Automated NLO QCD Corrections in WHIZARD

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WHIZARD : Some facts

- Multi-purpose event generator for lepton and hadron colliders
- Current release version: WHIZARD 2.2.7 (August 8th, 2015)
- Download: http://whizard.hepforge.org E-Mail: whizard@desy.de
- WHIZARD Team: Wolfgang Kilian, Thorsten Ohl, Jürgen Reuter
  Simon Braß, Bijan Chokoufé, Marco Sekulla, So Young Shim, CW, Zhiejie Zhang

2nd International WHIZARD Forum, Würzburg, March 2015

Structure of WHIZARD

WHIZARD has a modular structure

Modules from the WHIZARD group:

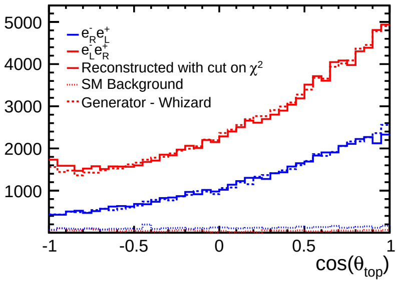
- O'Mega: Matrix element generator via directed acyclical graphs [Ohl,2000]
- VAMP: Adaptive multi-channel Monte-Carlo integrator [Ohl,1999]
- CIRCE 1/2: Lepton Collider Beam Spectra [Ohl,1997]

External packages which can be linked to WHIZARD include:
FastJet, HepMC, Pythia6(8), LCIO, GoSam, OpenLoops, GuineaPig, LHAPDF4/5/6,...

Creating Simulations with SINDARIN

ExampleBeamPol.sin

```
 beams = e1, E1
process eett = e1, E1 => t, T

#e_L e_R - polarization
beams_pol_density = @(-1), @(+1)
beams_pol_fraction = 1.0, 1.0
integrate (eett)
{iterations = 5:10000:‘‘gw’’ }
simulate (eett) {n_events = 10000}

#e_R e_L - polarization
beams_pol_density = @(+1), @(-1)
beams_pol_fraction = 1.0, 1.0
integrate (eett)
{iterations = 5:10000:‘‘gw’’}
simulate (eett) {n_events = 10000}
```



[Amjad et.al., 1307.8102]

WHIZARD has native support for polarized lepton beams.
Upcoming release 2.2.8: Also at NLO.

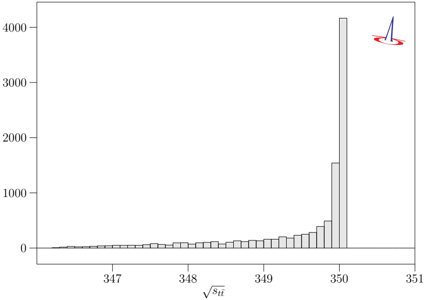
Lepton beam spectra using CIRCE

TestCirce.sin

```
 # Creates a histogram of the
# invariant top pair mass with
# ISR effects.

sqrts = 350 GeV
beams = e1, E1 => circe1
process ttbar = e1, E1 => t, T

circe1_sqrts = 500 GeV
circe1_ver = 10
$circe1_acc = ‘‘ILC’’

histogram ilc500 (346, 351, 0.1)
simulate (ttbar) {
$sample = ‘‘ilc500’’
analysis = record ilc500
(eval M / 1 GeV [combine[t,T]])
}
```

2 ILC 350 w/ILC 500 beam spectra

$e^+e^- \to t\bar{t}$ w/beamstrahlung from CIRCE1



Data within bounds:
$\langle\text{Observable}\rangle = 349.503 \pm 0.0082$ $[n_{\text{entries}} = 10000]$

All data:
$\langle\text{Observable}\rangle = 349.503 \pm 0.0082$ $[n_{\text{entries}} = 10000]$

