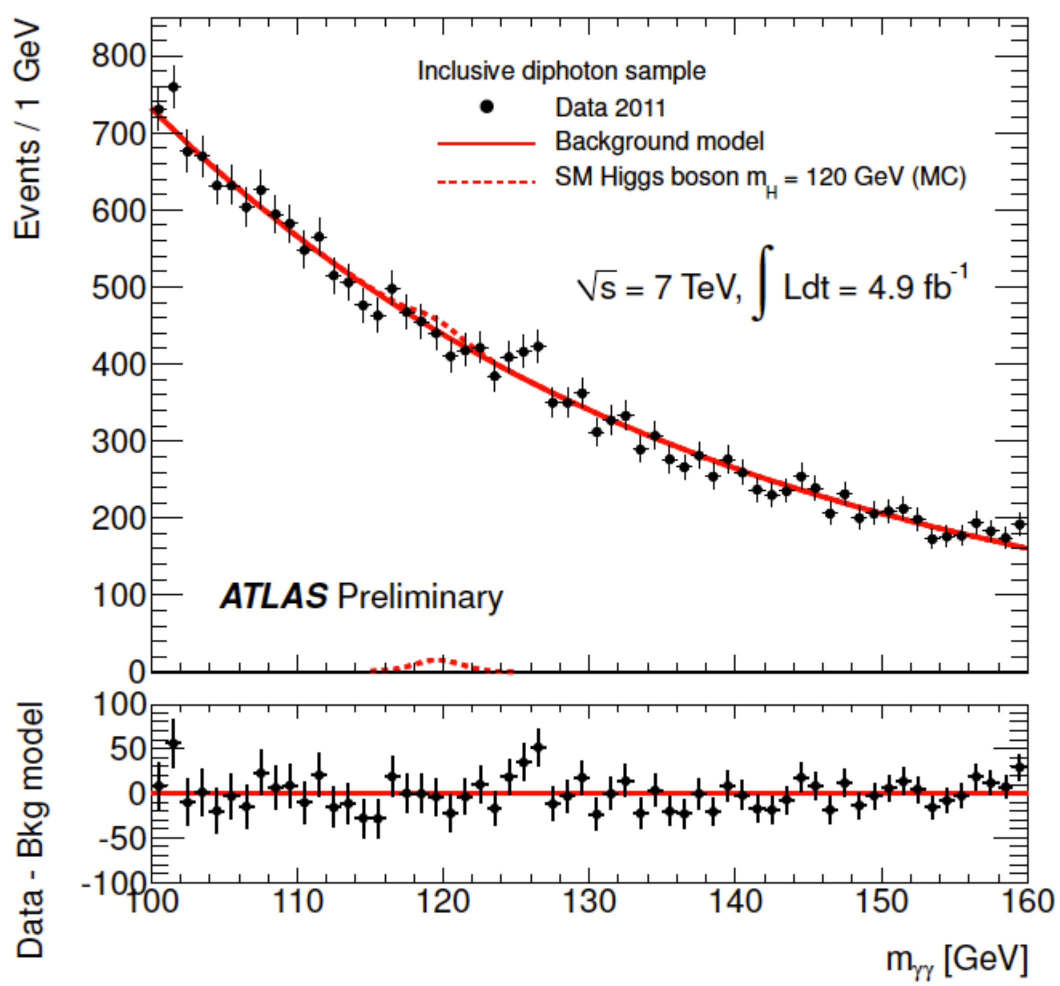
- Large contribution should be computed more accurately if possible.
- Next order = 2 loops: hard, but complete calculation tractable because first order is finite.

