Focus topic MC needs: top threshold

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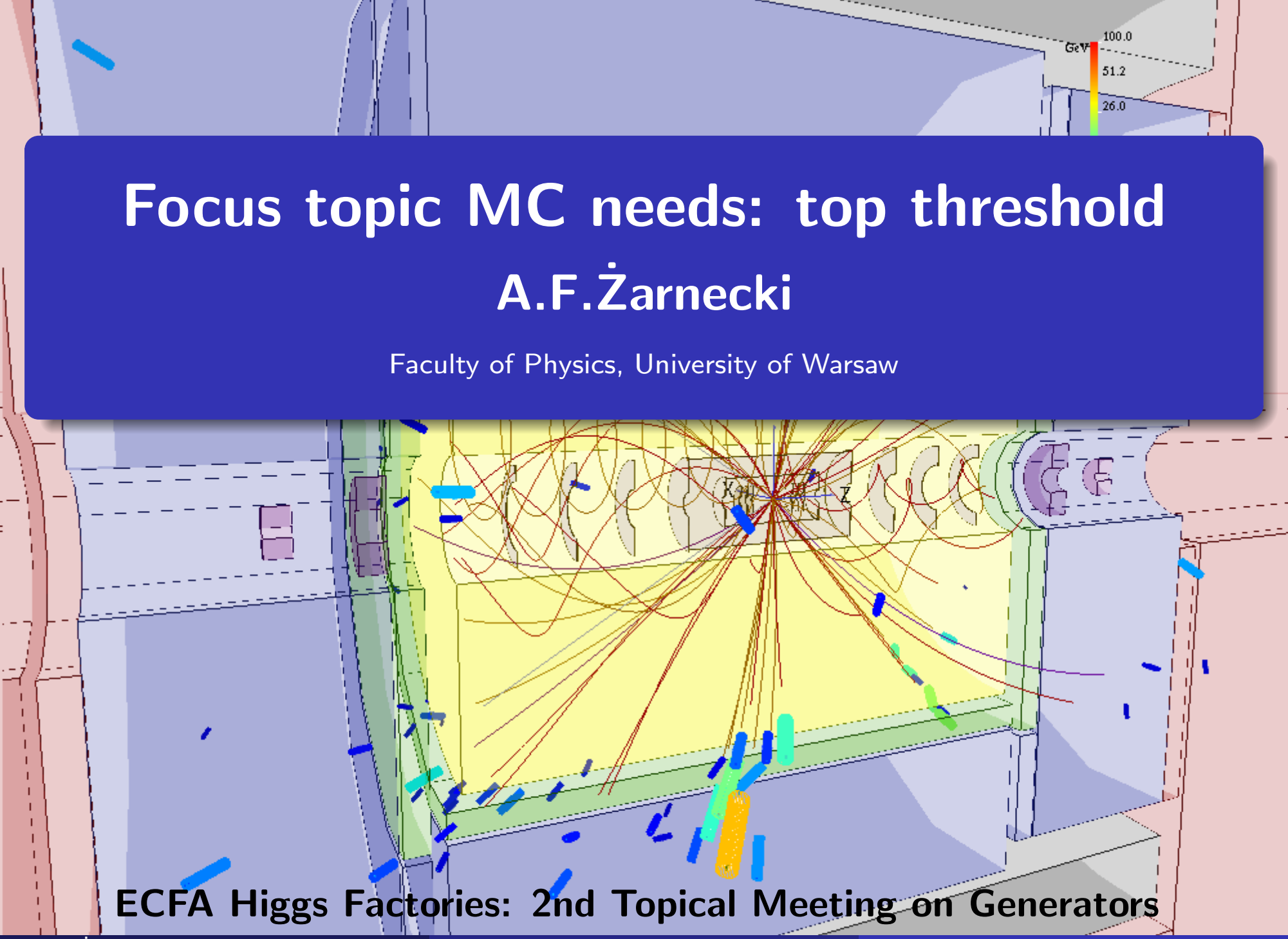


ECFA Higgs Factories: 2nd Topical Meeting on Generators

Top threshold MC needs

Outline

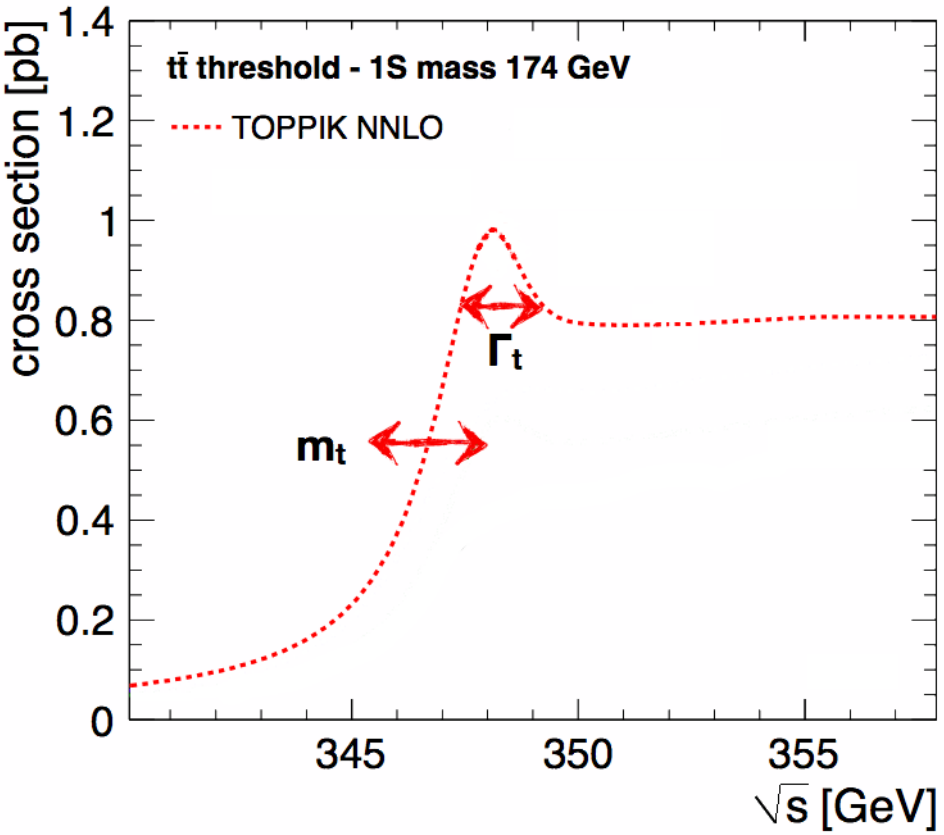
Based on personal experience from threshold scan analysis with WHIZARD completed already some time ago...

Motivation

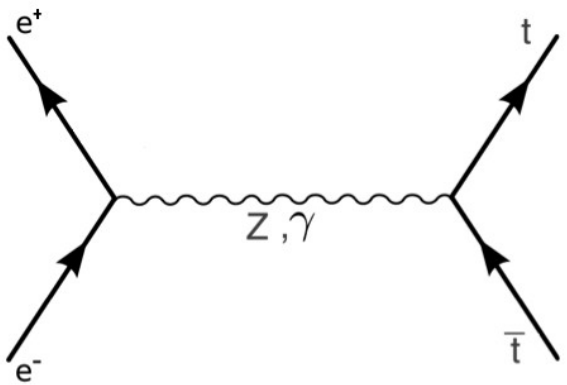
Top pair production cross section around threshold:

resonance-like structure corresponding to narrow $t\bar{t}$ bound state.