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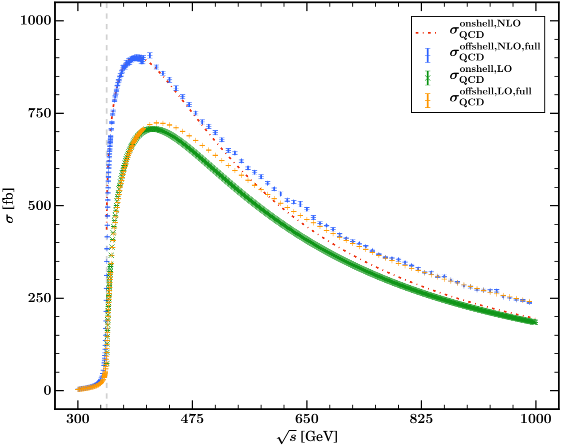
[CW, Chokoufe, Kilian, Reuter: 1510.02666]

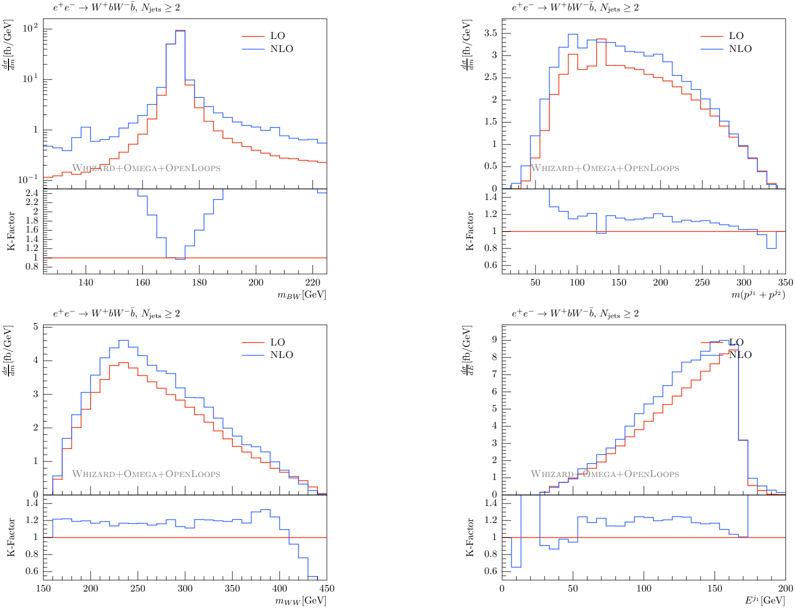
WHIZARD + NLO:

- Automated NLO framework for QCD corrections in lepton collisions.
- Uses FKS subtraction.
- No user contributions required.

$e^-e^+ \to t\bar{t}$ and $e^-e^+ \to W^+W^-b\bar{b}$:



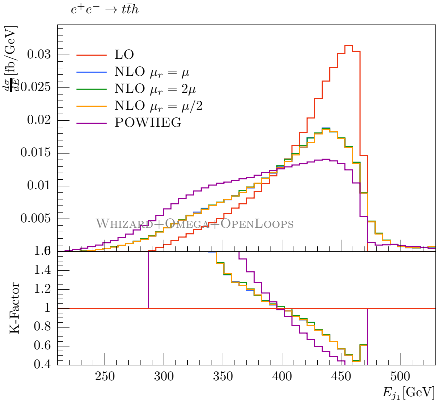
Review - EPS 2015: Top decay and background

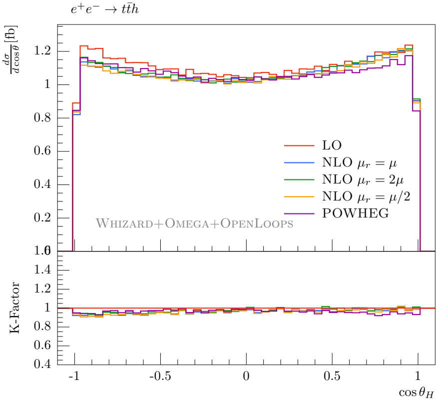


$$\sqrt{s} = 500\text{GeV},\ \Gamma_t^{LO} = 1.538\text{GeV},\ \Gamma_t^{NLO} = 1.408\text{GeV}$$

Interfacing NLO events to a parton shower requires matching procedures to separate emissions from the matrix element generator from those done by the parton shower.