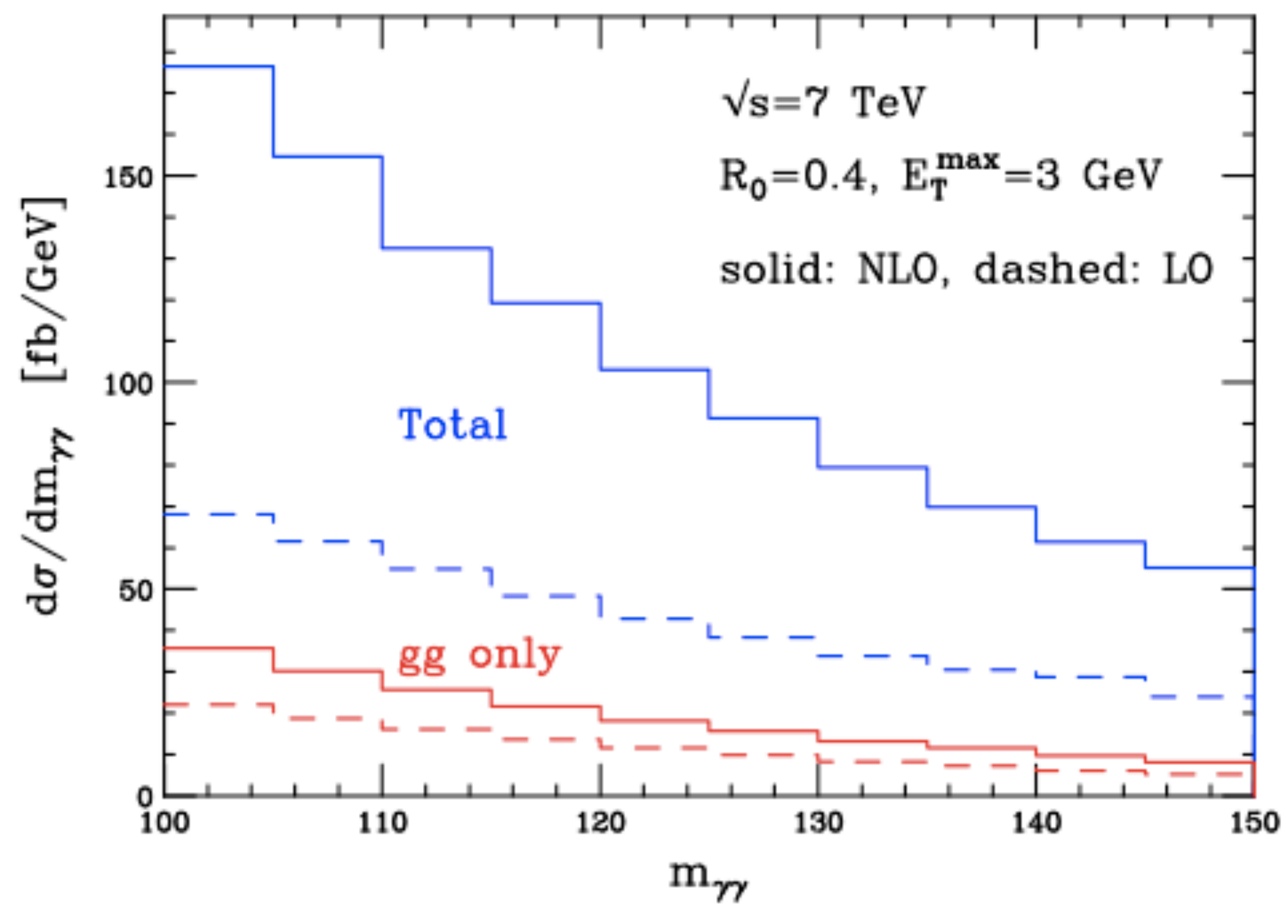
  Bern, De Freitas, Dixon (01); Bern, Dixon and Schmidt (02)
- Similar parton-level approaches:
  - gamma2MC: Frixione-style isolation only; Schmidt
  - Diphox: glue-glue pieces at LO only, but fragmentation treated at NLO; Binoth et al.
  - 2γNNLO: full NNLO calculation, Frixione-style isolation. Catani et al. (Oct. 11)

