The event generator WHIZARD

Jürgen R. Reuter, DESY

W,HIggs,Z And Respective Decays

Jürgen R. Reuter, DESY

The WHIZARD Event Generator

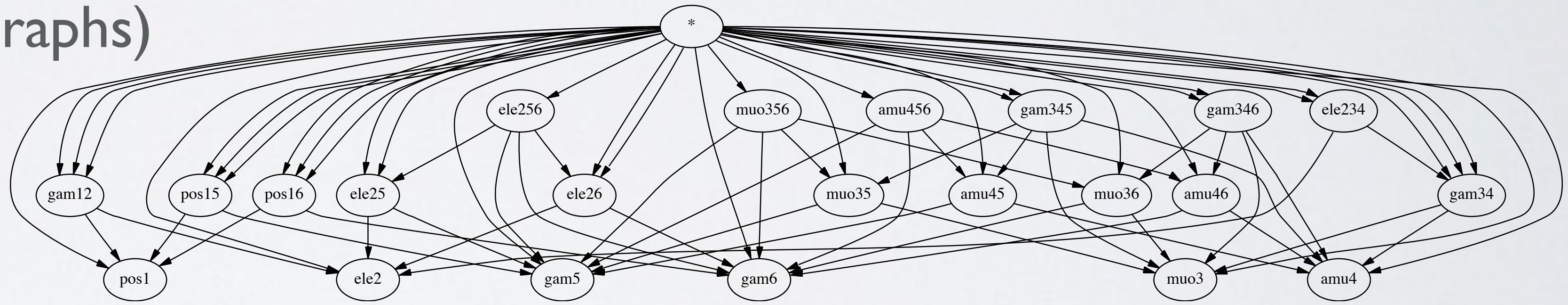
WHIZARD v2.3.1 (25 Aug. 2016) http://whizard.hepforge.org <whizard@desy.de>

WHIZARD Team: *Wolfgang Kilian, Thorsten Ohl, JRR, Simon Braß/Bijan Chokoufé/C. Fleper/Marco Sekulla/So Young Shim/Florian Staub/Christian Weiss/Zhijie Zhao* + *2 Master*

EPJ C71 (2011) 1742

- Universal event generator for lepton and hadron colliders
- Modular package:
  - Phase space parameterization (resonances, collinear emission, Coulomb etc.)
  - O'Mega optimized matrix element generator (recursiveness via Directed Acyclical Graphs)

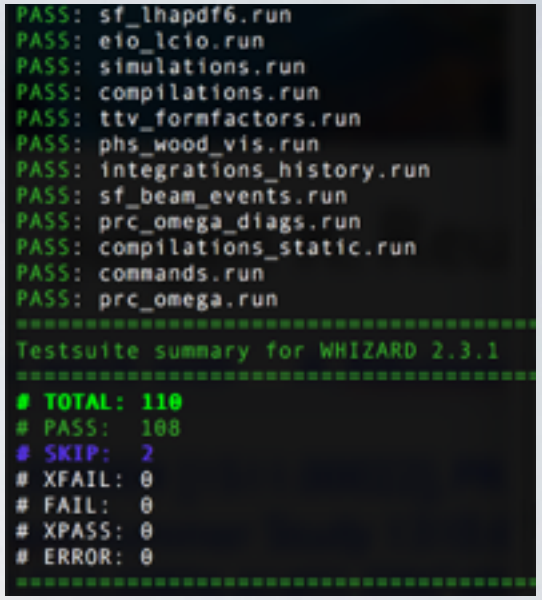
Ω

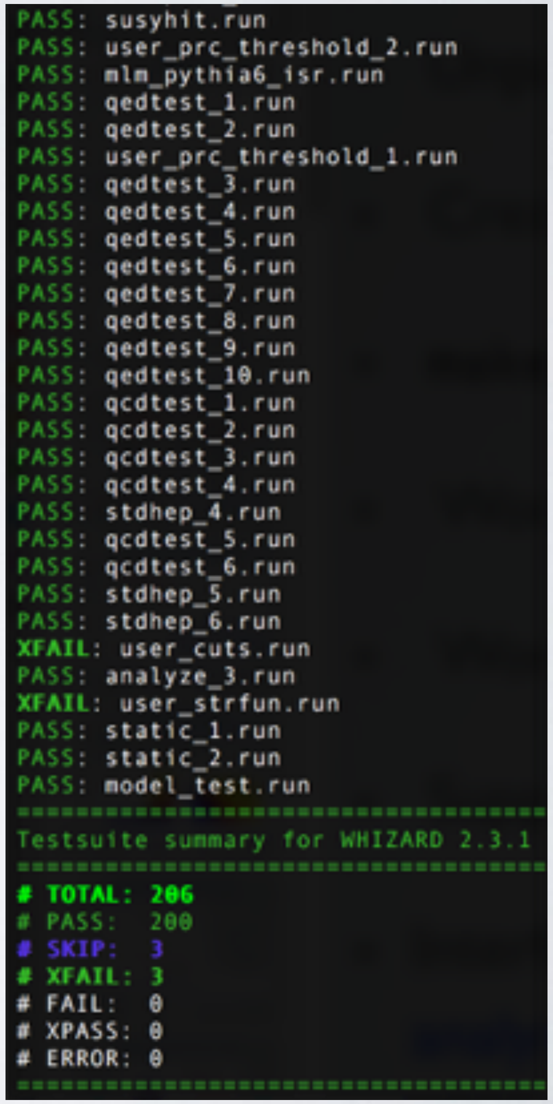


  - VAMP: adaptive multi-channel Monte Carlo integrator
  - CIRCE1/2: generator/simulation tool for lepton collider beam spectra
  - Lepton beam ISR — Kuraev/Fadin, 1986; Skrzypek/Jadach, 1991
  - Color flow formalism — Stelzer/Willenbrock, 2003; Kilian/Ohl/JRR/Speckner, 2011

WHIZARD: Installation and Run

- Download: http://www.hepforge.org/archive/whizard/whizard-2.3.1.tar.gz
- Unpack it, intended to be installed in `/usr/local` (or locally)
- Create `build` directory and do `./configure`
- `make`, `[ make check ]`, `make install`
- Working directory: create `SINDARIN` steering file `<input>.sin`
- Working directory: run `whizard <input>.sin`
- Supported event formats: LHA, StdHep, LHEF (i-iii), HepMC, LCIO, div. ASCII
- Interfaces to external packages for Feynman rules, hadronization, event formats, analysis, jet clustering etc.: `FastJet, GoSam, GuineaPig(++), HepMC, HOPPET, LCIO, LHAPDF(4/5/6), LoopTools, OpenLoops, PYTHIA6, [PYTHIA8], StdHep [internal]`





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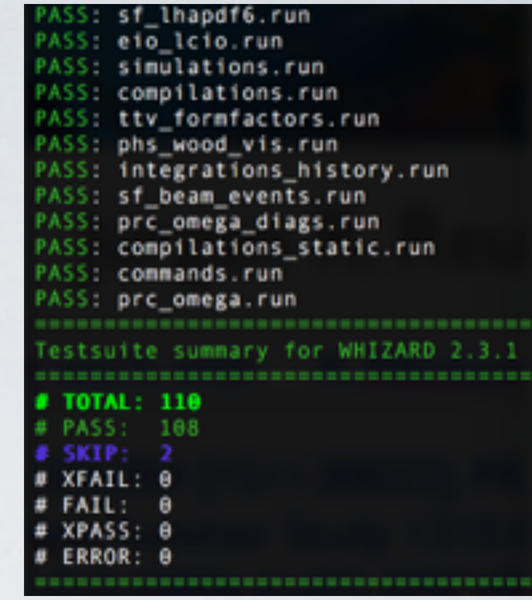


Decay processes / auto_decays

WHIZARD cannot only do scattering processes, but also decays

Example Energy distribution electron in muon decay:

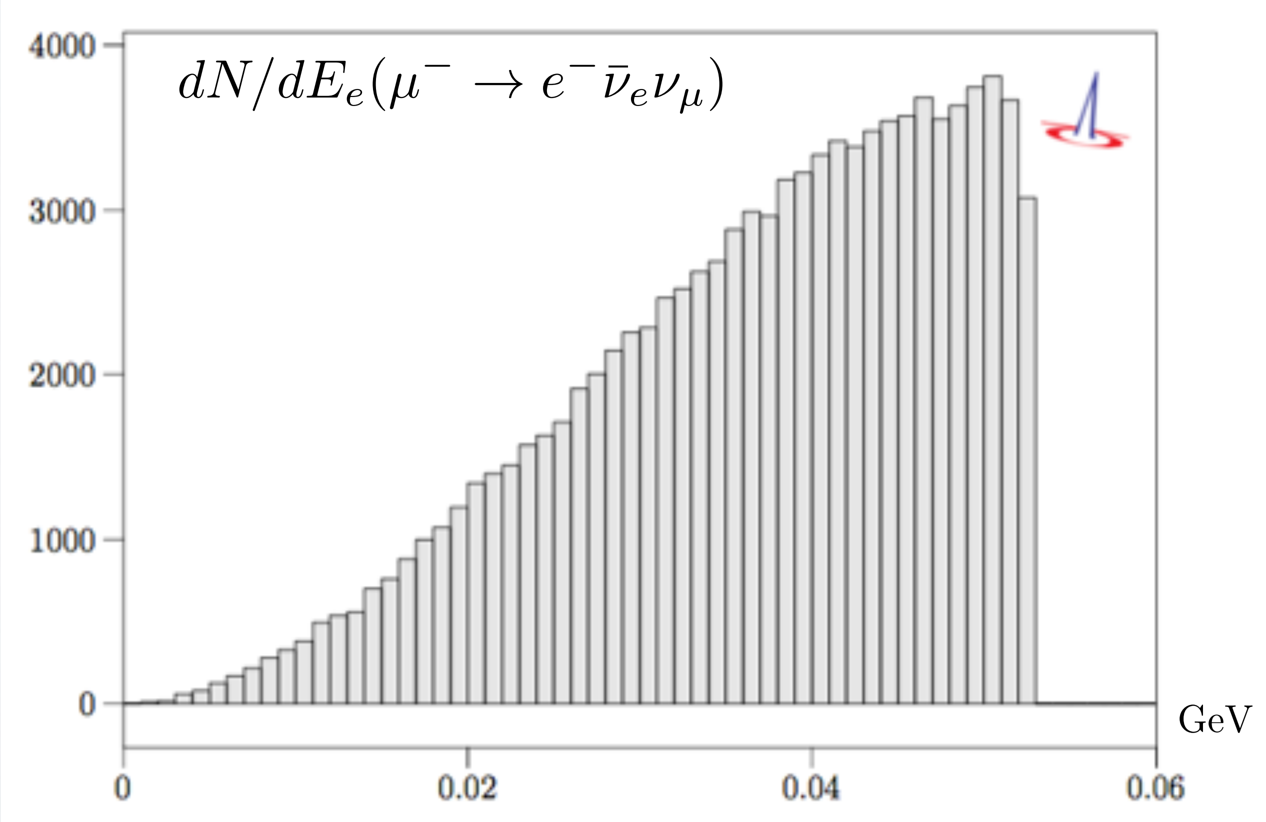
```
model = SM
process mudec = e2 => e1, N1, n2
integrate (mudec)

histogram e_e1 (0, 60 MeV, 1 MeV)
analysis = record e_e1 (eval E [e1])

n_events = 100000

simulate (mudec)

compile_analysis { $out_file = "test.dat" }
```



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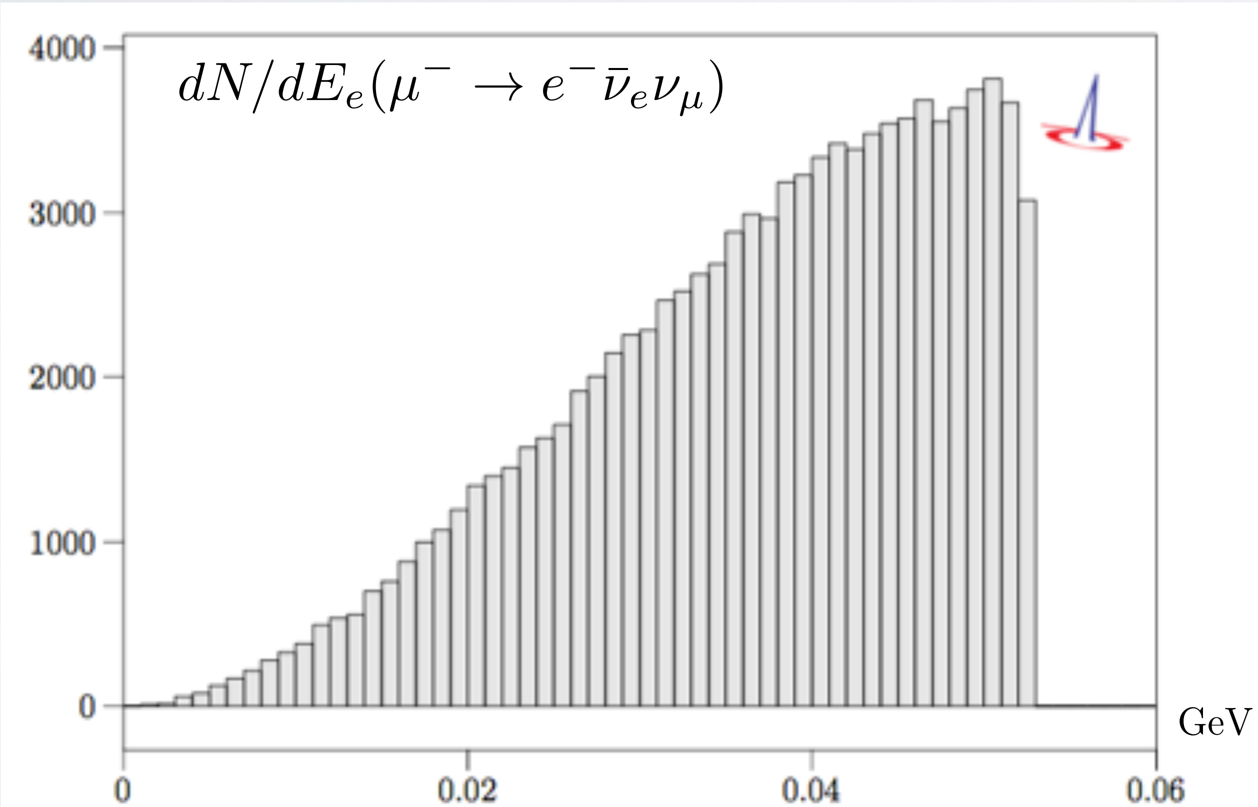

Automatic integration of particle decays

```
auto_decays_multiplicity = 2
?auto_decays_radiative = false

unstable Wp () { ?auto_decays = true }
```

```
|==================================================================
| It      Calls  Integral[GeV] Error[GeV]  Err[%]    Acc
|==================================================================
   1        100  2.2756406E-01  0.00E+00    0.00    0.00*
|------------------------------------------------------------------
   1        100  2.2756406E-01  0.00E+00    0.00    0.00
|==================================================================
| Unstable particle W+: computed branching ratios:
|   decay_p24_1: 3.3337068E-01   dbar, u
|   decay_p24_2: 3.3325864E-01   sbar, c
|   decay_p24_3: 1.1112356E-01   e+, nue
|   decay_p24_4: 1.1112356E-01   mu+, numu
|   decay_p24_5: 1.1112356E-01   tau+, nutau
|   Total width = 2.0478471E+00 GeV (computed)
|               = 2.0490000E+00 GeV (preset)
|   Decay options: helicity treated exactly
```

BSM Models in WHIZARD

MODEL TYPE	with CKM matrix	trivial CKM
QED with e, μ, τ, γ	–	QED
QCD with d, u, s, c, b, t, g	–	QCD
Standard Model	SM_CKM	SM
SM with anomalous gauge coupl.	SM_ac_CKM	SM_ac
SM with anomalous top coupl.	SMtop_CKM	SMtop
SM for e^+e^- top threshold	—	SM_tt_threshold
SM with anom. Higgs coupl.	—	SM_rx / NoH
SM ext. for VV scattering	—	SSC / SSC2/ AltH
SM ext. for unitarity limits	—	SM_ul
SM with Z'	—	Zprime
2HDM	2HDM_CKM	2HDM
MSSM	MSSM_CKM	MSSM
MSSM with gravitinos	—	MSSM_Grav
NMSSM	NMSSM_CKM	NMSSM
extended SUSY models	—	PS/E/SSM
Littlest Higgs	—	Littlest
Littlest Higgs with ungauged $U(1)$	—	Littlest_Eta
Littlest Higgs with T parity	—	Littlest_Tpar
Simplest Little Higgs (anomaly-free/univ.)	—	Simplest[_univ]
3-site model	—	Threeshl
UED	—	UED
SM with gravitino and photino	—	GravTest
Augmentable SM template	—	Template

2.2.8: SM_dim6

- Automated models: interface to SARAH/BSM Toolbox   Staub, 0909.2863; Ohl/Porod/Staub/Speckner, 1109.5147
- Automated models: interface to FeynRules   Christensen/Duhr; Christensen/Duhr/Fuks/JRR/Speckner, 1010.3251
- Automated models: UFO interface [in connection with new WHIZARD/O'Mega model format]

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SM ext. for VV scattering	—	SSC / SSC2/ AltH
SM ext. for unitarity limits	—	SM_ul
SM with Z'	—	Zprime
2HDM	2HDM_CKM	2HDM
MSSM	MSSM_CKM	MSSM
MSSM with gravitinos	—	MSSM_Grav
NMSSM	NMSSM_CKM	NMSSM
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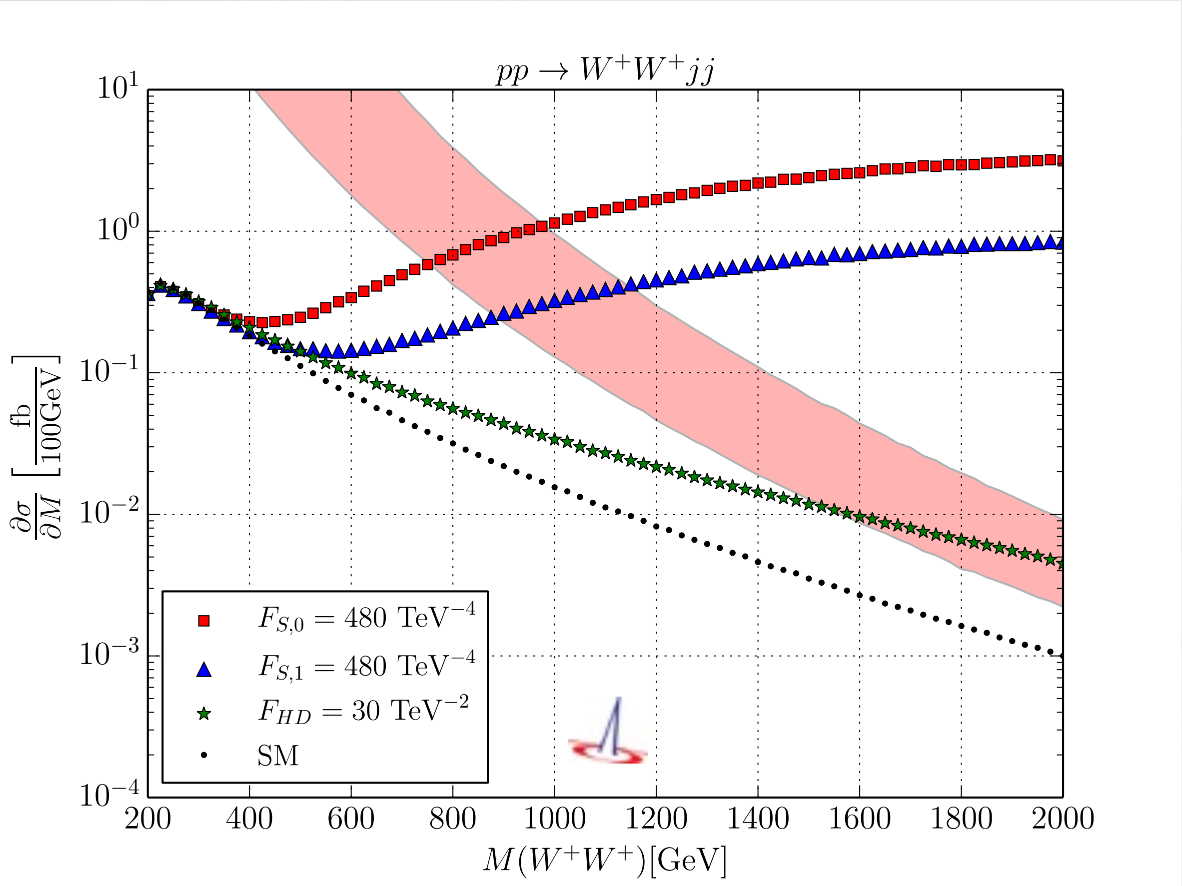
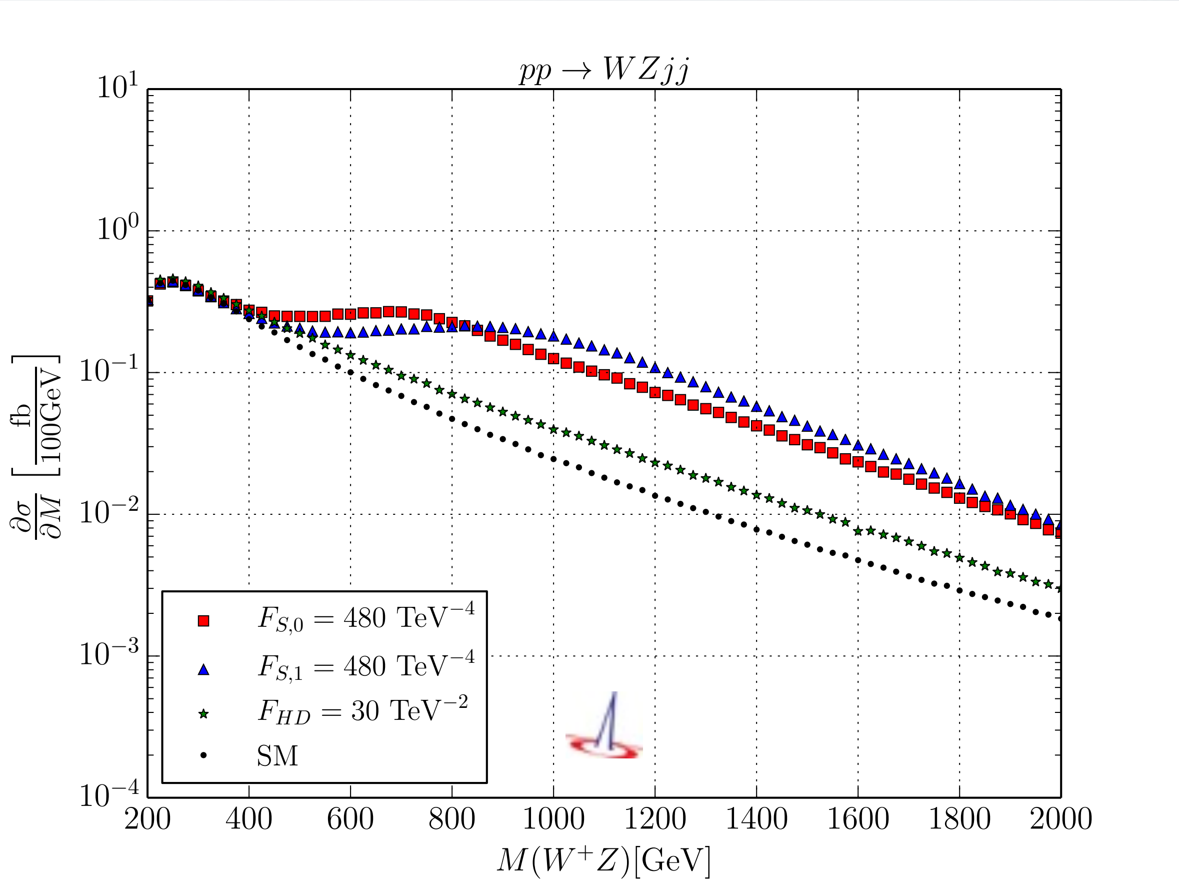
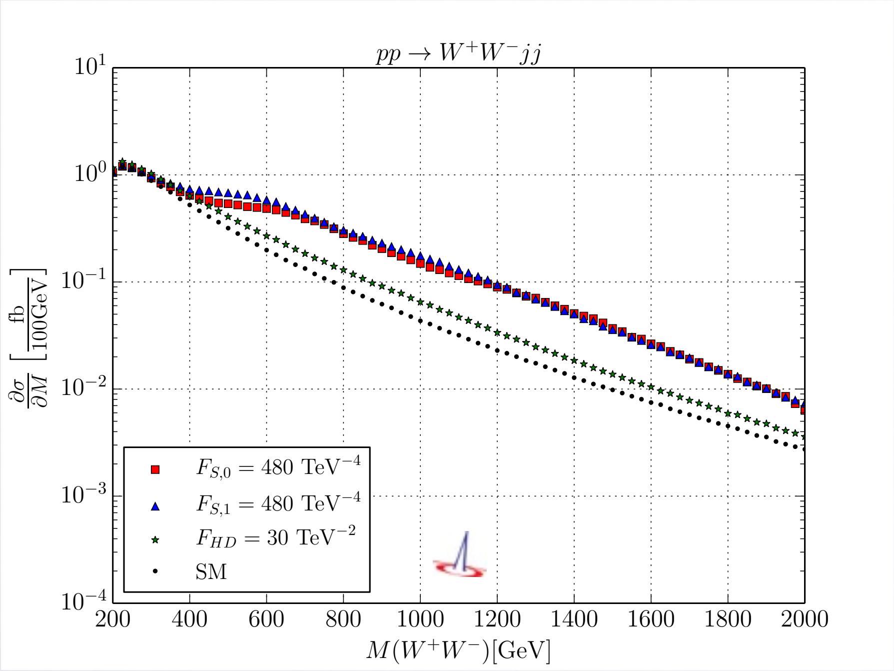
Unitarity bounds in VBS with WHIZARD







Alboteanu/Kilian/Ohl/JRR: JHEP 0811.010 [0806.4145]

Kilian/Ohl/JRR/Sekulla: PRD91(15),096007 [1408.6207]

`model = SM_rx` `model = SM_ul`

General cuts: $M_{jj} > 500\,\text{GeV};\ \Delta\eta_{jj} > 2.4;\ p_T^j > 20\,\text{GeV};\ |\Delta\eta_j| < 4.5$

Differential spectra in VBS

Kilian/Ohl/JRR/Sekulla: PRD91(15),096007 [1408.6207]

$$pp \to e^+\mu^+\nu_e\nu_\mu jj \qquad \sqrt{s} = 14\,\text{TeV} \qquad \mathcal{L} = 1\,\text{ab}^{-1}$$

```
model = SM_rx
```

$$M_{jj} > 500\,\text{GeV}; \quad \Delta\eta_{jj} > 2.4; \quad p_T^j > 20\,\text{GeV}; \quad |\Delta\eta_j| < 4.5; \quad p_T^\ell > 20\,\text{GeV}$$