Very sensitive to top properties and model parameters:



- top quark mass m_t
- top quark width Γ_t



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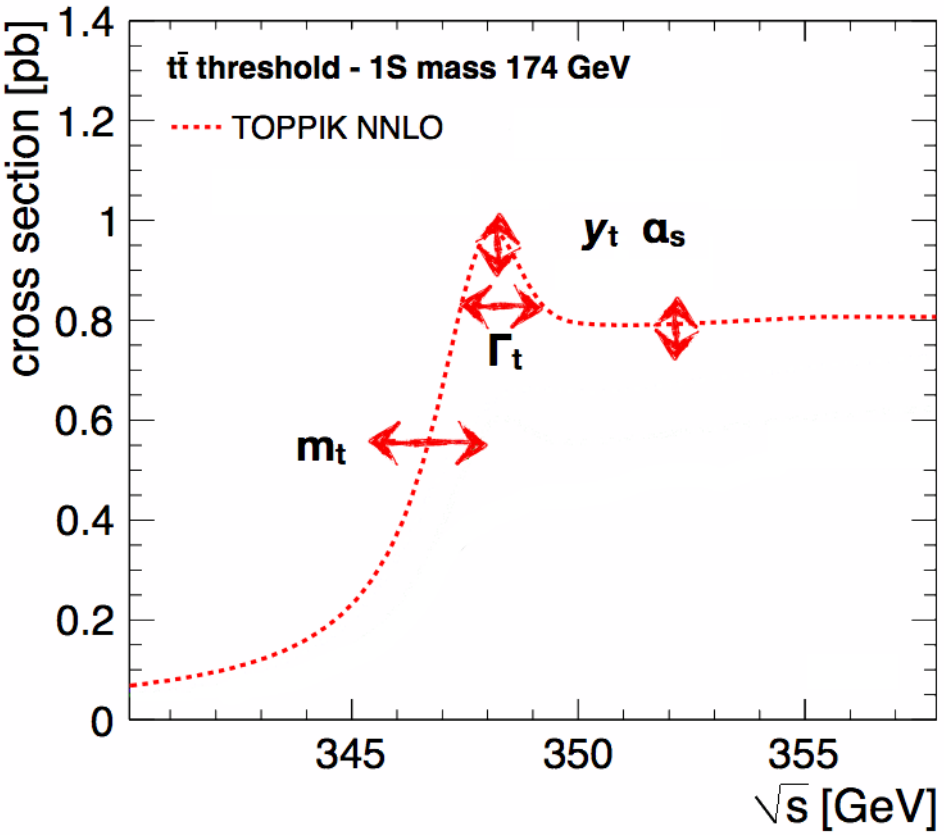
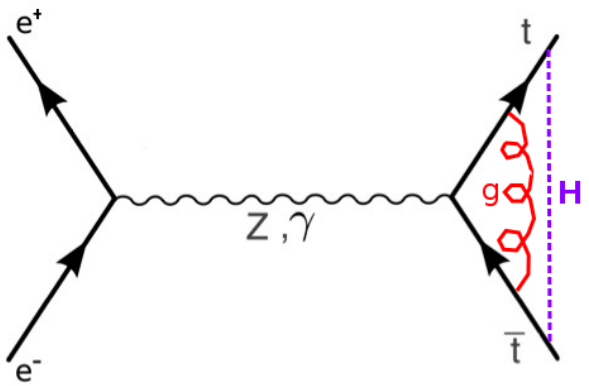


- top quark mass m_t
- top quark width Γ_t
- strong coupling α_s
- top Yukawa coupling y_t



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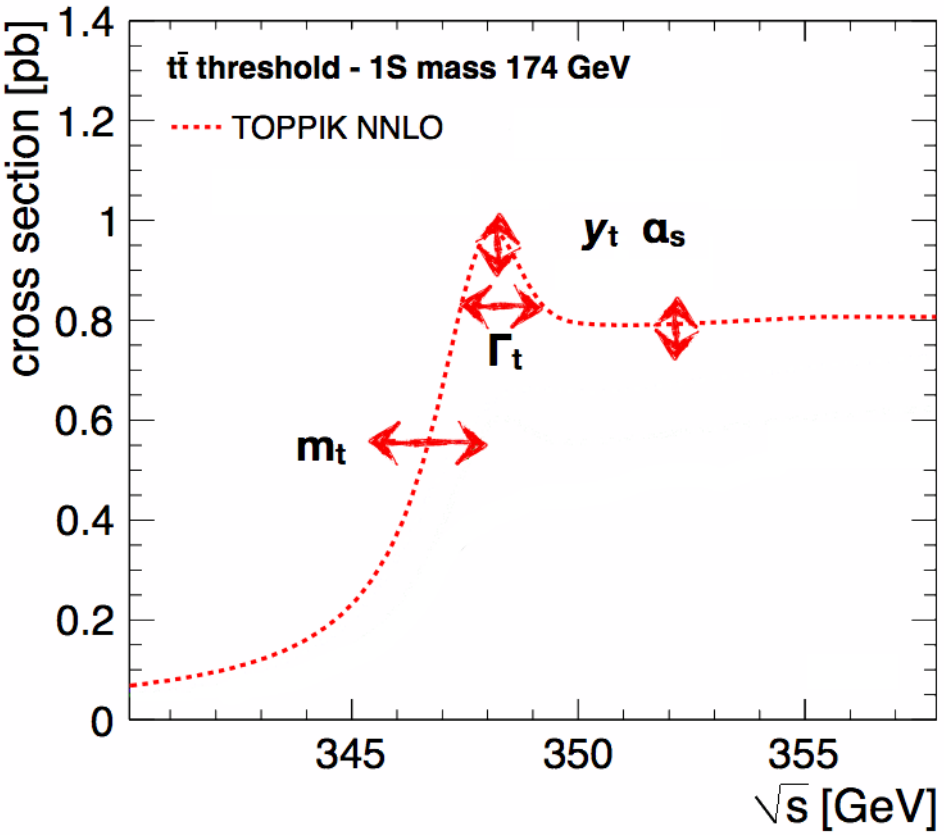
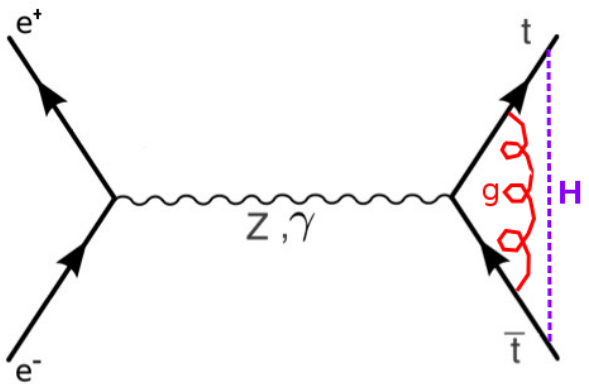


Fit to the threshold scan results:

- top quark mass m_t
- top quark width Γ_t
- strong coupling α_s
- top Yukawa coupling y_t