Example

- Analysis performed using staggered photon cuts:

$$p_T^{\gamma_1} > 40 \text{ GeV} \;, \quad p_T^{\gamma_2} > 25 \text{ GeV}$$

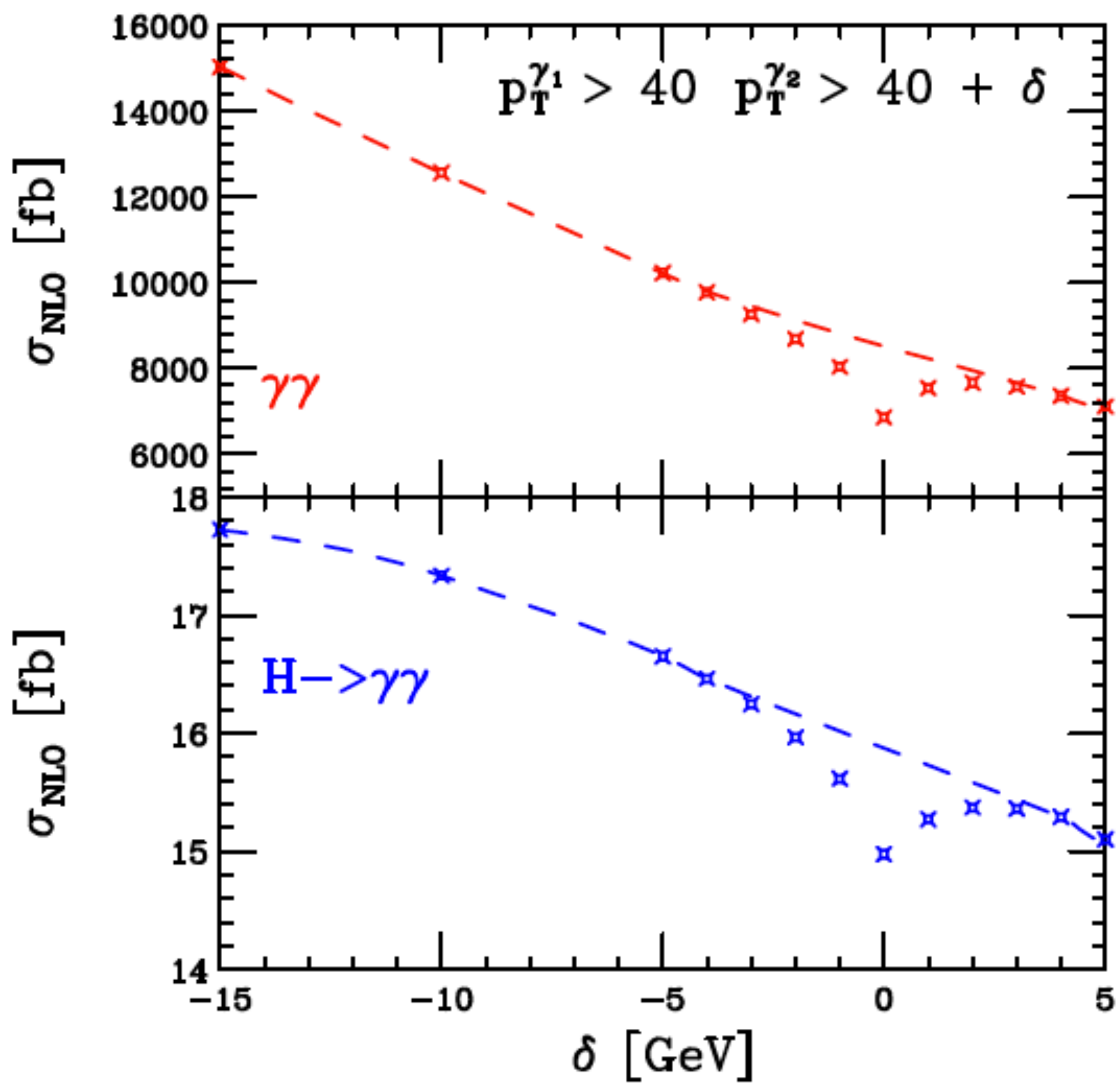




- Cuts induce a large NLO correction since photons must be produced with equal p_T at LO.