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```
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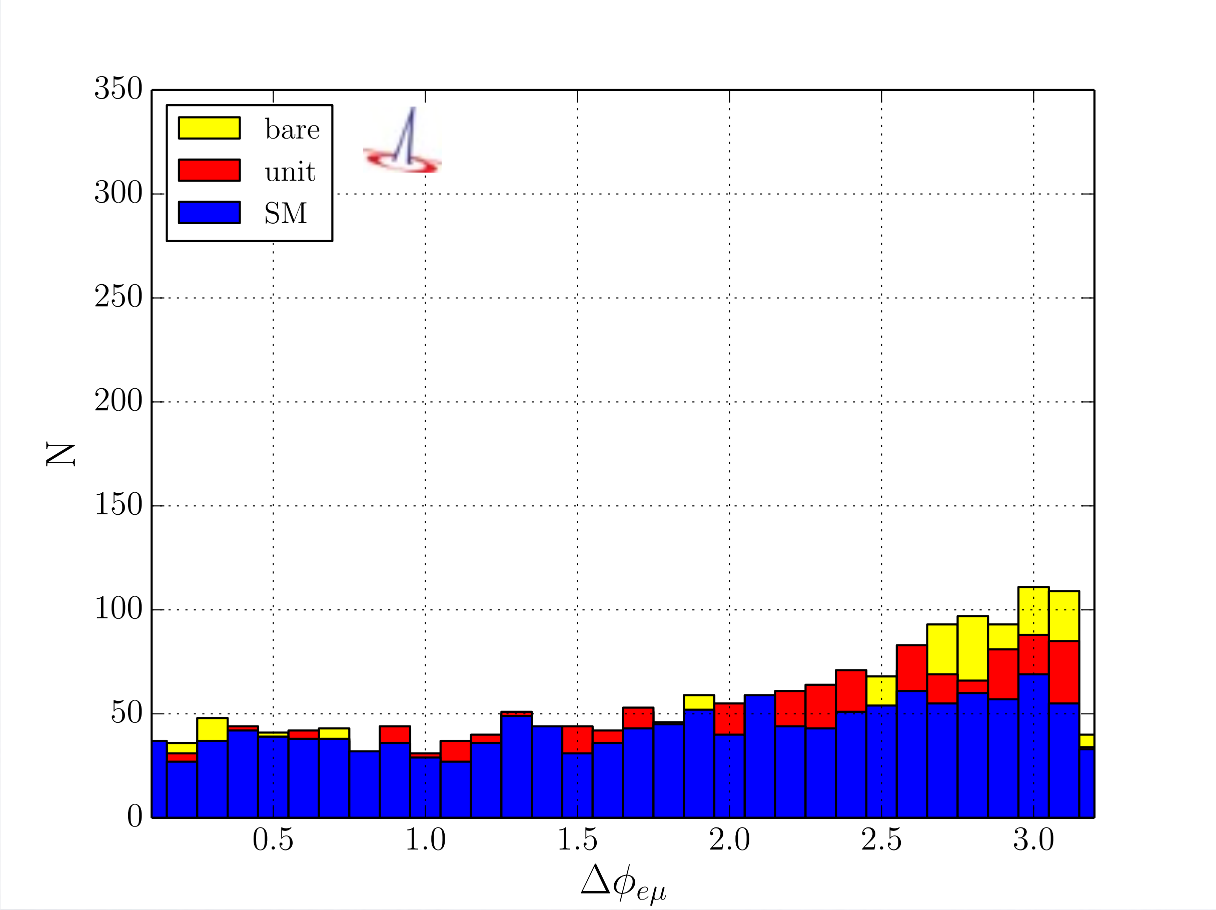
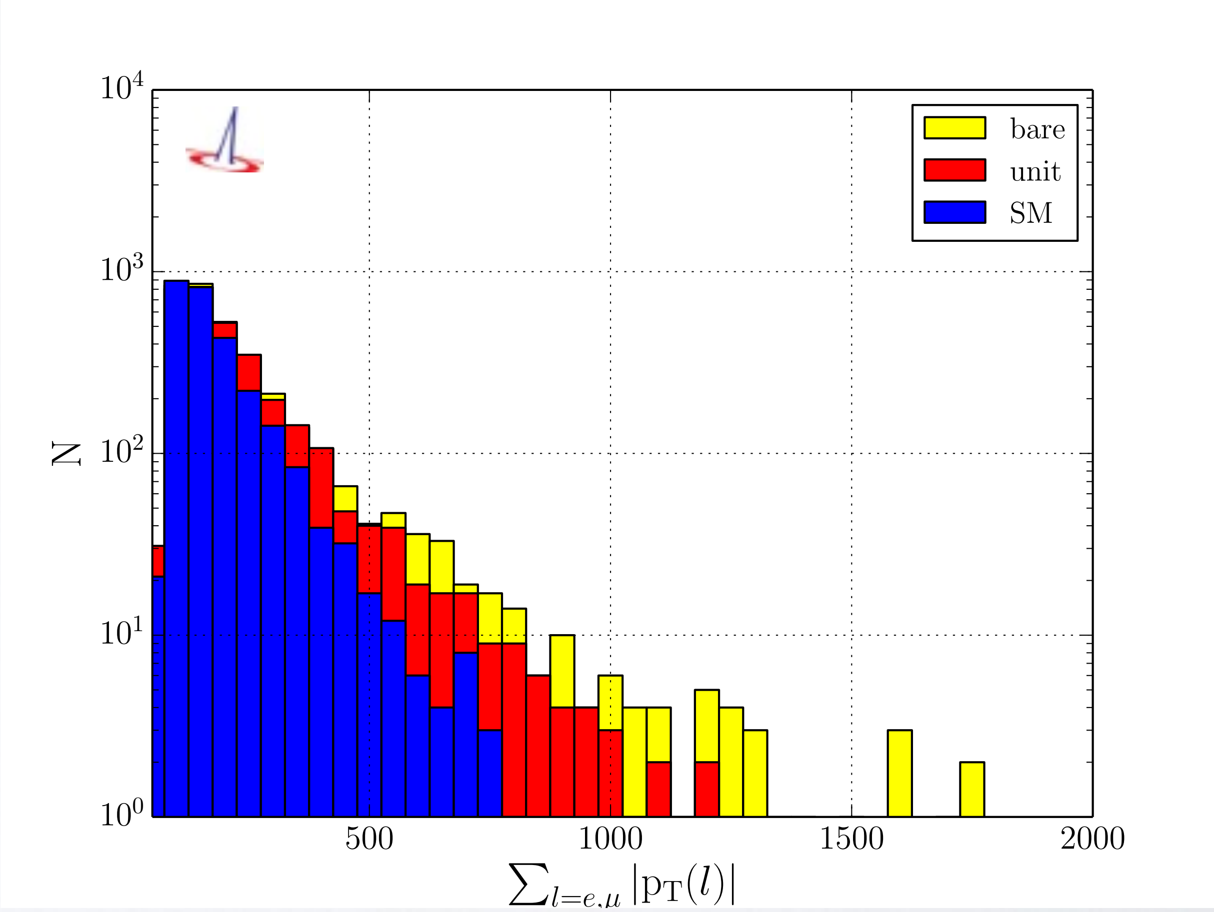
```

$$F_{HD} = 30\ \text{TeV}^{-2}$$





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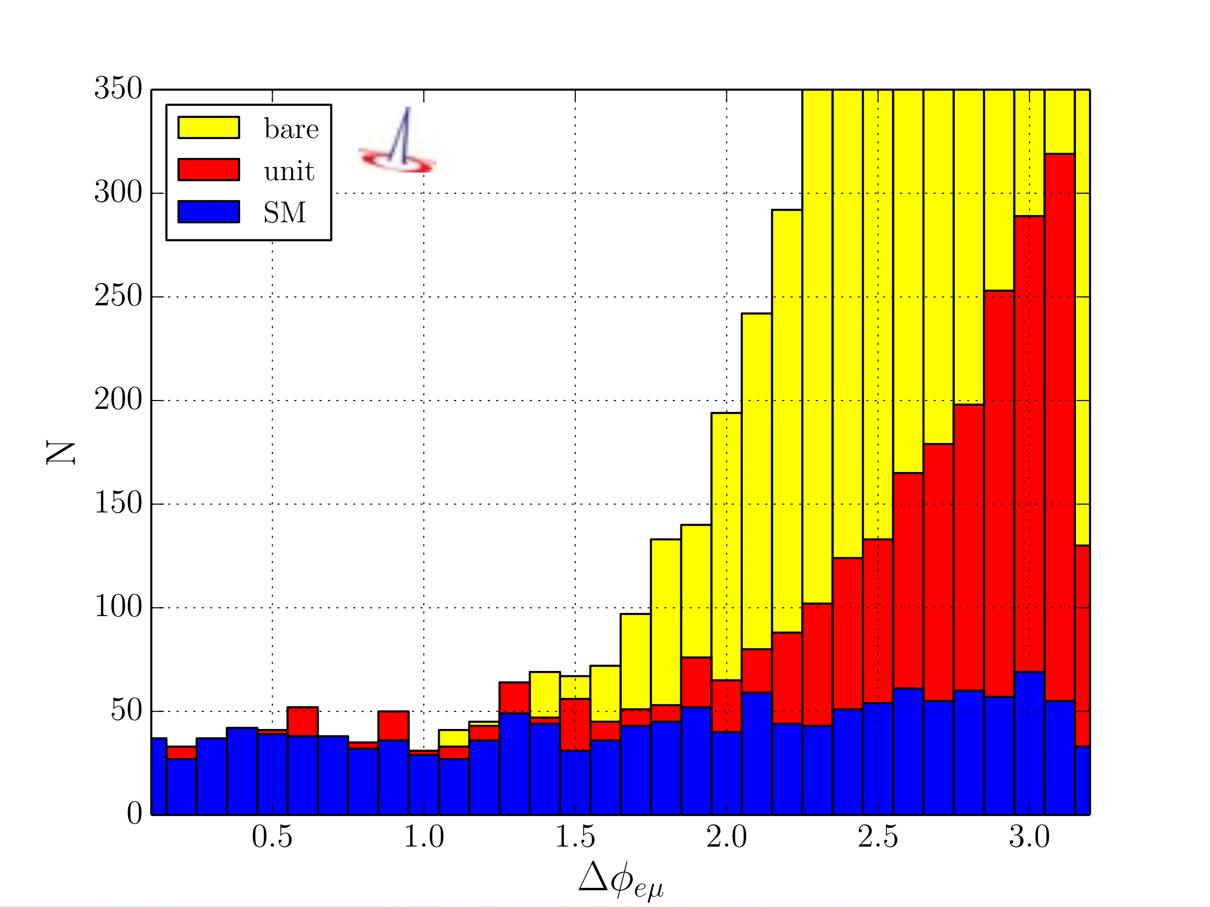
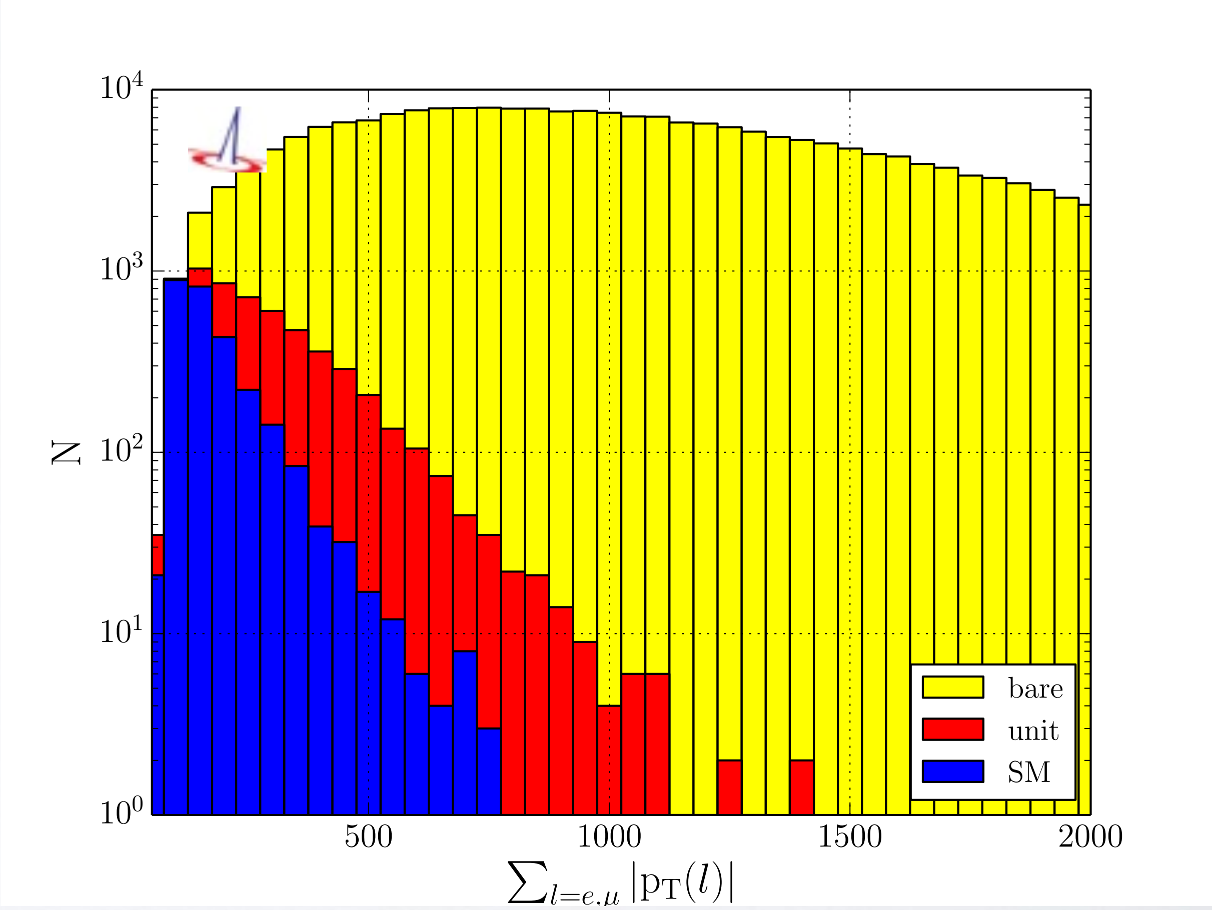
```
model = SM_rx
```

$$F_{S,0} = 480\ \text{TeV}^{-4}$$





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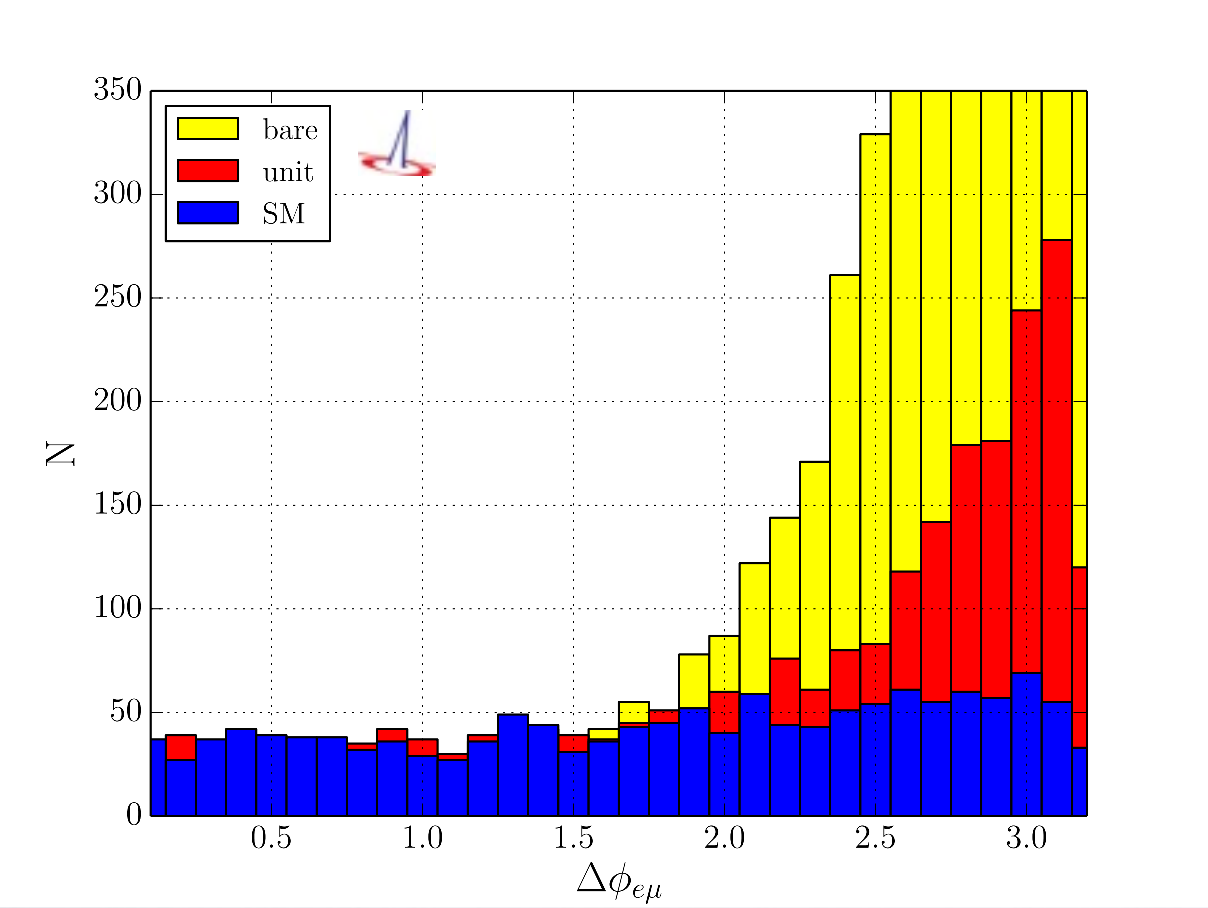
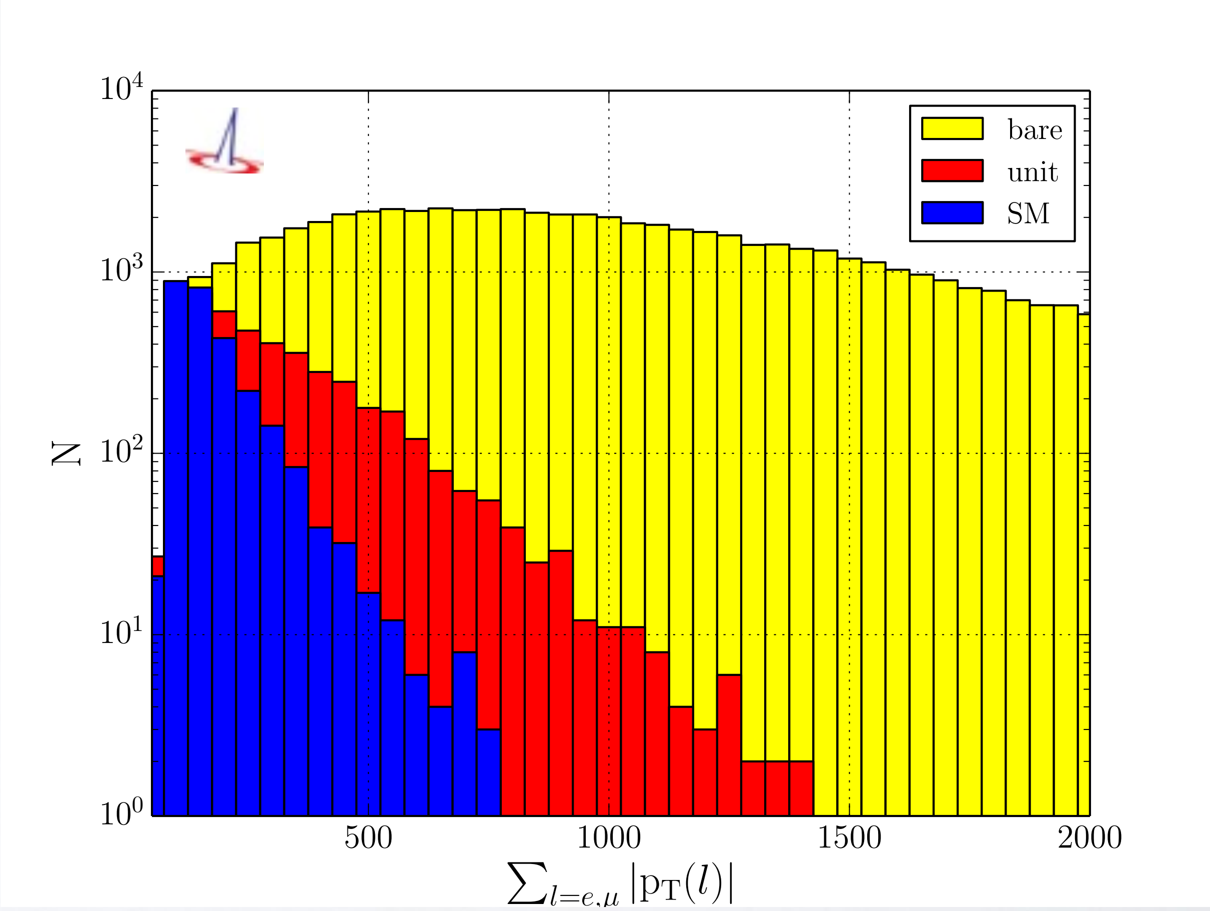
```
model = SM_rx
```

$$F_{S,1} = 480\ \mathrm{TeV}^{-4}$$





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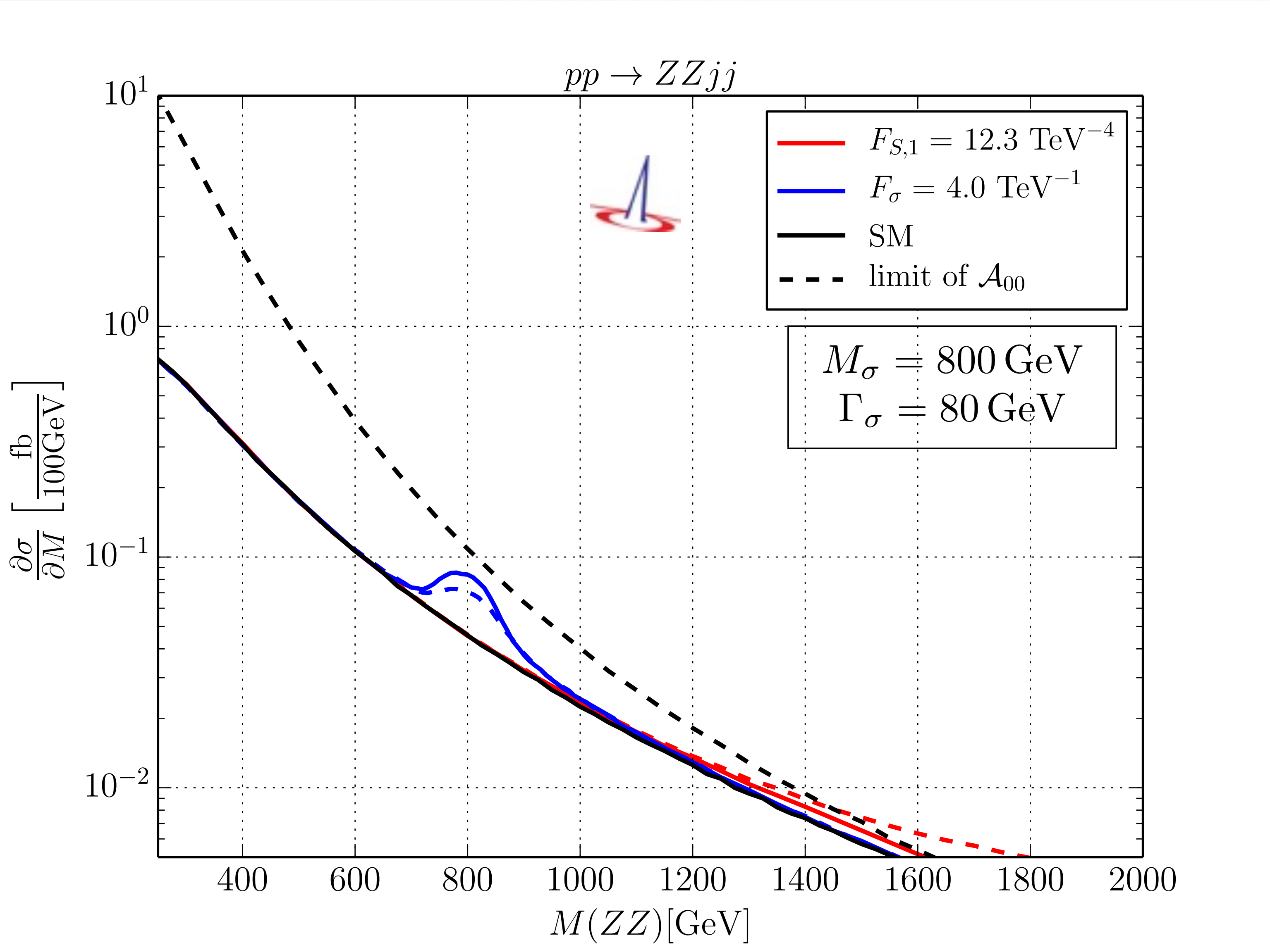
Comparison: Simplified Models & EFT

Kilian/Ohl/JRR/Sekulla: PRD93(16),3. 036004 [1511.00022]



Black dashed line: saturation of $\mathcal{A}_{22}(W^+W^+)/\mathcal{A}_{00}(ZZ)$

- EFT fails at resonance
- aQGC describe rise of resonance
- Unitarization applied
- Tensor resonances better visible than scalars

$32\pi\Gamma/M^5$

	σ	ϕ	f	X
$F_{S,0}$	$\frac{1}{2}$	2	15	5
$F_{S,1}$	–	$-\frac{1}{2}$	-5	-35

$M_{jj} > 500\,\text{GeV};\ \Delta\eta_{jj} > 2.4;\ p_T^j > 20\,\text{GeV};\ |\Delta\eta_j| < 4.5$

$|F_{S,0}| < 480\ \text{TeV}^{-4} \qquad |F_{S,1}| < 480\ \text{TeV}^{-4}$

ATLAS PRL 113(2014)14, 141803 [1405.6241]

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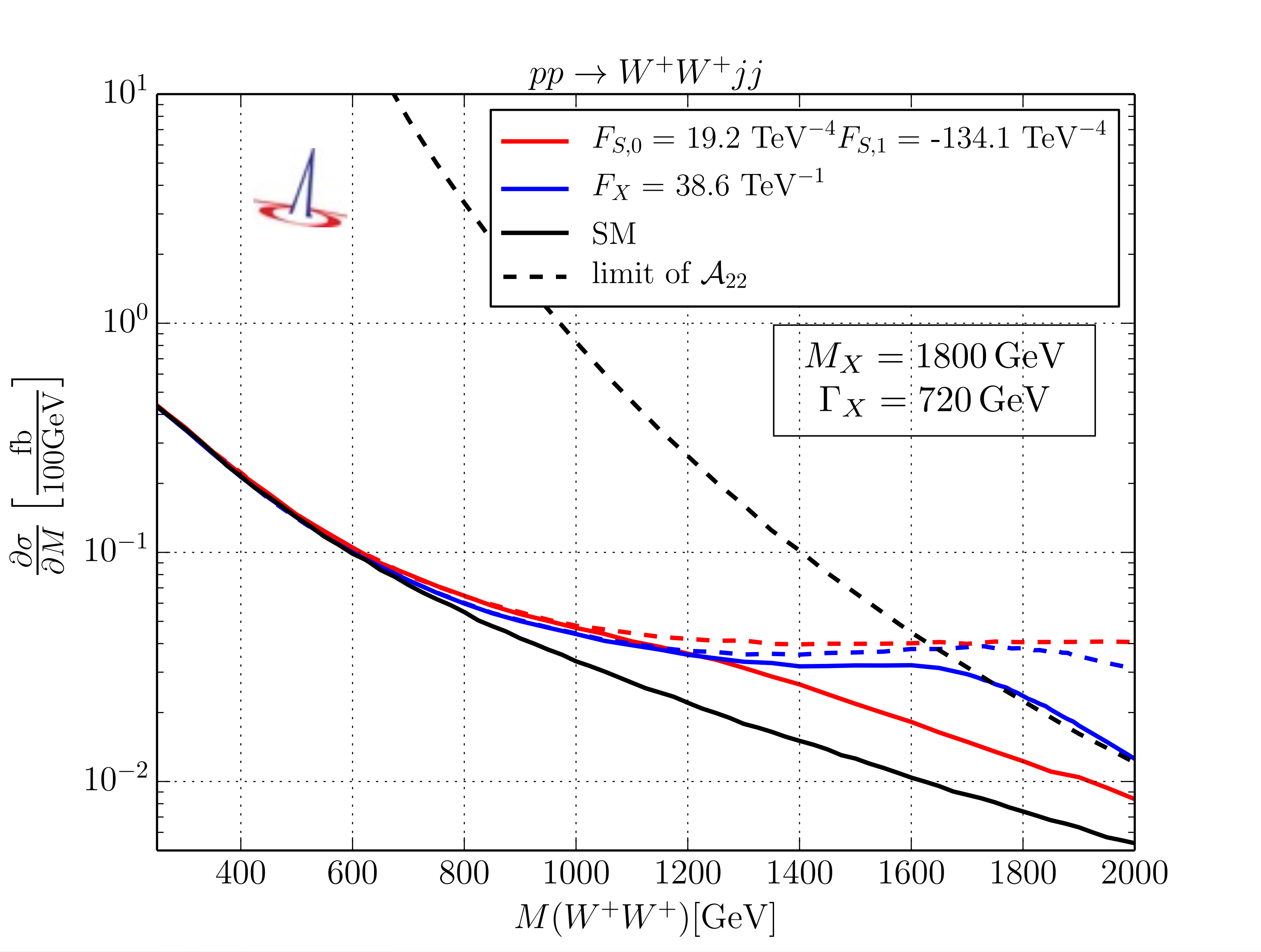

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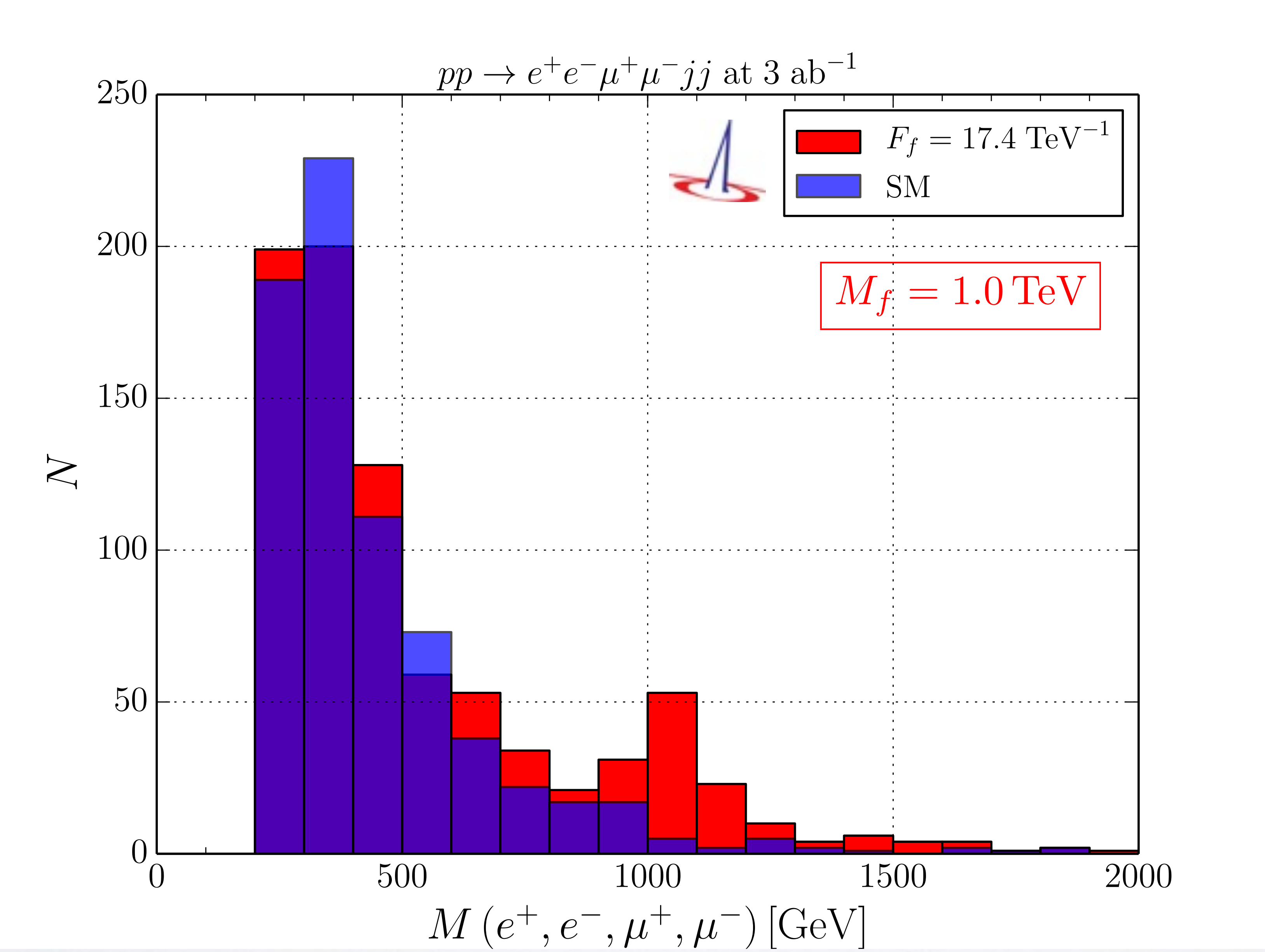
$|F_{S,0}| < 480$ TeV^{-4} $|F_{S,1}| < 480$ TeV^{-4}

ATLAS PRL 113(2014)14, 141803 [1405.6241]

Complete LHC VBS process at 14 TeV

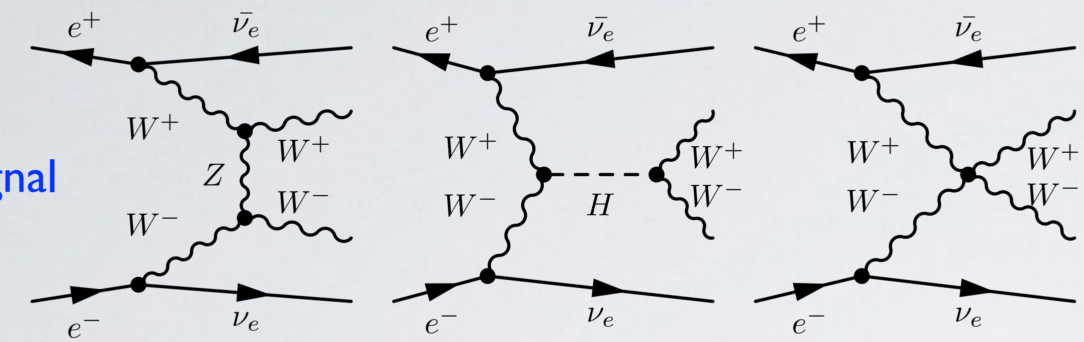


Work in progress: unitarization for transversal polarisations & for tribosons ($pp \to VVV$)

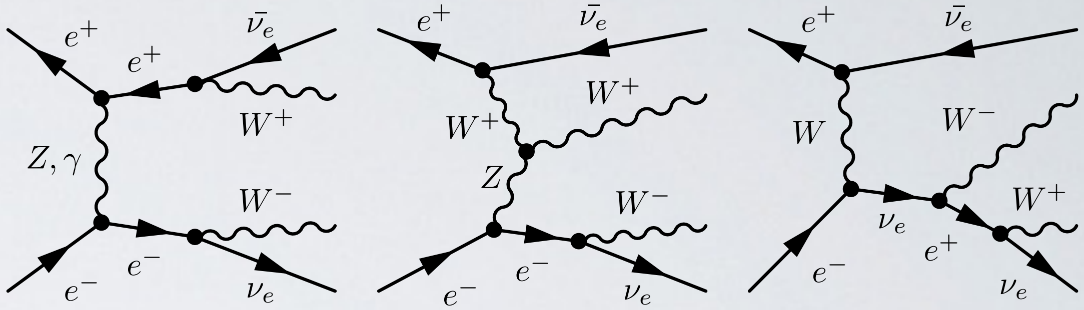
Recent WHIZARD Study for CLIC

Fleper/Kilian/JRR/Sekulla: 1607.03030 (tbp EPJC)

Signal



Bkgd.



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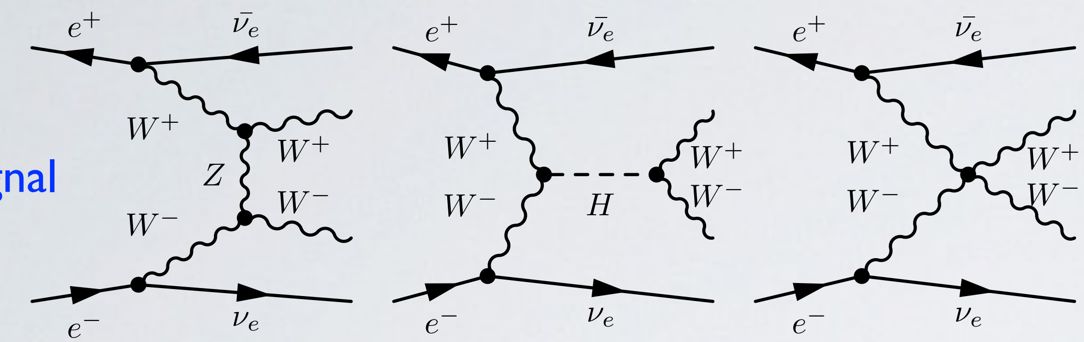

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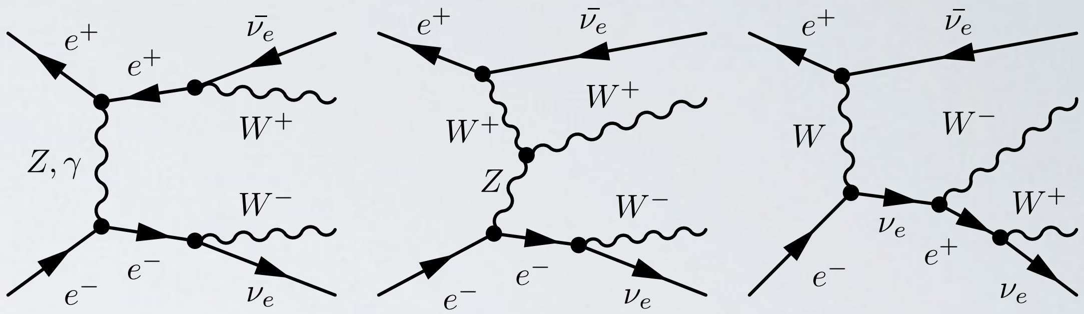

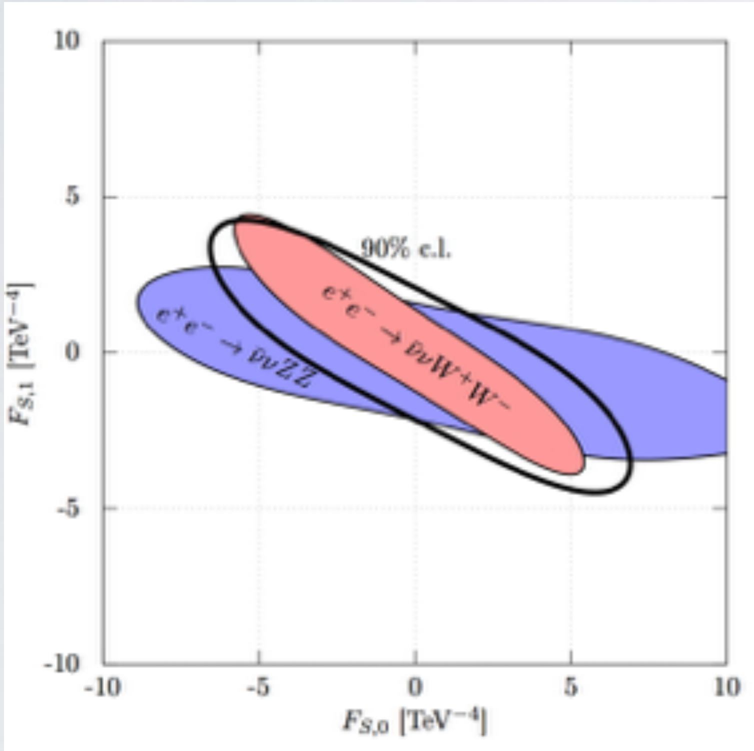

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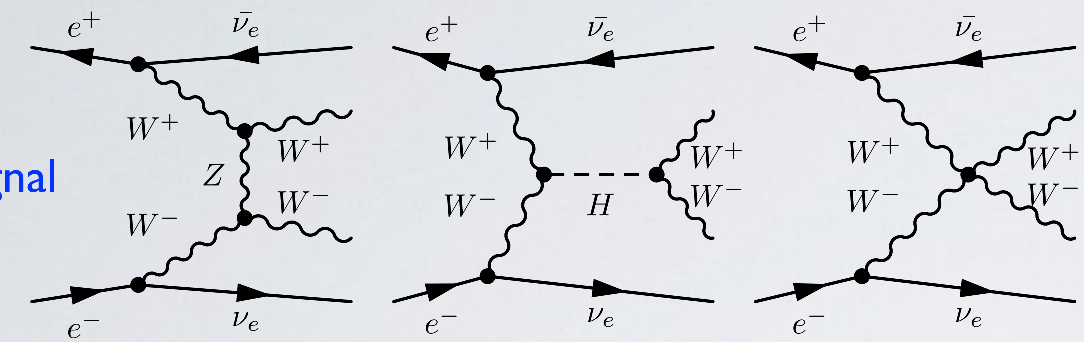

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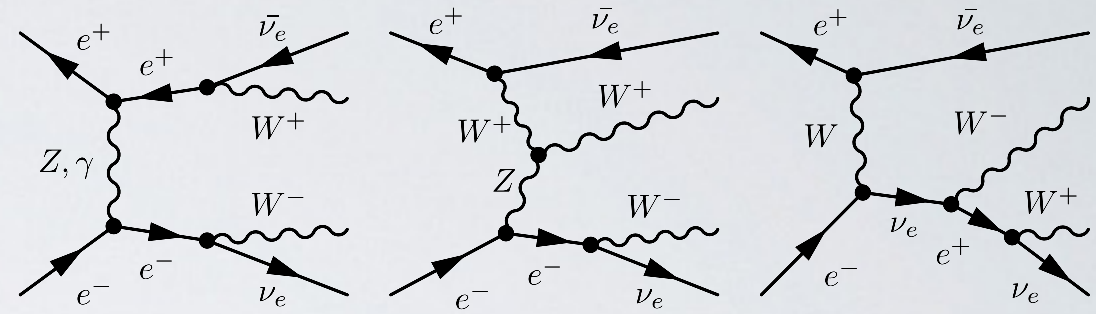

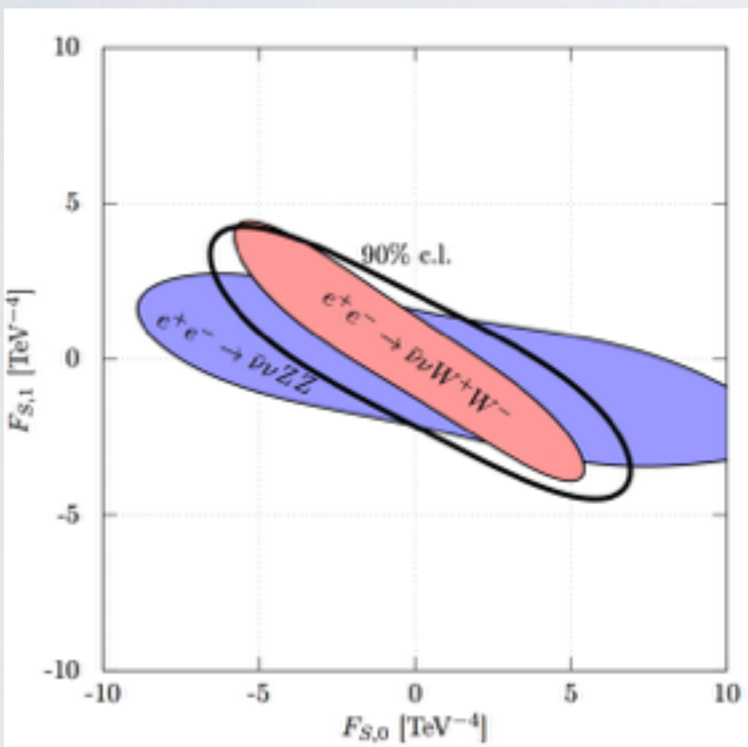

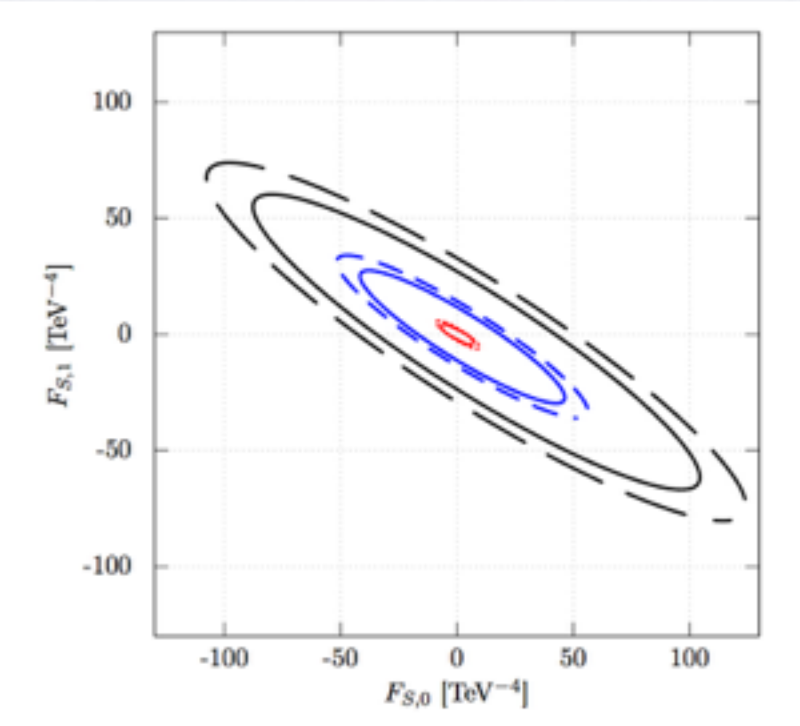

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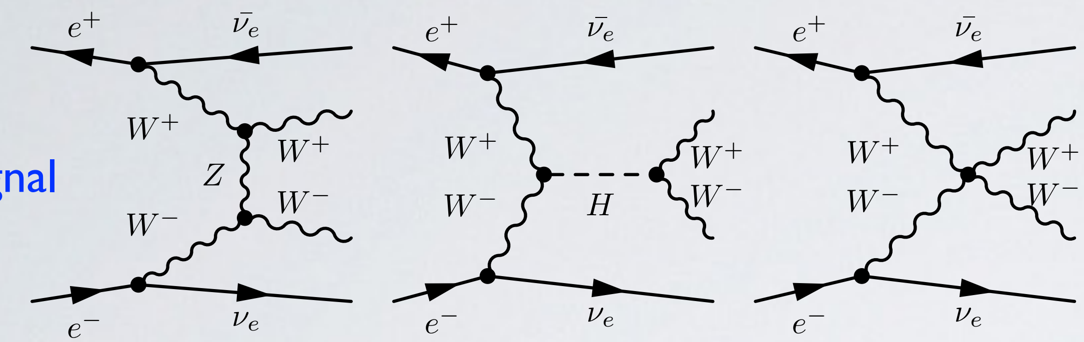

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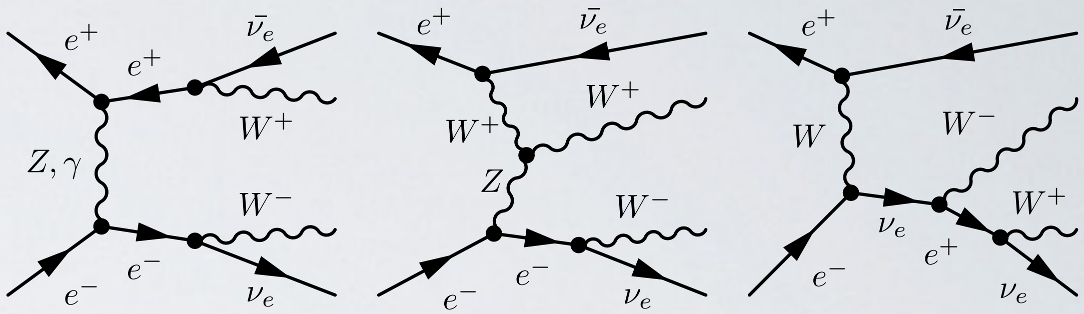
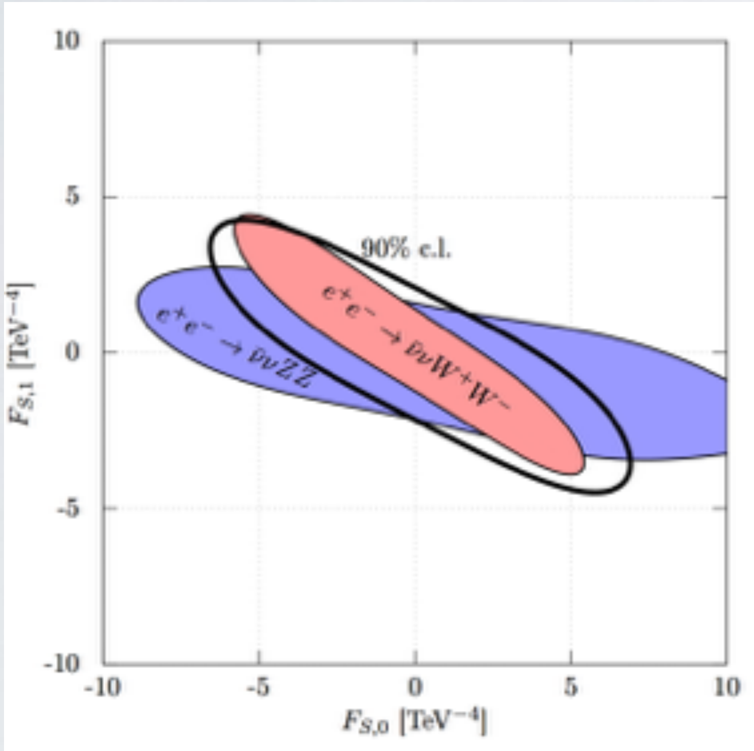
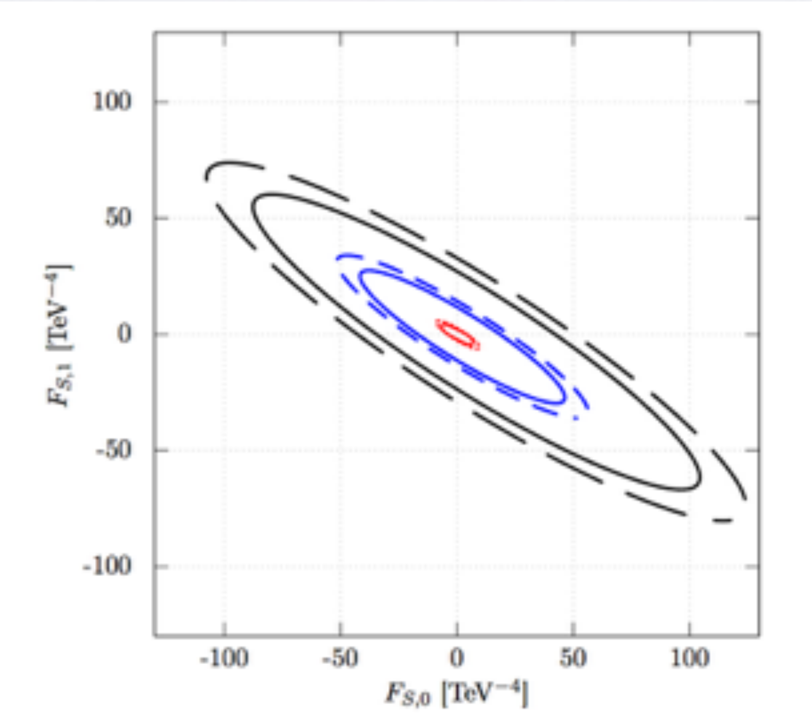
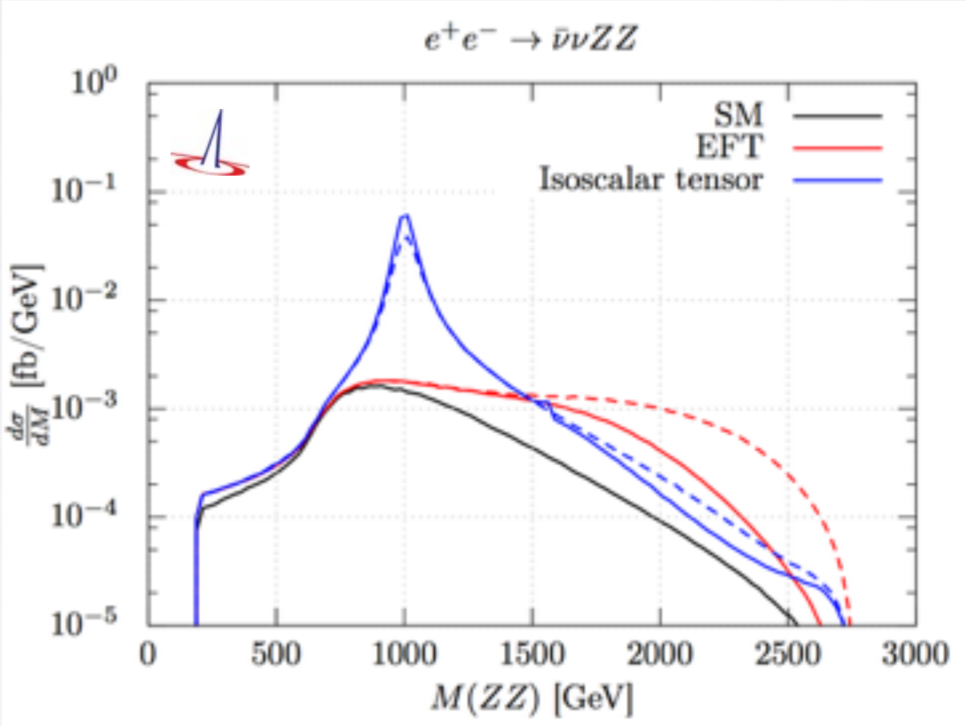




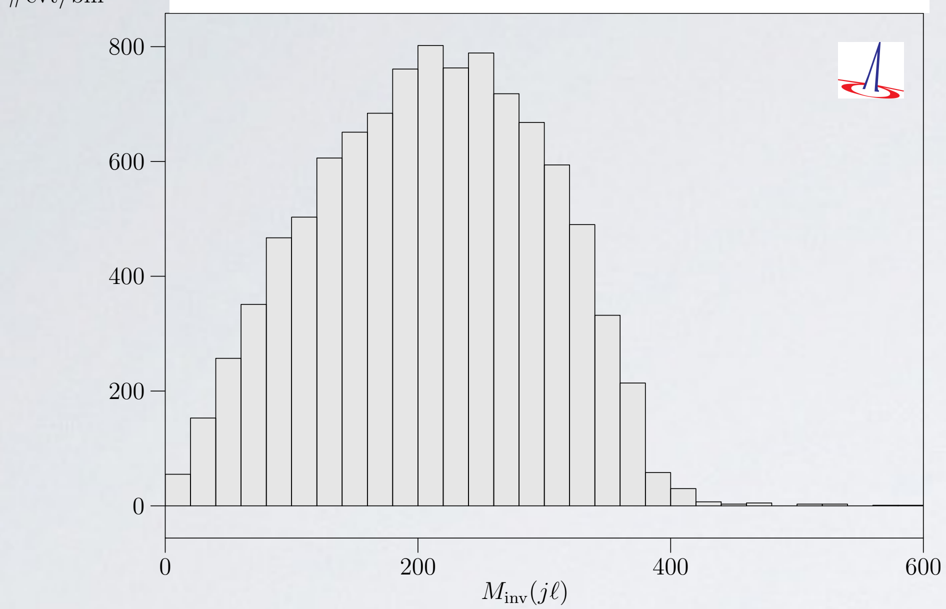




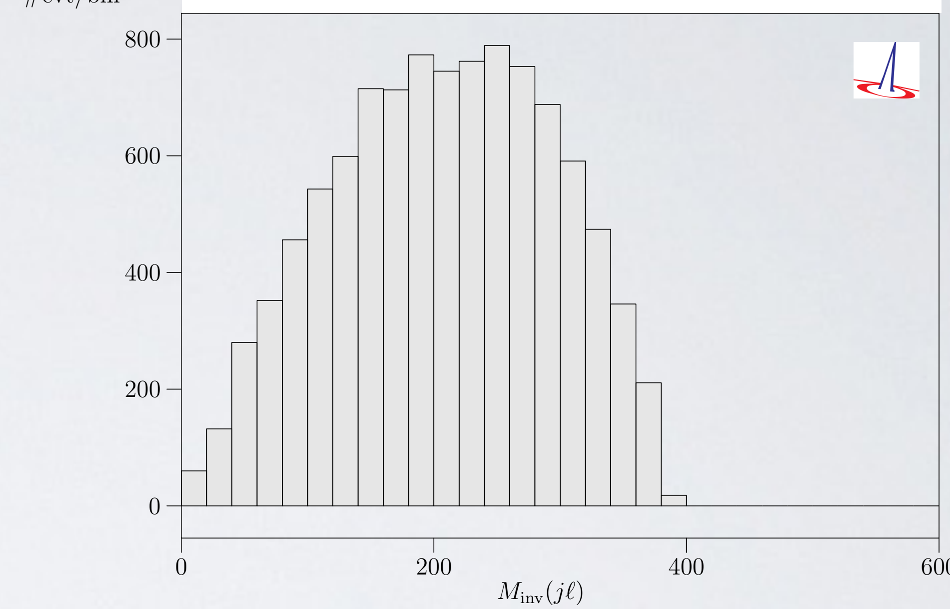
Spin Correlation and Polarization in Cascades

Cascade decay, factorize production and decay

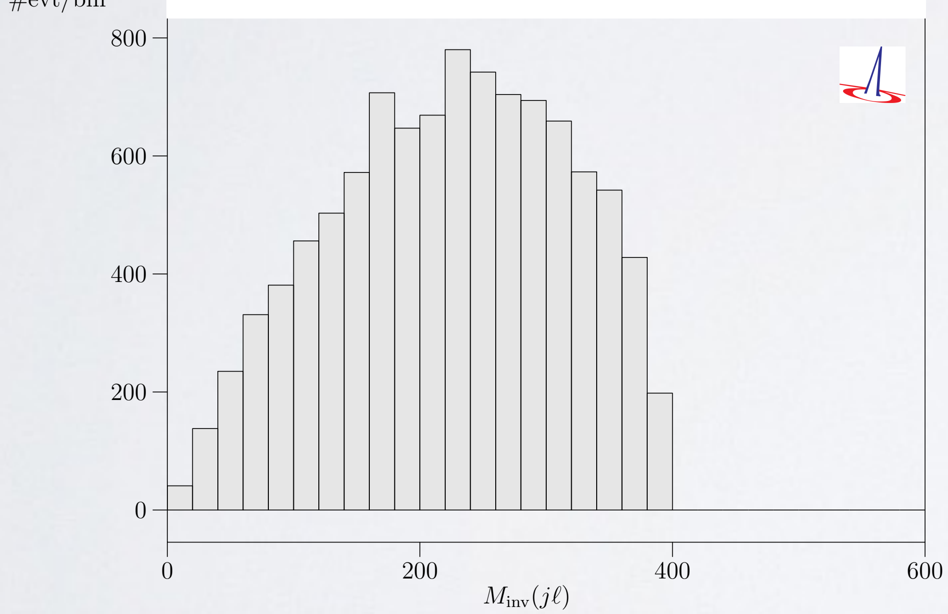
`simulate (fullproc)`



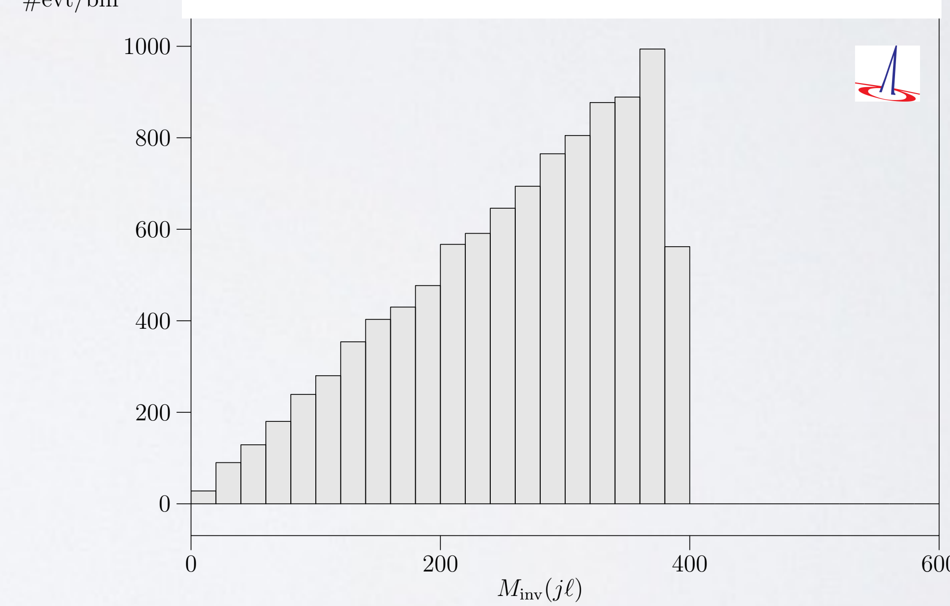
`simulate (casc)`



`?diagonal_decay = true`



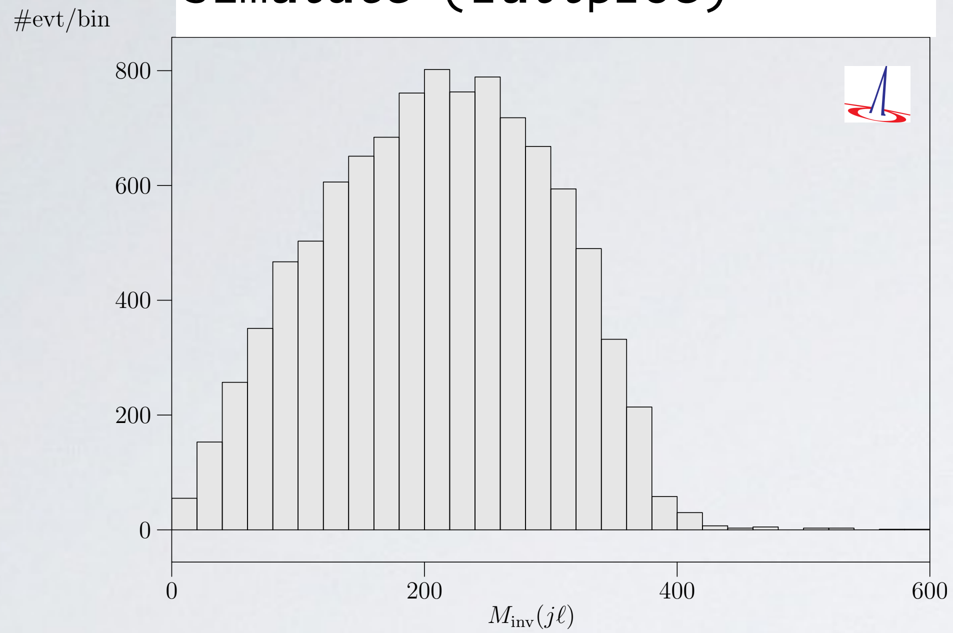
`?isotropic_decay = true`



Spin Correlation and Polarization in Cascades

Cascade decay, factorize production and decay

`simulate (fullproc)`



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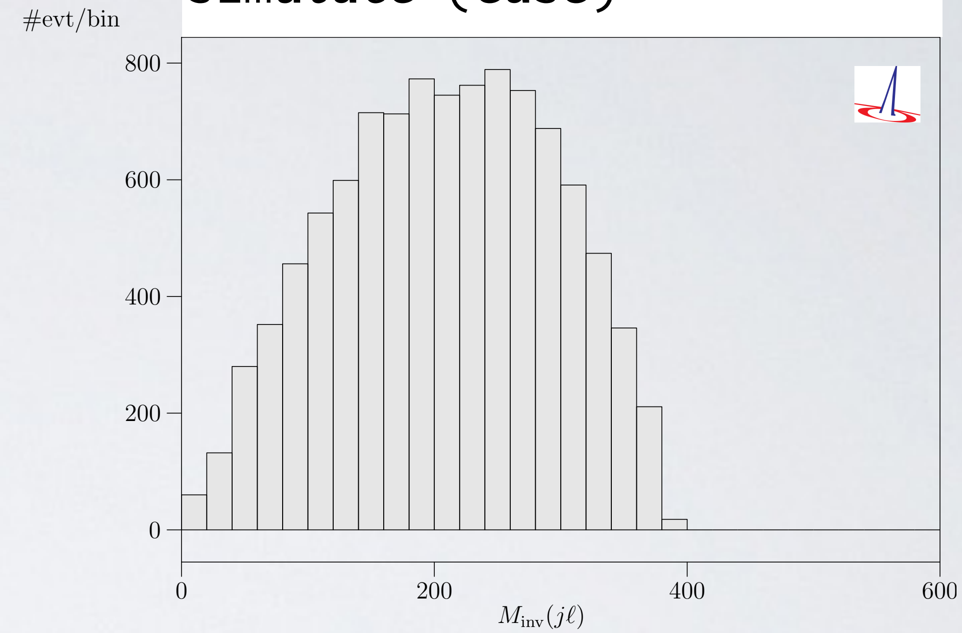

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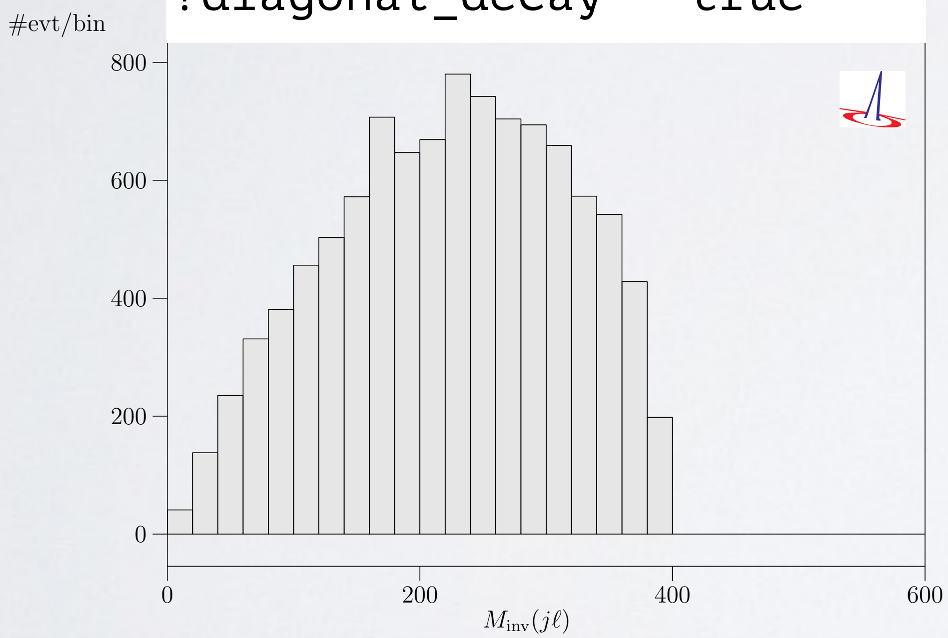

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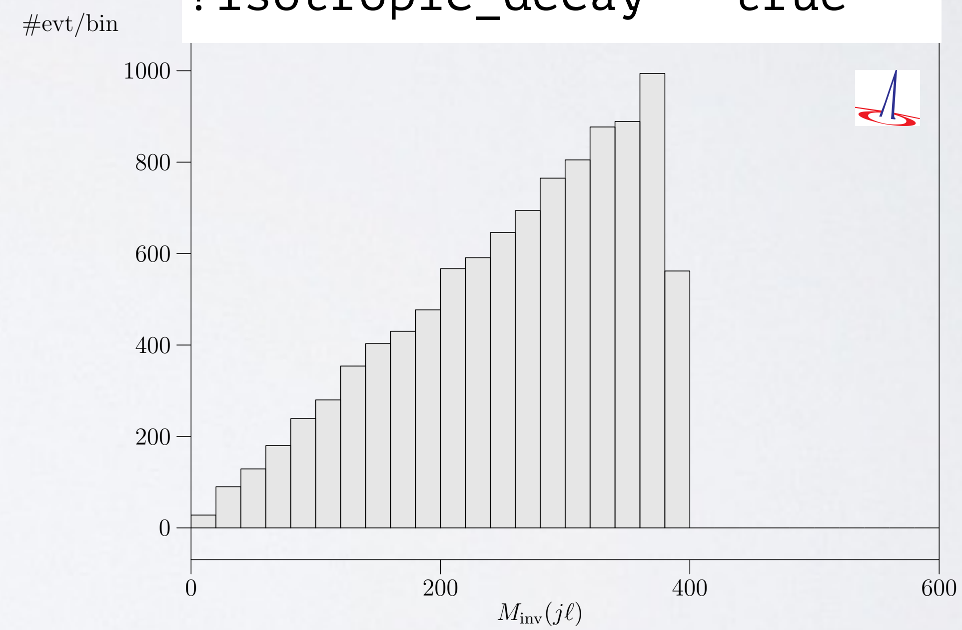


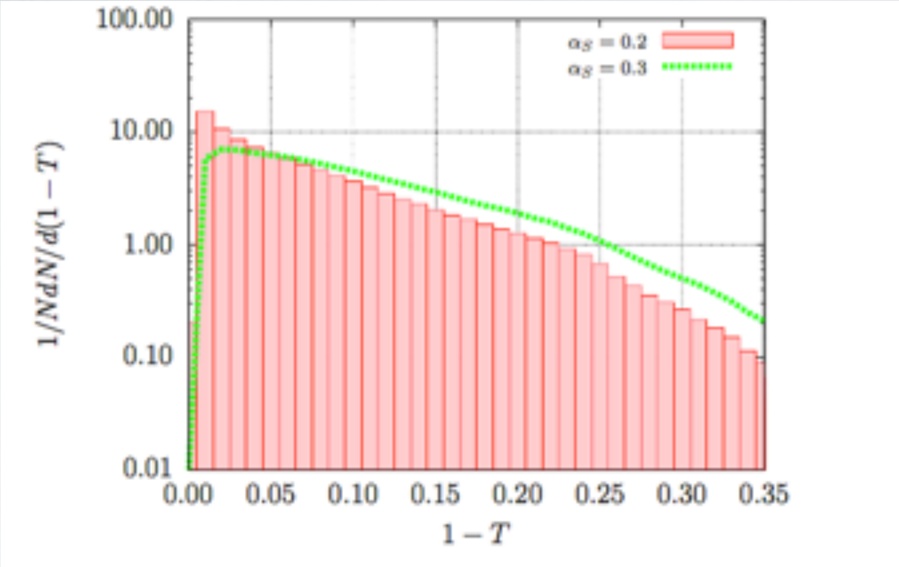
Possibility to select specific helicity in decays!

