QCD radiation effects on Higgs boson searches in the WW channel at the LHC

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together with

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and

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KET Workshop, Zurich, June 2008

Outline

- Importance of the WW channel and selection cuts
- calculating the Higgs boson cross-section
  - from LO to NNLO cross-sections
  - from inclusive to differential cross-sections
- NNLO results for the signal cross-section
- comparison of fixed-order results with parton-shower algorithms and the resummed Higgs p_T-spectrum
- sensitivity to jet algorithms and the underlying event
- Conclusions

Higgs discovery in the WW channel

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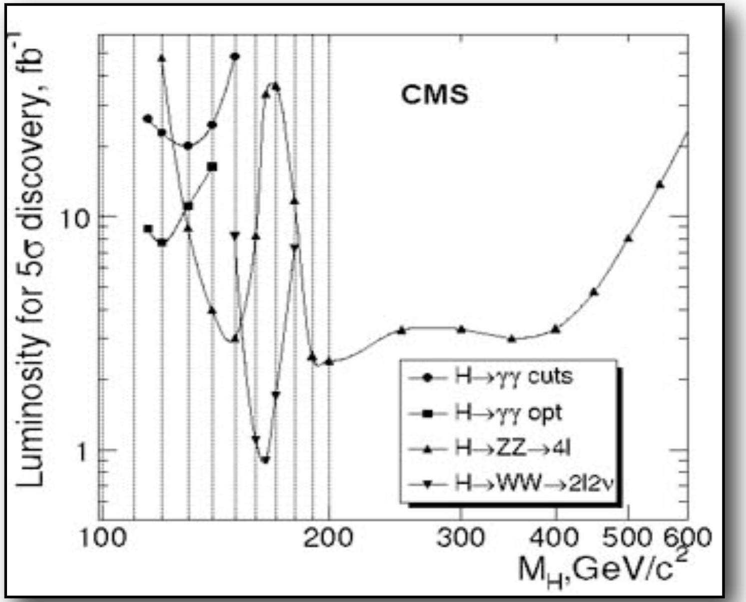
- many channels are exploited to discover the Higgs at the LHC
- in the mass region ~2 m_W the $H \rightarrow WW$ channel is most promising ($BR(H \rightarrow WW) \sim 1$)
- but... in the leptonic W decay modes there are neutrinos in the final state



Davatz, Dittmar, Giolo-Nicollerat

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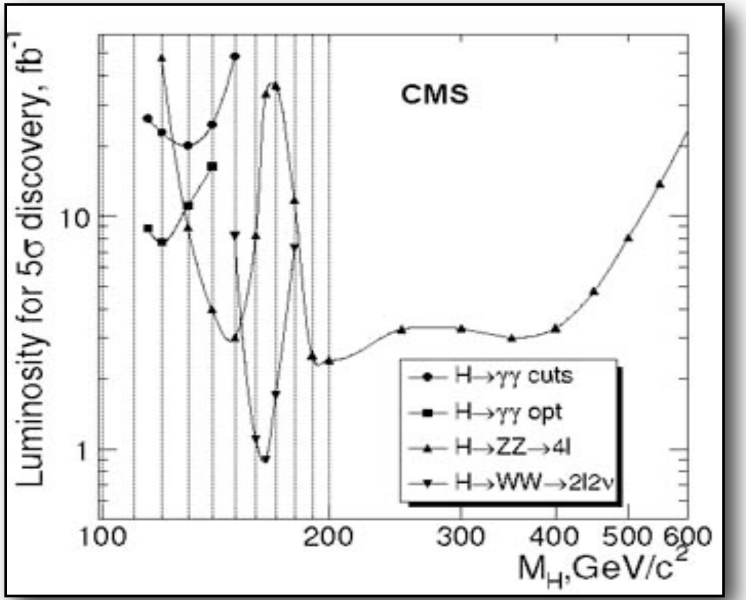
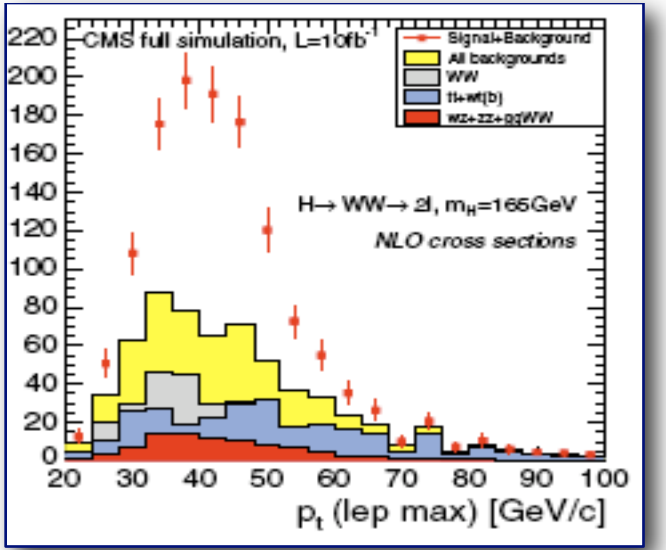
- but... in the leptonic W decay modes there are neutrinos in the final state
  - **no invariant mass peak can be reconstructed**
  - an ‘excess’ only detectable via counting experiment
  - understanding of signal and background properties is essential





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Signal and Background processes

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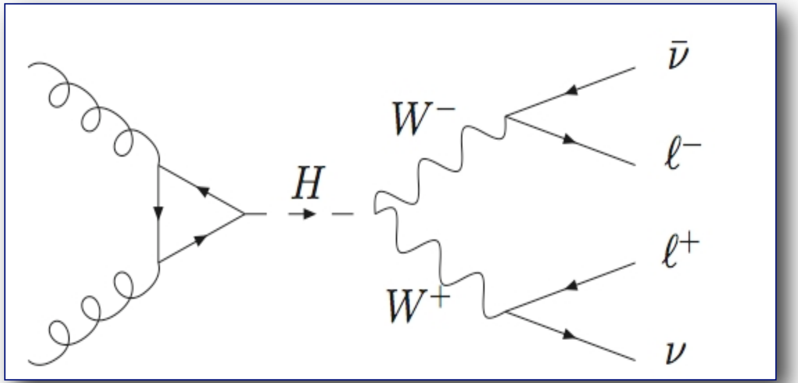
Gluon-Fusion Signal



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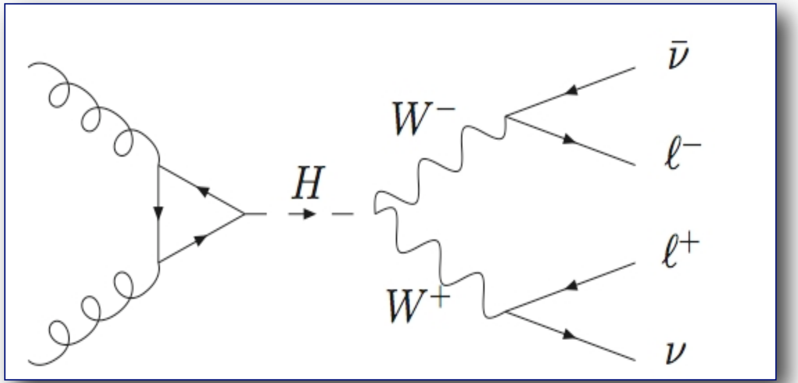
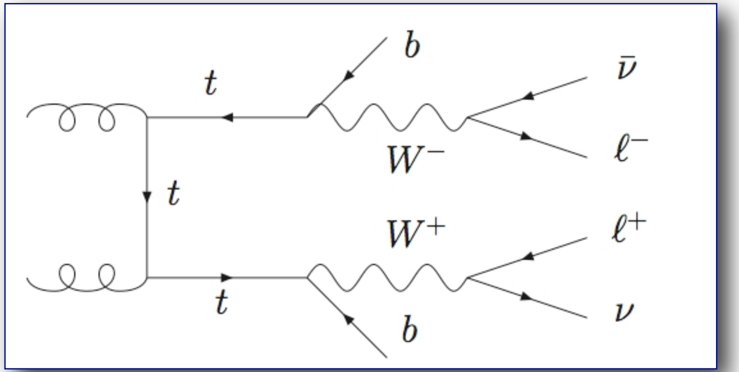


Top-Pair Background



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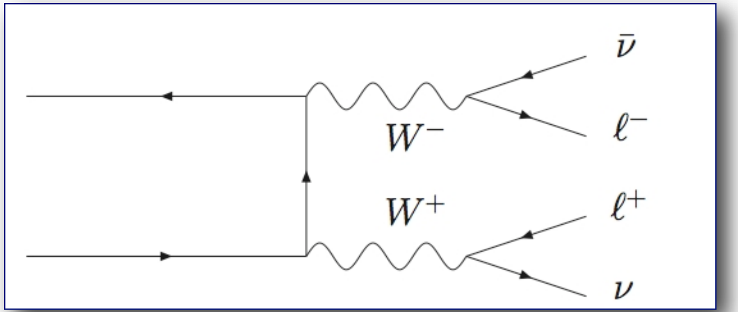