Staggered cuts in perturbation theory

* Investigate removing staggered requirement.
* Replace with cuts: $p_t^{\gamma_1} > 40 \text{ GeV}\ , \quad p_T^{\gamma_2} > 40 + \delta \text{ GeV}$



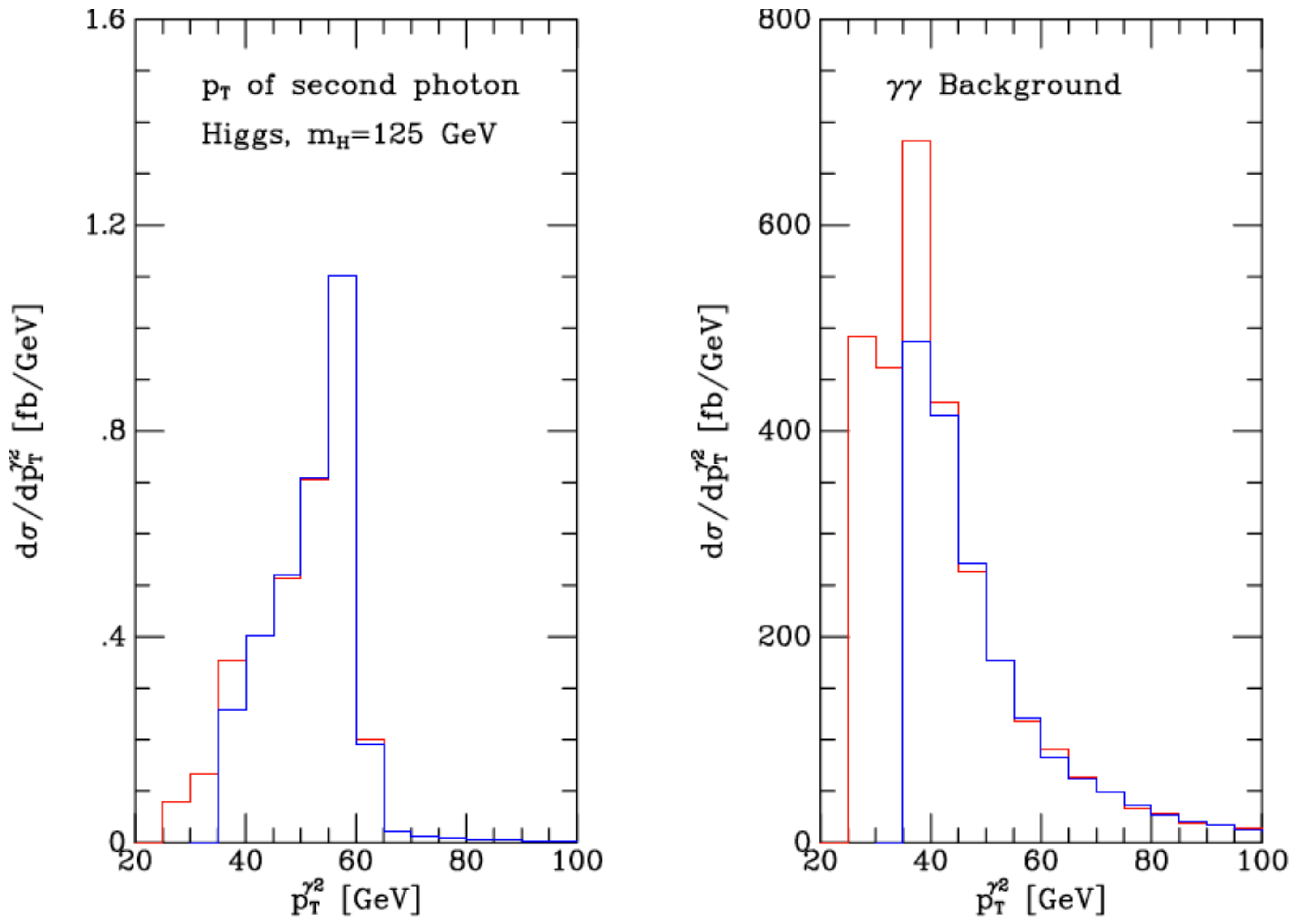
* Cross section contains terms ∝ δ log δ.