```
unstable "W+" { decay_helicity = 0 }
```

WHIZARD Parton Shower

- Two independent implementations: kT-ordered QCD and Analytic QCD shower
- Analytic shower: no shower veto ⇒ exact shower history known, allows reweighting

Kilian/JRR/Schmidt/Wiesler, JHEP **1204** 013 (2012)



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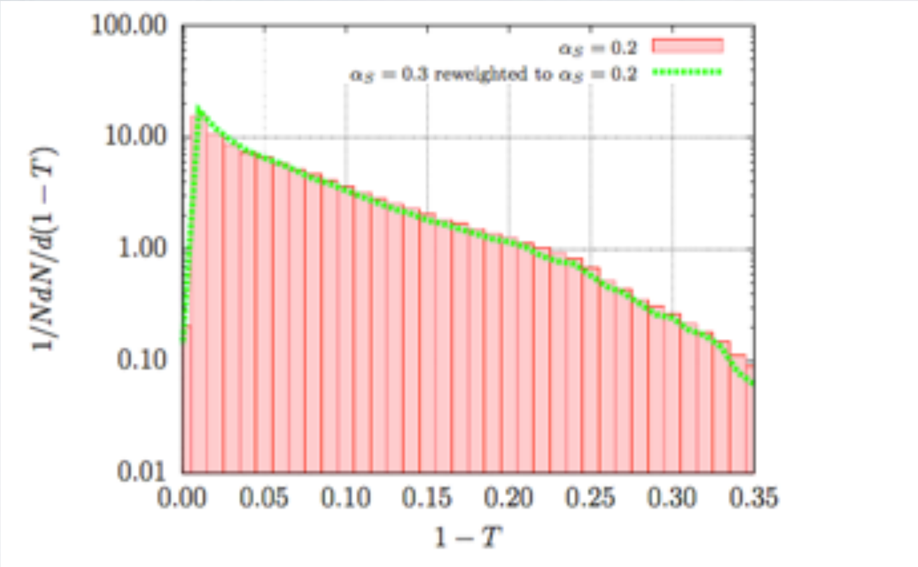

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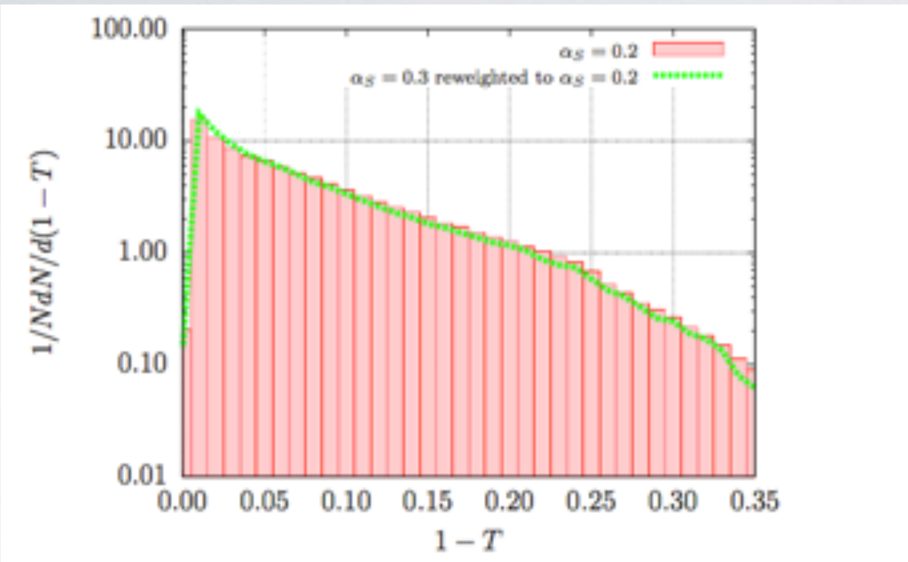
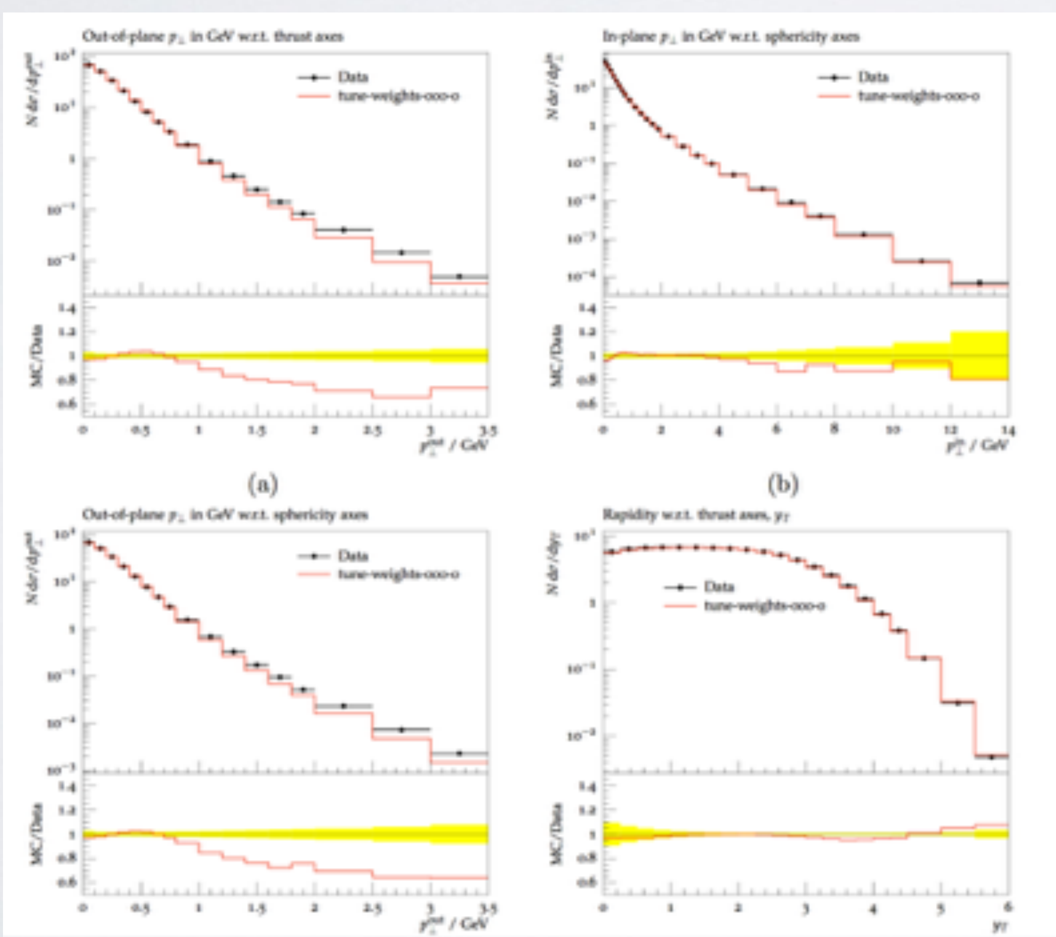


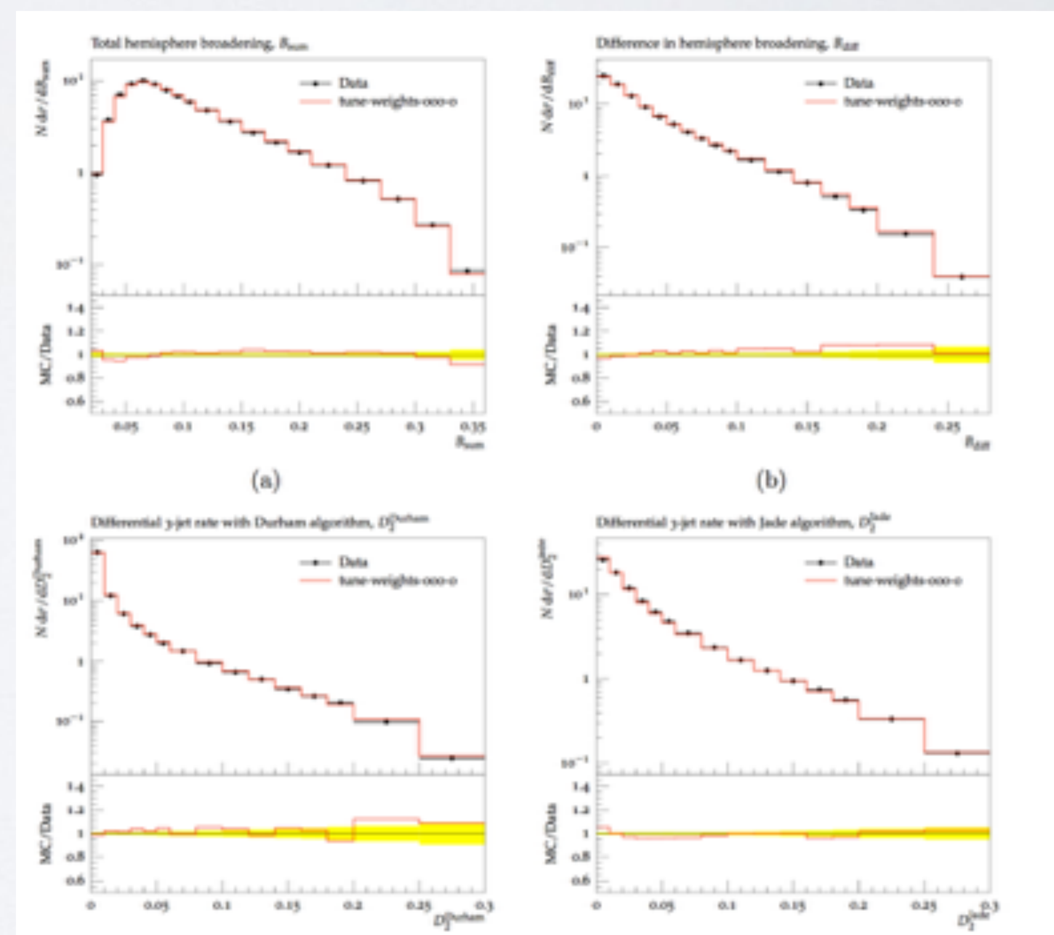
Kilian/JRR/Schmidt/Wiesler, JHEP **1204** 013 (2012)

- First tunes of kT-ordered & Analytic QCD shower

Chokoufe/Englert/JRR, 2015

- Di-/Multijet LEP as given in `RIVET` analysis
- Usage of the `PROFESSOR` tool for best fit [Buckley et al., 2009]





NLO Development in WHIZARD

- QCD corrections done, start work on QED and electroweak corrections
- Automated FKS subtraction
- WHIZARD provides Born, reals, all subtraction terms
- Virtual amplitudes linked externally

Working NLO interfaces to:

- ⋆ GoSam [G. Cullen et al.]
- ⋆ OpenLoops [F. Cascioli et al.]
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→ work by summer student! [A. Motornenko]

- Plan to also support NJet [Badger et al.]

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WHIZARD v2.3.1 contains beta version

QCD corrections (massless and massive emitters)