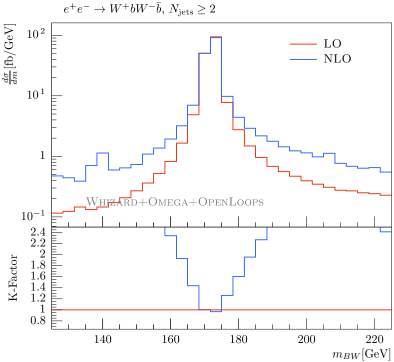
`WHIZARD` $\rightarrow$ Powheg Matching

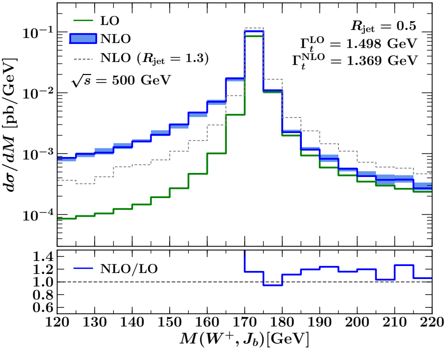




[Chokoufe, Kilian, Reuter, CW: 1510.02739]

Recently, [Liebler, Moortgat-Pick, Papanastasiou: 1511.02350] performed a similar analysis.





In our analysis, $R_{jet} = 1.0$. `WHIZARD` and `Madgraph` are consistent!

The BLHA interface

- Standardized protocol for One-Loop Providers (OLP)
- `WHIZARD` generates protocol, OLP generates code
- OLP reads contract, NLO matrix element library loaded into `WHIZARD` .
- Working BLHA interfaces to:
  - `GoSam` [G.Cullen et.al.]
  - `OpenLoops` [F.Cascioli et.al.]

eett_NLO_LOOP.olp

```
 # BLHA order written by WHIZARD
2.2.7

# BLHA interface mode:  OpenLoops
# process:  eett_NLO_LOOP
# model:  SM
InterfaceVersion BLHA2
CorrectionType QCD
Extra AnswerFile eett_NLO_LOOP.olc
IRregularisation CDR
CouplingPower QCD 0
CouplingPower QED 2
extra use_cms 0

# Process definitions



AmplitudeType Loop
-11 11 -> 6 -6

AmplitudeType ccTree
-11 11 -> 6 -6
```

Using SINDARIN for NLO processes

eett_nlo.sin

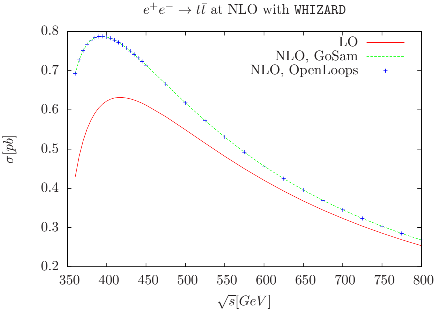
```
 ...
# Choose the external one-loop
program
$loop_me_method = ''openloops''

# LO coupling powers
alpha_power = 2
alphas_power = 0

process nlo_tt = E1, e1 => t, T
{nlo_calculation = ''Full''}

# Tuning parameters for FKS mapping
fks_dij_exp1 = 1.0
fks_mapping_type = 1

integrate (nlo_tt) {iterations =
5:10000:''gw''}
...
```



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Beam polarizations at a linear collider

A distinct feature of linear colliders is the ability to operate with polarized electrons and positrons simultaneously.
Possible applications are:

- Determination of top properties, especially CP-violating or FCN couplings.
- Separation of production processes and background supression:

Configuration (P_{e^-}, P_{e^+})	Scaling factors $e^+e^- \to H\nu\bar{\nu}$	Scaling factors $e^+e^- \to HZ$
(80%, 0%)	0.23	0.83
(-80%, 0%)	1.788	1.17
(80%, -30%)	0.18	1.006
(-80%, 30%)	2.31	1.47

- Precision electroweak measurements, e.g. gauge boson couplings.