  Frixione, Ridolfi (97)

* Resummation required for small |δ| (<3 GeV).

Less asymmetric cuts.

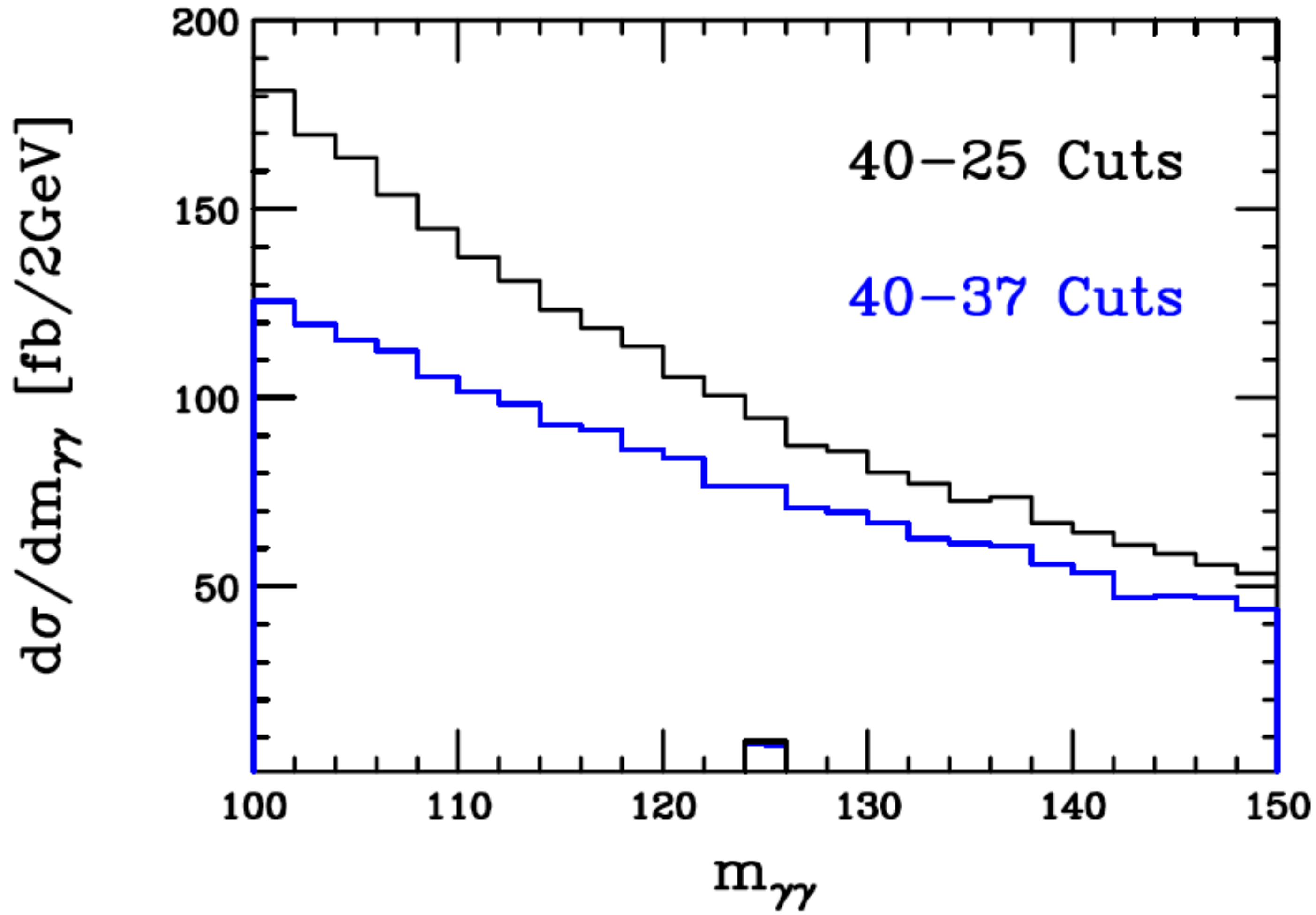
- The p_T distributions of the second photon for the signal and background are quite different.