```
alpha_power = 2
alphas_power = 0

process eett = e1,E1 => t, tbar
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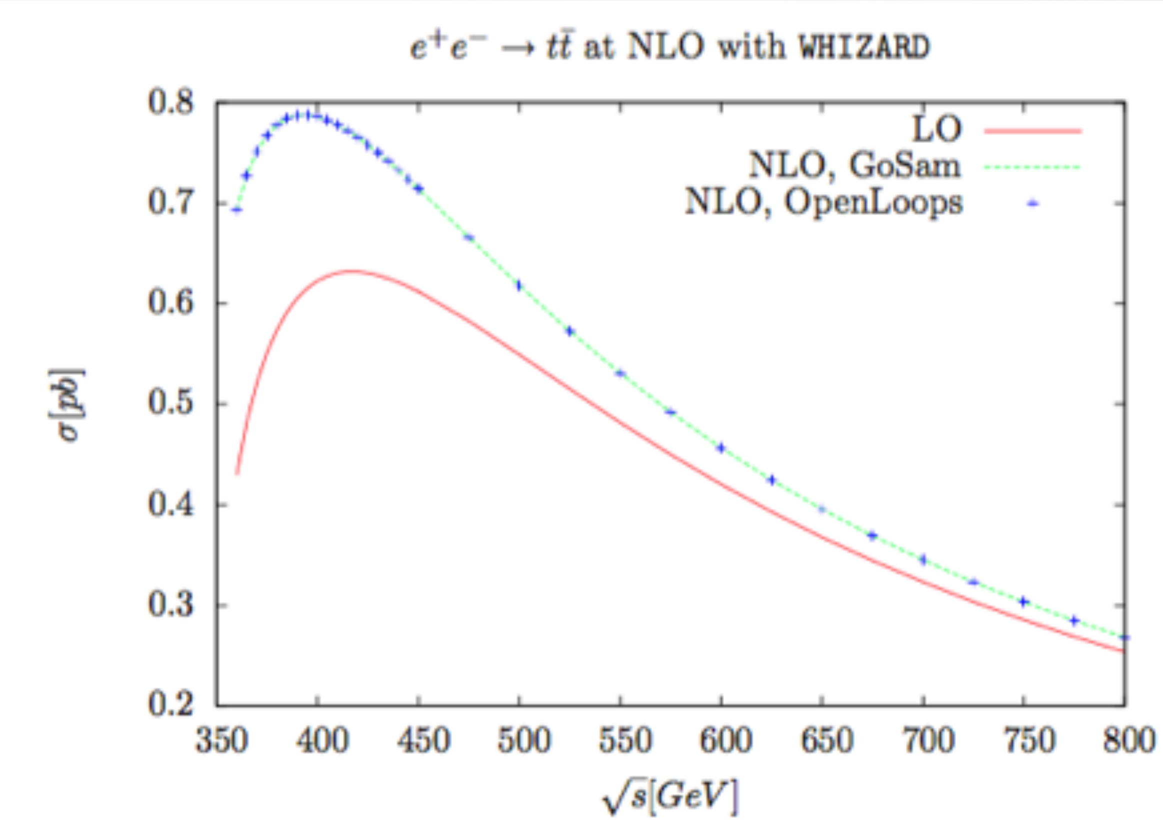

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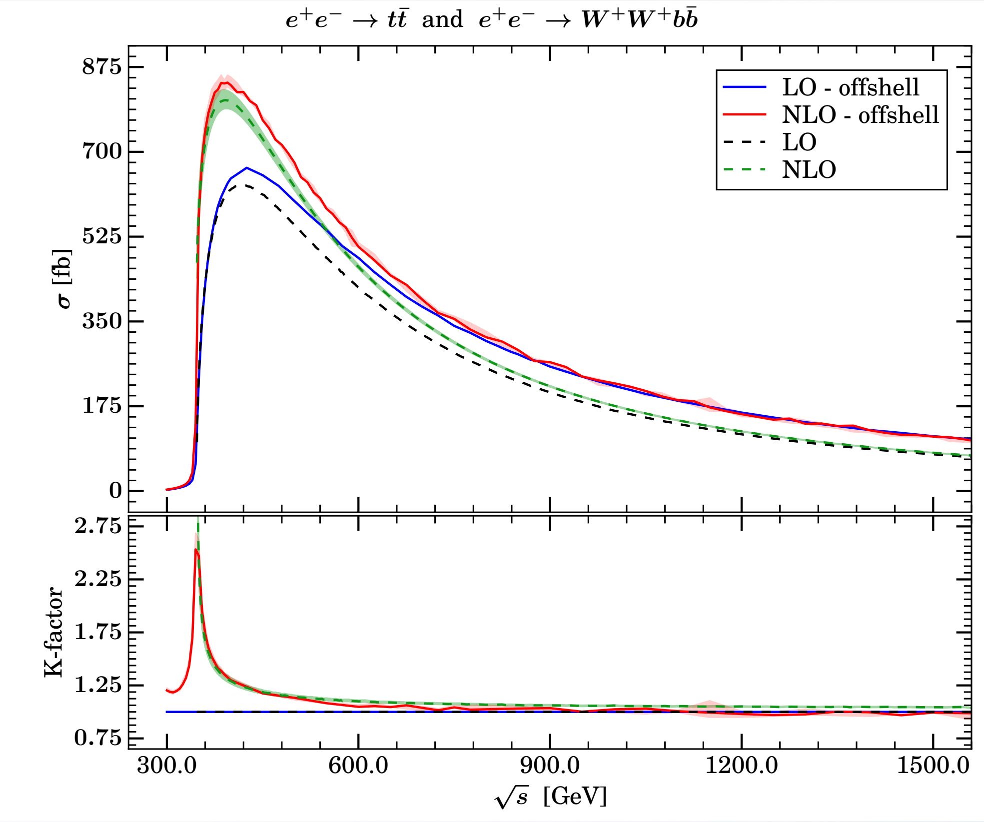

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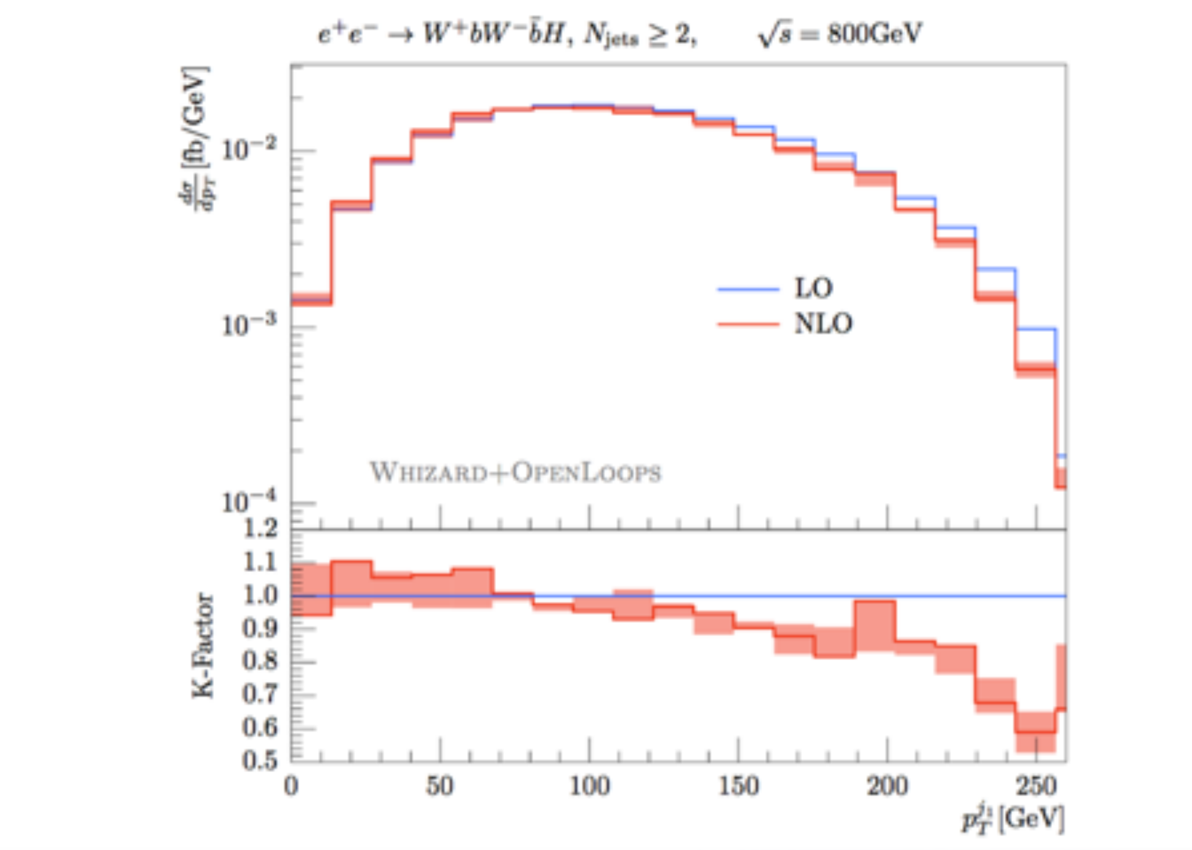
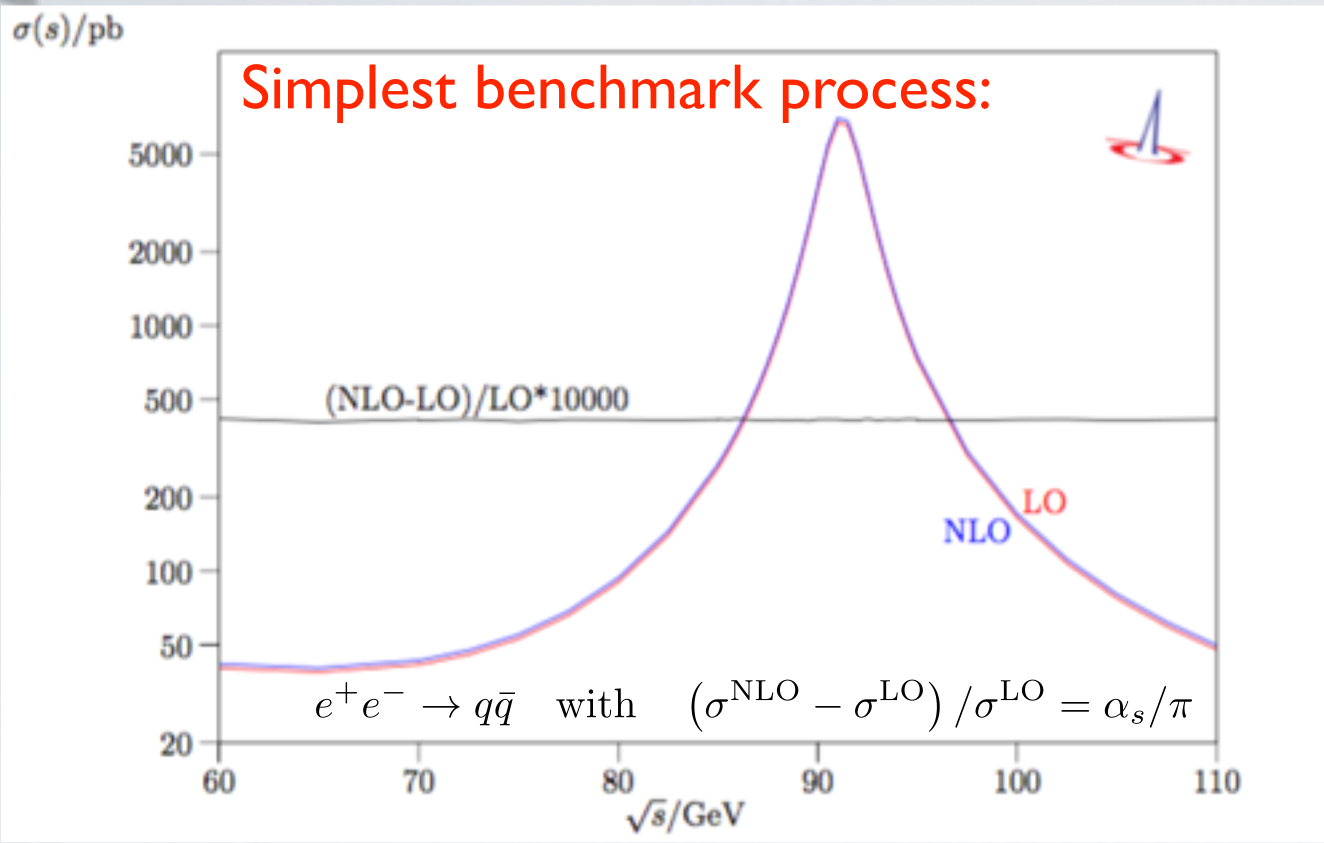