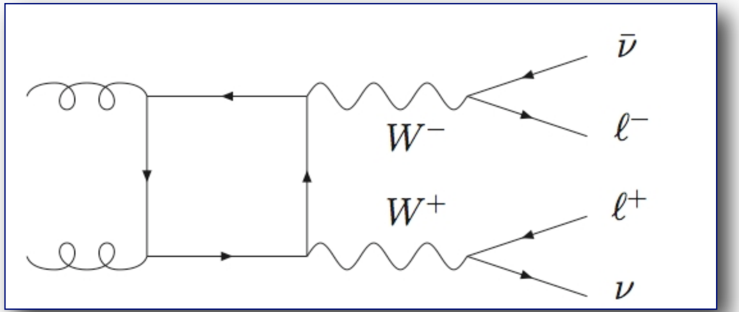

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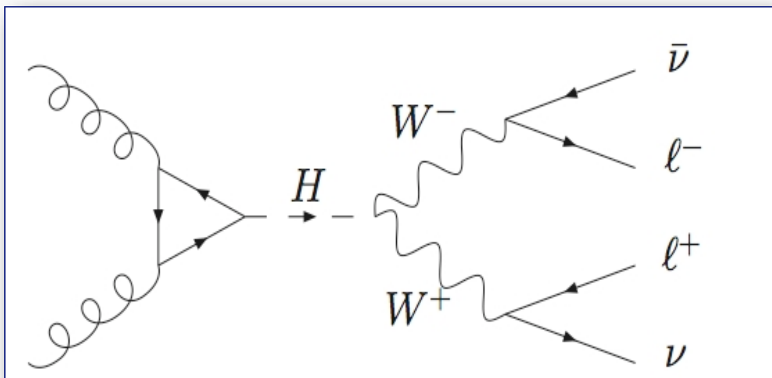

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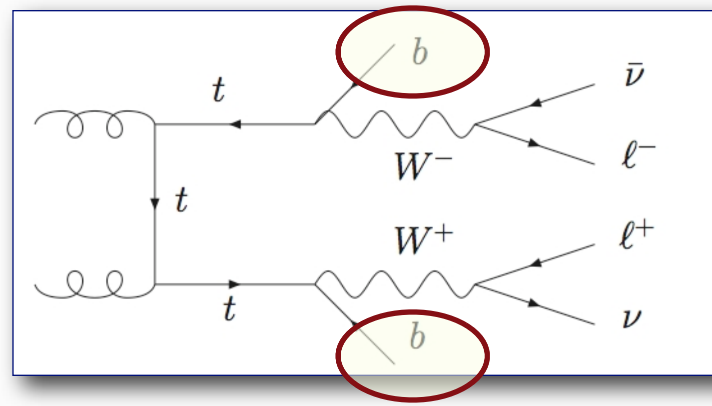

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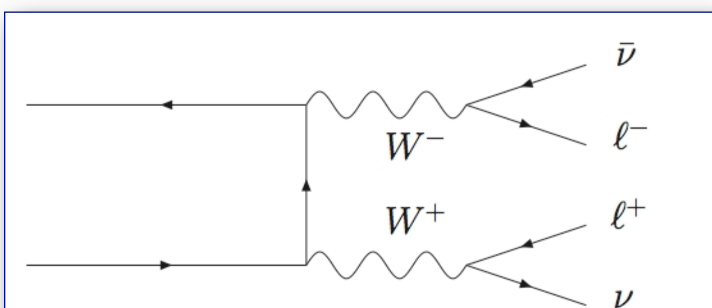

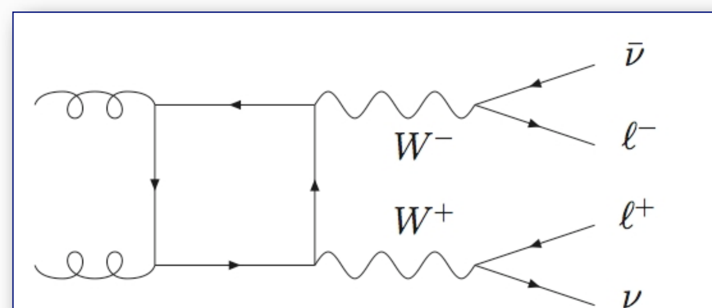

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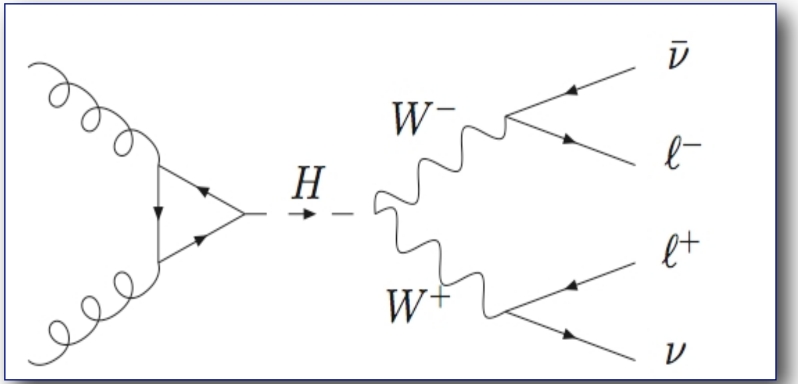

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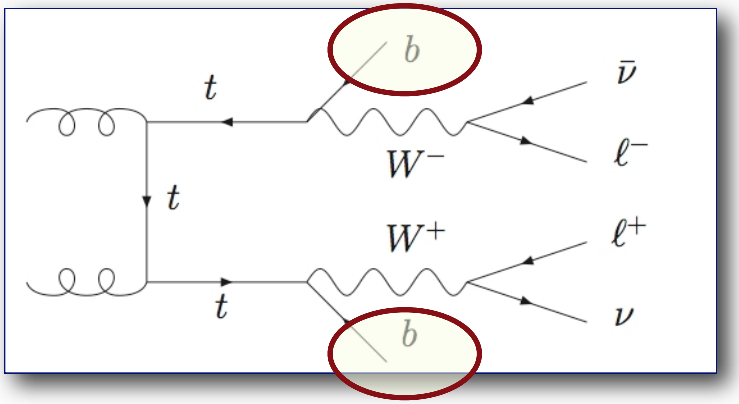

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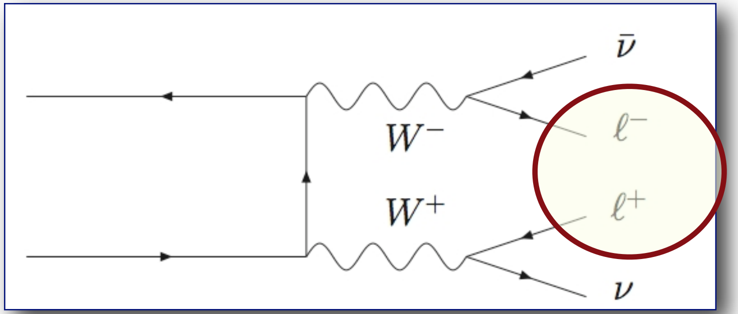

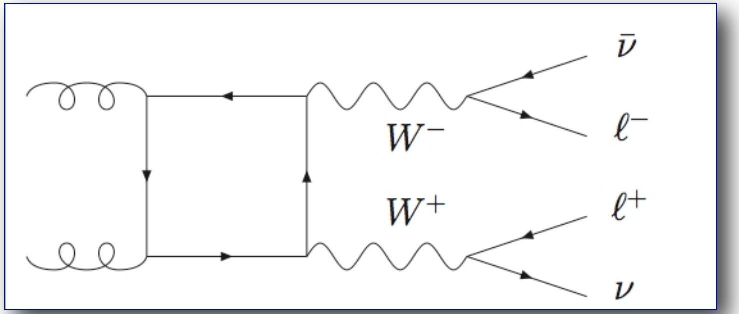

Magnitude of Signal & Background

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Cross-sections after basic selection:

- 2 isolated high p_T (> 20 GeV) opposite charge leptons (e,μ)

process	m_H=165 GeV	tt	qq→WW	gg→WW
σ [pb]	0.4	15.7	1.4	0.1

- Signal/Background ratio ~ 2 %
  - need very restricting additional cuts to improve this ratio
    - ➡ Dittmar & Dreiner 1997
  - **angular correlations** to reduce WW backgrounds
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σ [fb]	46	10	12	4

- very severe cuts: only about 2% of the initially produced Higgs events survive: Do we understand these cross-sections in such a small region of phase-space?