- indicates that less staggered cuts are advantageous.
- $p_{T\,min}$ = 25 GeV vs 37 GeV.

Reducing the stagger

- Modest decrease of background by increasing pt(min) of second photon from 25 to 37 GeV.
- At very least it would be nice to see the plots for different values of the stagger.

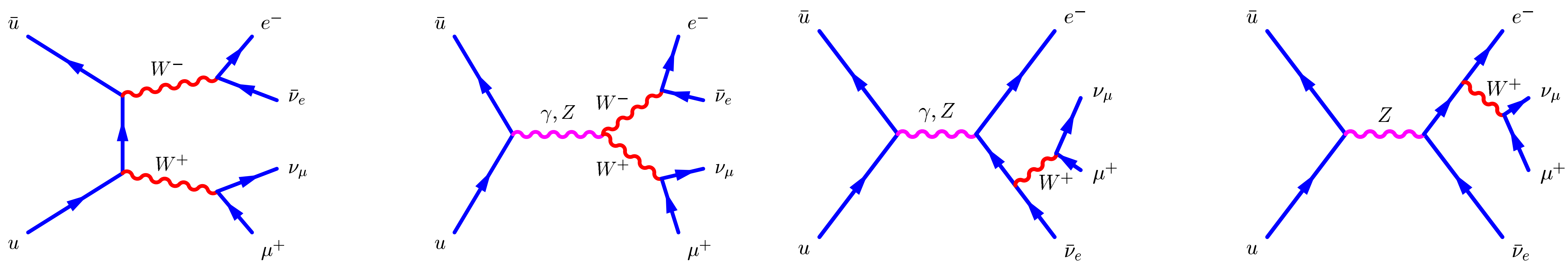


Conclusions

- MCFM offers the possibility of “one stop shopping” for Higgs signal and background (and much more), calculated consistently at NLO.
- Analytic results for $gg \to WW$ through (t,b) loops available - small effect on cross section but significant for interference with Higgs diagrams.
- For the most sensitive WW process, “signal” can be increased and background decreased by performing transverse mass cut.
- $H \to ZZ$: Interesting to exchange style of cuts of 2 experiments
- $H \to \gamma\gamma$: Interesting to revisit/present results with less stagger.