Examples and Validation



Excerpt of validated QCD NLO processes

- $e^+e^- \to q\bar{q}$
- $e^+e^- \to q\bar{q}g$
- $e^+e^- \to \ell^+\ell^- q\bar{q}$
- $e^+e^- \to \ell^+\nu_\ell q\bar{q}$
- $e^+e^- \to t\bar{t}$
- $e^+e^- \to tW^-b$
- $e^+e^- \to W^+W^-b\bar{b}$
- $e^+e^- \to t\bar{t}H$

- Cross-checks with `MG5_aMC@NLO`, `Sherpa`, `MUNICH`
- Phase space integration performs great (*V, R, S*)

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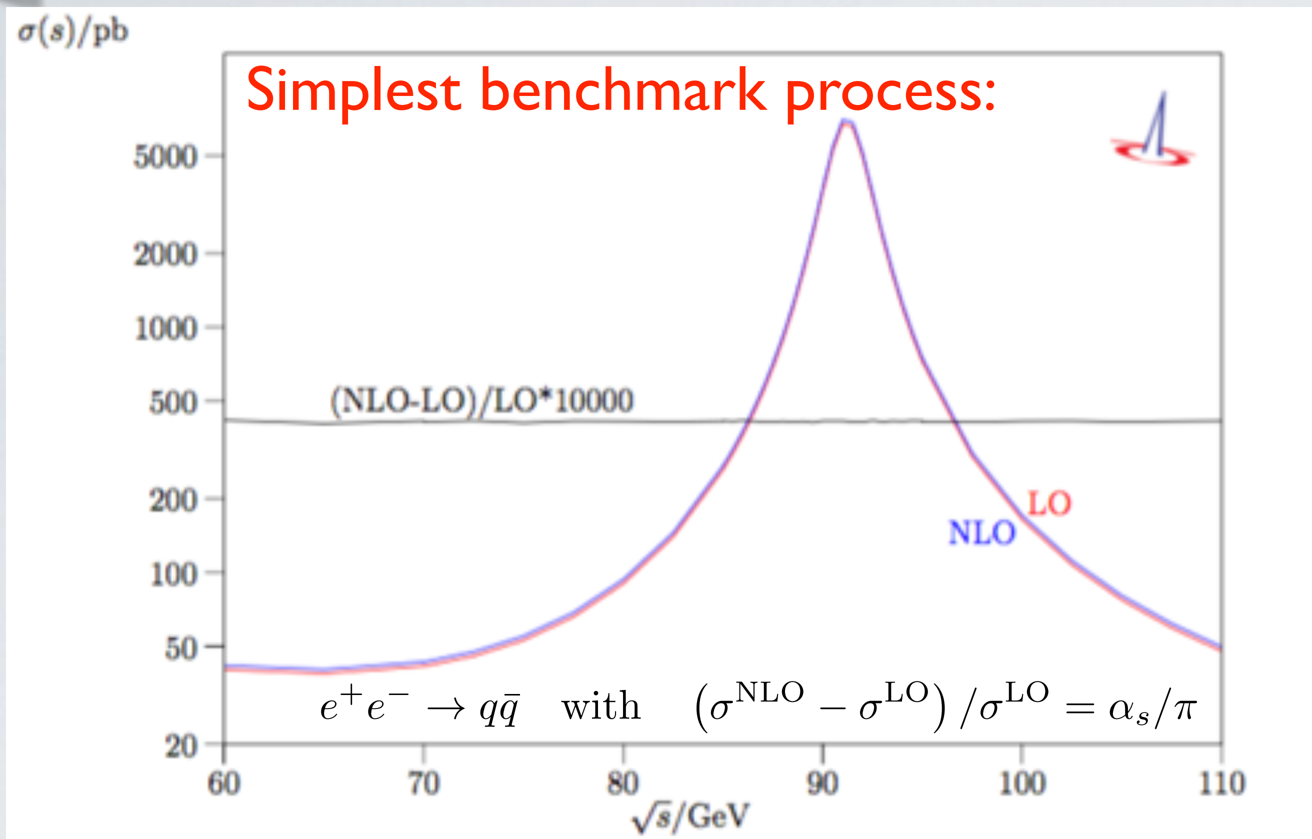

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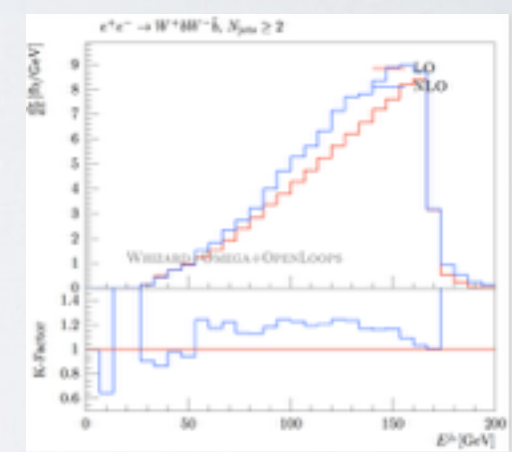

NLO Fixed Order Events

- Add weights of real emission events to weight of Born kinematics using the FKS mapping
- Output weighted events in `WHIZARD` (e.g. using HepMC), then analysis with `Rivet`

Resonance mappings for NLO processes

↪ Talk by Carlo

- Amplitudes (except for pure QCD/QED) contain resonances (Z, W, H, t)
- In general: resonance masses *not* respected by modified kinematics of subtraction terms
- Collinear (and soft) radiation can lead to mismatch between Born and subtraction terms

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- Avoids double logarithms in the resonances' width
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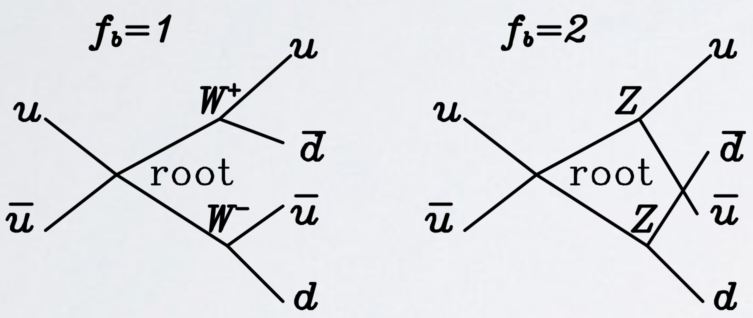

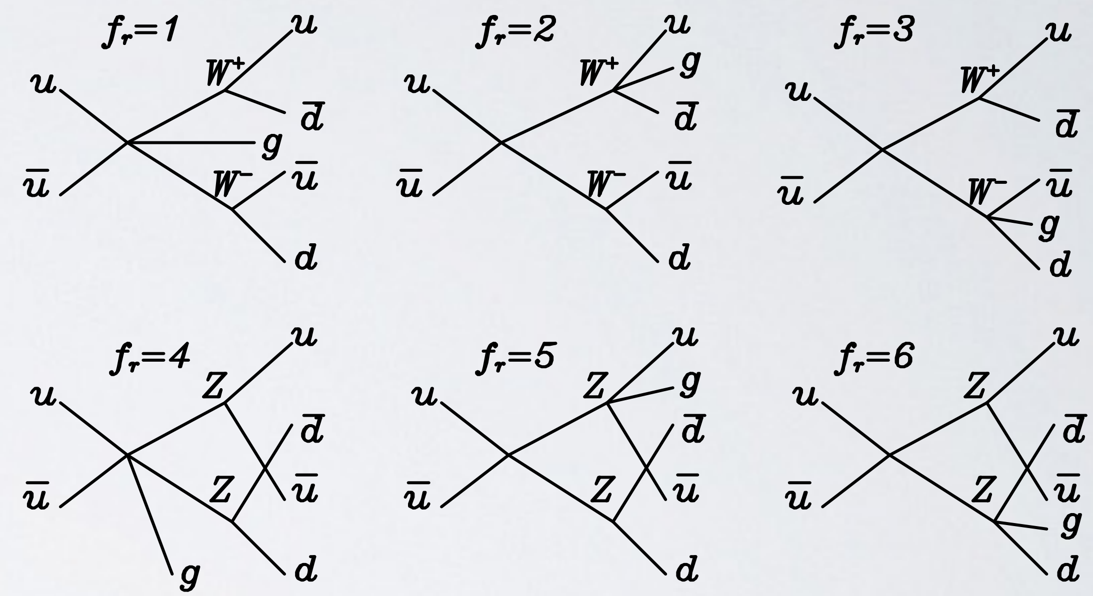

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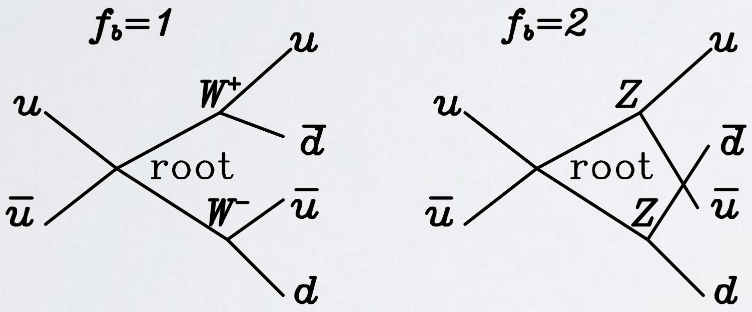

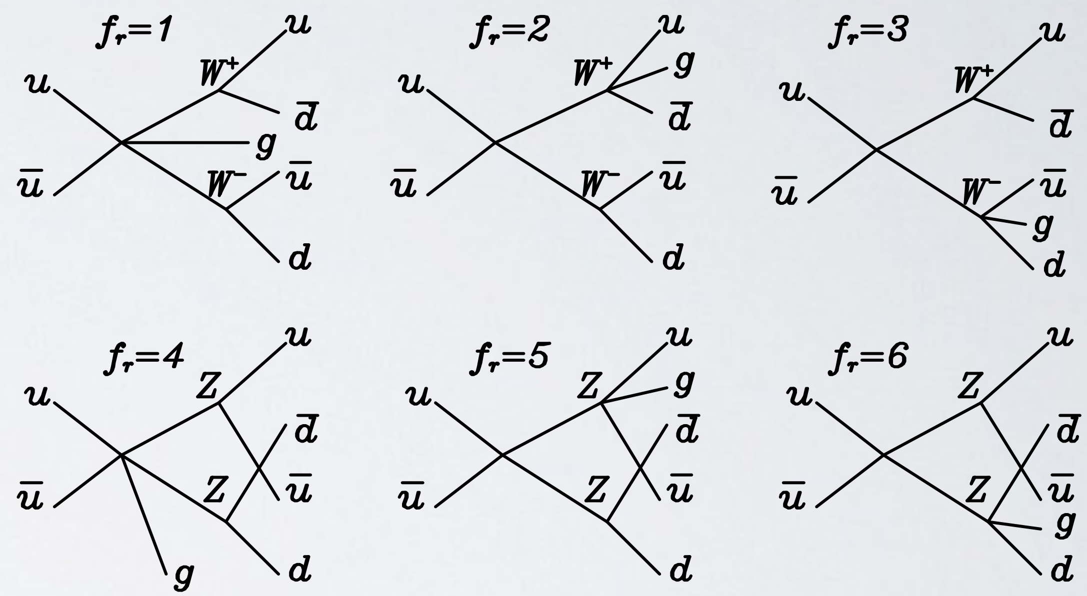

- `WHIZARD` complete automatic implementation: example $e^+ e^- \to \mu\mu bb$ (*ZZ, ZH* histories)

It	Calls	Integral[fb]	Error[fb]	Err[%]	Acc	Eff[%]	Chi2	N[It]
1	11988	9.6811847E+00	6.42E+00	66.30	72.60*	0.65		
2	11959	2.8539703E+00	2.35E-01	8.25	9.02*	0.69		
3	11936	2.4907574E+00	6.54E-01	26.25	28.68	0.35		
4	11908	2.7695559E+00	9.67E-01	34.91	38.09	0.30		
5	11874	2.4346151E+00	4.82E-01	19.80	21.57*	0.74		
5	59665	2.7539078E+00	1.97E-01	7.15	17.47	0.74	0.49	5

standard FKS

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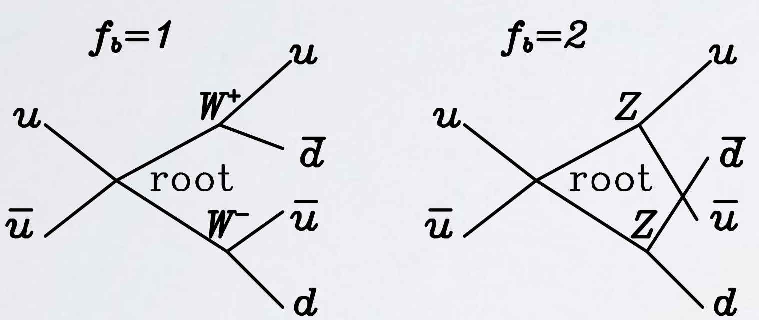

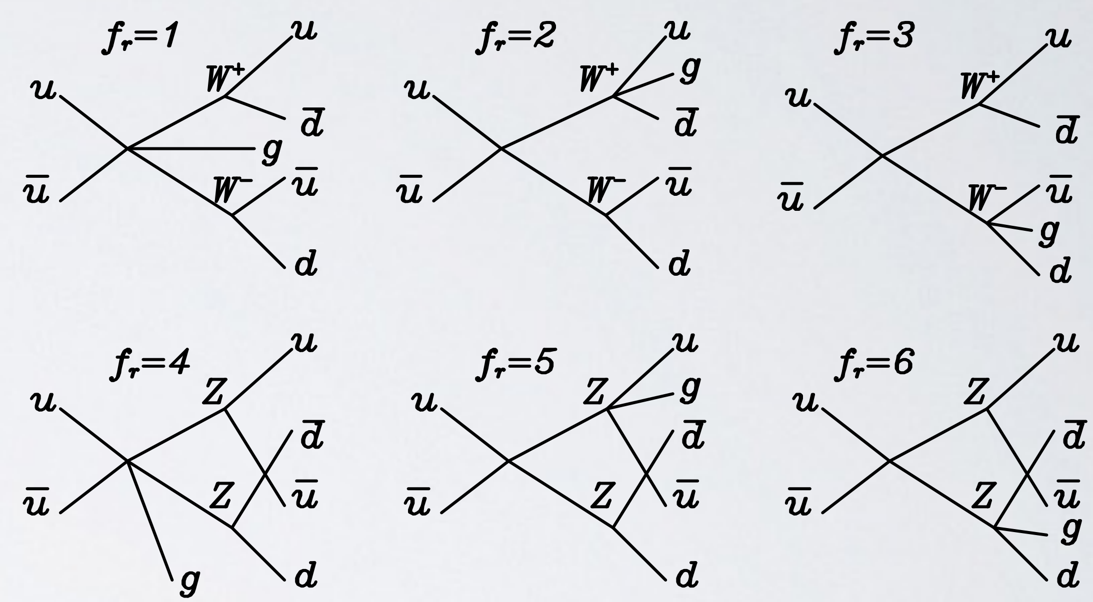

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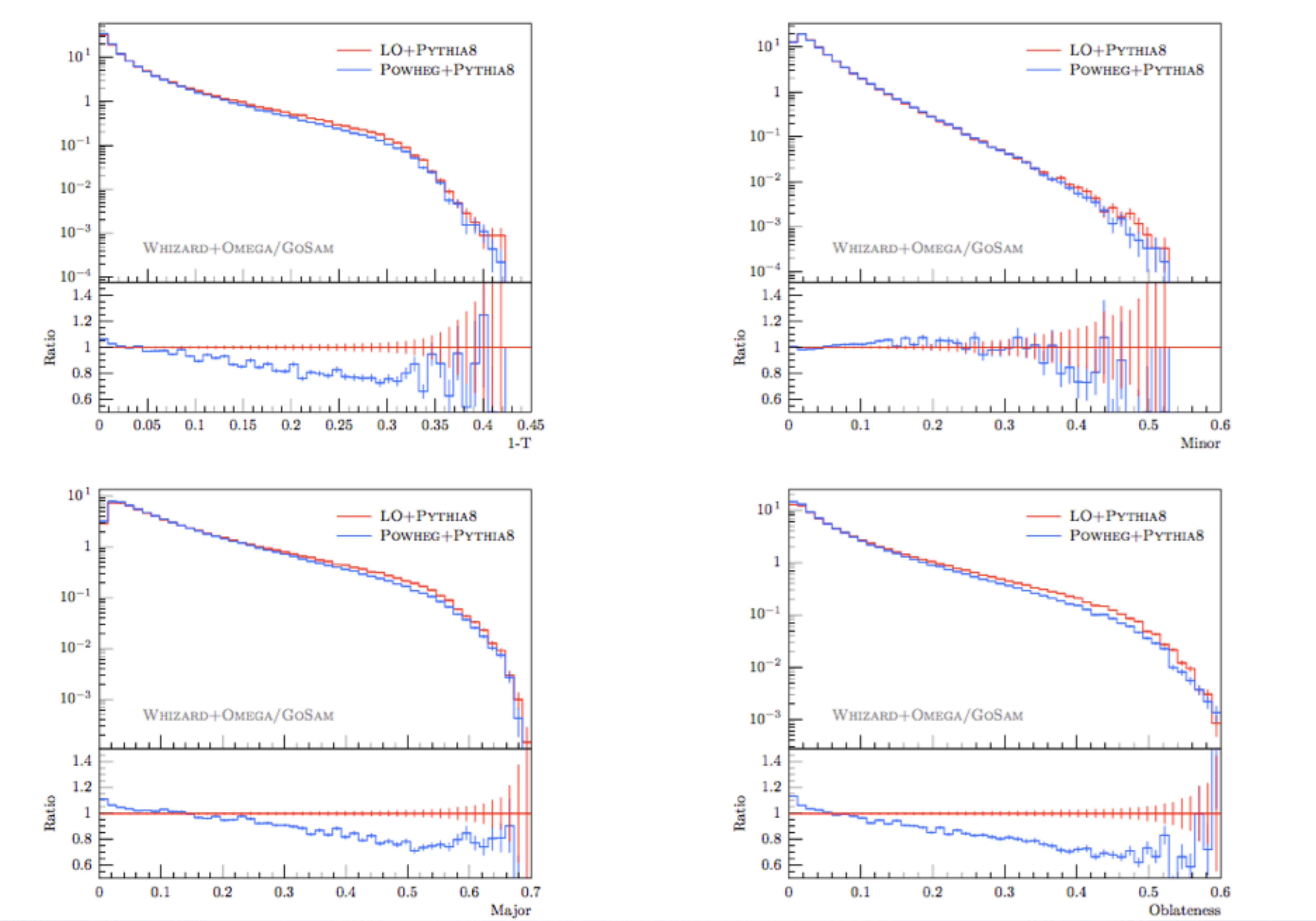
2	11962	2.8591952E+00	5.20E-02	1.82	1.99*	10.91		
3	11936	2.9277880E+00	4.09E-02	1.40	1.52*	14.48		
4	11902	2.8512337E+00	3.98E-02	1.40	1.52*	13.70		
5	11874	2.8855399E+00	3.87E-02	1.34	1.46*	17.15		
5	59662	2.8842006E+00	2.04E-02	0.71	1.72	17.15	0.53	5

FKS with resonance mappings

Automated POWHEG Matching, e.g.: $e^+e^- \to jj$



WHIZARD LHC example: Drell-Yan

- Simplest hadron collider processes: $pp \to (Z \to ll) + X$, $pp \to (W \to l\nu) + X$, $pp \to ZZ + X$
- Standard candle processes

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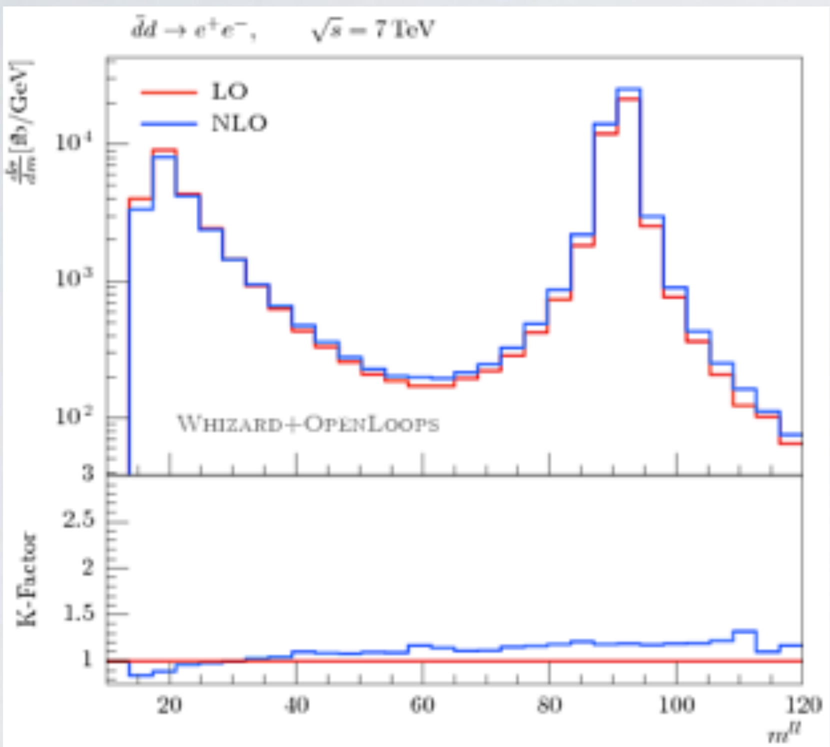

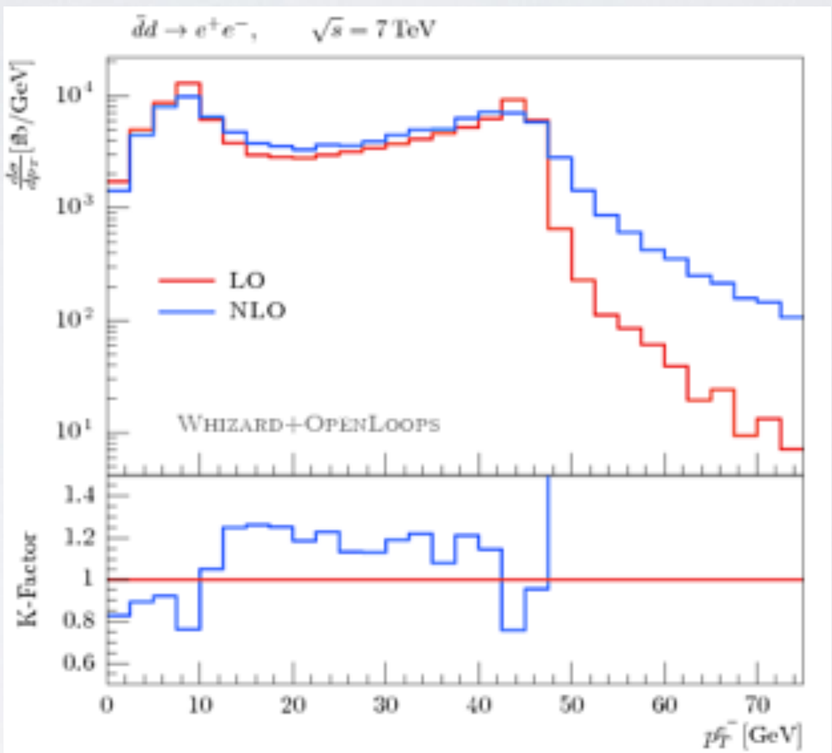

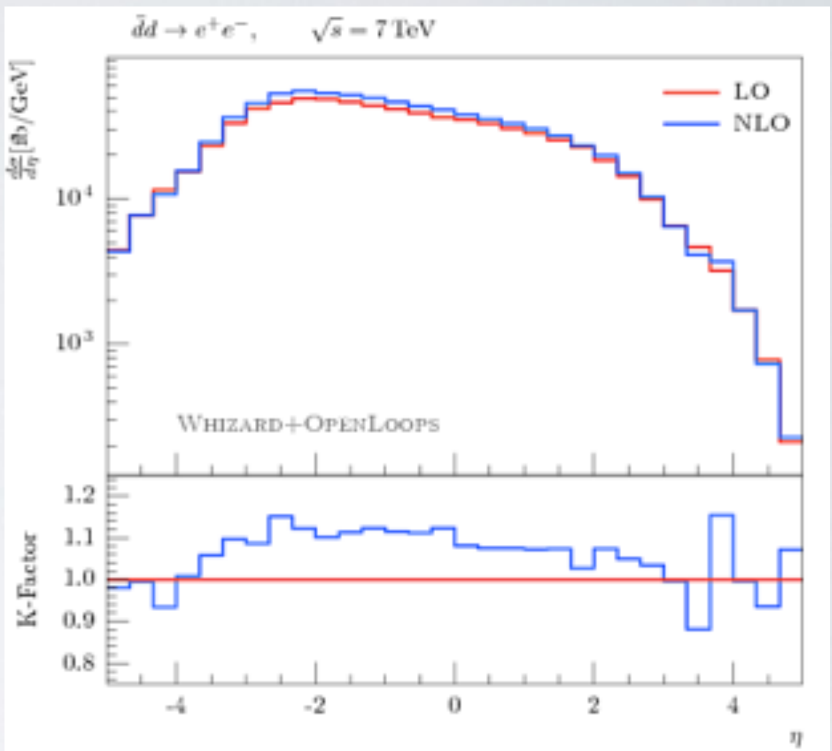

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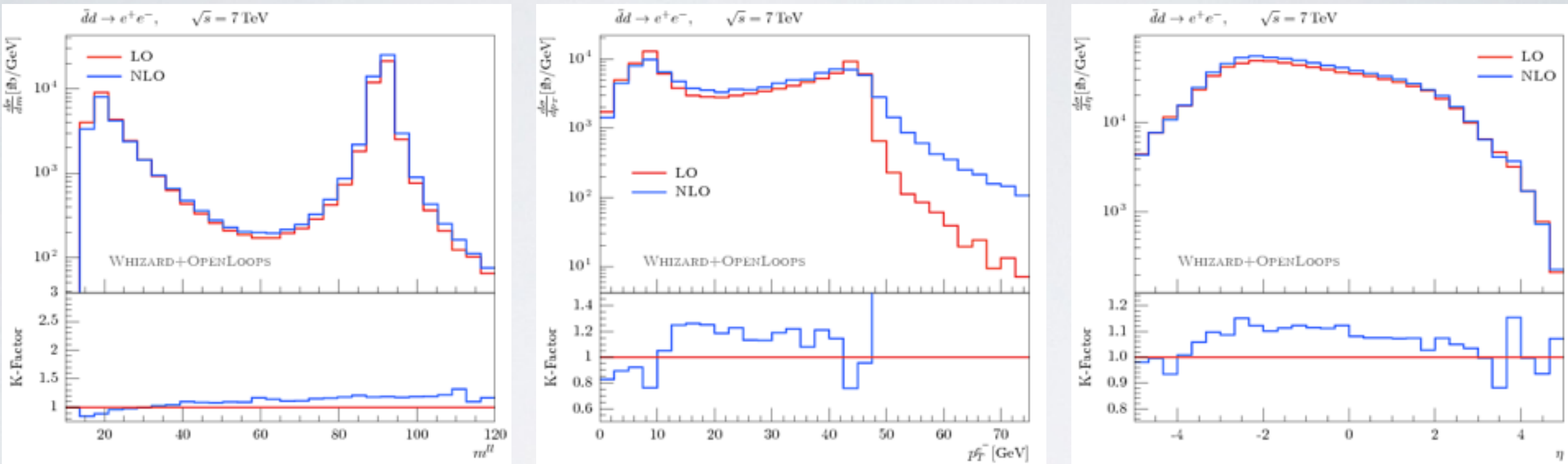


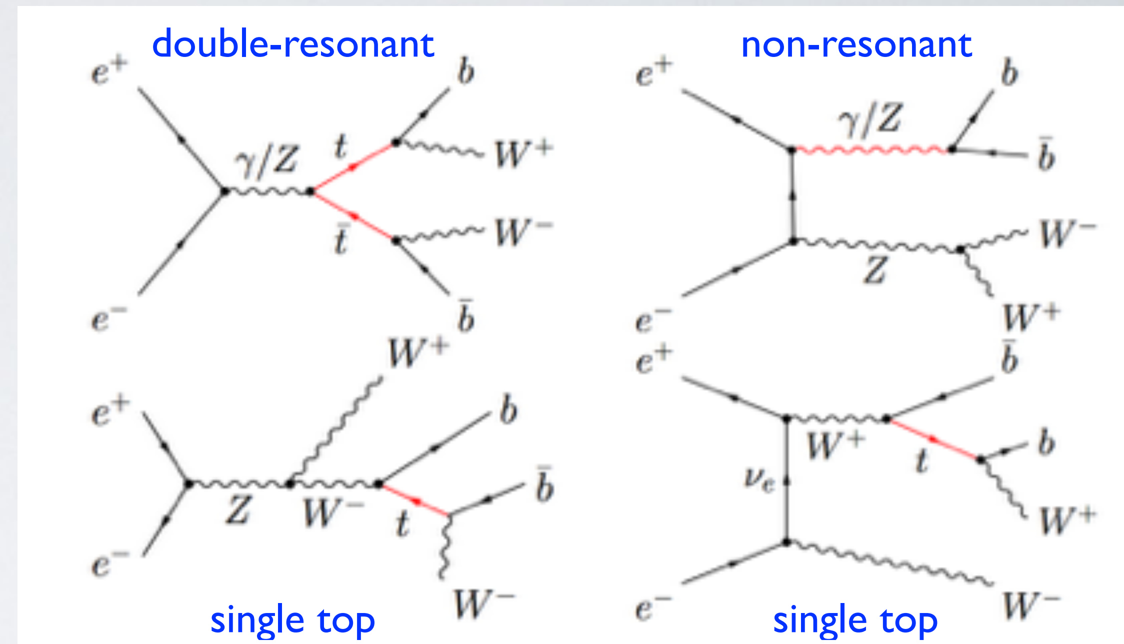
To be fully validated:

- Flavor sums in fixed-order event generation
- Color in initial and final state (already validated for top decay)
- Gluons in the initial state
- Next processes: $pp \to Zj + X$, $pp \to tt + X$, $pp \to jj + X$
- automated POWHEG matching for hadron collider

WHIZARD ee example: *tt* & *ttH* (on-/off-shell)

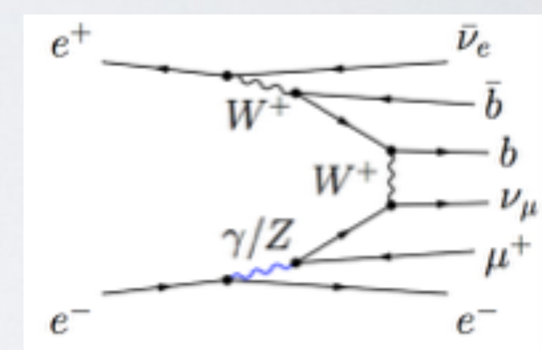
Chokoufé/Kilian/Lindert/Pozzorini/JRR/Weiss, 1608.XXXXX