“Scary” cut efficiencies

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- Cut efficiencies for all process are of the order or less than 1%
- What is the impact of QCD radiation corrections on these efficiencies?
- Theoretical work was/is needed in all four processes
- In a real experiment:
  - Background events can be measured in signal-free regions and extrapolated into the ‘signal-region’
- The signal can only be studied theoretically!

Inclusive Higgs cross-section

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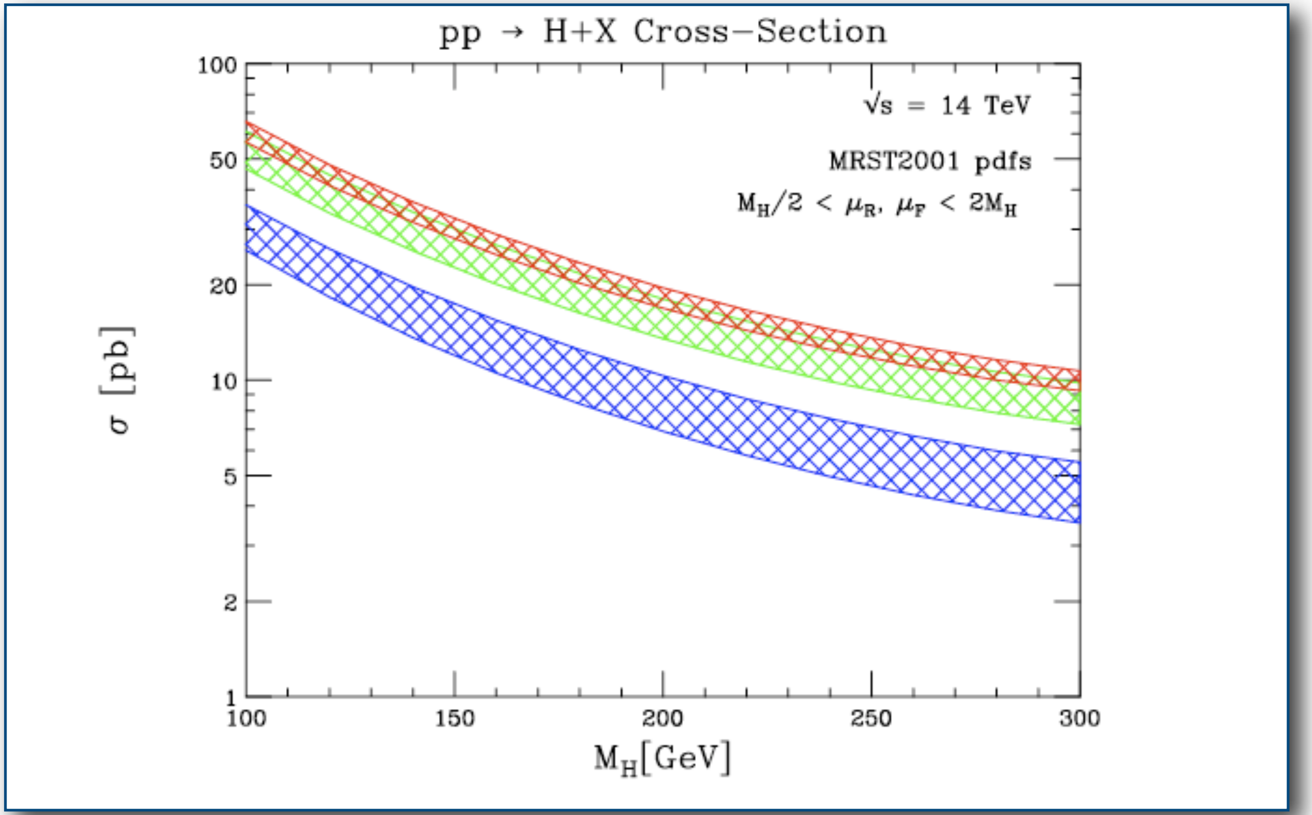
- Higgs cross-section in the Gluon-Fusion channel receives large pertubative corrections:

σ(NLO) ~ 1.7 x σ(LO) (Dawson; Spira, Djouadi, Zerwas)

σ(NNLO) ~ 2.0 x σ(LO) (Harlander, Kilgore; Anastasiou, Melnikov; Ravindran, Smith, van Neerven)



Differential cross-sections

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- need fully differential cross-sections in order to impose experimental cuts
- at NLO any cross-section can be computed if the virtual amplitudes are known
  Giele, Glover, Kosower; Frixione, Kunszt, Signer; Catani, Seymour ...
- for NNLO collider processes the list is rather short:
  - Drell-Yan rapidity distribution Anastasiou, Dixon, Melnikov, Petriello (03)
  - $ee \to 2$ jets Anastasiou,Melnikov,Petrielle (04); Gehrmann,Gehrmann,Glover (04); Weinzierl (06)
  - $pp \to H+X$ Anastasiou, Melnikov, Petriello (04)
  - $pp \to H+X \to \gamma\gamma+X$ Anastasiou, Melnikov, Petriello (04), Catani, Grazzini (07)
  - $pp \to W,Z+X$ Melnikov, Petriello (06)
  - $pp \to H+X \to WW+X \to l\nu l\nu+X$ Anastasiou, GD, Stöckli (07), Grazzini (08)
  - $ee \to 3$ jets Gehrmann, Gehrmann, Glover, Heinrich (07)

H → WW at NNLO (Anastasiou, GD, Stöckli)

- used the fully differential NNLO program FEHiP for $pp \to H+X$ Anastasiou, Melnikov, Petriello

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$H \rightarrow WW$ at NNLO (Anastasiou, GD, Stöckli)

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- used the fully differential NNLO program FEHiP for $pp \rightarrow H+X$ Anastasiou, Melnikov, Petriello
- added decay matrix-element for the process $H \rightarrow WW \rightarrow l\nu l\nu$
- large phase-space rejection required remodeling the numerical integration strategy
  - independent, parallelized VEGAS integration for individual sectors (FEHiP is based on Sector Decomposition)
  - large improvement of integration adaptation (from no-adaptation to adaptation within a few VEGAS iterations)
  - easy exploitation of cluster computing

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- all numbers/plots in the paper required about one week of running time on an average of 450 CPU's

$H \rightarrow WW$: selection cuts

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- we investigate the higher-order corrections on the cross-section **after experimental cuts** on the following variables:
  - *angle between the charged leptons in the transverse plane*
  - *missing transverse energy*
  - *maximum transverse energy of the harder lepton*
  - *invariant mass of the charged lepton-pair*

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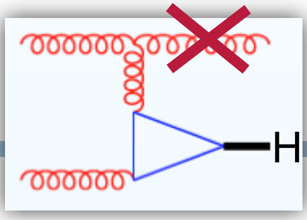
- we study the cumulative cross-section in the variable X as

$$\sigma_{\rm cum}(X^{\rm cut}) = \int_0^{X^{\rm cut}} \frac{d\sigma}{dX}\, dX$$

- i.e. we integrate the differential cross-section up to some cut-off value $X^{\rm cut}$, which mimics an experimental cut

Jet Veto

e.g.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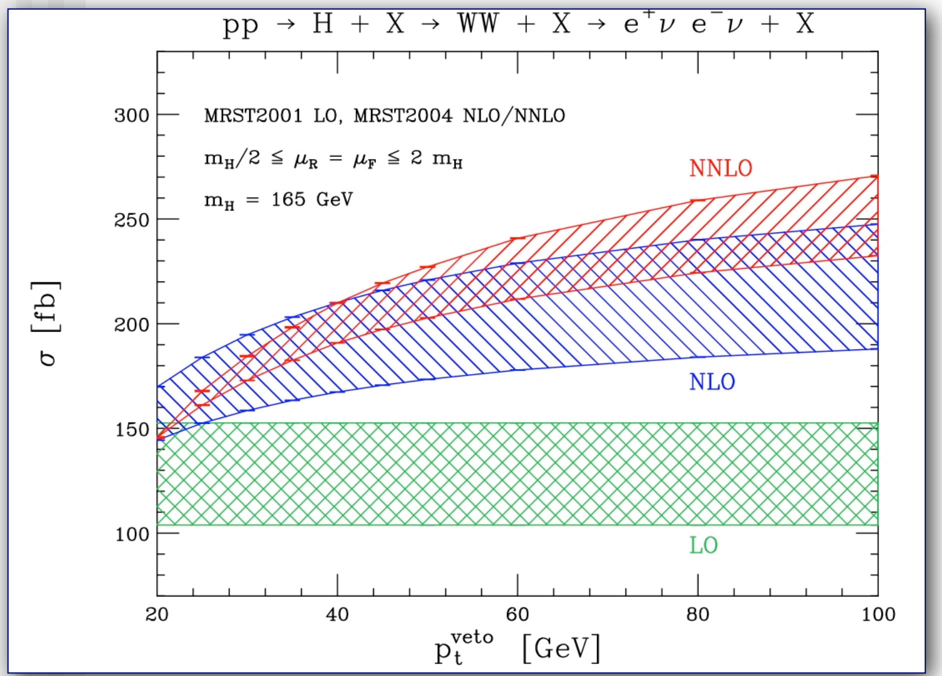
pp → H + X → WW + X → e+ν e−ν + X
MRST2001 LO, MRST2004 NLO/NNLO
mH/2 ≤ μR = μF ≤ 2 mH
mH = 165 GeV
NNLO
NLO
LO
σ [fb]
300
250
200
150
100
20
40
60
80
100
pt veto [GeV]