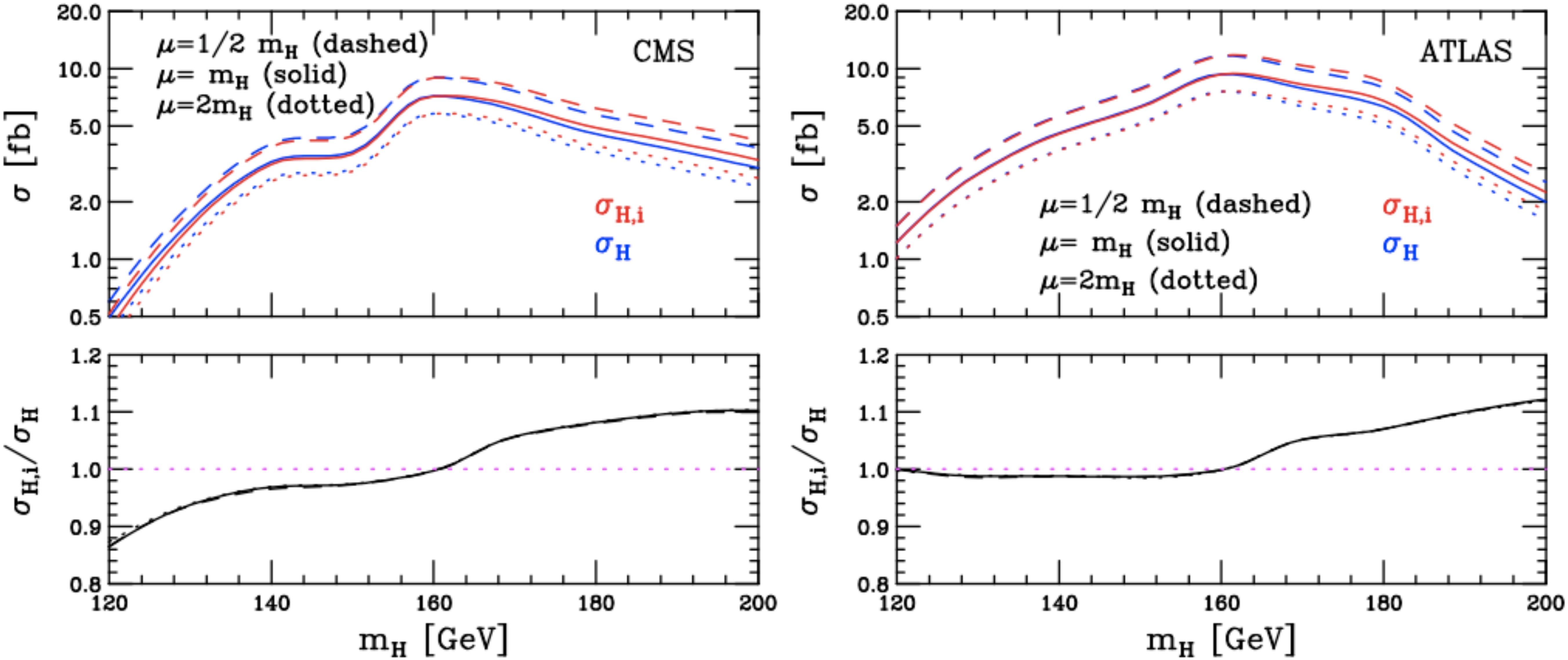
Preliminaries

- Important to retain spin correlations in W/Z decays, e.g. for analysing angle between leptons for H→WW.
- Equivalent of "radiation in decay" is "singly resonant" diagrams, in contrast to the usual doubly-resonant set.



- Both WW and ZZ also receive contributions from glue-glue initiated processes.
- For this talk, ignore WZ (nothing new there).