- Paradigm processes at lepton colliders: precision determination of m_t and Y_t
- Major bkgd. for EW processes (*VVV*, VBS); many BSM searches
- Processes of increasing complexity: 2→2, 2→4, 2→6

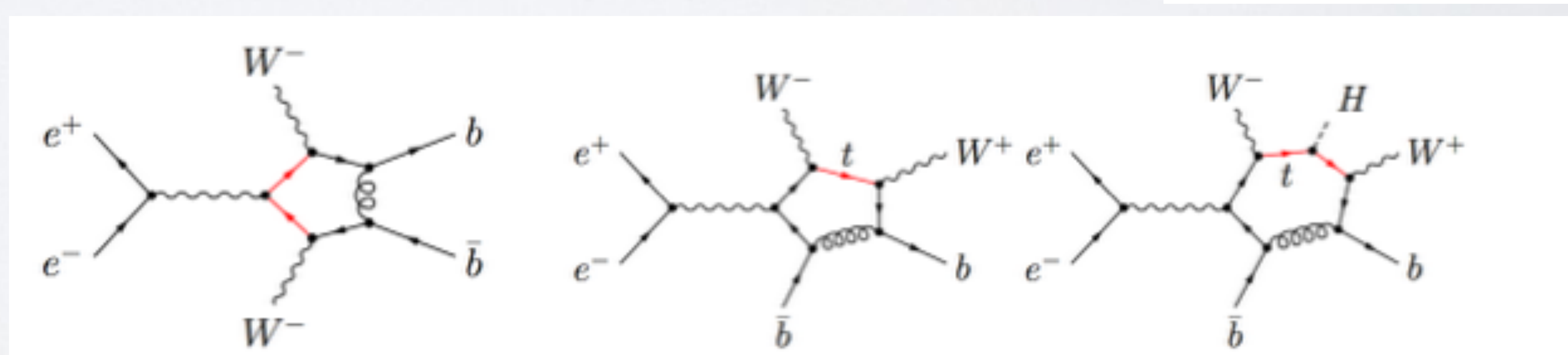


$e^+e^- \to$	$n_{\text{loop diags}}$	Max. prop.	n_{hel}
$t\bar{t}$	2	3	16
$W^+W^-b\bar{b}$	157	5	144
$b\bar{b}\bar{\nu}_e e^- \nu_\mu \mu^+$	830	5	16
$t\bar{t}H$	17	4	16
$bW^+\bar{b}W^-H$	1548	6	144
$b\bar{b}\bar{\nu}_e e^- \nu_\mu \mu^+ H$	7436	6	16

- Cross checks for 2→2, 2→4 with `Sherpa`, `Munich`, `Madgraph5_aMC@NLO`
- Using massive *b* quarks: no cuts necessary for $e^+e^- \to W^+W^-bb$
- Full process $e^+e^- \to \mu^+\nu_\mu e^-\nu_e bb$ exhibits collinear singularity:



- Typical pentagon/hexagon diagrams:



WHIZARD ee example: *tt* & *ttH* (on-/off-shell)

$$m_Z = 91.1876\,\text{GeV}, \qquad m_W = 80.385\,\text{GeV}$$
$$m_b = 4.2\,\text{GeV}, \qquad m_t = 173.2\,\text{GeV}.$$

$$\Gamma^{\text{LO}}_{t\to Wb} = 1.4986\,\text{GeV}, \qquad \Gamma^{\text{NLO}}_{t\to Wb} = 1.3681\,\text{GeV},$$
$$\Gamma^{\text{LO}}_{t\to f\bar{f}b} = 1.4757\,\text{GeV}, \qquad \Gamma^{\text{NLO}}_{t\to f\bar{f}b} = 1.3475\,\text{GeV}.$$

$$m_H = 125\ \text{GeV} \qquad \Gamma_H = 0.000431\ \text{GeV}$$

$$\Gamma^{\text{LO}}_Z = 2.4409\,\text{GeV}, \qquad \Gamma^{\text{NLO}}_Z = 2.5060\,\text{GeV},$$
$$\Gamma^{\text{LO}}_W = 2.0454\,\text{GeV}, \qquad \Gamma^{\text{NLO}}_W = 2.0978\,\text{GeV}.$$

complex mass scheme:

$$\mu_i^2 = M_i^2 - \mathrm{i}\Gamma_i M_i \qquad \text{for } i = \mathrm{W, Z, t, H}$$

$$s_w^2 = 1 - c_w^2 = 1 - \frac{\mu_\mathrm{W}^2}{\mu_\mathrm{Z}^2}$$

Chokoufé/Kilian/Lindert/Pozzorini/JRR/Weiss, 1608.XXXXX

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$$\Gamma_W^{\mathrm{LO}} = 2.0454\,\mathrm{GeV}, \qquad \Gamma_W^{\mathrm{NLO}} = 2.0978\,\mathrm{GeV}.$$

$$\Gamma^{\mathrm{LO}}_{t\to Wb} = 1.4986\,\mathrm{GeV}, \qquad \Gamma^{\mathrm{NLO}}_{t\to Wb} = 1.3681\,\mathrm{GeV},$$
$$\Gamma^{\mathrm{LO}}_{t\to f\bar{f}b} = 1.4757\,\mathrm{GeV}, \qquad \Gamma^{\mathrm{NLO}}_{t\to f\bar{f}b} = 1.3475\,\mathrm{GeV}.$$

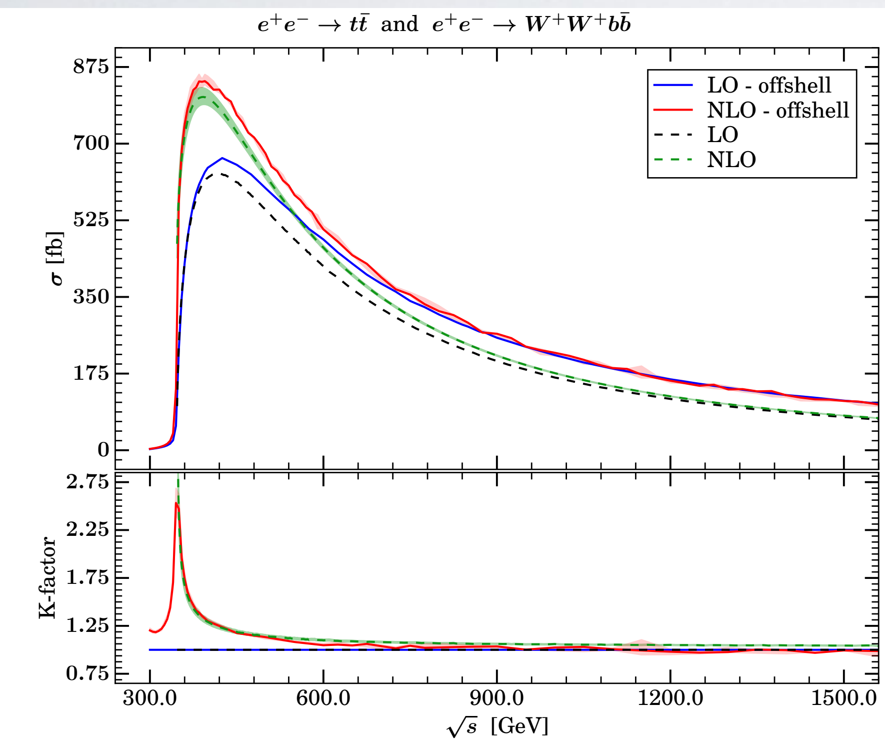
$$m_H = 125\ \mathrm{GeV} \qquad \Gamma_H = 0.000431\ \mathrm{GeV}$$

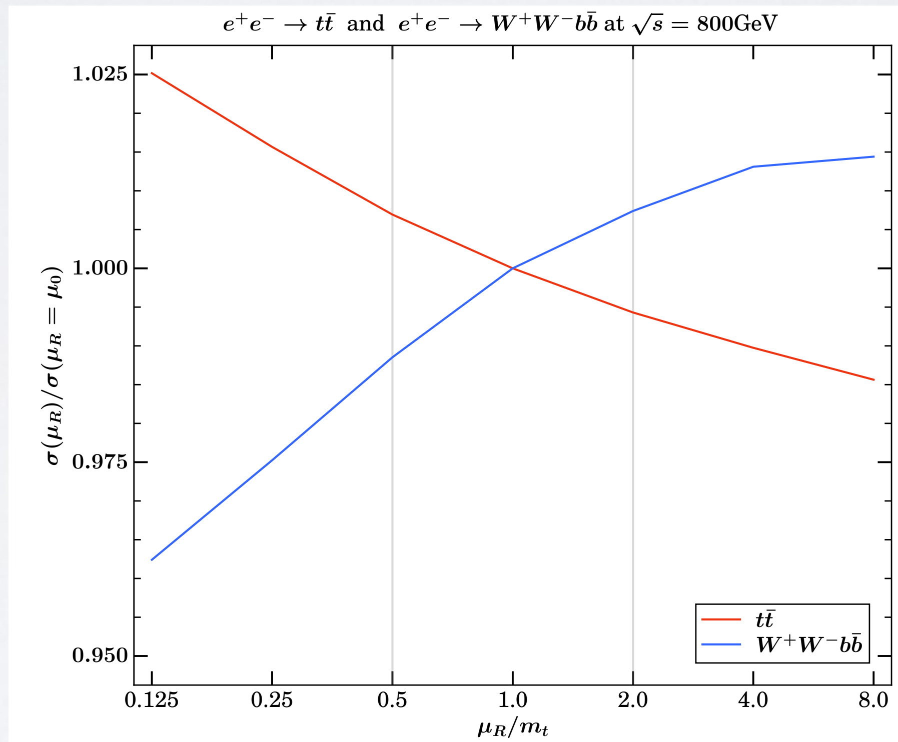
complex mass scheme:

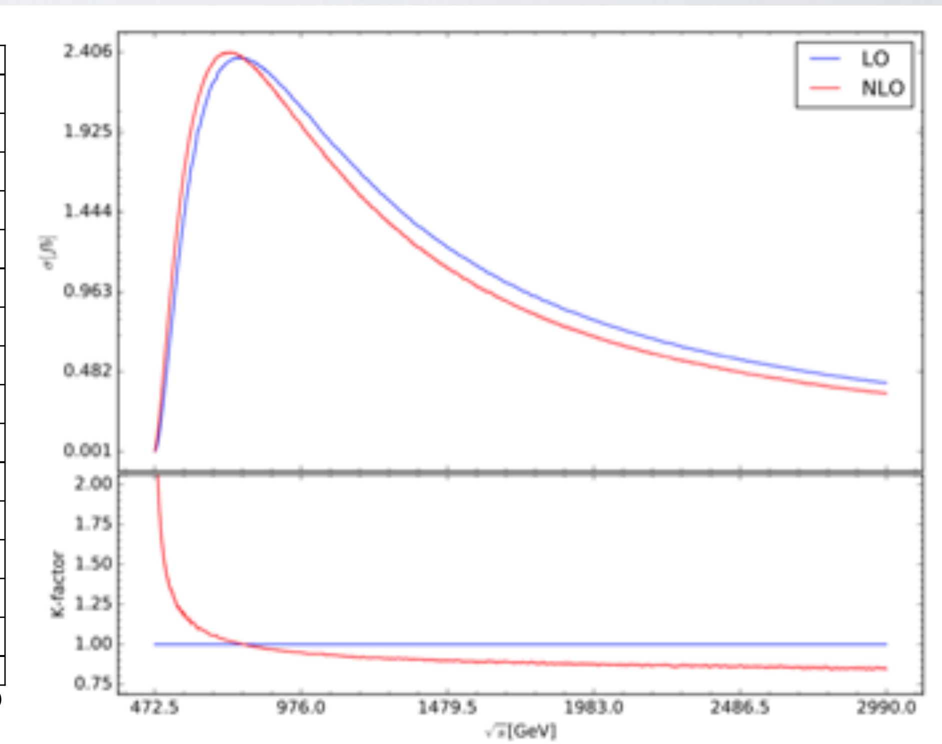
$$\mu_i^2 = M_i^2 - \mathrm{i}\Gamma_i M_i \qquad \text{for } i = \mathrm{W, Z, t, H}$$

$$s_w^2 = 1 - c_w^2 = 1 - \frac{\mu_W^2}{\mu_Z^2}$$

Chokoufé/Kilian/Lindert/Pozzorini/JRR/Weiss, 1608.XXXXX







Choose $\sqrt{s}$ = 800 GeV because its the maximum of the *ttH* cross section

WHIZARD ee example: *tt* & *ttH* (on-/off-shell)

$$m_Z = 91.1876\,\text{GeV}, \qquad m_W = 80.385\,\text{GeV}$$
$$m_b = 4.2\,\text{GeV}, \qquad m_t = 173.2\,\text{GeV}.$$

$$\Gamma_Z^{\text{LO}} = 2.4409\,\text{GeV}, \qquad \Gamma_Z^{\text{NLO}} = 2.5060\,\text{GeV},$$
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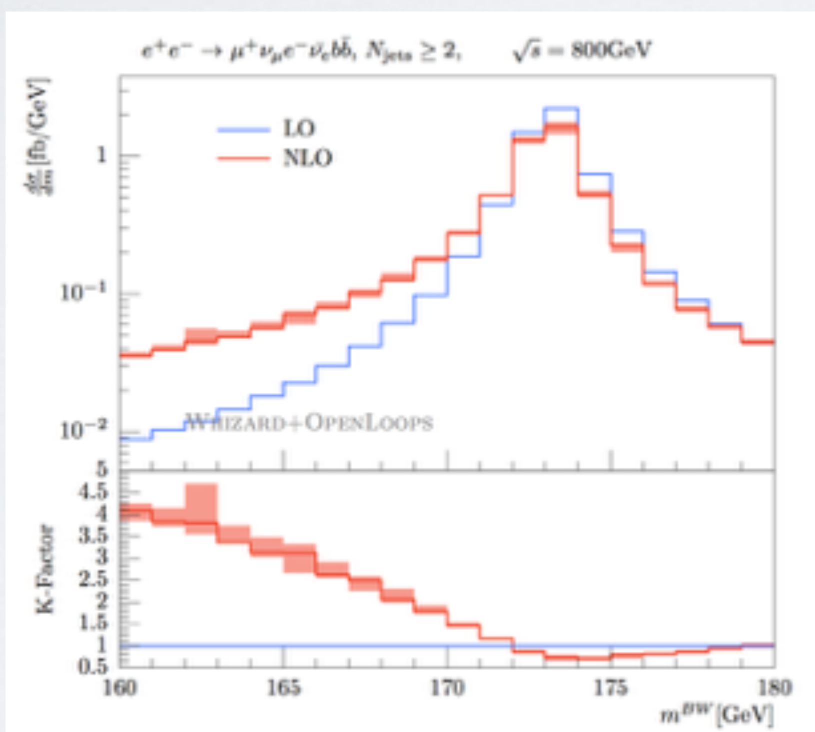

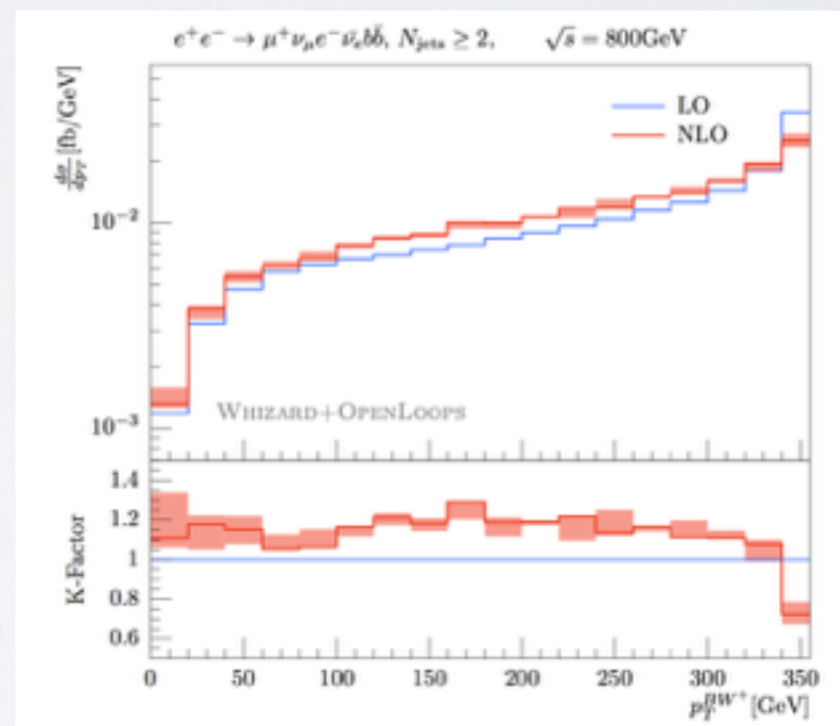

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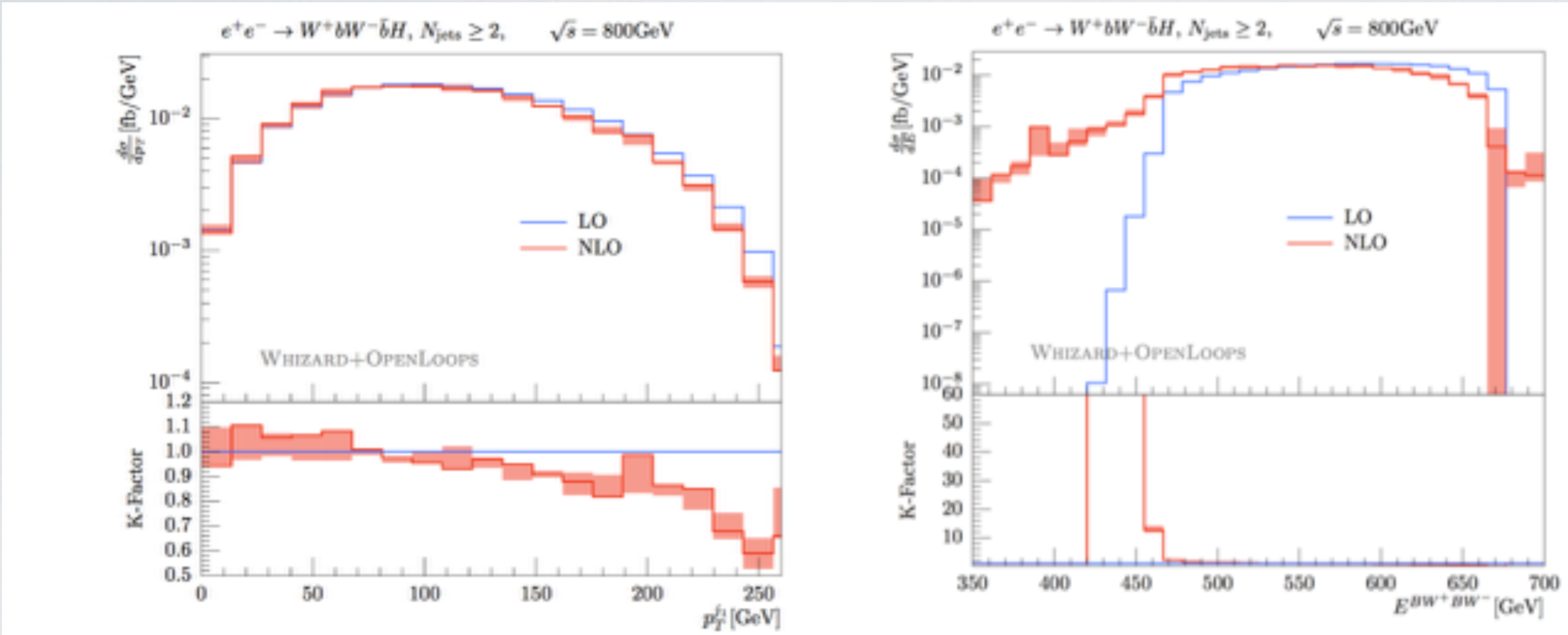
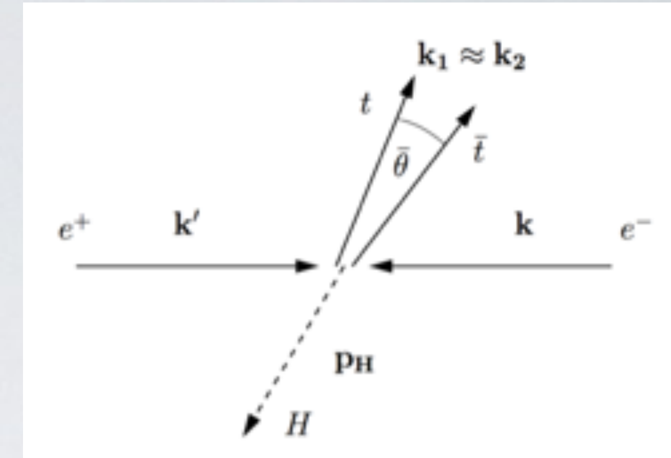
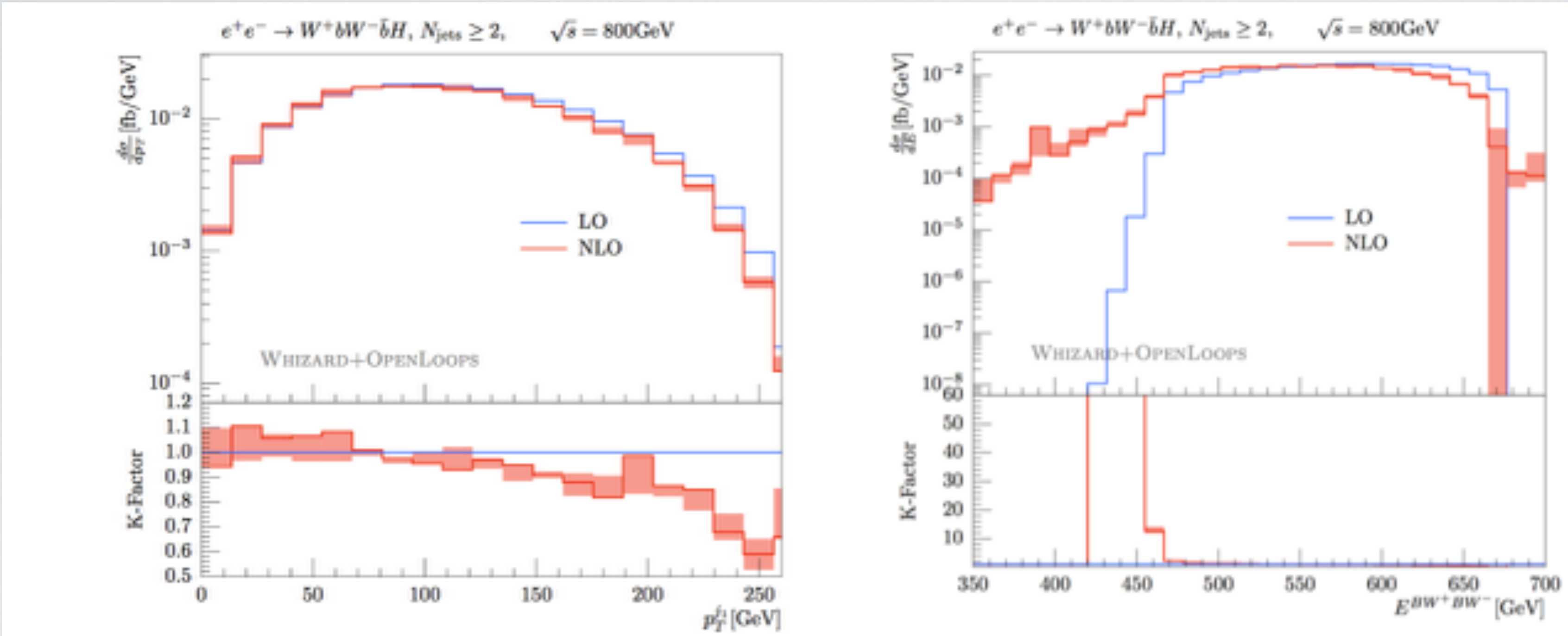


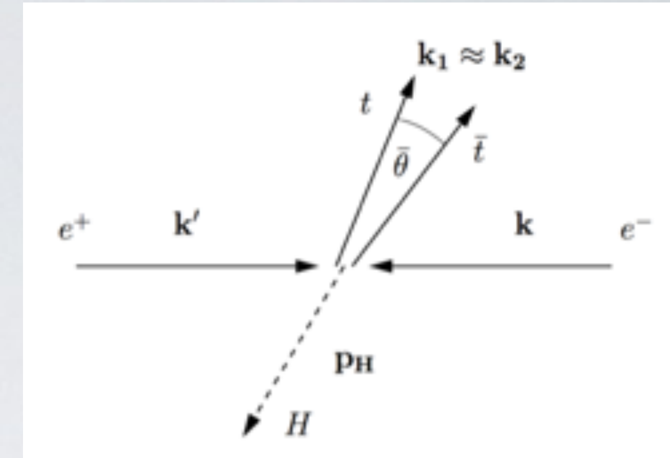


$$E_h = \frac{1}{2\sqrt{s}}\left[s + M_h^2 - (k_1 + k_2)^2\right]$$

Chokoufé/Kilian/Lindert/Pozzorini/JRR/Weiss, 1608.XXXXX

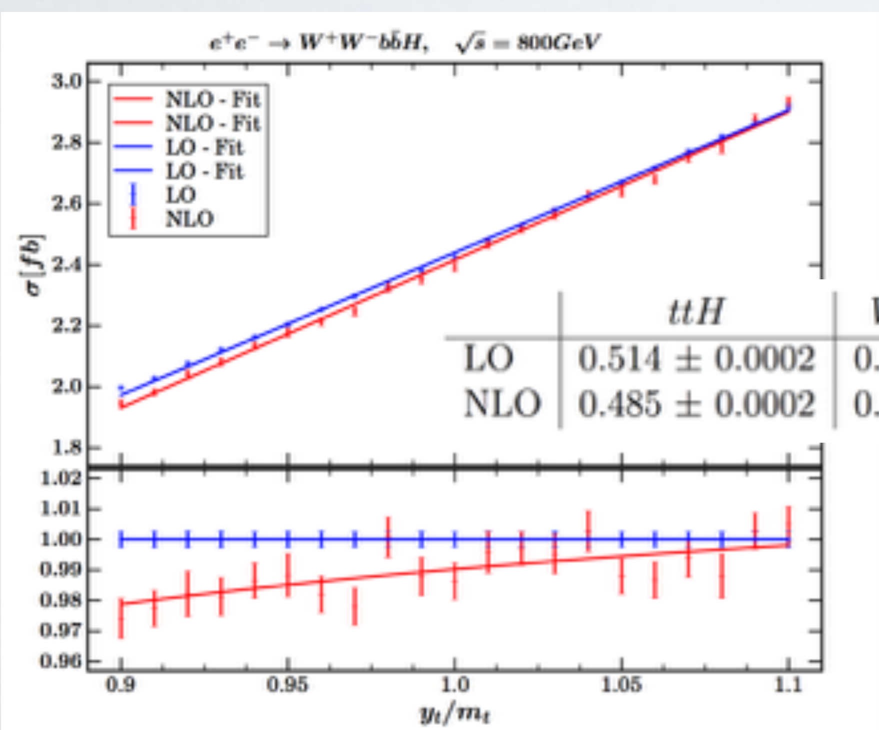
WHIZARD ee example: *tt* & *ttH* (on-/off-shell)





$$E_h = \frac{1}{2\sqrt{s}} \left[s + M_h^2 - (k_1 + k_2)^2 \right]$$

Determination of top Yukawa coupling (*ttH*)



	ttH	$W^+W^-b\bar{b}H$
LO	0.514 ± 0.0002	0.520 ± 0.001
NLO	0.485 ± 0.0002	0.497 ± 0.002

Chokoufé/Kilian/Lindert/Pozzorini/JRR/Weiss, 1608.XXXXX

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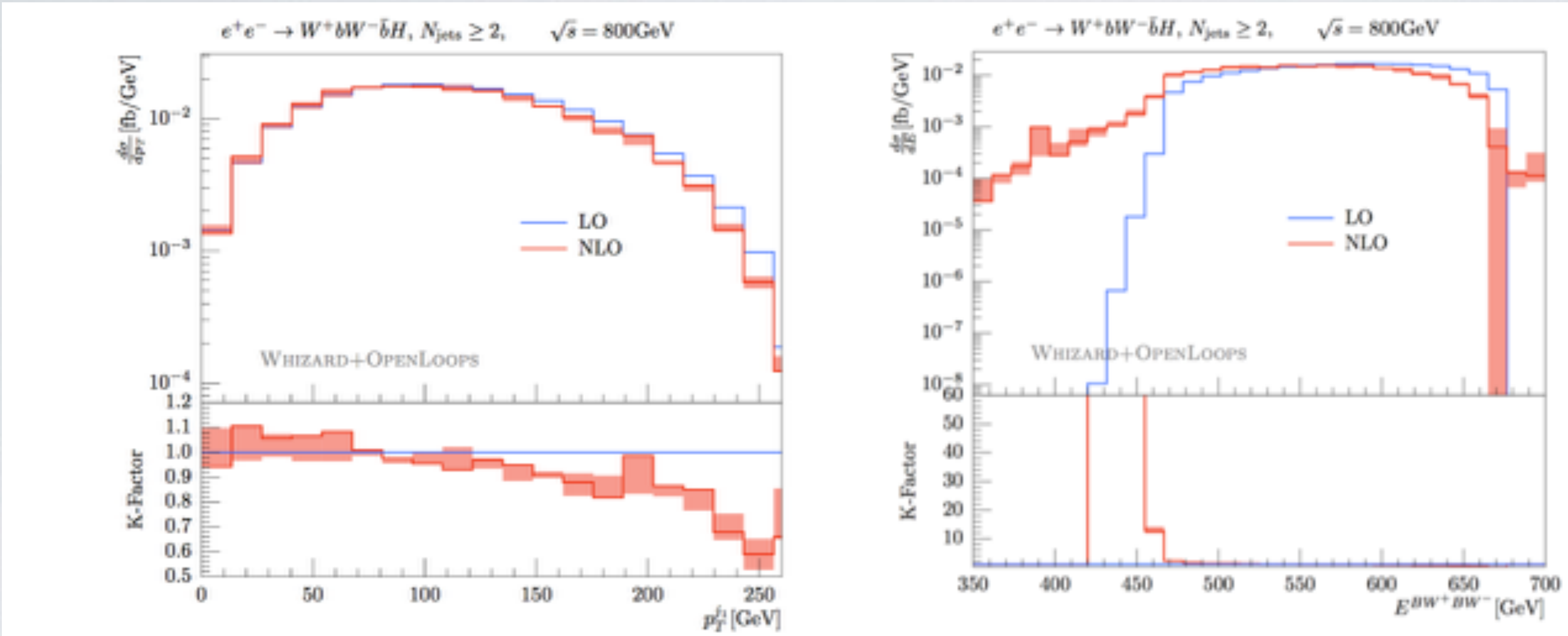