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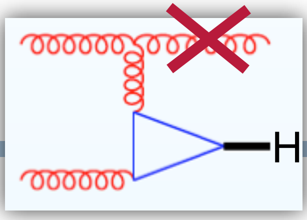
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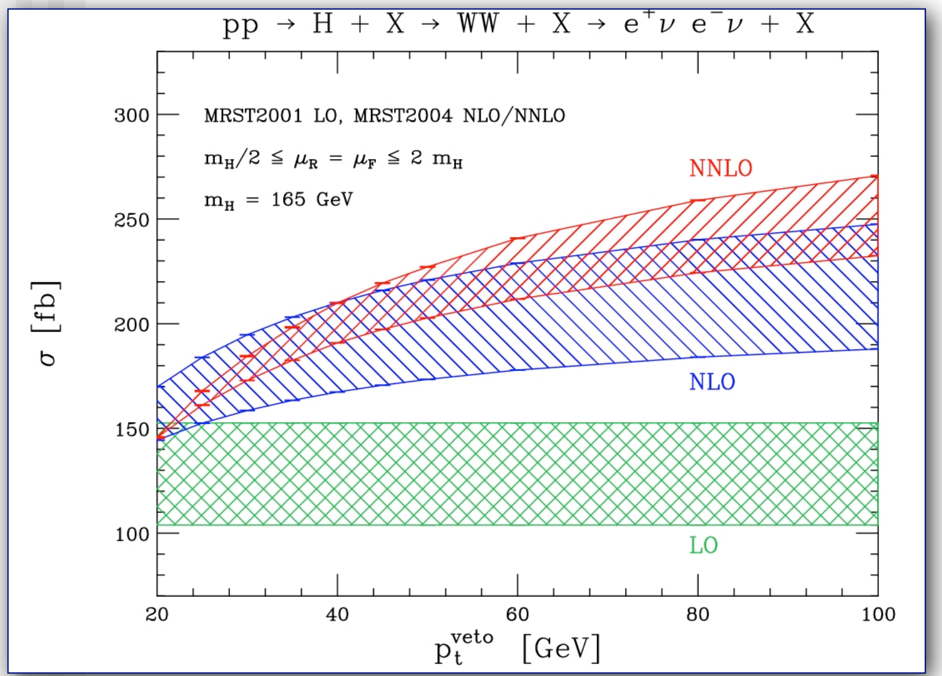
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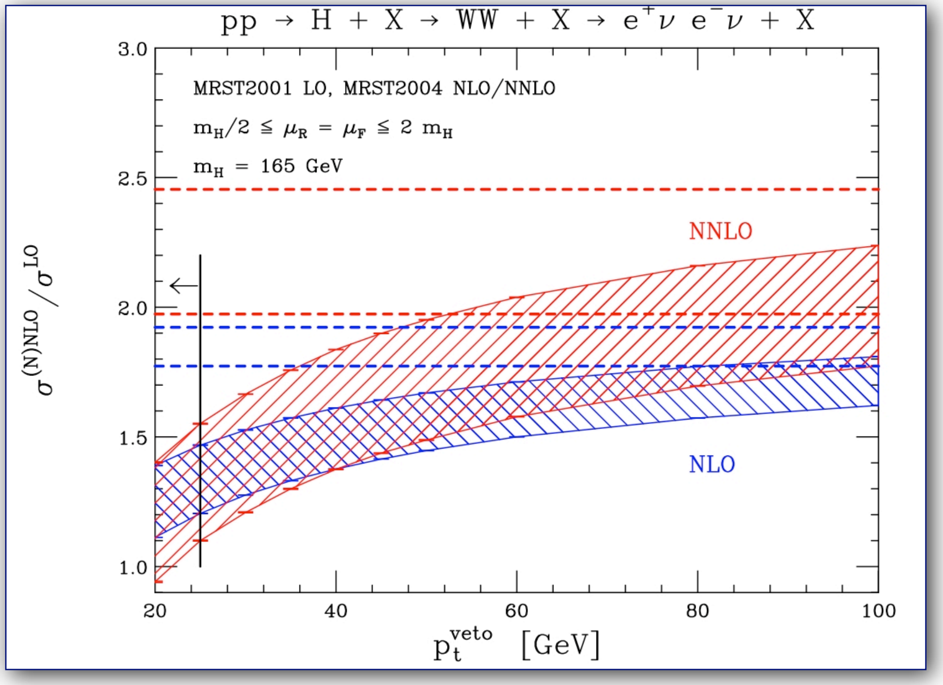
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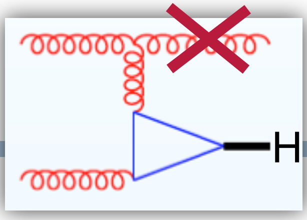
mH = 165 GeV
NNLO
NLO
σ(N)NLO / σLO
3.0
2.5
2.0
1.5
1.0
20
40
60
80
100
pt veto [GeV]

Jet Veto

e.g.