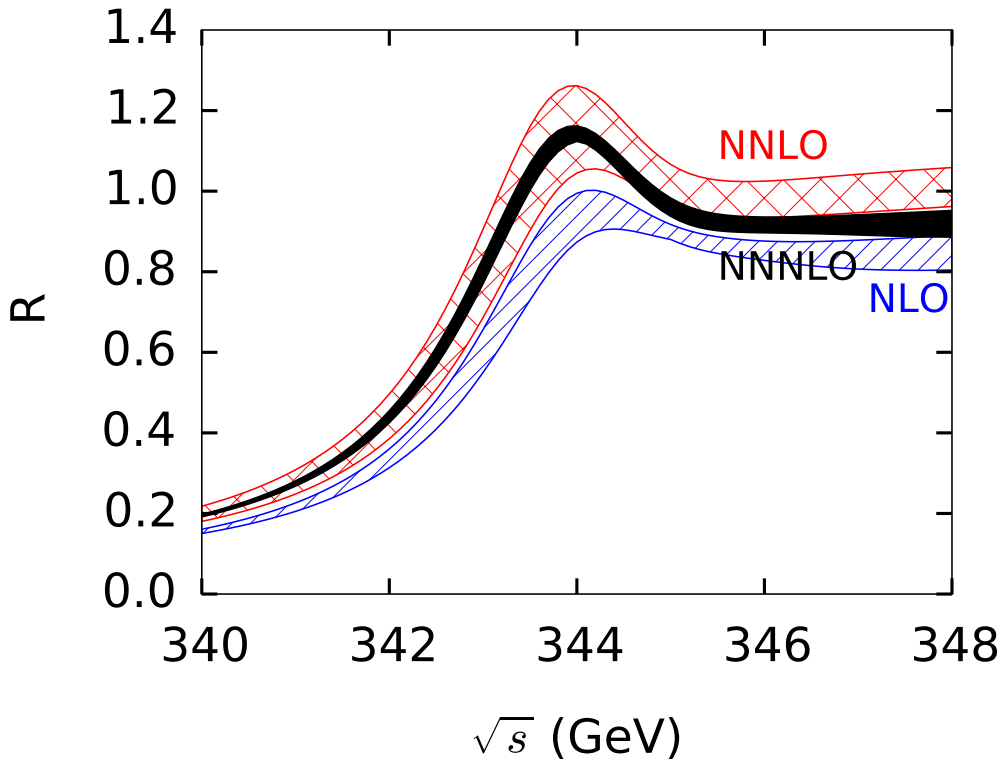
\+ signal and bg normalization systematic uncertainties

Theoretical calculations

Top quark mass measurement @ LHC dominated by systematics
Threshold study should allow for much higher precision, $\mathcal{O}$(10 MeV)

Total cross section calculations at NNNLO available

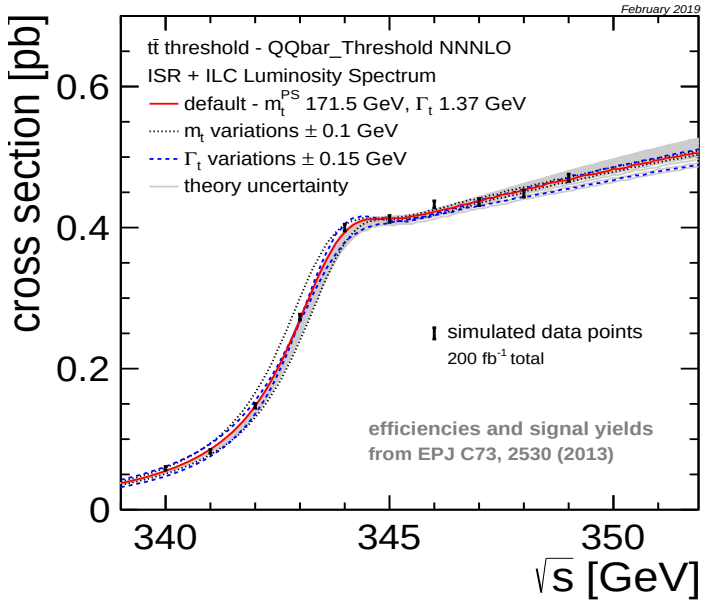
M.Beneke et al., Phys. Rev. Lett. 115, 192001 (2015)

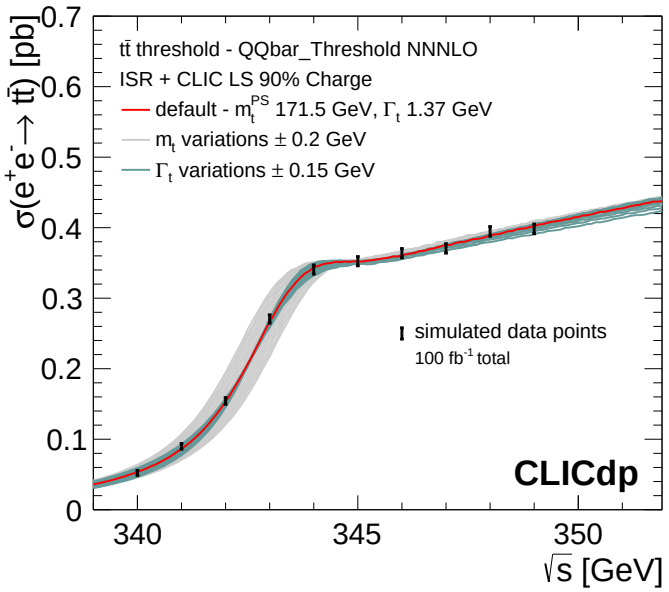


Threshold scan

Precision top mass measurement possible already with 100-200 fb^{-1}

Baseline scan scenario: 10 cross section measurements, 10-20 fb^{-1} each





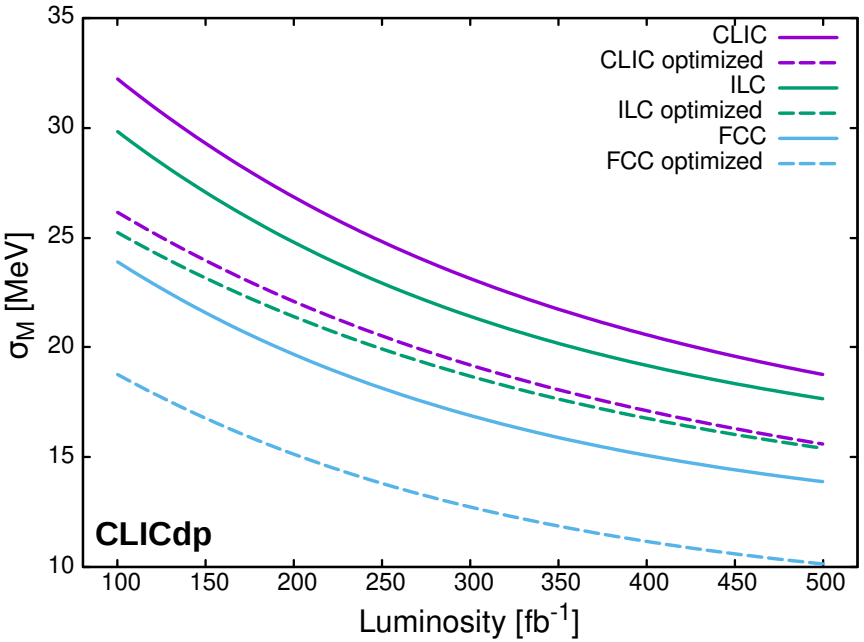
arXiv:1903.01629 arXiv:1807.02441

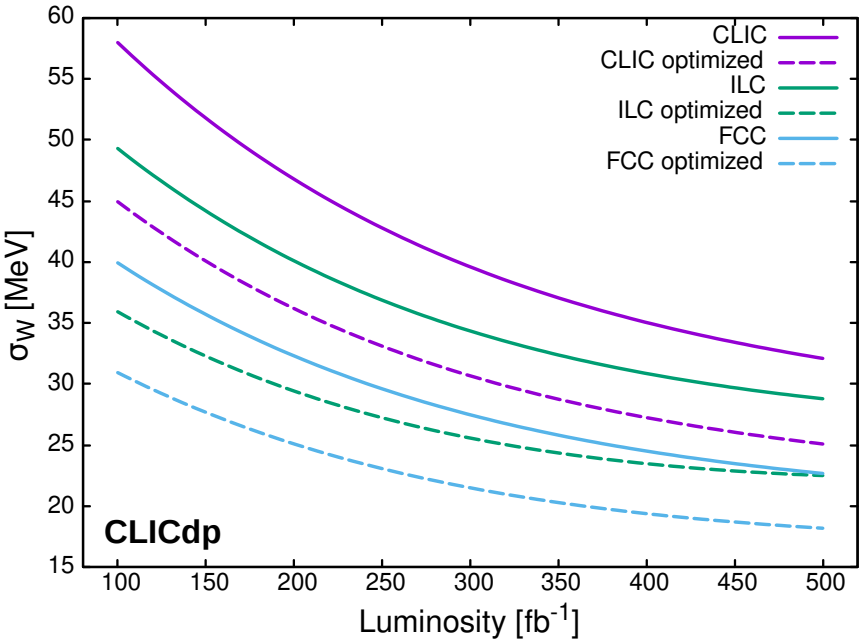
About 20 MeV statistical uncertainty on mass expected from the threshold cross section fit with top-quark mass and width as parameters...