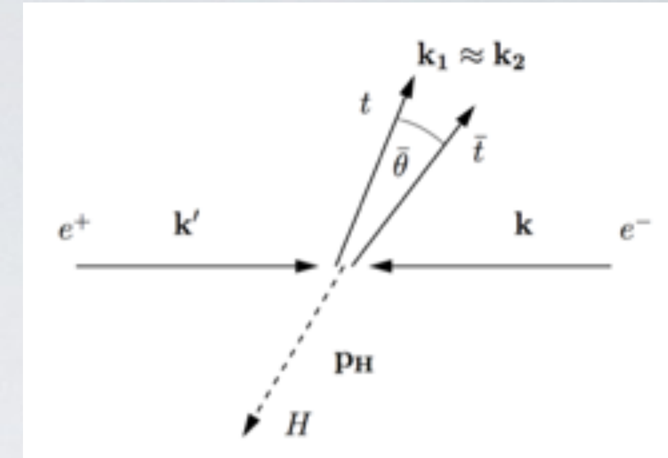

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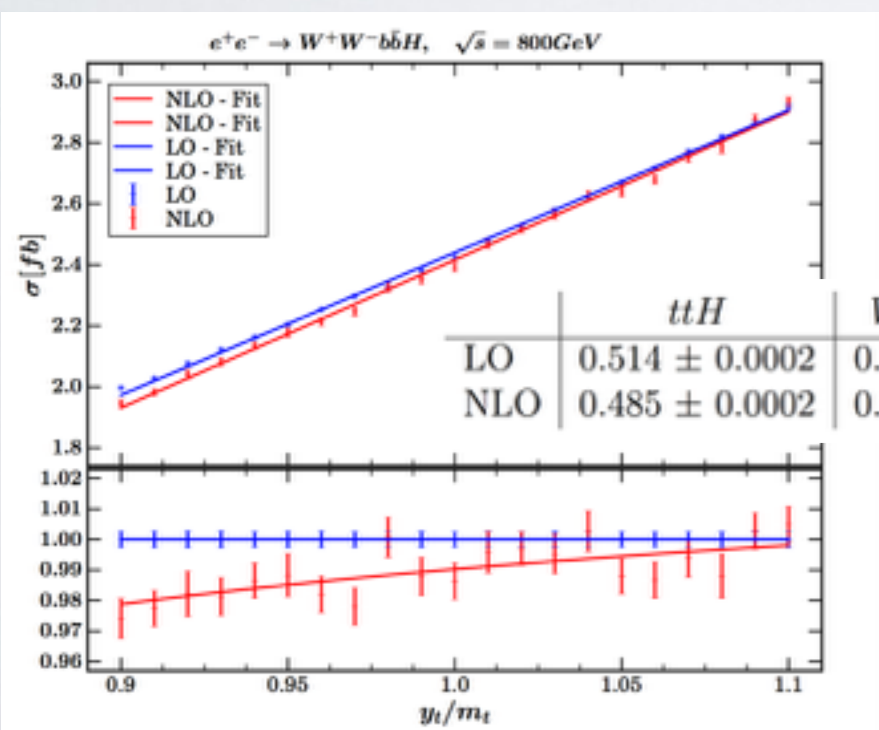


	$t\bar{t}H$	$W^+W^-b\bar{b}H$
LO	0.514 ± 0.0002	0.520 ± 0.001
NLO	0.485 ± 0.0002	0.497 ± 0.002

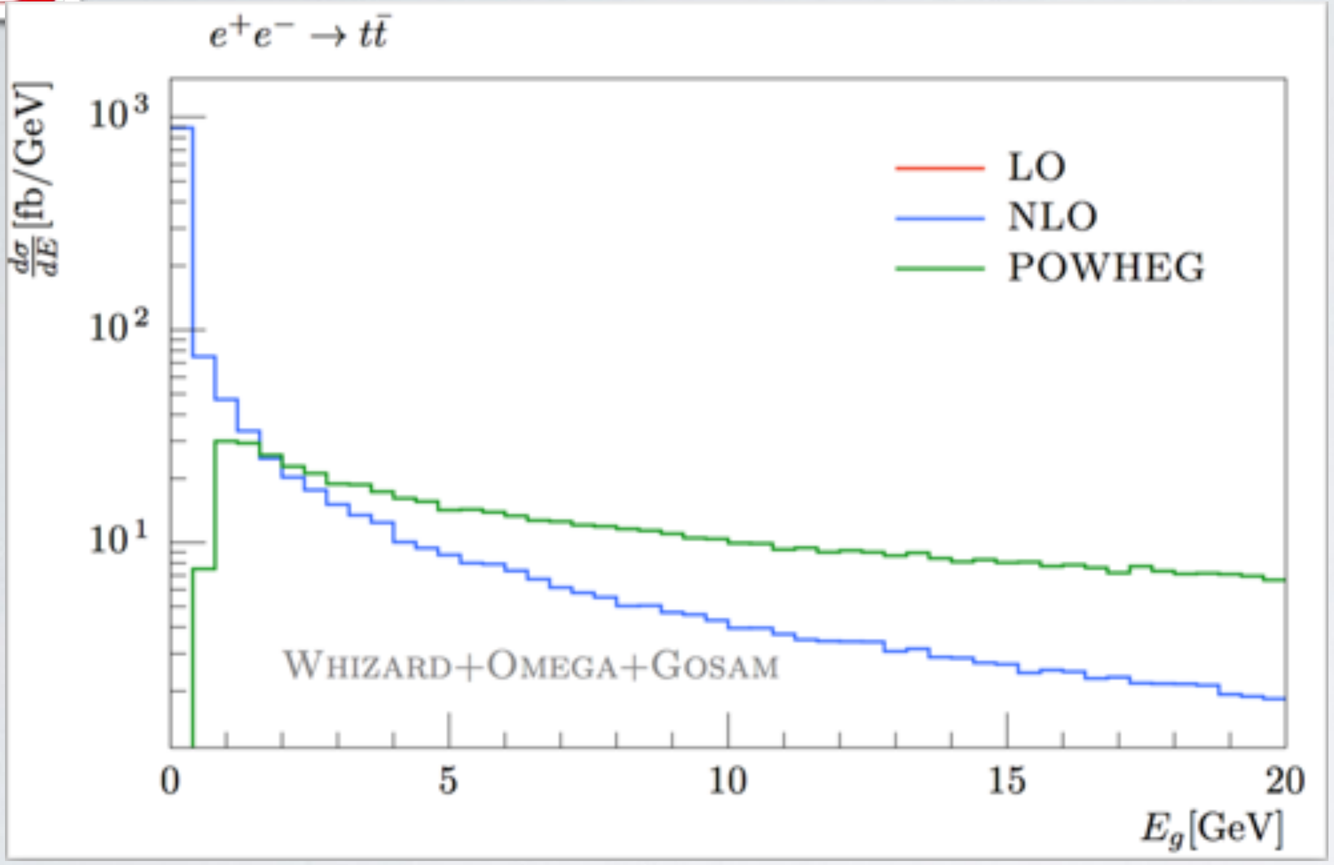
Polarized Results (*tt*)

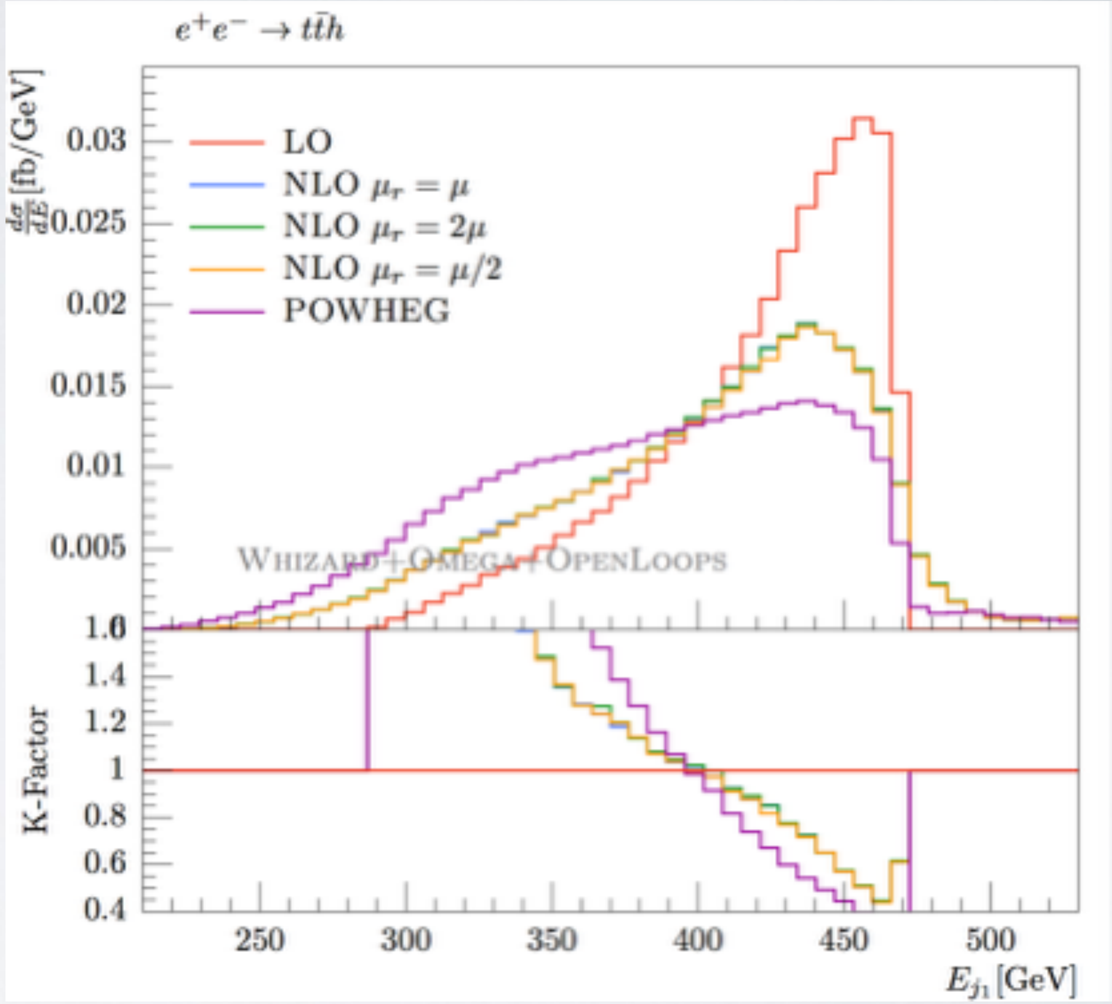
- ILC will always run polarized
- Polarized 1-loop amplitudes beyond BLHA

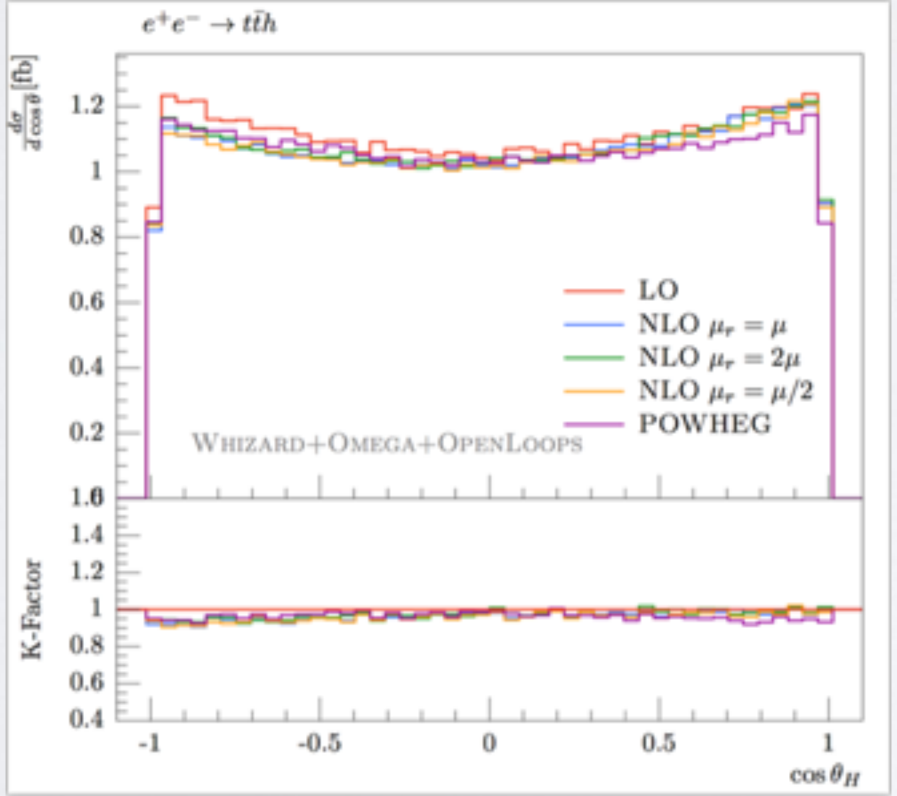
		$\sqrt{s} = 800$ GeV			$\sqrt{s} = 1500$ GeV		
$P(e^-)$	$P(e^+)$	σ^{LO}[fb]	σ^{NLO}[fb]	K-factor	σ^{LO}[fb]	σ^{NLO}[fb]	K-factor
0%	0%	253.7	272.8	1.075	75.8	79.4	1.049
-80%	0%	176.5	190.0	1.077	98.3	103.1	1.049
+80%	0%	176.5	190.0	1.077	53.2	55.9	1.049
-80%	30%	420.8	452.2	1.074	124.9	131.0	1.048
-80%	60%	510.7	548.7	1.074	151.6	158.9	1.048
80%	-30%	208.4	224.5	1.077	63.0	66.1	1.049
80%	-60%	240.3	258.9	1.077	72.7	76.3	1.049

Chokoufé/Kilian/Lindert/Pozzorini/JRR/Weiss, 1608.XXXXX

POWHEG-matched results for *tt* and *ttH*



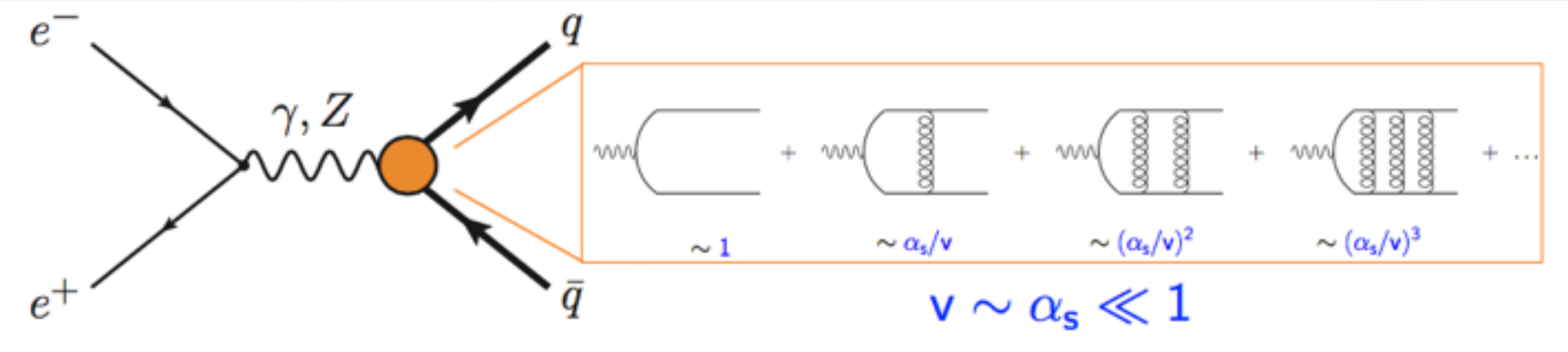




Threshold-continuum matching: e.g. top

ILC top threshold scan best-known method to measure top quark mass, ΔM ~ 30-50 MeV

Threshold region:
top velocity $v \sim \alpha_s \ll 1$



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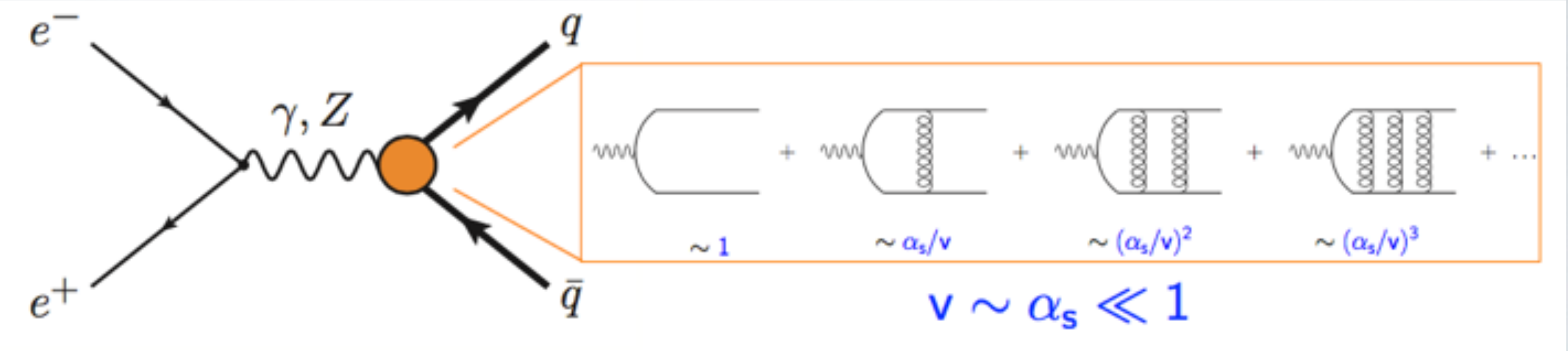

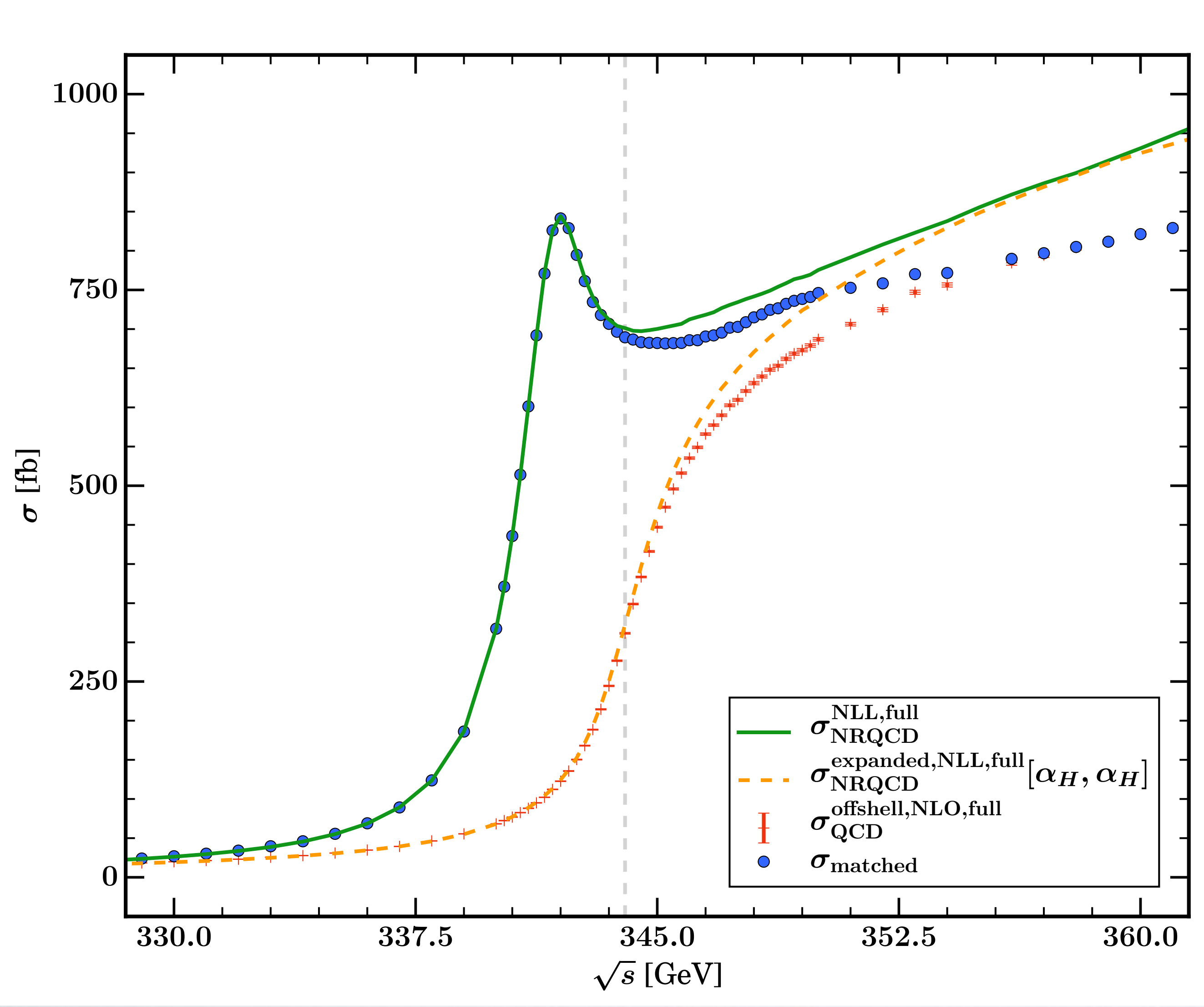

For (almost) fully exclusive description:

proper matching between vNRQCD NLL resummation and NLO QCD continuum

Bach/Chokoufé/Hoang/Kilian/JRR/Stahlhofen/Teubner/Weiss, 2016 & *work in progress*

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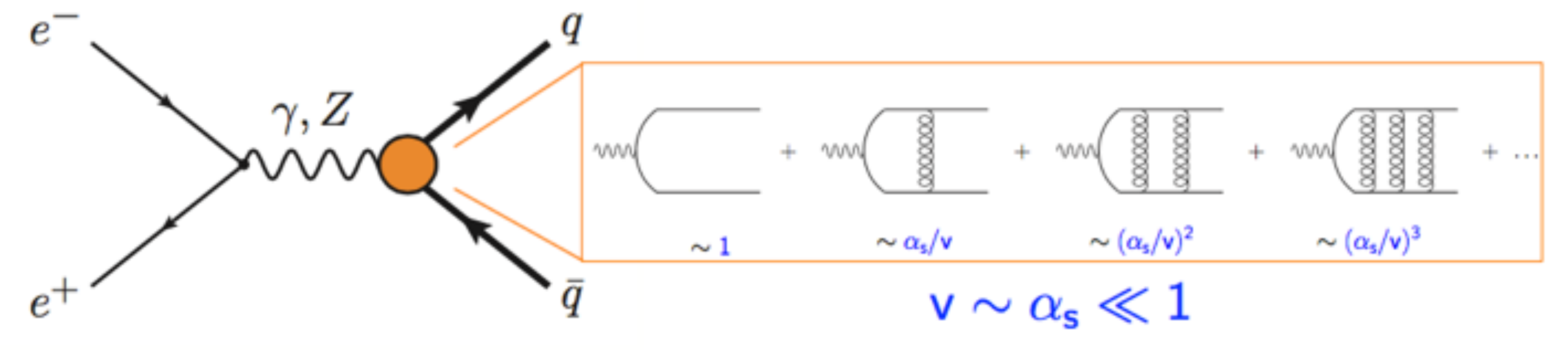

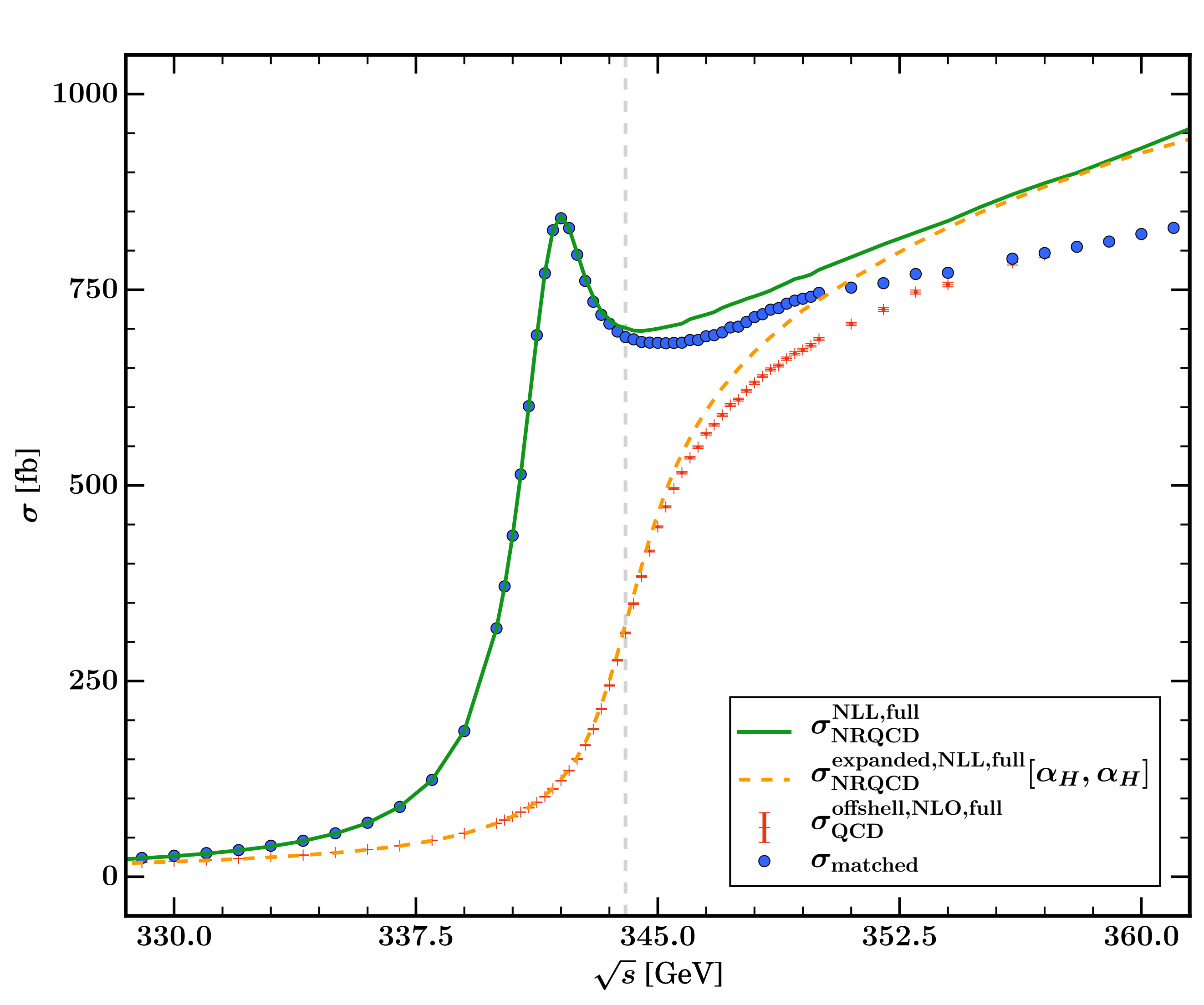

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Similar matching for *WW* threshold !
(in prep.)

Conclusions & Outlook

- `WHIZARD 2.3` event generator for collider physics (ee, pp, ep)
- BSM: focus on VBS simplified models / unitarization / full dim. 6 SM EFT
- Unitarization for transversal bosons & for tribosons [work in progress]
- UFO support [still in validation phase]
- NLO automation: reals and FKS subtraction [+ virtuals externally]

  [QCD almost completed, EW started] → `WHIZARD 3.0`
- Can produce NLO fixed-order histograms
- Automated POWHEG matching [other schemes in progress]
- NLL NRQCD threshold / NLO continuum matching (e.g. in ee → *tt*)
- Performance: Virtual Machine for MEs, MPI parallelization [validated], …

- Plans & projects: showers, merging, MPI, inclusion in `CheckMate`, … , …


New
WHIZARD
QUANTUM
HIGH PERFORMANCE GREASE
Higher Performance
Superior Protection
Learn More

BACKUP SLIDES

WHIZARD: Manual

- **WHIZARD**
- **HOME**
  - Main Page
- **MANUAL, WIKI, NEWS**
  - Manual
  - Wiki Page
  - News
  - Tutorials
  - ChangeLog
- **REPOSITORY, BUG TRACKER**
  - Subversion Repository
  - SVN Browser
  - Bug Tracker
- **DOWNLOADS**
  - Download Page
  - Patches/Unofficial versions
- **CONTACT**
  - Contact us
- **INTERNAL WHIZARD PAGE**
  - You Shall Not Pass!