Polarized NLO top production in WHIZARD

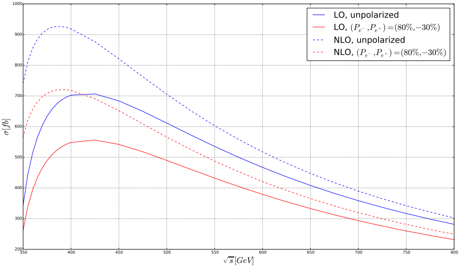
- Private `OpenLoops`-libraries for polarized initial-states in loop amplitudes.
- Modified BLHA entry for each helicity configuration

eett_polsel.olp

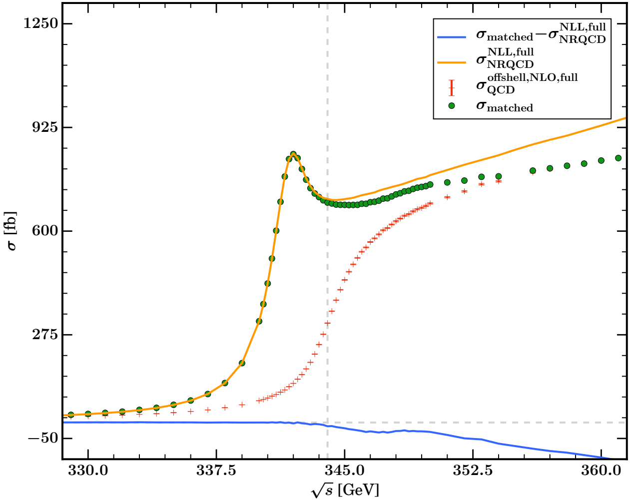
```
...

# Process definitions

AmplitudeType Loop
-11(1) 11(1) -> 6 -6
-11(1) 11(-1) -> 6 -6
-11(-1) 11(1) -> 6 -6
-11(-1) 11(-1) -> 6 -6
```

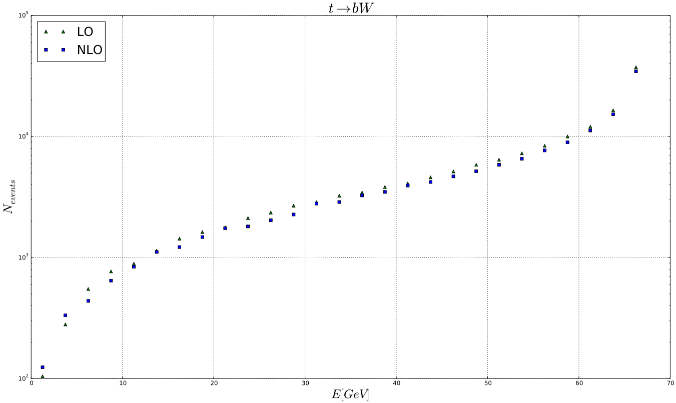


NLL Threshold Matching



At the threshold, non-relativistic top quarks yield large logarithms $\rightarrow$ resummation.
See Bijan Chokoufé's talk on Wednesday.

Top decay at NLO



- $\Gamma^{\mathrm{LO}}_{\mathrm{WHIZARD}} = 1.542\,\mathrm{GeV} \quad \Gamma^{\mathrm{NLO}}_{\mathrm{WHIZARD}} = 1.407\,\mathrm{GeV}$
- Developed in the course of NLL Threshold Matching
- Next step: Factorized production & decay at NLO

Ongoing Projects and Plans

Present & Near Future:

- Non-relativistic top threshold resummation matching
- Powheg matching

Medium time scale:

- Factorized production + decay at NLO
- Automated photon corrections to polarized beams
- Automated QCD NLO corrections for hadron collisions