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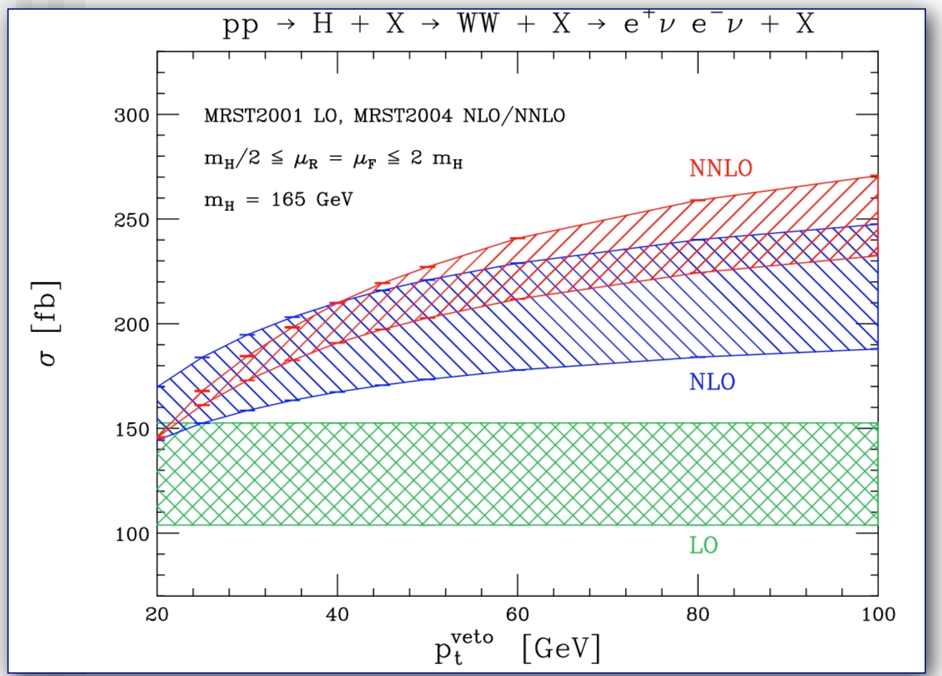
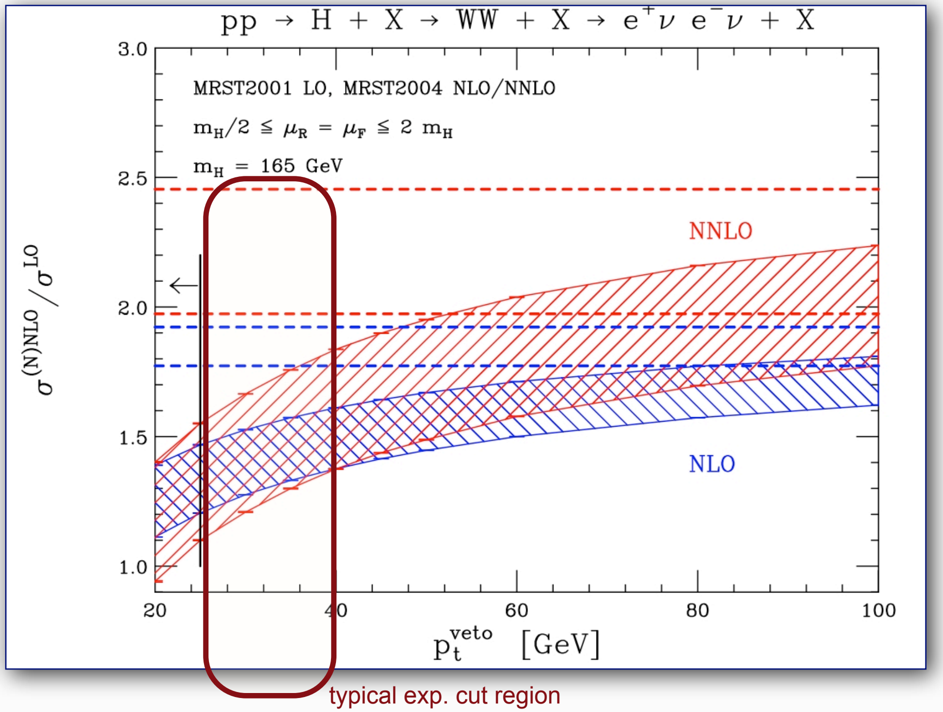
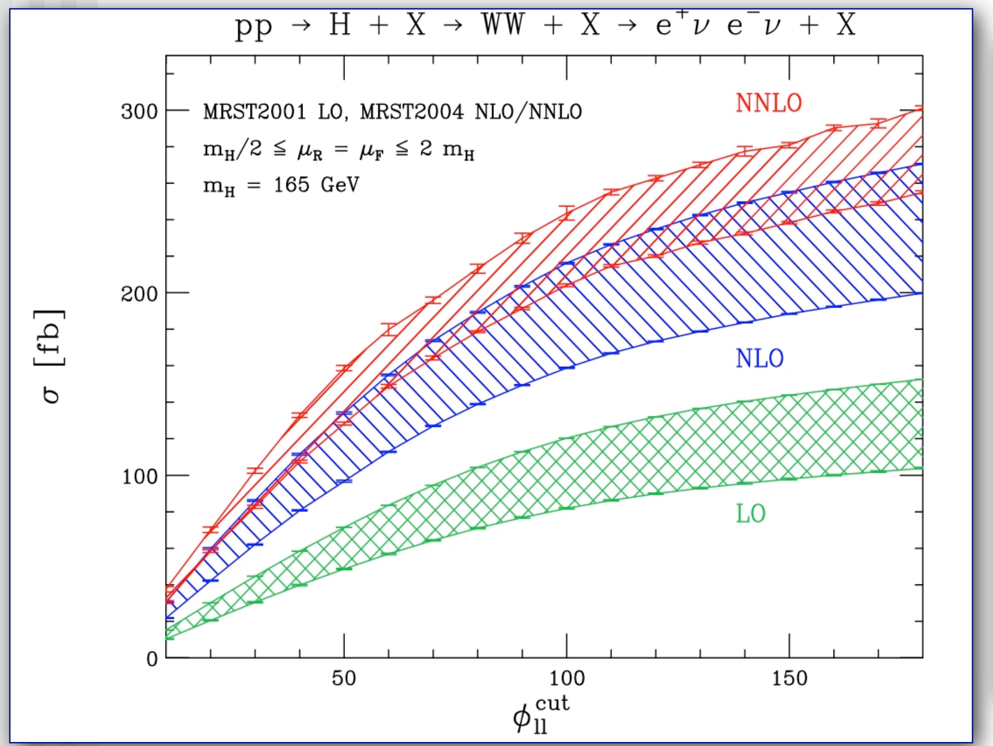
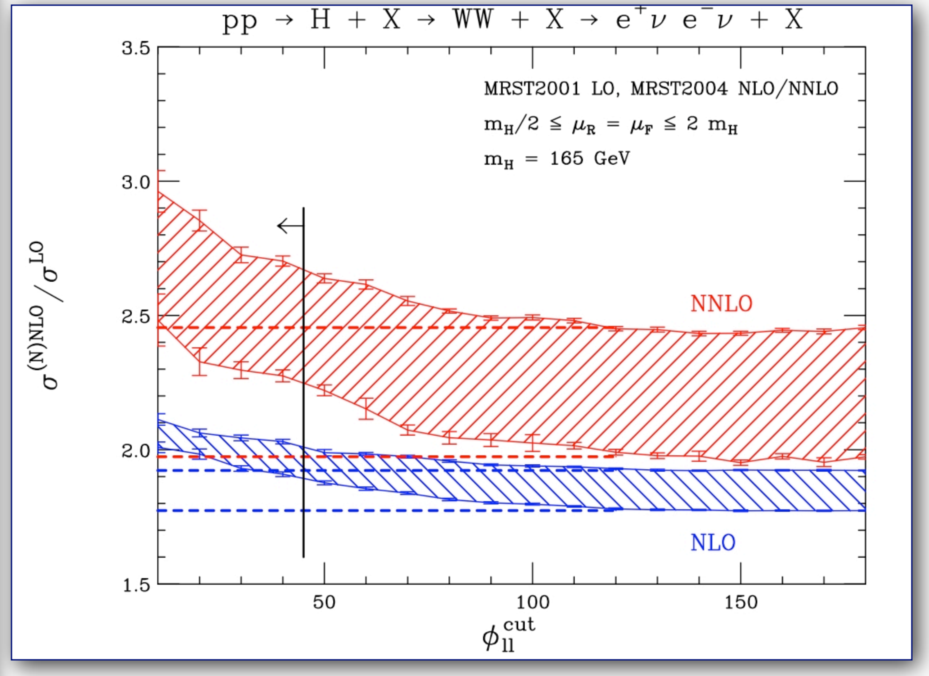




- jet-veto has no impact at LO (no partons in final state)
- jet-veto decreases the NLO and NNLO corrections
- jet-veto at NLO corresponds to cut on Higgs transverse momentum
- K-factors ($\sigma^{(N)NLO}/\sigma^{LO}$) depend heavily on cut-value!
  - **inclusive K-factors would fail to describe the picture reliably**

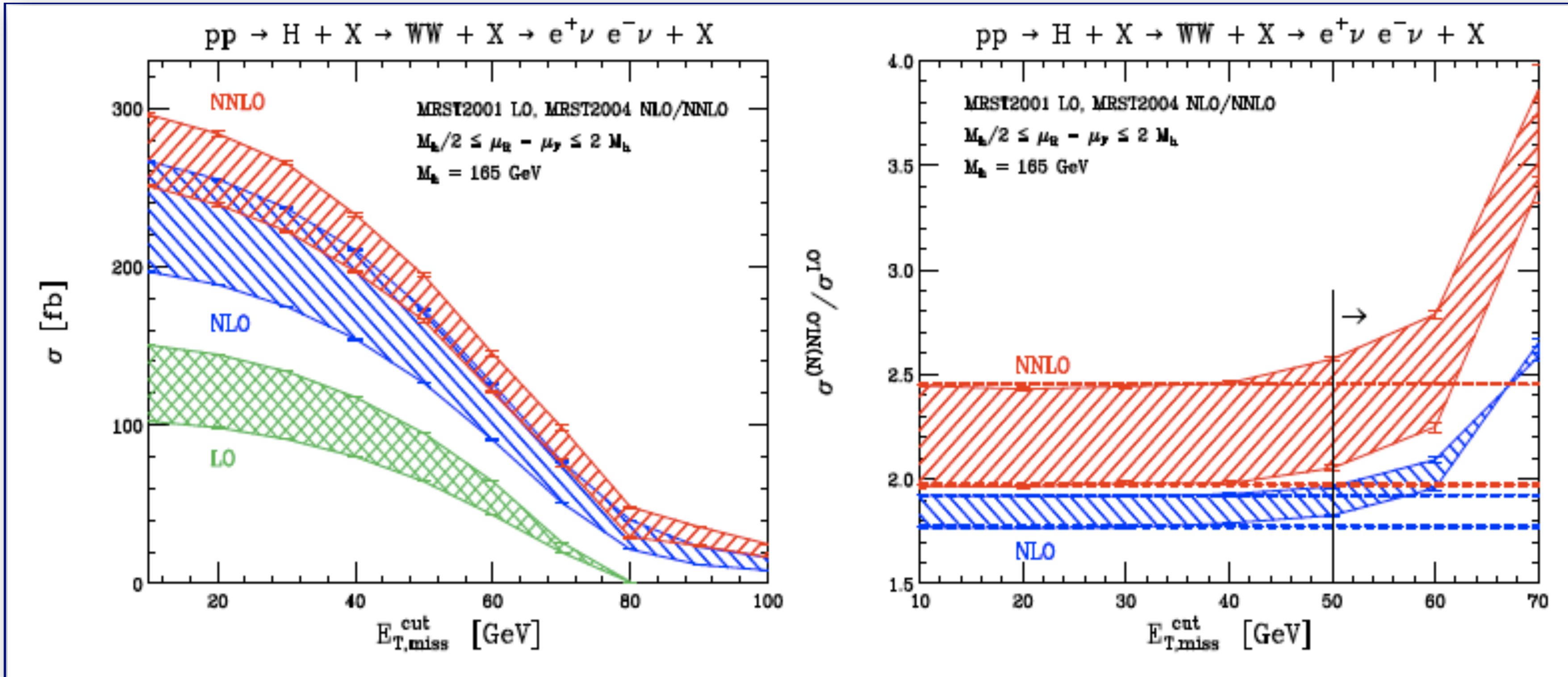
Transverse lepton angle





- in contrast to the jet-veto:
  the K-factors increase when lowering the cut value on the lepton angle
- cut is placed where the NNLO and NLO corrections are approximated by the K-factor for the total cross section