Motivation

K.Nowak, A.F.Żarnecki

"Optimising top-quark threshold scan at CLIC using genetic algorithm"





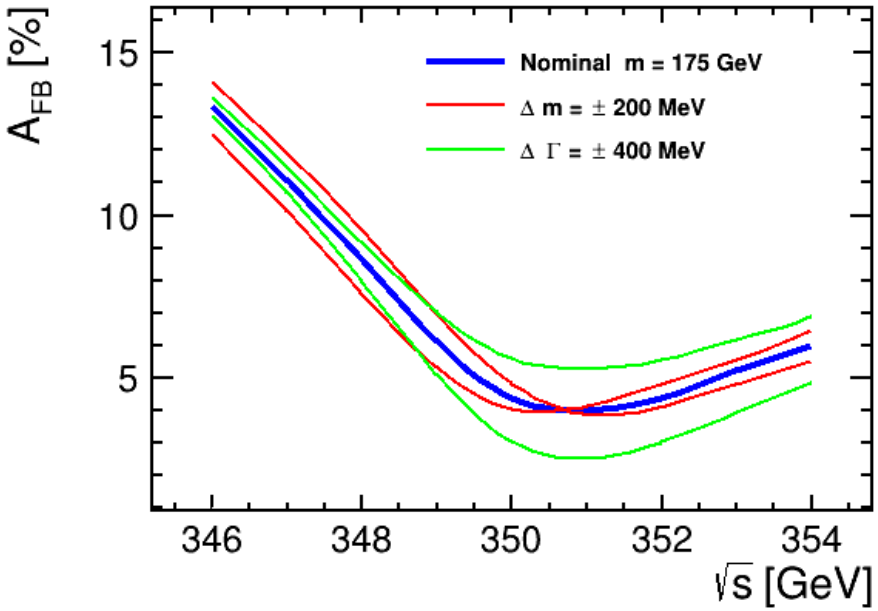
Published in: JHEP 07 (2021) 070, arXiv:2103.00522

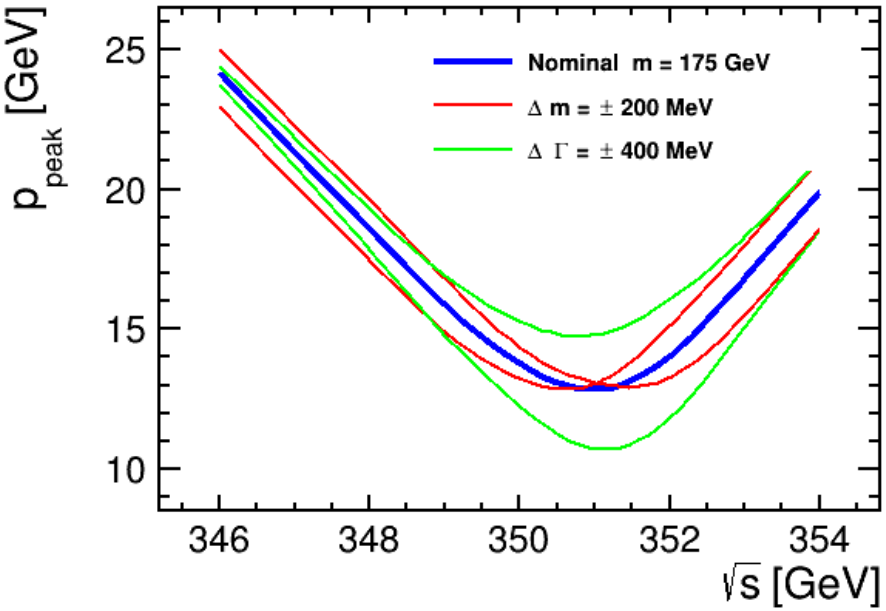
Top quark mass fit based on cross section measurements only,
beam polarisation not included...

This is clearly not the optimal approach...

Motivation

Top forward-backward asymmetry and top-quark momentum distribution are also sensitive to the top quark mass and could be included in the fit:





Adapted from: M. Martinez, R. Miquel, "Multiparameter fits to the t anti-t threshold observables at a future e^+ e^- linear collider", Eur. Phys. J. C 27, 49–55 (2003).

$\Rightarrow$ include differential cross sections in the mass extraction procedure...
Clear need for detailed event simulation at the threshold !

Impact of beam polarisation can also be important!