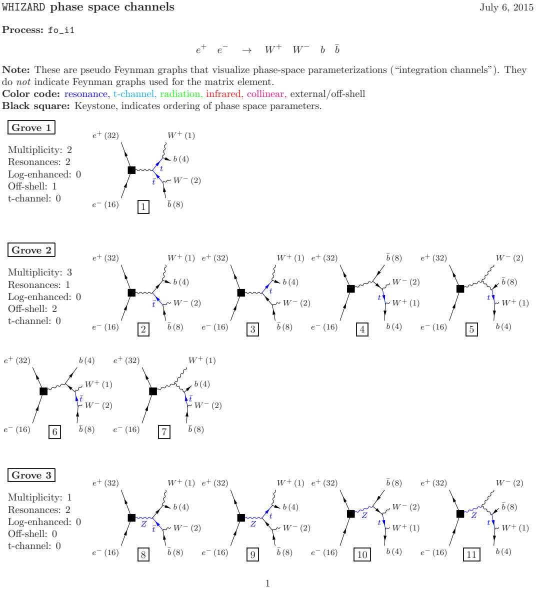
Long time scale:

- Automated QED/electroweak NLO implementation
- MC@NLO or Nagy-Soper matching

Backup Slides

Phase space channels

- The phase space is partitioned into channels, each of them having one distinct mapping $\rightarrow$ Optimized sampling of grids.
- Mappings include `resonant`, `t-channel`, `radiation`, `infrared`, `collinear`, `off-shell`.
- Alternative: Factorization into process and decay.



WHIZARD **phase space channels** July 6, 2015

Process: fo_i1

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

Note: These are pseudo Feynman graphs that visualize phase-space parameterizations ("integration channels"). They do *not* indicate Feynman graphs used for the matrix element.
Color code: resonance, t-channel, radiation, infrared, collinear, external/off-shell
Black square: Keystone, indicates ordering of phase space parameters.

Grove 1

Multiplicity: 2
Resonances: 2
Log-enhanced: 0
Off-shell: 1
t-channel: 0

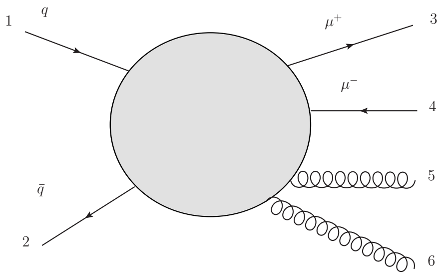
Grove 2

Multiplicity: 3
Resonances: 1
Log-enhanced: 0
Off-shell: 2
t-channel: 0

Grove 3

Multiplicity: 1
Resonances: 2
Log-enhanced: 0
Off-shell: 0
t-channel: 0

1



i) Find all tuples of particle indices which can give rise to a singularity, e.g.

$$\mathcal{I} = \{(1,5),(1,6),(2,5),(2,6),(5,6)\}$$

ii) Partition the phase space:

$$1 = \sum_{\alpha\in\mathcal{I}} S_\alpha(\Phi),$$

such that the real matrix element $\mathcal{R}$

$$\mathcal{R} = \sum_{\alpha\in\mathcal{I}} \mathcal{R}_\alpha, \qquad \underbrace{\mathcal{R}_\alpha}_{\text{Singular only for one tuple!}} = \mathcal{R} S_\alpha$$

iii) Add subtraction terms for each singular region.

Constructing Subtraction Terms

Real subtraction: Factorization in the soft and collinear limit

$$|\mathcal{A}^{(n+1)}(\Phi_{n+1})|^2 \to \mathcal{D}_{\mathcal{I}} \otimes |\mathcal{A}^{(n)}(\Phi_n)|^2$$

$\otimes$: Convolution over spin and color.

Soft subtraction involves color-correlated matrix elements:

$$\mathcal{B}_{kl} \sim -\sum_{\substack{\text{color}\\\text{spin}}} \mathcal{A}^{(n)} \vec{\mathcal{Q}}(\mathcal{I}_k) \cdot \vec{\mathcal{Q}}(\mathcal{I}_l) \mathcal{A}^{(n)*},$$

with

$$\vec{\mathcal{Q}}(\mathcal{I}) = \{t^a\}_{a=1}^{8}, \{-t^{aT}\}_{a=1}^{8}, \{T^a\}_{a=1}^{8}$$