Missing Transverse Energy



- The cut removes a significant part of the two-loop contribution
- The LO phase-space is below 80 GeV

Signal cross-section after cuts

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σ(fb)	LO	NLO	NNLO
$\mu = \frac{M_h}{2}$	21.002 ± 0.021	22.47 ± 0.11	18.45 ± 0.54
$\mu = M_h$	17.413 ± 0.017	21.07 ± 0.11	18.75 ± 0.37
$\mu = 2M_h$	14.529 ± 0.014	19.50 ± 0.10	19.01 ± 0.27

- K-factors are at the order of 1
  - depending on scale choice even < 1
  - **! inclusive K-factors predict an increase by a factors of 2 !**
- very small scale variation after cuts are applied
- Is this a very precise prediction for the cross-section?

Are these results reliable?

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- We could hurry and declare “victory” of the fixed-order perturbation theory for the signal cross-section:
  - smaller higher-order corrections after cuts
  - smaller scale variation after cuts
- But...
  - is this accidental?

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- But...
  - is this accidental?
  - are effects beyond NNLO important?
- The cuts restrict the phase-space significantly, especially the jet-veto (but not exclusively) restricts the Higgs boson phase-space to the low transverse momentum region...
- ... where fixed-order theory might break down!
- ... do we need resummation for an accurate prediction?

A validation Ansatz

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  - MC@NLO (Frixione, Webber)
    - incorporates NLO matrix elements with the parton shower from HERWIG
  - resummed Higgs p_T distribution (Bozzi, Catani, de Florian, Grazzini)
    - matches NNLO with NNLL
    - combines to the 'highest posssible' accuracy fixed order and resummation effects
    - but available only for this distribution, not for any variable and after cuts

Earlier comparisons

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- NNLO vs MC@NLO for pp→H→γγ (GD, Holzner, Stöckli)
- NNLO vs MC@NLO for pp→W→eν (Melnikov, Petriello; Frixione, Mangano)
- In both cases very good agreement for the cut efficiencies
- But cuts for these processes restrict the Higgs / W boson phase-space 'democratically', i.e. not explicitly to the low transverse momentum region

What can we learn?

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- It is not obvious from first principles that the efficiencies in the event generators and the fixed-order prediction agree:
- The physics approximations in fixed-order and parton showers are different; therefore ...
  - ... a disagreement would mean that at least one of these approaches does not describe the physics process correctly in the signal phase-space (i.e. after the selection cuts)
- On the other hand: A good agreement would give confidence in our tools

Higgs p_T spectrum

- we know that if we integrate the fixed-order cross-section over a large enough region the effects of multiple soft and collinear radiation become negligible... But how ‘large’?
- we compare the cumulative cross-section in p_T^H ...

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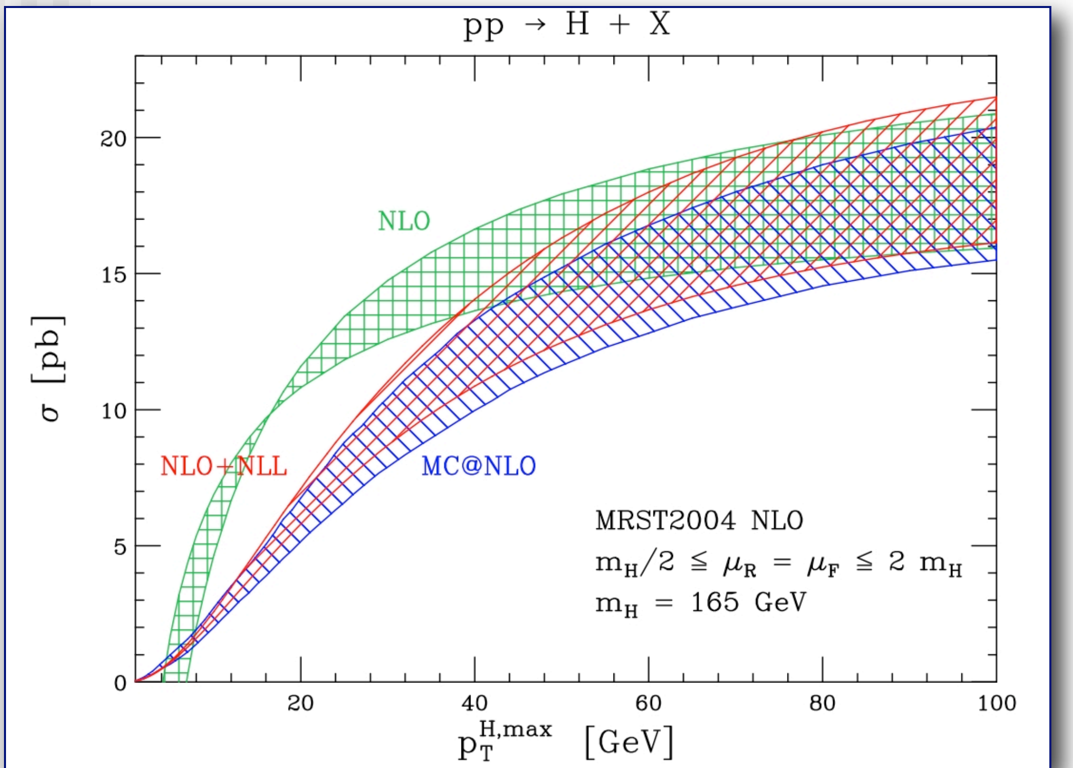

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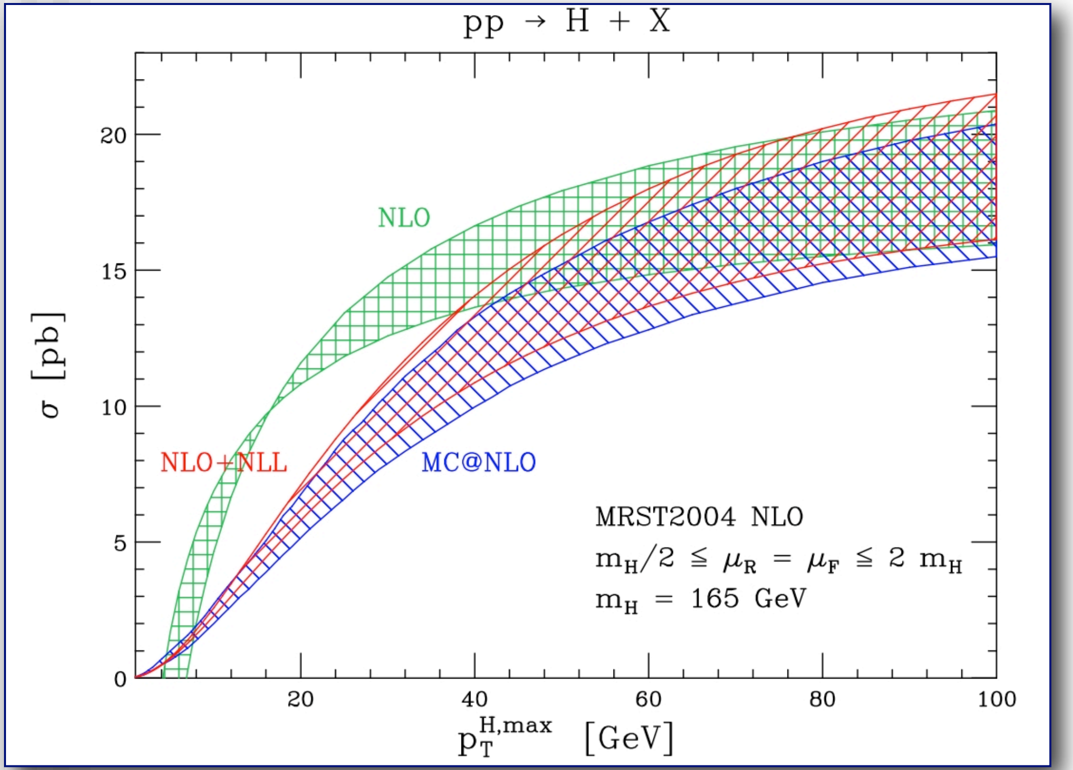

- NLO+NLL and MC@NLO agree very well
- need to integrate the fixed-order NLO spectrum up to about 70 GeV to get an agreement
- NLO prediction will fail when restricting to smaller regions!