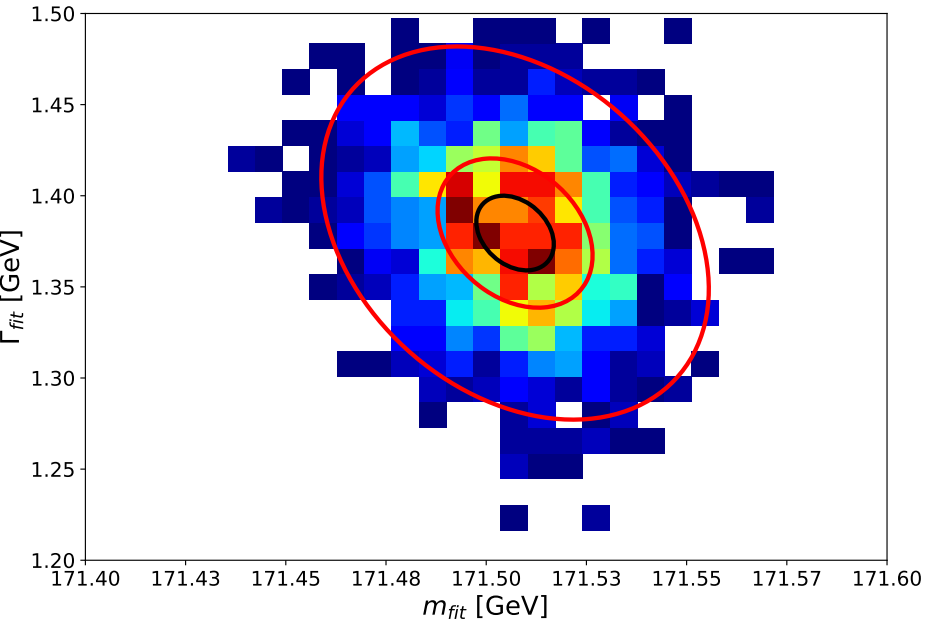
Motivation

Test results K.Nowak, MSc. thesis 2022 10×10 fb^{-1} in 1 GeV steps

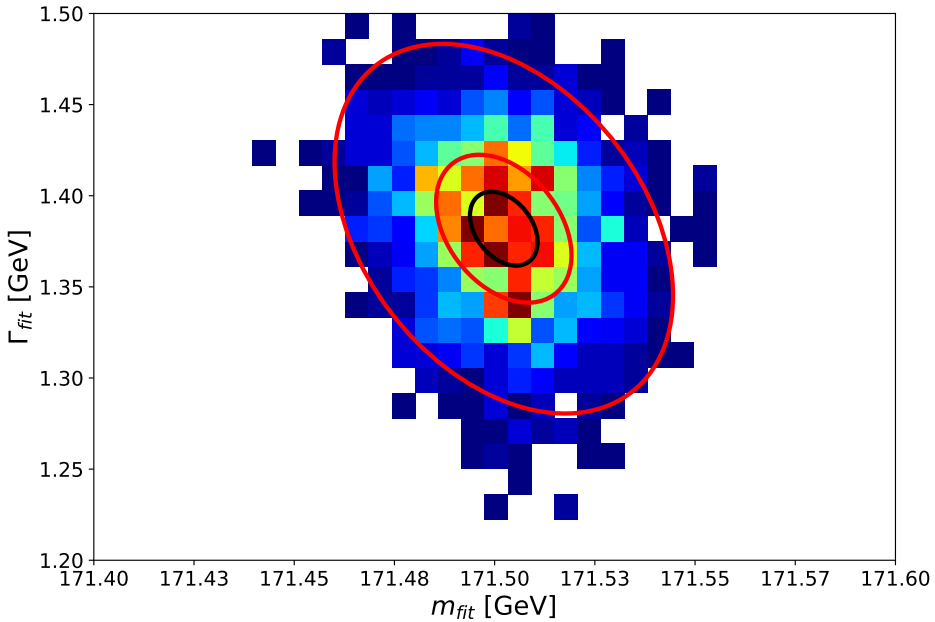
LO simulation scaled to NNNLO cross section, no polarisation!

Fitted top-quark mass and width values, from the most general (5D) fit.

To cross sections only:



To momentum distributions:

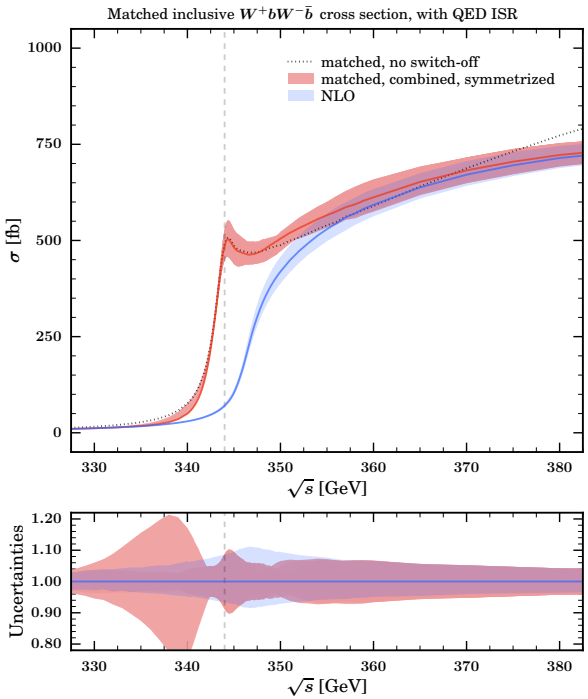


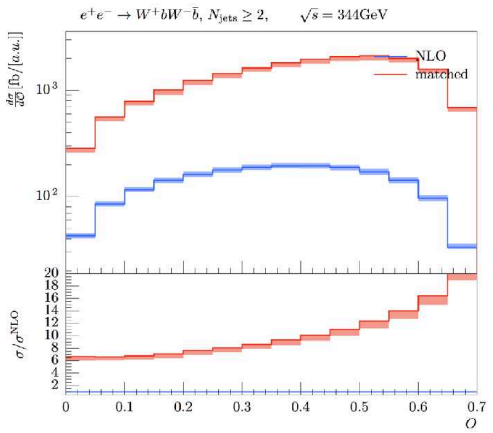
With reconstructed top-quark momentum distribution taken into account, mass precision improves by about 15%...

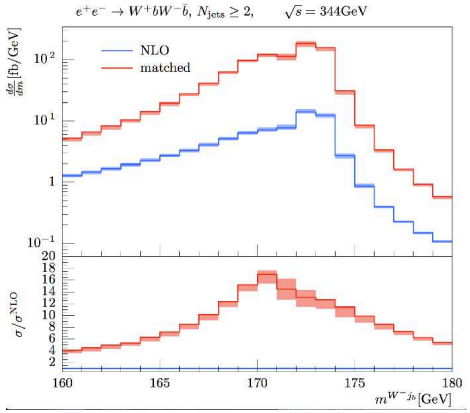
NLO QCD in WHIZARD

Available since some time, also for top threshold:

- Exclusive Top threshold NLL-NLO QCD matched available
- Implemented for v2.5.1, revalidated in v3.0 parallelized
- Recent improvement in axial form factor matching
- Started to work on this implementation again








```
model = SM_tt_threshold

nrqcd_order = 1
FF = 1    ! NLL resummed
mpole_fixed = 1
Vtb = 1
m1S = 172 GeV
scale = m1S

$method = "threshold"
process eett_threshold = E1, e1 => Wp, Wm, b, B {
  $restrictions = "3+5~t && 4+6~tbar" nlo_calculation = real }

sqrts = 350 GeV
integrate (eett_threshold)
```

Chokoufé/Hoang/Kilian/JRR/Stahlhofen/Teubner/Weiss, 1712.02220

NLO QCD in WHIZARD

NLO QCD corrections calculated in Whizard for arbitrary process
also for top pair production in the continuum...

However, top threshold simulation is a special case:

- resummed threshold effects implemented as effective vertex

(based on TOPPIK by M. Jezabek, T. Teubner; arXiv:hep-ph/9904468)

- dedicated matching from threshold NLL to continuum NLO

Six terms in the cross section calculation at the threshold:

- 3 NLO terms (born, real and virtual)
- 3 terms from "matched" NLL contribution (born, real and virtual)