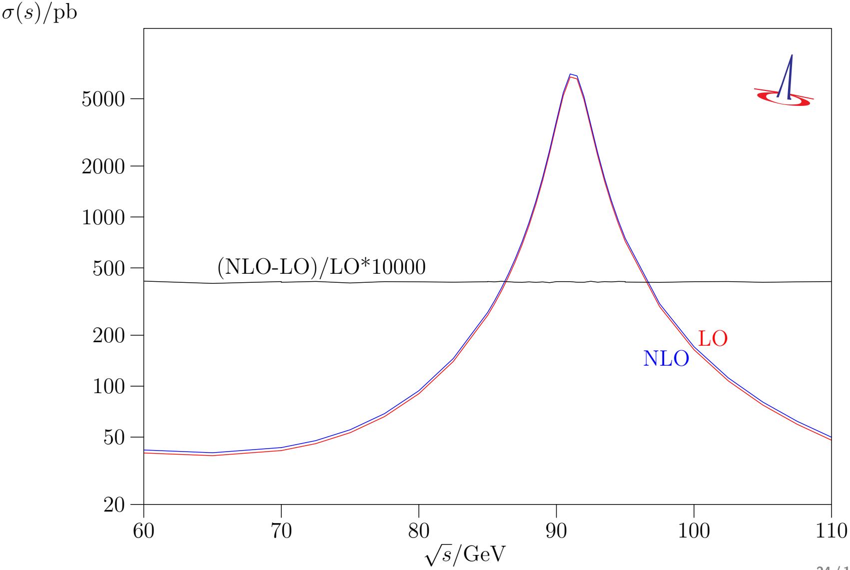
Collinear subtraction involves spin-correlated matrix elements:

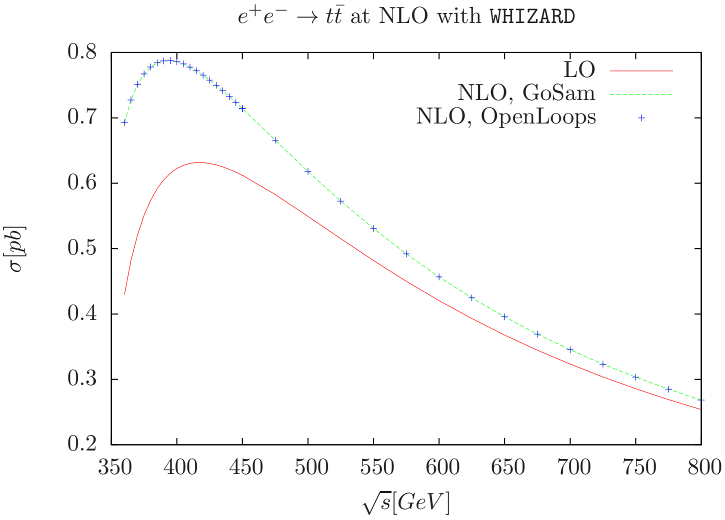
$$\mathcal{B}_{+-} \sim Re \left\{ \frac{\langle k_{\text{em}} k_{\text{rad}} \rangle}{[k_{\text{em}} k_{\text{rad}}]} \sum_{\substack{\text{color}\\\text{spin}}} \mathcal{A}_{+}^{(n)} \mathcal{A}_{-}^{(n)*} \right\}$$

Virtual subtraction: Same structure

$$|\mathcal{M}_n^{virt}|^2 \to \mathcal{V}_{\mathcal{I}} \otimes |\mathcal{M}_n|^2, \quad \mathcal{V}_{\mathcal{I}} = \int d\Phi_{\text{rad}} \mathcal{D}_{\mathcal{I}}$$