Higgs p_T spectrum...

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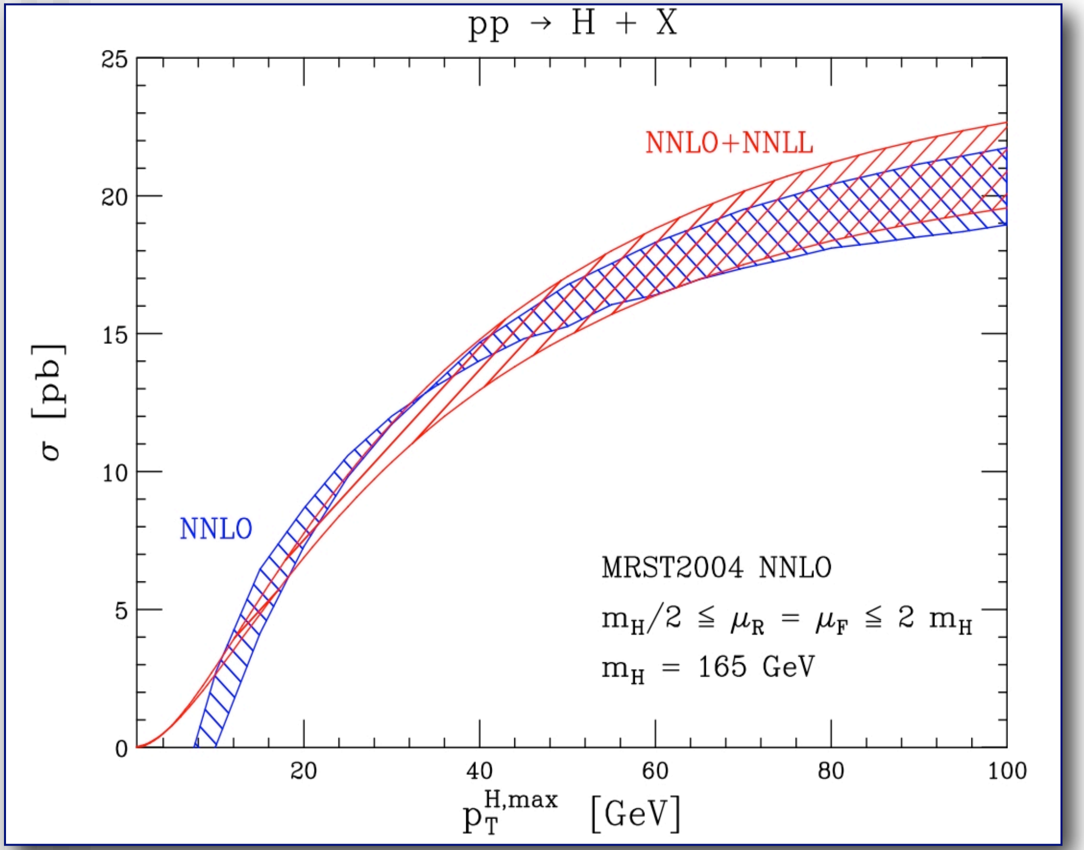
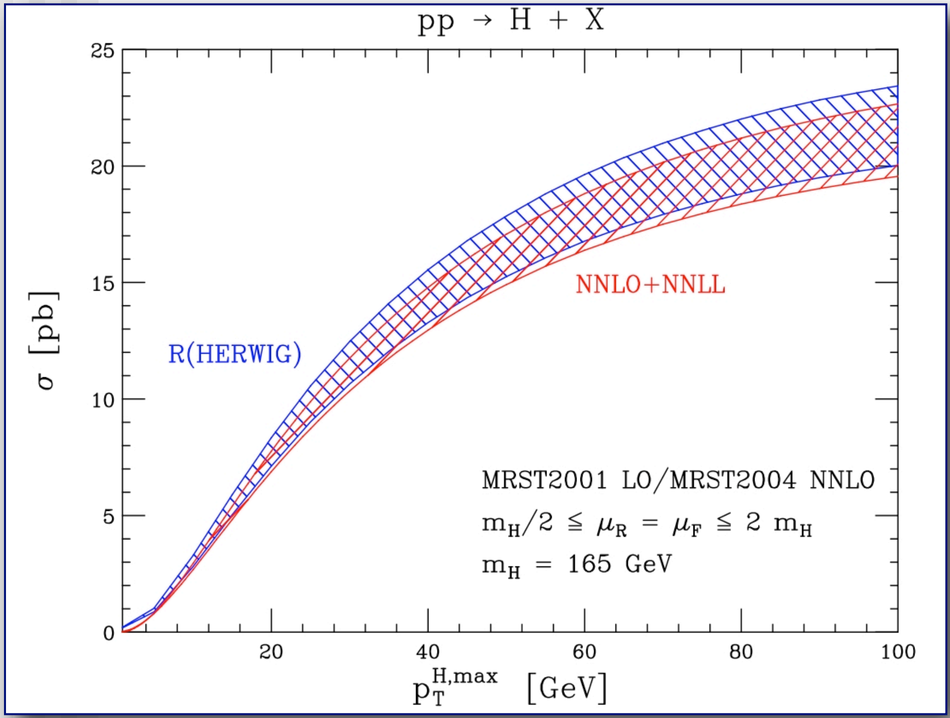
- ... and at NNLO:

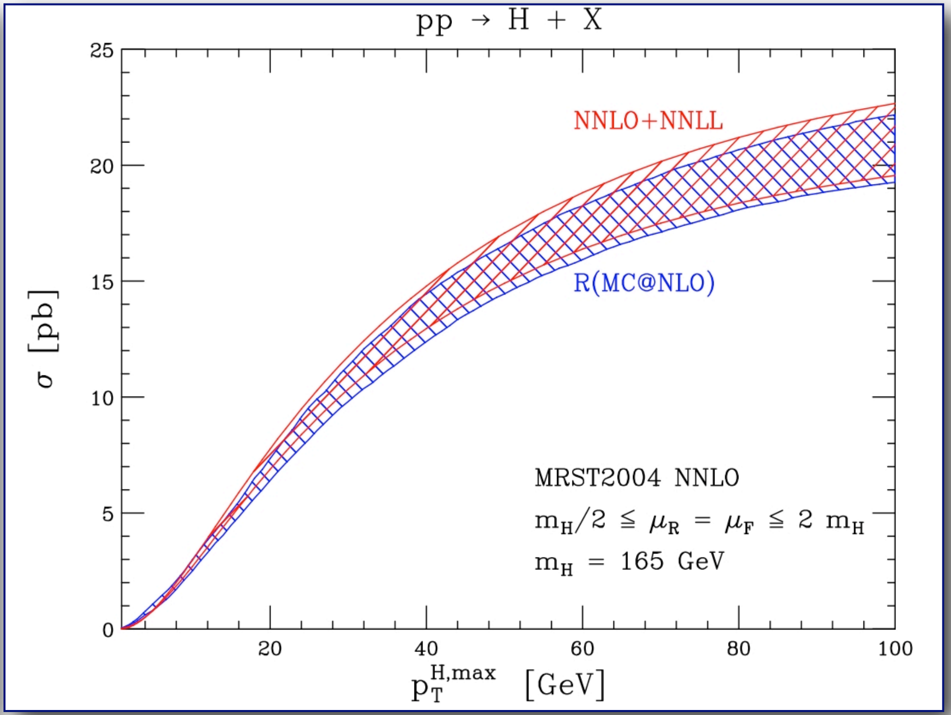


- both spectra agree much better down to much smaller regions
- we can ‘trust’ the NNLO spectrum already for a p_T^{max} value of about **20 GeV**!
- **reminder**: we veto on jets with $p_T > 25$ GeV

Rescaled generator spectra

- we also compare the inclusively rescaled generator spectra (HERWIG, MC@NLO) to the 'best' prediction:





- both agree nicely, with HERWIG slightly over- and MC@NLO slightly under-estimating the cross-section