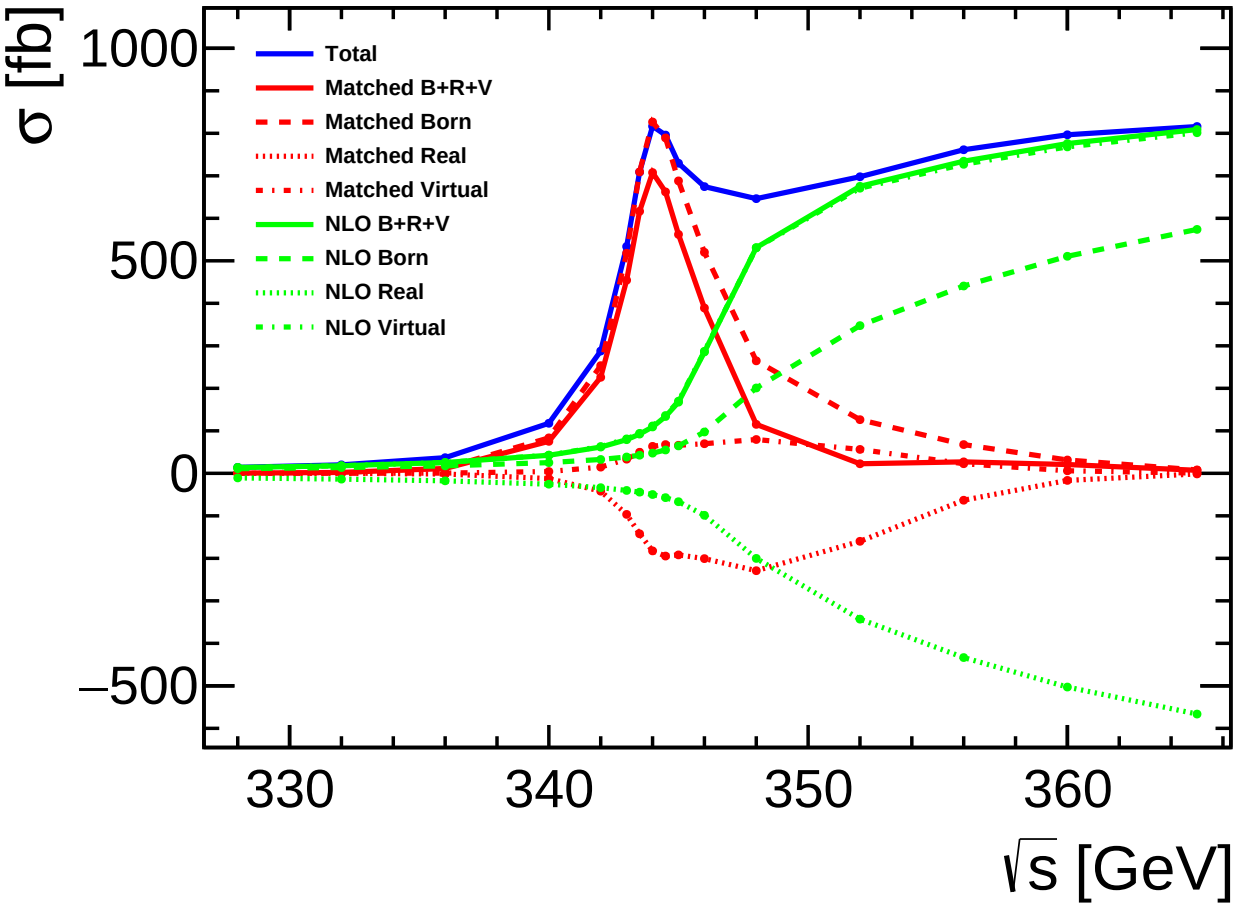
Results presented in the following based on Whizard 3.0.1 and 3.0.2

Event simulation

Cross section for:

$$e^+e^- \rightarrow W^+b\ W^-\bar{b}$$

no ISR, no beam spectra, no polarisation



NLO QCD in WHIZARD

Fixed-order NLO events can also be produced in three different modes:

- Separate weighted
  each of the six components integrated and generated separately
- Combined weighted
  two contributions calculated: full (born+real+virtual) matched NLL and full (born+real+virtual) NLO
- Combined unweighted
  as above, clearly preferred for event simulation and analysis
  but only possible when both contributions positive
  matching component can be negative when ISR included...

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  matching component can be negative when ISR included...

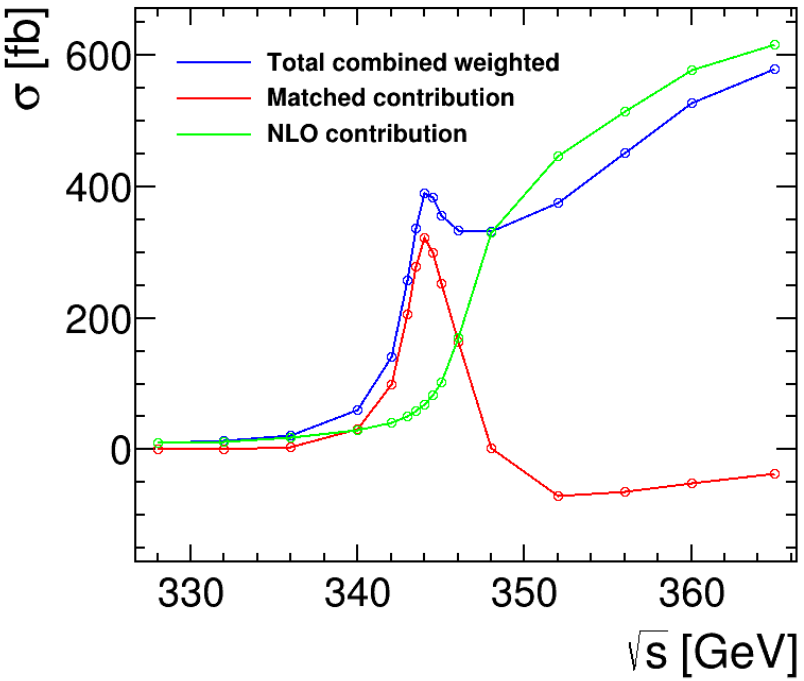
Detailed analysis with large statistics of MC events, based on **full detector simulation** $\Rightarrow$ only **unweighted events** are useful !

Beam spectra

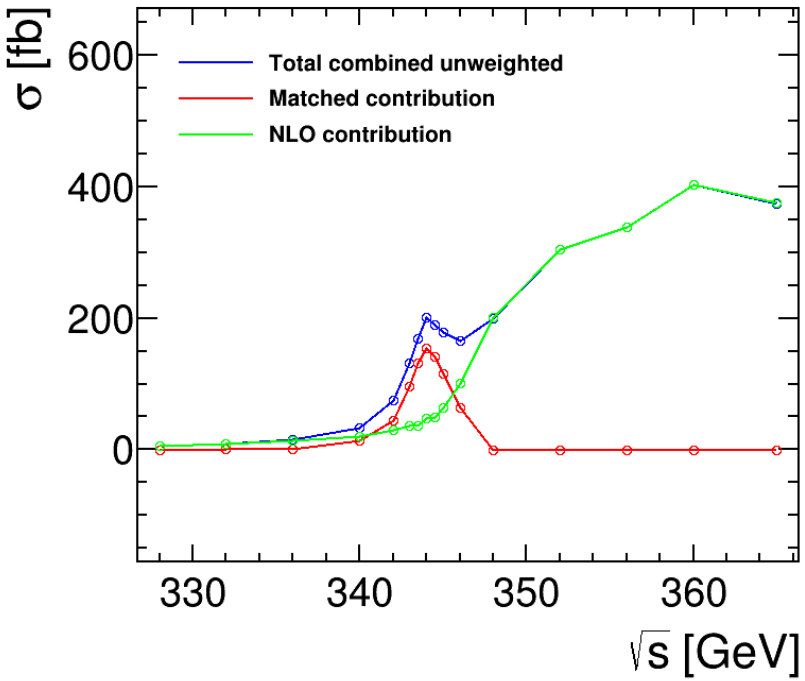
Threshold cross section as a function of collision energy:

$$e^+e^- \rightarrow W^+b\ W^-\bar{b}$$

no beam spectra



with beam spectra



No negative results with spectra?! Problem for matched contribution!

Cross section integration very unstable ! Very large spread of weights !

Whizard problems

Event unweighting not specific to top threshold simulation!

Weighted events can be efficiently used for cross section calculation.

However, this is very inefficient (time consuming) for studies based on any detector simulation (even the fast one)!
When beam spectra is taken into account this is almost impossible
(100 000 generated events equivalent to one unweighted event)

Even without beam spectra, up to a factor of 200 increase in statistics of generated events is needed (compared to unweighted generation)...

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Unweighted events can not be generated "out of the box",
as matched contribution becomes negative above the threshold...