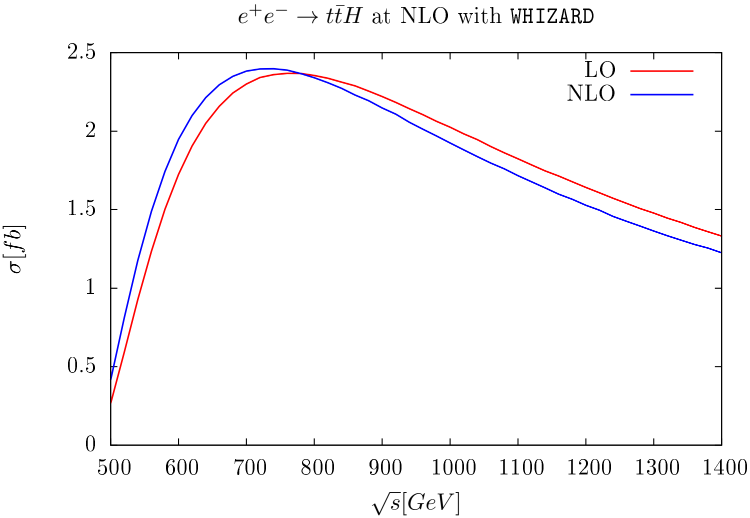
Total cross section for the process $e^+e^- \to u\bar{u}$





$e^+e^- \to t\bar{t}$ at NLO with WHIZARD
LO
NLO, GoSam
NLO, OpenLoops
0.8
0.7
0.6
0.5
0.4
0.3
0.2
$\sigma[pb]$
350
400
450
500
550
600
650
700
750
800
$\sqrt{s}[GeV]$

$e^+e^- \to t\bar{t}H$


$e^+e^- \to t\bar{t}H$ at NLO with WHIZARD
LO
NLO
$\sigma[fb]$
$\sqrt{s}[GeV]$
0
0.5
1
1.5
2
2.5
500
600
700
800
900
1000
1100
1200
1300
1400

Non-relativistc QCD Threshold Resummation

Consider top production $e^+e^- \to t\bar{t}$ close to the production threshold. It is

$$v \sim \alpha_s \ll 1.$$

$\to$ Large logarithms $\log \frac{\alpha_s}{v}$!

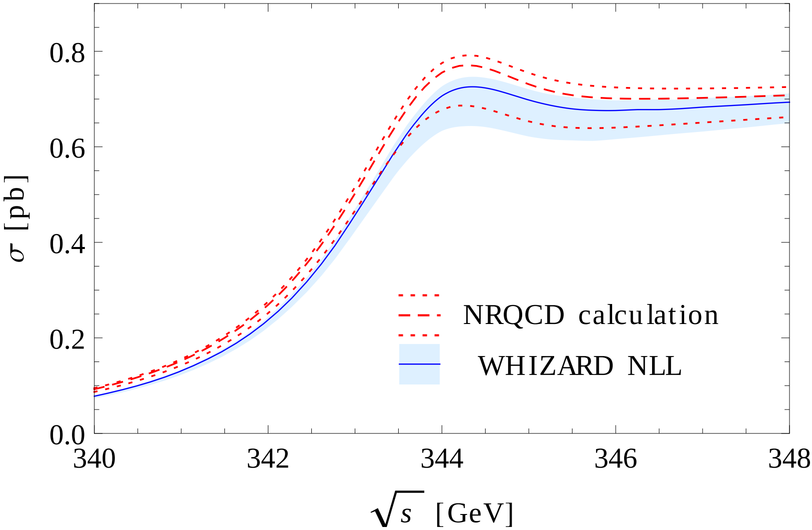
Resummation of large logarithms

$$R = \frac{\sigma_{tt}}{\sigma_{\mu\mu}} = v \sum_k \left(\frac{\alpha_s}{v}\right)^k \sum_i (\alpha_s \log v)^i \times$$
$$\times \left\{1(LL); \alpha_s, v(NLL); \alpha_s^2, \alpha_s v, v^2(NNLL); \ldots\right\}$$

R-ratio split up into form factors:

$$R(s) = F^v(s)R^v(s) + F^a(s)R^a(s)$$

Implemented in `WHIZARD` via `TOPPIK`[Hoang, Teubner, 1999]



0.8
0.6
0.4
0.2
0.0
σ [pb]
340
342
344
346
348
$\sqrt{s}$ [GeV]
NRQCD calculation
WHIZARD NLL

WHIZARD vs. Madgraph