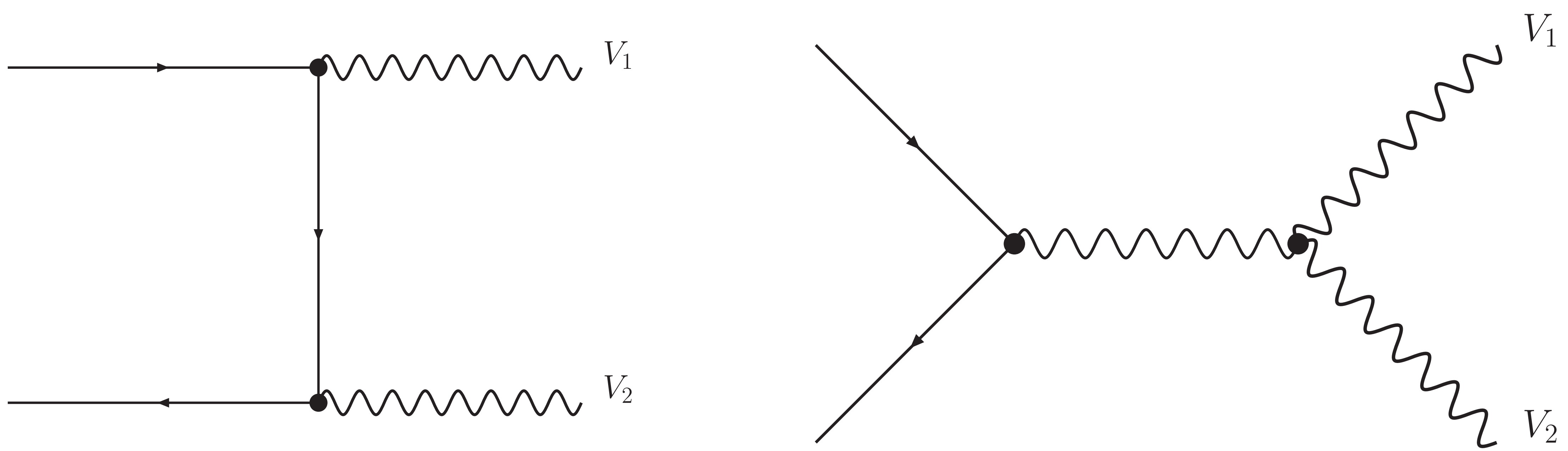
Interference under search cuts



- Similar behavior for large Higgs masses.
- What is responsible for the difference at smaller m_H?

Motivation

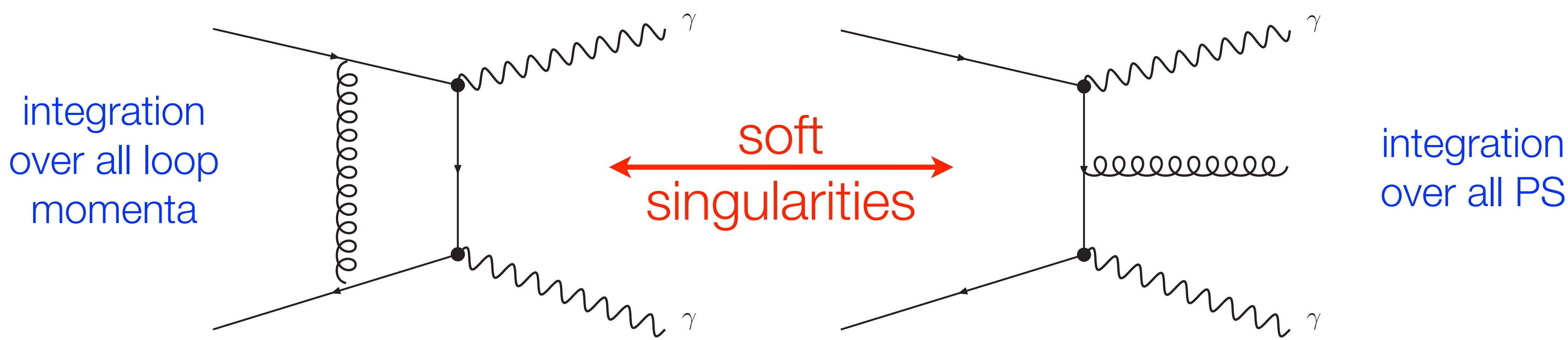
- Irreducible backgrounds.
  - in various combinations: leptons, jets, missing E_T;
  - searches for the Higgs, supersymmetry, ...



- Test of the gauge structure of the Standard Model.
  - limits on anomalous boson couplings.

Cone problems

- Removing quark-photon singularities in this way would be acceptable (but only up to NLO).
- However, a physically meaningful prediction would also require the same cut on gluons.
- Enforcing such a cut would prohibit the emission of soft gluons inside the cone and be infrared-unsafe: cancellation of virtual/real singularities not complete.



Conventional approach

- Usually, isolation cone allows a small amount of hadronic energy inside.

$$\sum_{\in R_0} E_T(\text{had}) < \epsilon_h \, p_T^\gamma \qquad \text{or} \qquad \sum_{\in R_0} E_T(\text{had}) < E_T^{\max}$$

- Okay for QCD infrared-safety, but collinear quark-photon singularity again exposed.
- Singularities can be handled by usual higher-order machinery, e.g. dipole subtraction, and exposed:

$$-\frac{1}{\epsilon}\frac{\Gamma(1-\epsilon)}{\Gamma(1-2\epsilon)}\left(\frac{4\pi\mu^2}{M_F^2}\right)\frac{\alpha}{2\pi}\, e_q^2 P_{\gamma q}(z)$$

- Just like initial-state collinear singularities are absorbed into pdfs, these can be defined away.