Possible fix: reintegrate the process with changed cross section sign

```
integrate (matched_nlodecay_Full){ weight = -1. }
```

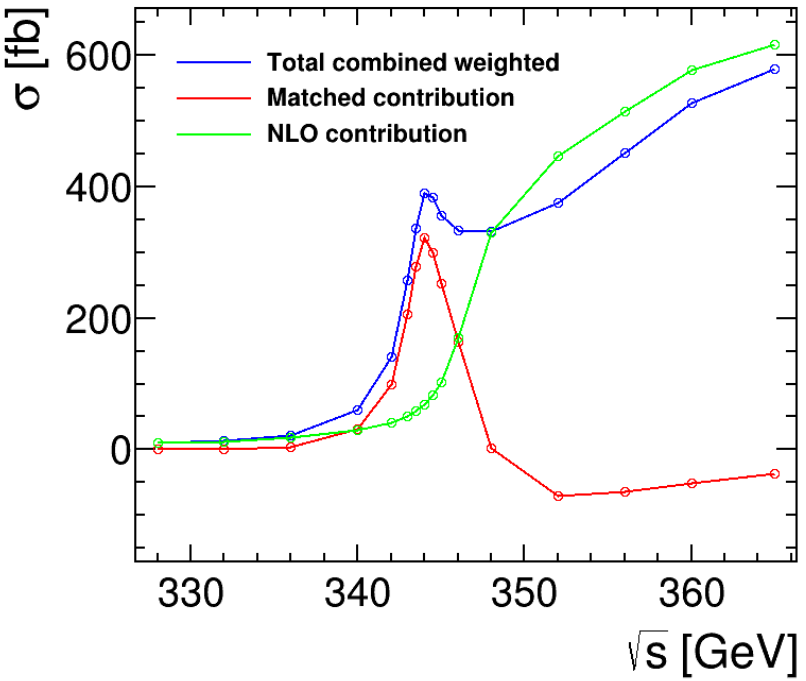
when the initial integration result is negative...

Whizard problems

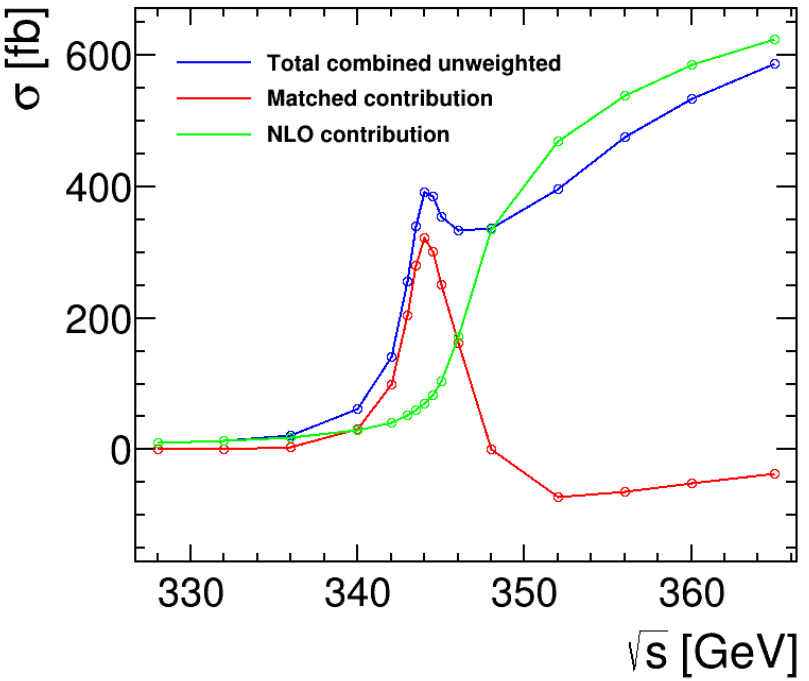
Threshold cross section as a function of collision energy:

$$e^+e^- \rightarrow W^+b\ W^-\bar{b}$$

weighted



unweighted



Consistent cross section results

Still, this fix is only a temporary/partial solution, rather for tests...

Events with negative weight problematic when MC statistics is limited...

Whizard problems

Beam polarisation

Beam polarisation can be set for the NLO contributions.

Some problems with normalization - to be clarified...

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However, integration of "matched" contribution always results in zero!

when beam polarization is set to non-zero values

Technical problem? Clearly needs to be sorted out !...

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when beam polarization is set to non-zero values

Technical problem? Clearly needs to be sorted out !...

No recent progress, as Whizard is suffering from a severe person-power problem...

If interested, you are welcome to join and help solving these problems!

Conclusions

Focus topic MC needs: top threshold

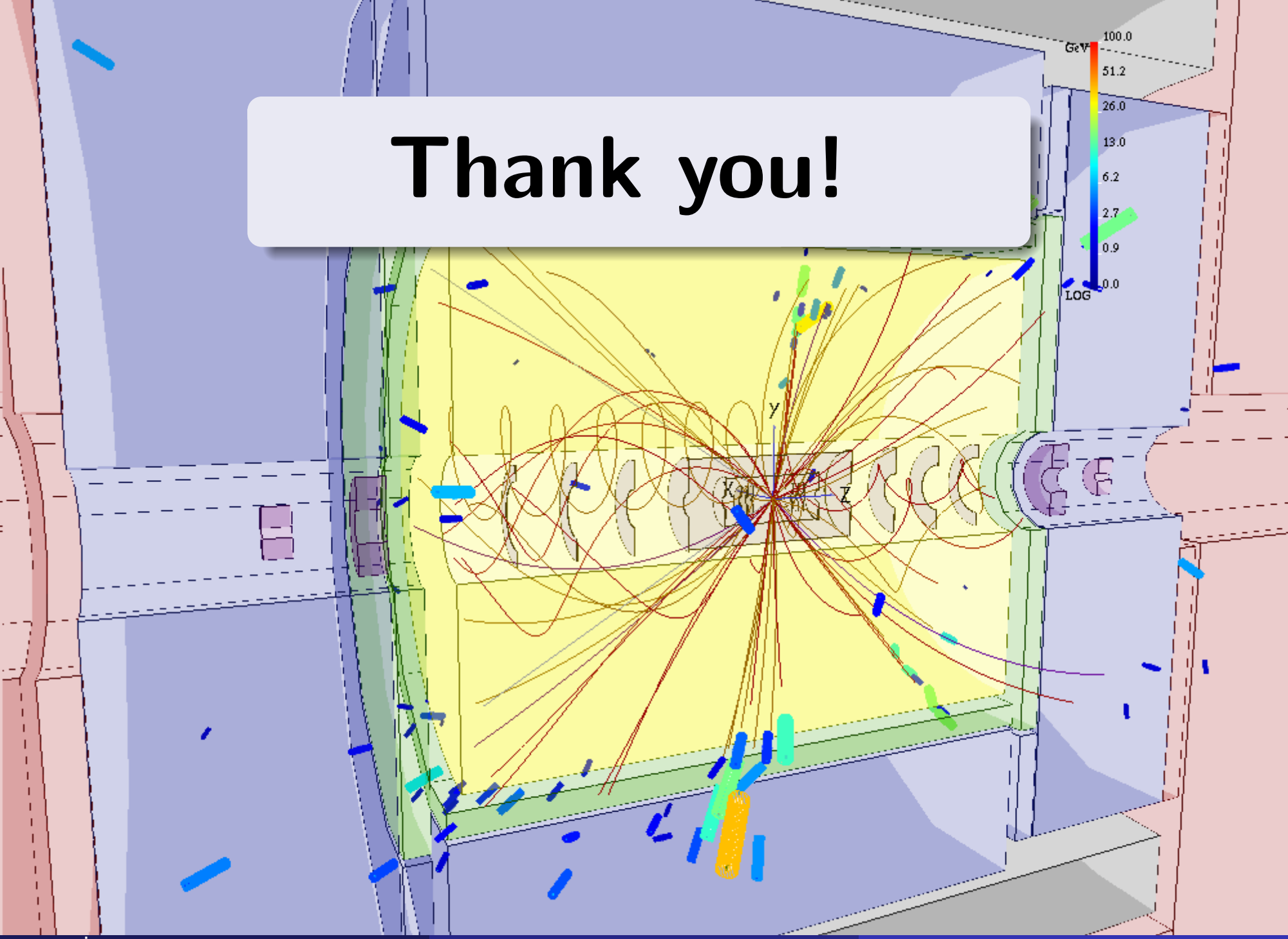
More information and with higher precision can be extracted from the top pair-production differential cross sections at the threshold.