Cut variables: NNLO vs MC@NLO

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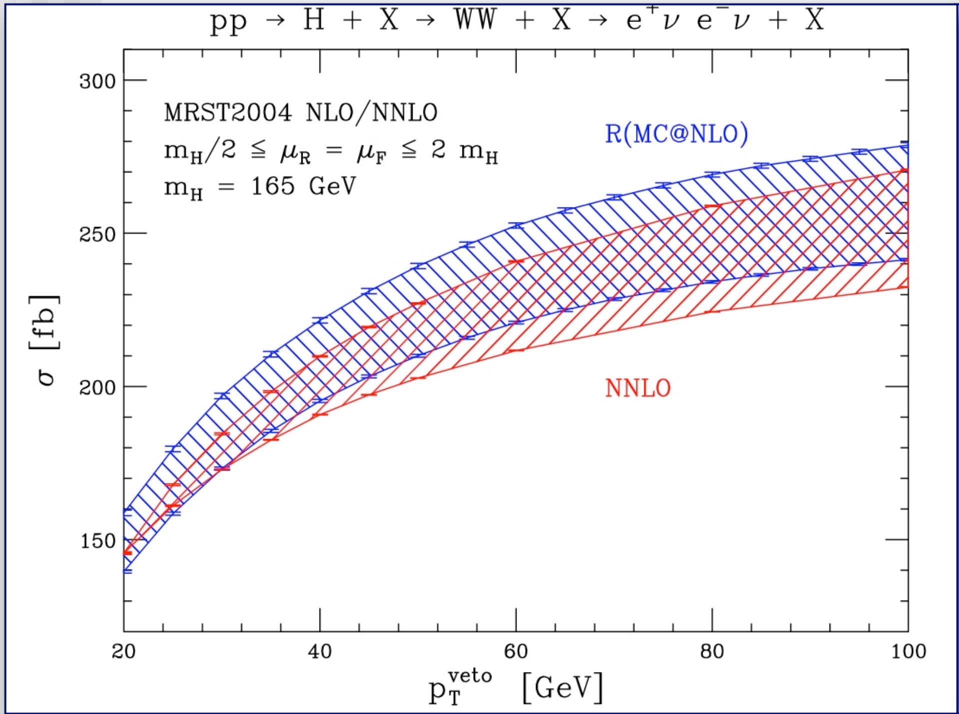
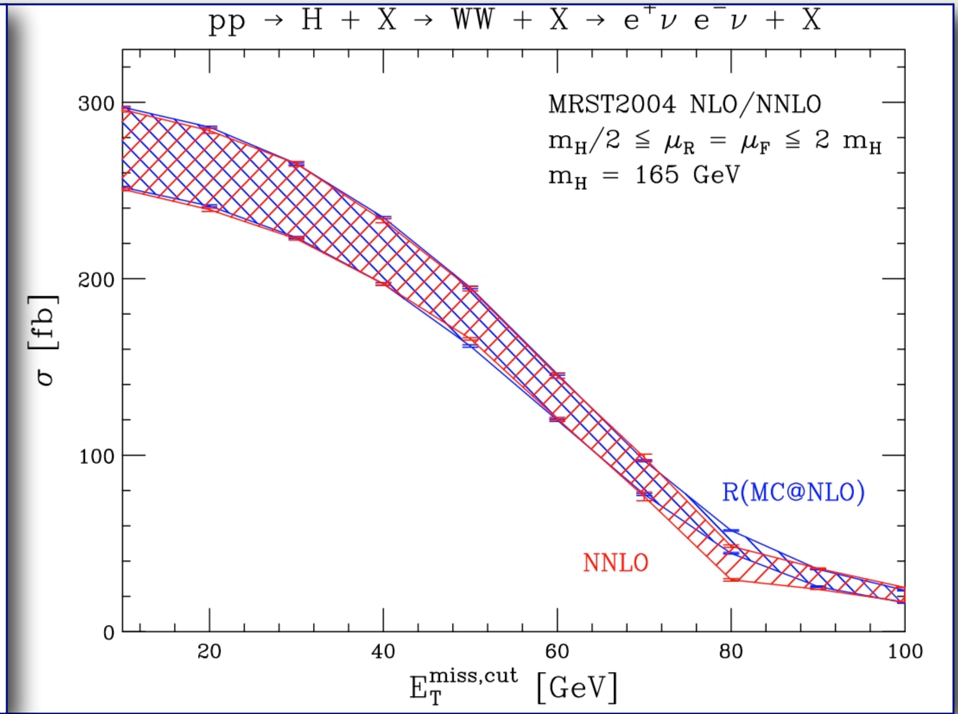
- inclusively rescaling MC@NLO, now after applying cuts:
  - Note : can not compare to NNLO+NNLL any more





- jet-veto:
  especially in the region where we are cutting very good agreement

- all other variables agree ‘perfectly’

Signal cross-section

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$\sigma_{\rm acc}$ [fb]	$\mu = \frac{m_{\rm H}}{2}$		$\mu = 2\, m_{\rm H}$	
jet algorithm	SISCone	$k_{\rm T}$	SISCone	$k_{\rm T}$
LO	21.00 ± 0.02		14.53 ± 0.01	
HERWIG	11.16 ± 0.04	11.59 ± 0.04	7.60 ± 0.03	7.89 ± 0.03
NLO	22.40 ± 0.06		19.52 ± 0.05	
MC@NLO	17.42 ± 0.08	18.42 ± 0.08	13.60 ± 0.06	14.39 ± 0.06
$R^{\rm NLO}$(HERWIG)	19.79 ± 0.07	20.56 ± 0.07	14.61 ± 0.05	15.17 ± 0.05
NNLO	18.84 ± 0.59	18.45 ± 0.54	18.76 ± 0.31	19.01 ± 0.27
$R^{\rm NNLO}$(MC@NLO)	19.33 ± 0.09	20.43 ± 0.09	17.24 ± 0.07	18.24 ± 0.07
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Hadronization & Underlying Event

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- we use a k_T algorithm with R=0.4 and **JIMMY** for the UE model

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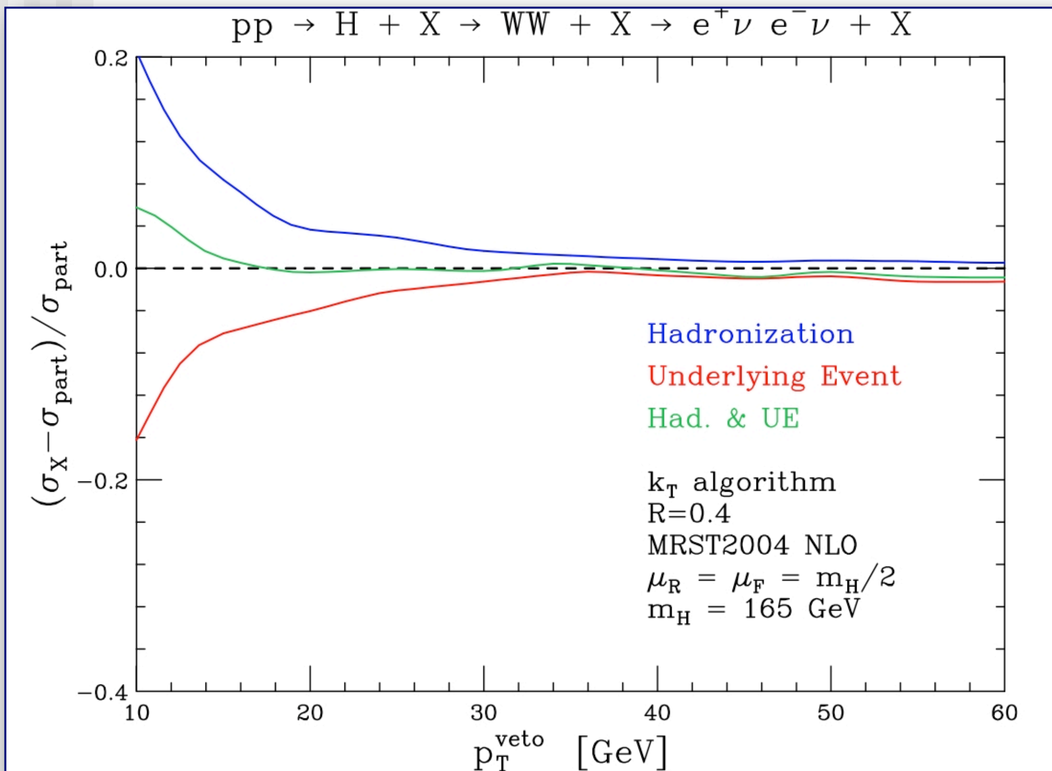

- for a given cone-size, there is a veto value where had. and UE effect cancel

⇒ for a give veto, there should be a cone-size to make the effects cancel each other!

Conclusions

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- a difficult, fully differential NNLO computation is available for the signal cross-section in the $H \rightarrow WW \rightarrow l\nu l\nu$ channel

- a unique validation opportunity for LO event generators, MC@NLO and NNLO for a process with large perturbative corrections and a largely reduced, 'tricky' final state phase-space

- very good agreement between MC@NLO and NNLO, while fixed-order NLO fails to predict the cross-section reliably

- robust theoretical prediction for the signal cross-section at the LHC (even with respect to had. and UE effects)

- working on the Tevatron numbers...