To study measurement prospects proper simulation of differential distributions, with all threshold effects taken into account, is required.

Still a lot of work to get NLO simulation in Whizard fully operational!

Main problems related to:

- event unweighting (generic NLO)
- beam spectra
- polarisation



Thank you!

Top Production & Decay: Theory References

On-Shell process: $e^+e^- \to t\bar{t}$

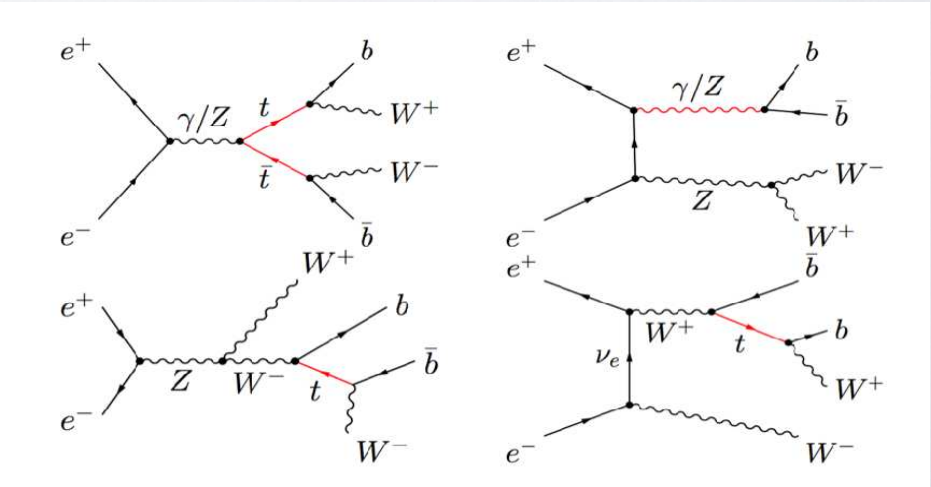
- NLO QCD [Jersak/Laermann/Zerwas, 1982]
- NNLO QCD [Chetyrkin/Kühn/Steinhauser, 1996; Harlander/Steinhauser, 1998; Chen/Dekkers/Heisler/Bernreuther/Si, 2016]
- NLO EW [Beenakker/von der Marck/Hollik, 1991; Beenakker/Denner/Kraft, 1993; Akhundov/Bardin/Leike, 1991]
- Threshold enhancement [Fadin/Khoze, 1987; Strassler/Peskin, 1991; Jezabek/Kühn/Teubner, 1992; Sumino et al., 1992]

Off-Shell process: $e^+e^- \to W^+\bar{b}W^-b$

- NLO QCD [Guo/Ma/Wang/Zhang, 2008] ✘
- NLO QCD diff. [Chokoufe/JRR/Weiss, 2015; Liebler/Moortgat-Pick/Papanasthasiou, 2015; Chokoufe/Kilian/Lindert/JRR/Pozzorini/Weiss, 2016]

Top width: $t \to W^+b$

- NLO QCD [Jezabek/Kühn, 1989]
- NNLO QCD [Guo/Li/Zhu, 2012]

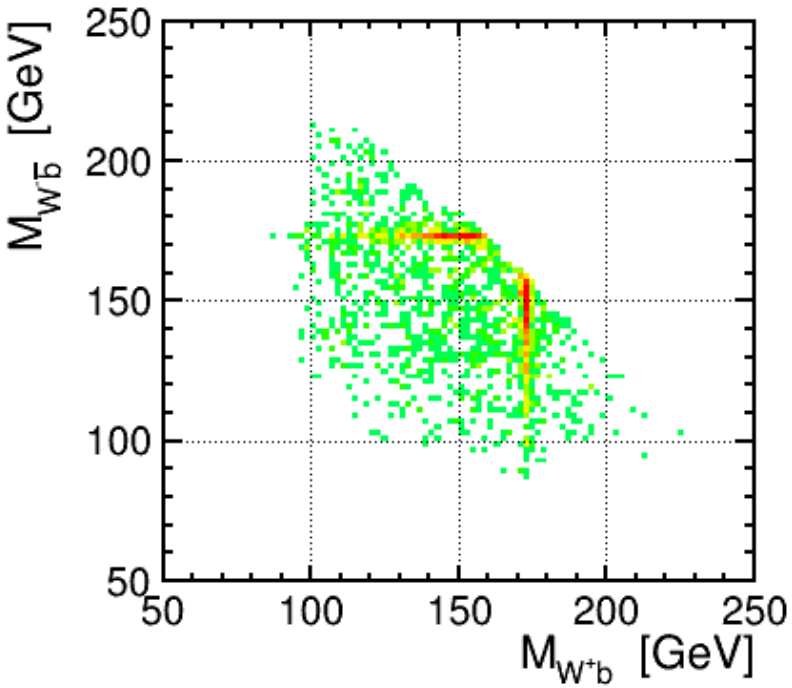


Problem with energy-momentum conservation to be checked

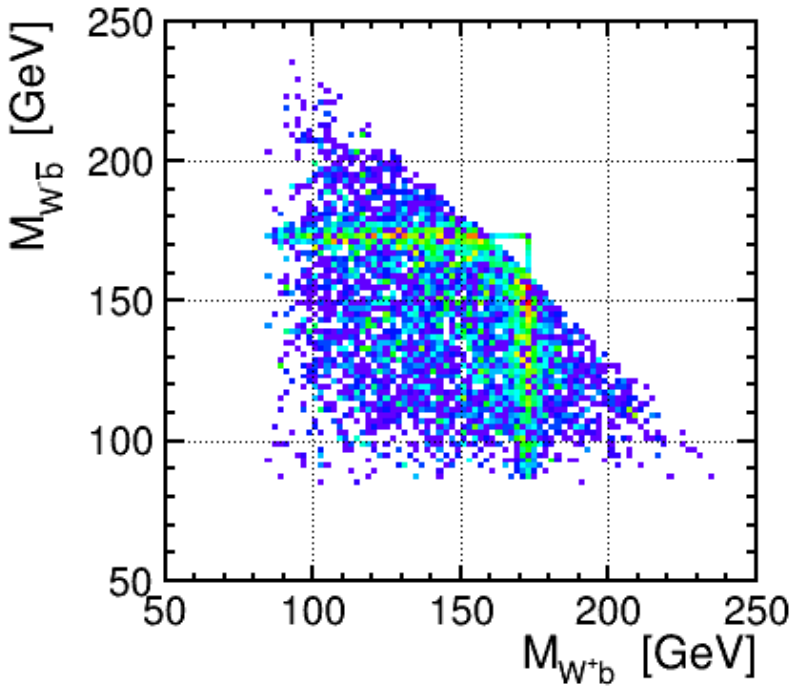
Correlation between masses of two top candidates for:

$$e^+e^- \rightarrow W^+b\ W^-\bar{b}$$

no ISR



with ISR $\sqrt{s} = 332\,\text{GeV}$



Clear problem with energy-momentum conservation when ISR included !?!

But not observed when POWHEG matching switched on ?!...