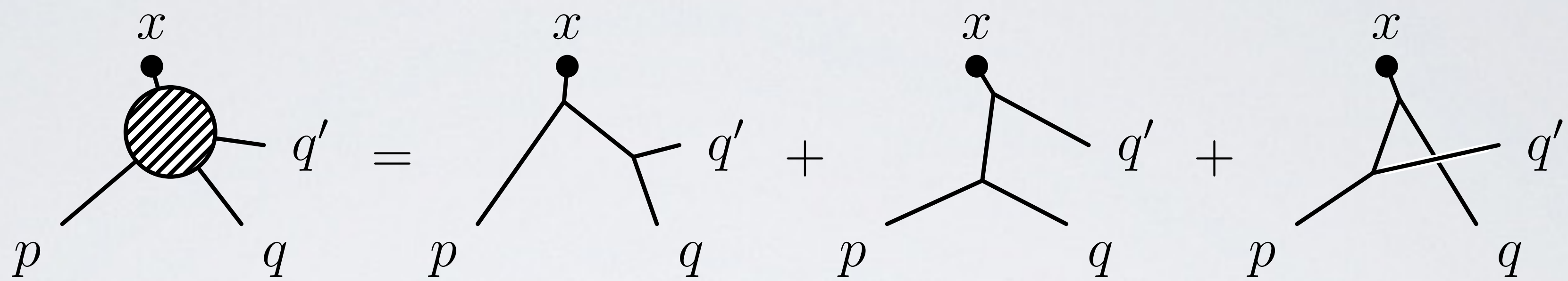
WHIZARD 2.2
A generic
Monte-Carlo integration and event generation package
for multi-particle processes
MANUAL [1]

Wolfgang Kilian,[2] Thorsten Ohl,[3] Jürgen Reuter,[4] with contributions from Fabian Bach, [5] Bijan Chokoufé Nejad, [6] Sebastian Schmidt, Christian Speckner [7], Florian Staub [8]

WHIZARD Manual @ HepForge

The Optimizing Matrix Element Generator (O'Mega)

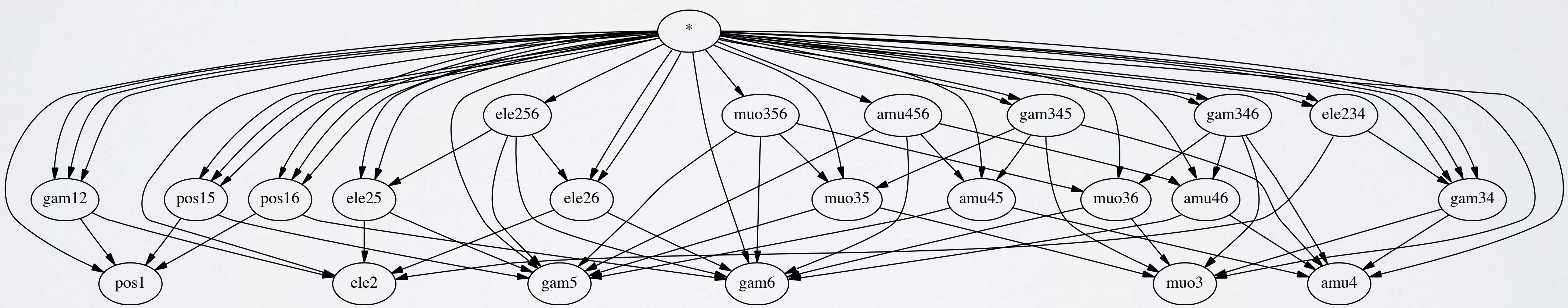
- `O'Mega` [Ohl, 2000; Moretti/Ohl/JRR, 2001; JRR, 2002] computes amplitudes with 1-particle off-shell wave functions (1POWs)



- Possible to construct set of all currents recursively (tree-/1-loop level)

- Keystones K to replace sum over Feynman diagrams

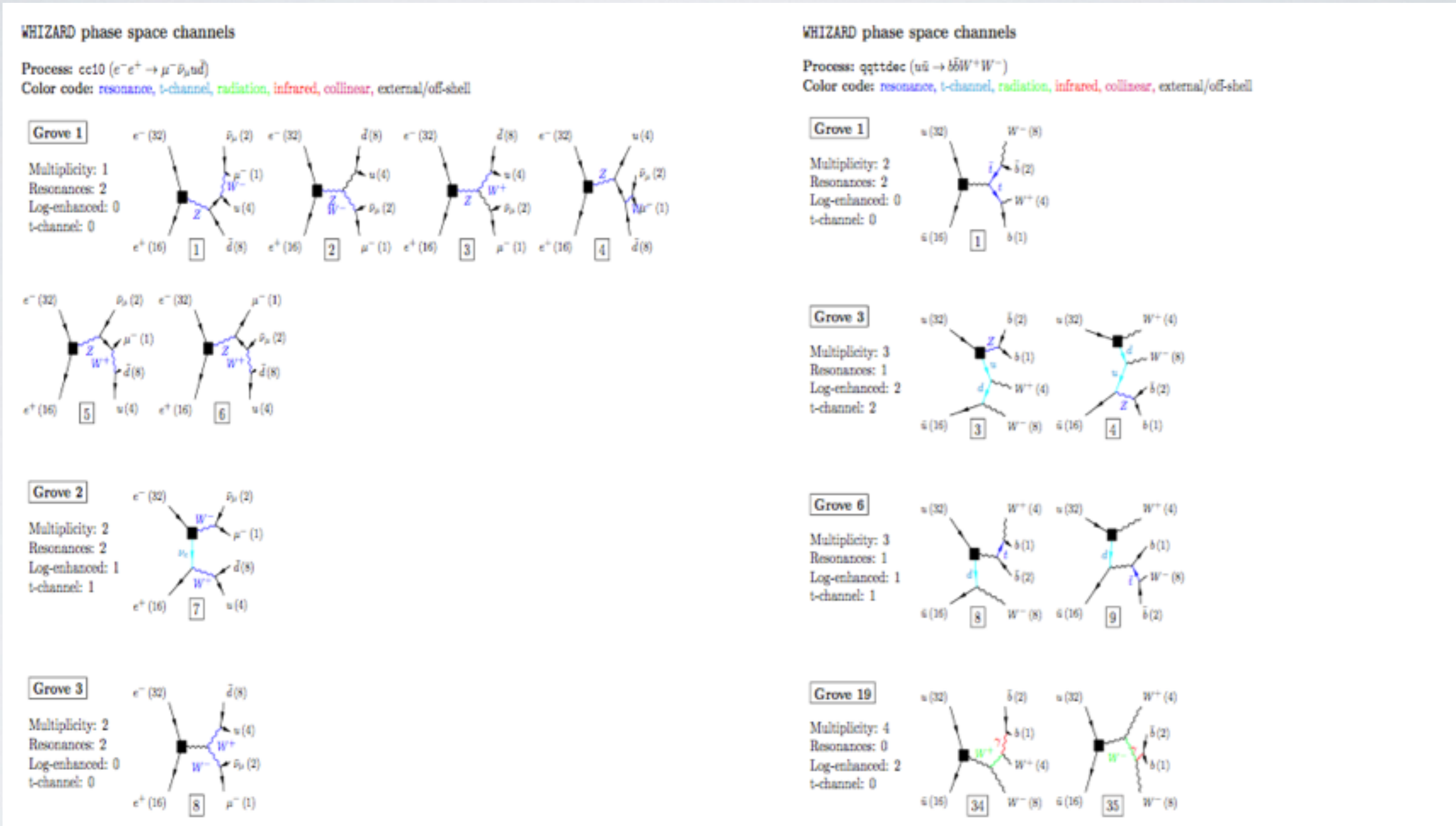
$$\sum_{i=1}^{F(n)} D_i = \sum_{k,l,m=1}^{P(n)} K^{(3)}_{f_k f_l f_m}(p_k, p_l, p_m) W_{f_k}(p_k) W_{f_l}(p_l) W_{f_m}(p_m)$$



- Calculation forms Directed Acyclical Graphs (DAGs), optimized to consist only of the minimal number of connections by `O'Mega`

Phase Space Setup

WHIZARD algorithm: heuristics to classify phase-space topology, adaptive multi-channel mapping $\Longrightarrow$ `resonant, t-channel, radiation, infrared, collinear, off-shell`



Complicated processes: factorization into production and decay with the `unstable` option

FKS Subtraction (Frixione/Kunszt/Signer)

Subtraction formalism to make real and virtual contributions separately finite

$$d\sigma^{\mathrm{NLO}} = \underbrace{\int_{n+1} \left(d\sigma^R - d\sigma^S\right)}_{\text{finite}} + \underbrace{\int_{n+1} d\sigma^S + \int_n d\sigma^V}_{\text{finite}}$$

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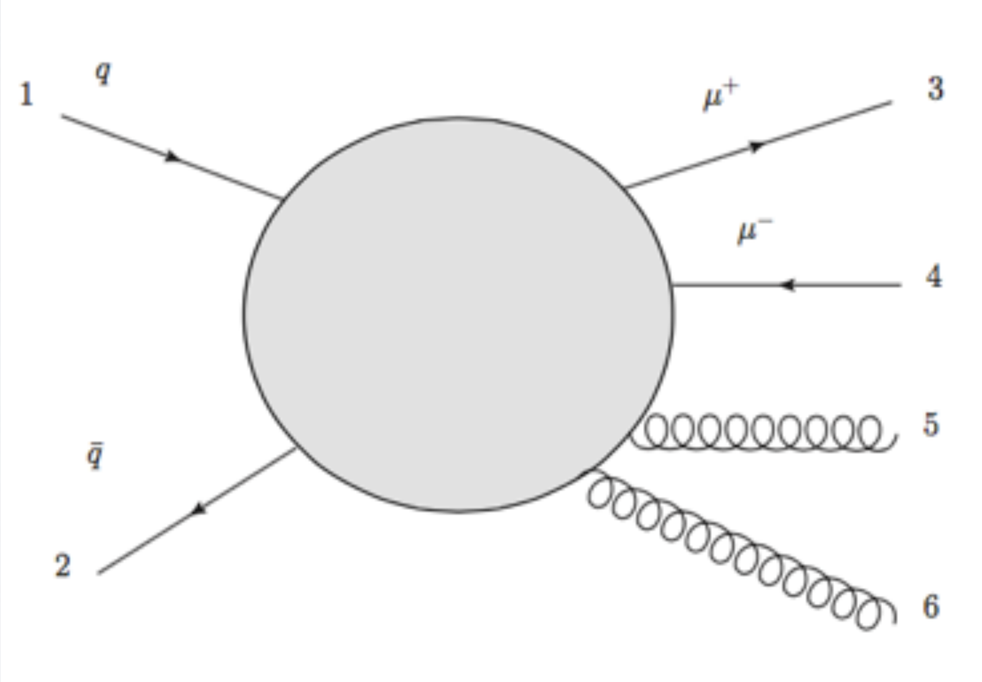

Automated subtraction terms in WHIZARD, algorithm:

- ✳ Find all singular pairs

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

- ✳ Partition phase space according to singular regions

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

- ✳ Generate subtraction terms for singular regions

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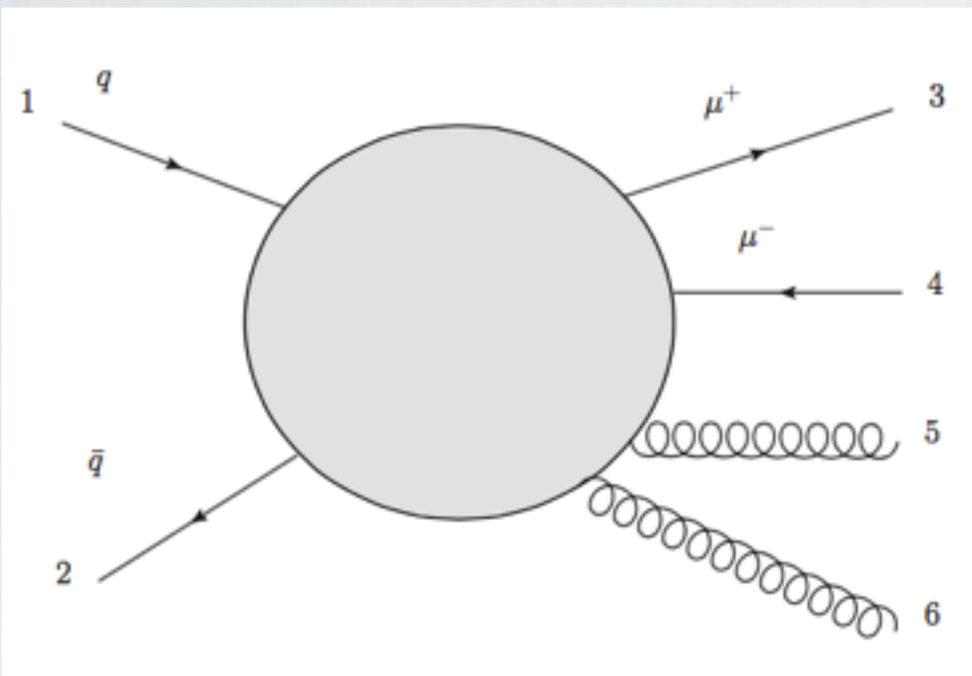

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- ✳ Generate subtraction terms for singular regions

Soft subtraction involves color-correlated matrix elements:

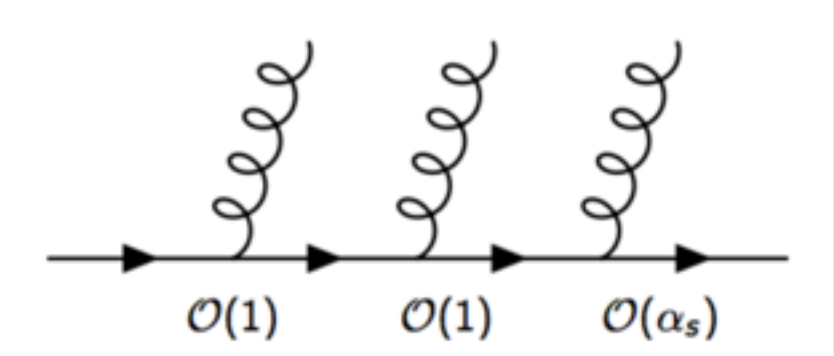
$$\mathcal{B}_{kl} \sim -\sum_{\substack{\text{color}\\\text{spin}}} \mathcal{A}^{(n)} \vec{\mathcal{Q}}(\mathcal{I}_k)\cdot\vec{\mathcal{Q}}(\mathcal{I}_l)\mathcal{A}^{(n)*},$$

Collinear subtraction involves spin-correlated matrix elements:

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

Automated POWHEG Matching in WHIZARD

- Soft gluon emissions before hard emission generate large logs
- Perturbative α_s : $|\mathcal{M}_{\mathrm{soft}}|^2 \sim \frac{1}{k_T^2} \to \log \frac{k_T^{\max}}{k_T^{\min}}$
- Consistent matching of NLO matrix element with shower
- POWHEG method: hardest emission first [Nason et al.]



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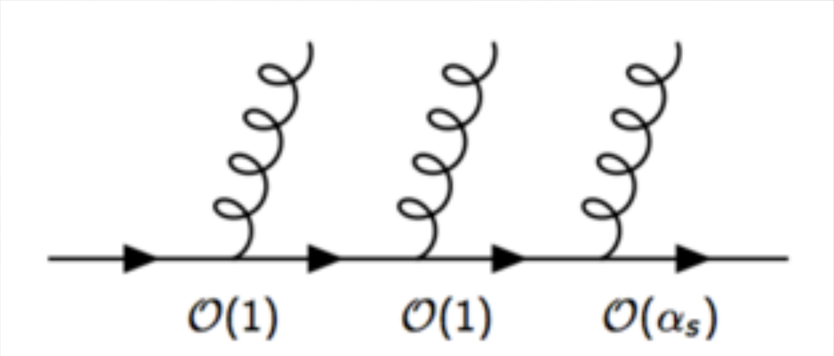

- Complete NLO events

$$\overline{B}(\Phi_n) = B(\Phi_n) + V(\Phi_n) + \int d\Phi_{\text{rad}} R(\Phi_{n+1})$$

- POWHEG generate events according to the formula:

$$d\sigma = \overline{B}(\Phi_n) \left[\Delta_R^{\text{NLO}}(k_T^{\min}) + \Delta_R^{\text{NLO}}(k_T) \frac{R(\Phi_{n+1})}{B(\Phi_n)} d\Phi_{\text{rad}} \right]$$

- Uses the modified Sudakov form factor:

$$\Delta_R^{\text{NLO}}(k_T) = \exp\left[- \int d\Phi_{\text{rad}} \frac{R(\Phi_{n+1})}{B(\Phi_n)} \theta(k_T(\Phi_{n+1}) - k_T) \right]$$

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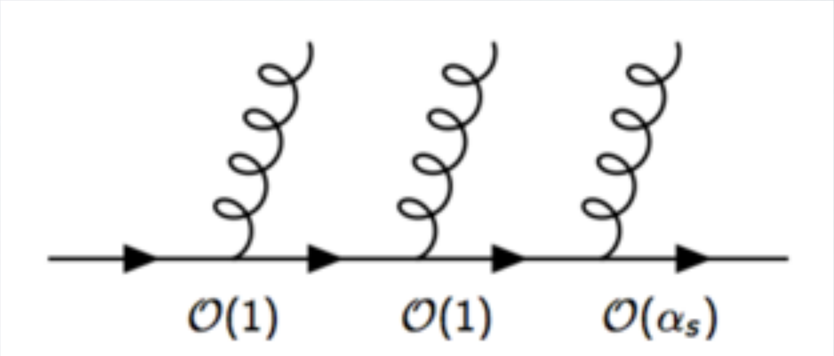

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- Hardest emission: $k_T^{\max}$; shower with imposing a veto
- $\overline{B} < 0$ if virtual and real terms larger than Born: shouldn't happen in perturbative regions
- Reweighting such that $\overline{B} > 0$ for all events
- POWHEG: Positive Weight Hardest Emission Generator own implementation in `WHIZARD`

Top-Forward Backward Asymmetry

$$A_{FB} = \frac{\sigma(\cos\theta_t > 0) - \sigma(\cos\theta_t < 0)}{\sigma(\cos\theta_t > 0) + \sigma(\cos\theta_t < 0)}.$$

Gluon emission symmetric in θ ⇒

NLO QCD corrections small

A_{FB} of the top quark

Final state	A_{FB}^{LO}	A_{FB}^{NLO}
$t\bar{t}$	-0.5935 ± 0.0017	-0.5983 ± 0.0048
$W^+W^-b\bar{b}$	-0.4847 ± 0.0017	-0.4778 ± 0.0114
$\mu^+e^-\nu_\mu\bar{\nu}_e b\bar{b}$	-0.5005 ± 0.0001	-0.4947 ± 0.0088
$\mu^+e^-\nu_\mu\bar{\nu}_e b\bar{b}$, without neutrinos	-0.4854 ± 0.0010	-0.4805 ± 0.0089

A_{FB} of the anti-top quark

Final state	A_{FB}^{LO}	A_{FB}^{NLO}
$t\bar{t}$	0.4764 ± 0.0017	0.4789 ± 0.0047
$W^+W^-b\bar{b}$	0.3674 ± 0.0017	0.3701 ± 0.0104
$\mu^+e^-\nu_\mu\bar{\nu}_e b\bar{b}$	0.3267 ± 0.0009	0.3264 ± 0.0084
$\mu^+e^-\nu_\mu\bar{\nu}_e b\bar{b}$, without neutrinos	0.2656 ± 0.0009	0.2603 ± 0.0083

Top Threshold Resummation in (p)NRQCD

- NRQCD is EFT for non-relativistic quark-antiquark systems: separate $M \cdot v$ and $M \cdot v^2$
- Integrate out hard quark and gluon d.o.f.
- Resummation of singular terms close to threshold (v = 0) Hoang/Teubner, 1999; Hoang et al., 2001

Phase space of two massive particles

$$R \equiv \frac{\sigma_{t\bar{t}}}{\sigma_{\mu\mu}} = v \sum_k \left(\frac{\alpha_s}{v}\right)^k \sum_i (\alpha_s \ln v)^i \times$$
$$\times \left\{1\,(\text{LL});\ \alpha_s, v\,(\text{NLL});\ \alpha_s^2, \alpha_s v, v^2\,(\text{NNLL})\right\}$$

(p/v)NRQCD EFT w/ RG improvement

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$$R \equiv \frac{\sigma_{t\bar{t}}}{\sigma_{\mu\mu}} = v \sum_k \left(\frac{\alpha_s}{v}\right)^k \sum_i (\alpha_s \ln v)^i \times$$
$$\times \left\{1\,(\mathrm{LL});\ \alpha_s, v\,(\mathrm{NLL});\ \alpha_s^2, \alpha_s v, v^2\,(\mathrm{NNLL})\right\}$$

(p/v)NRQCD EFT w/ RG improvement

$$R^{\gamma,Z}(s) = \underbrace{F^v(s) R^v(s)}_{\text{s-wave: LL+NLL}} + \underbrace{F^a(s) R^a(s)}_{\text{p-wave}\sim v^2\text{:NNLL}}$$

but contributes
at NLL differentially!

Top Threshold Resummation in (p)NRQCD

- NRQCD is EFT for non-relativistic quark-antiquark systems: separate $M \cdot v$ and $M \cdot v^2$
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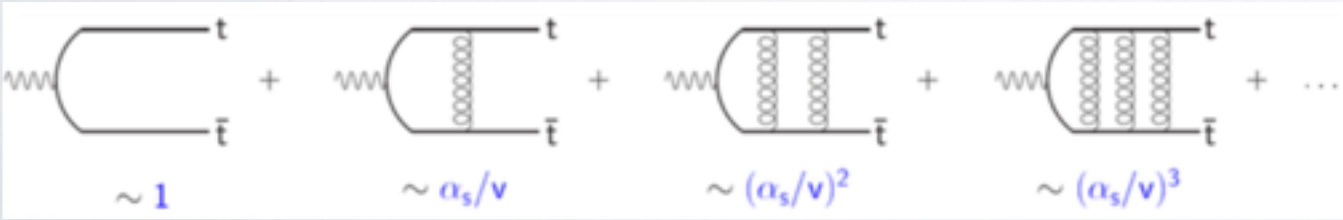
Coulomb potential gluon ladder resumption



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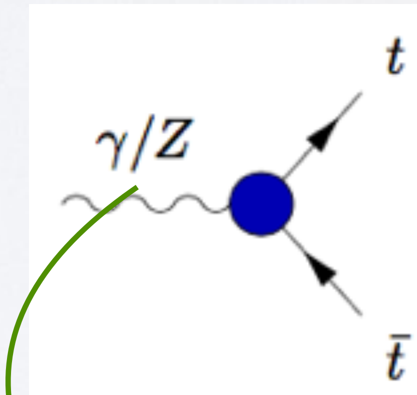
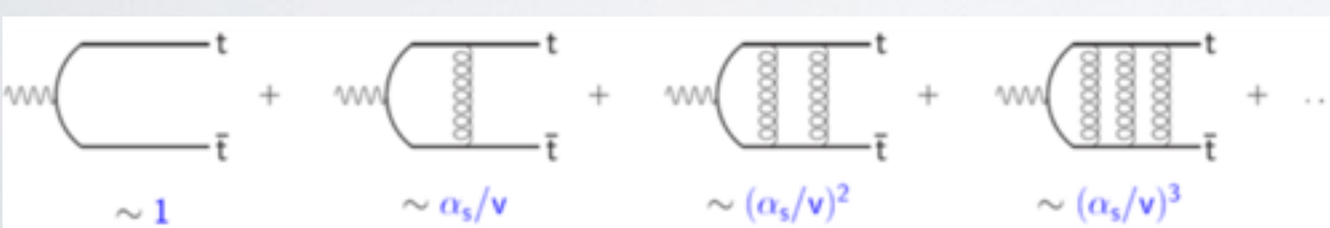
can be mapped onto effective *ttV* vertex



$$\sim \sqrt{R^{v/a}_{\mathrm{(N)LL}}} \sim \frac{\mathcal{G}^{v/a}_{\mathrm{(N)LL}}}{\mathcal{G}^{v/a}\big|_{\alpha_s=0}} \longrightarrow 1$$

far away from threshold

Coulomb potential gluon ladder resummation



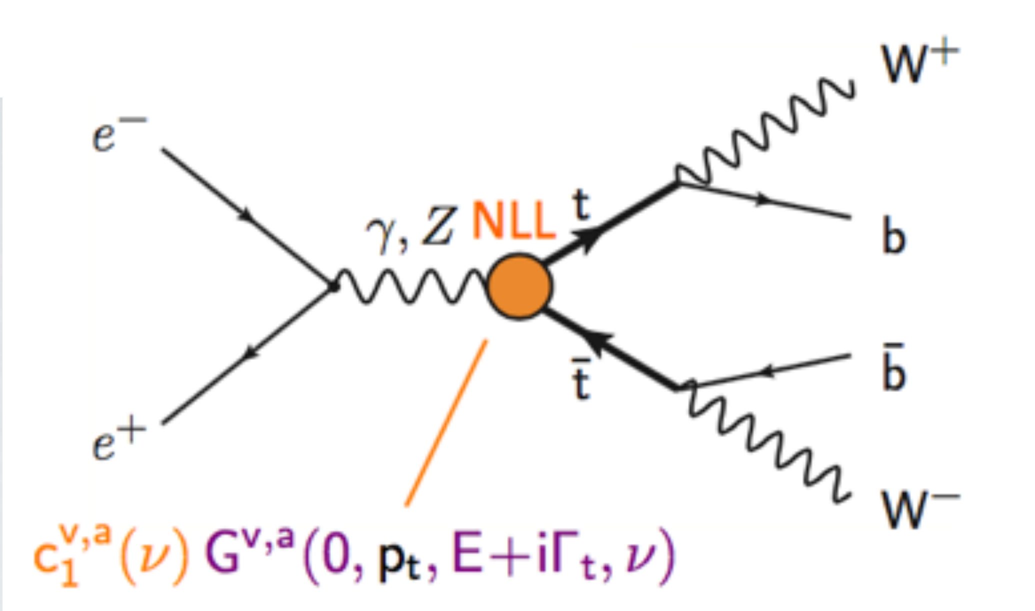
$$\mathbb{C} \ni \mathcal{G}^{v/a}_{\mathrm{(N)LL}} = \mathcal{G}^{v/a}_{\mathrm{(N)LL}}(\alpha_s, M_t^{\mathrm{pole}}, \sqrt{s}, |\vec{p}_t|, \Gamma_t)$$

differential in off-shell *tt* phase space

Top Threshold in WHIZARD

with B. Chokoufé/A. Hoang/M. Stahlhofen/T. Teubner/C. Weiss

- Implement resummed threshold effects as effective vertex [form factor] in `WHIZARD`
- $G^{v,a}(0, p_t, E + i\Gamma_t, \nu)$ from TOPPIK code [Jezabek/Teubner], included in `WHIZARD`



- Default parameters:

$$\mathbf{M^{1S} = 172\,GeV},\ \Gamma_t = 1.54\,\mathrm{GeV},\quad \alpha_s(M_Z) = 0.118$$

$$M^{1S} = M_t^{pole}(1 - \Delta^{LL/NLL}_{(Coul.)})$$ Marquard et al.

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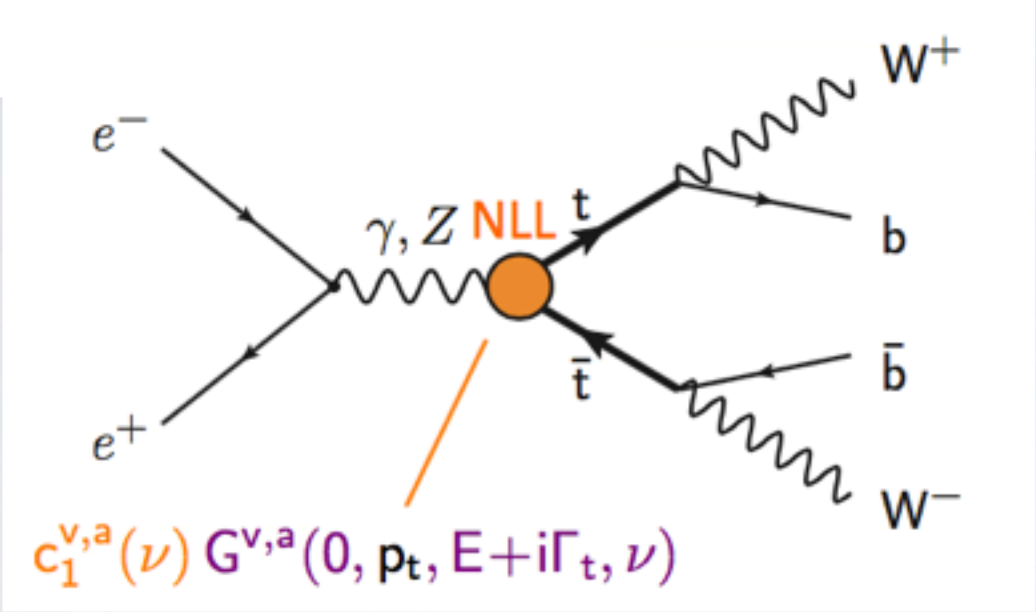

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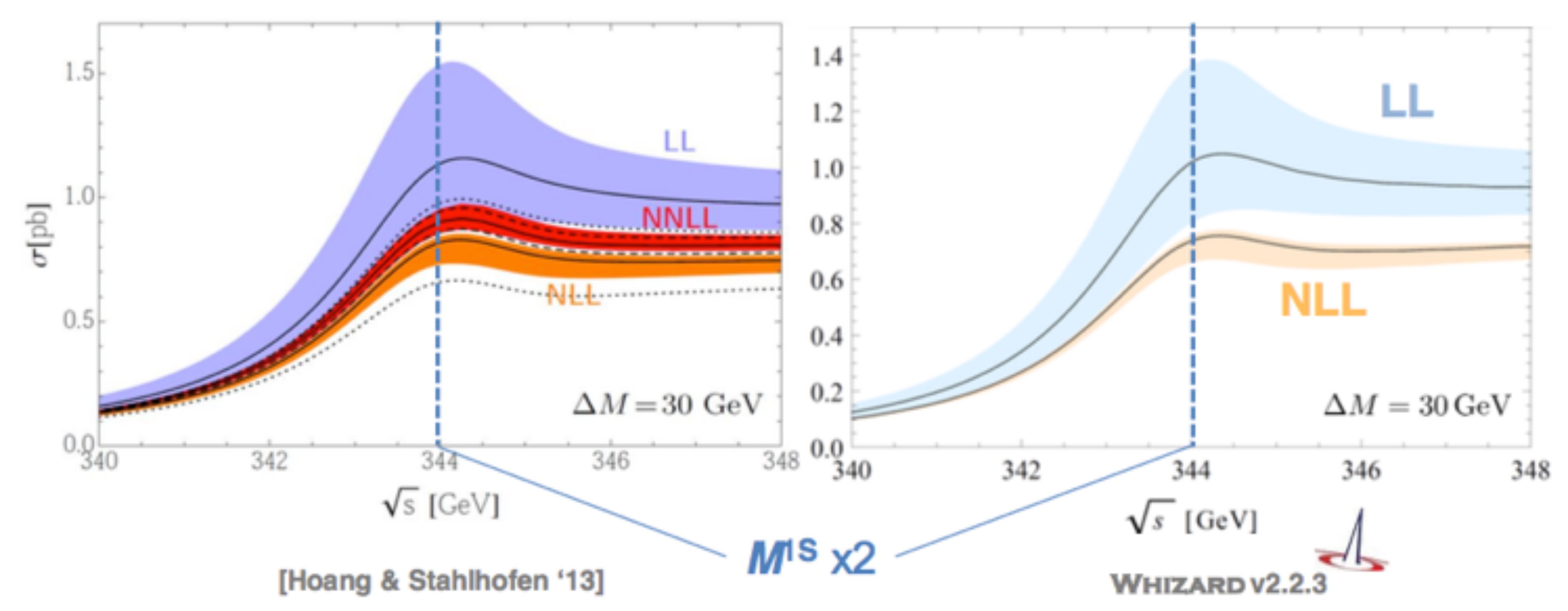

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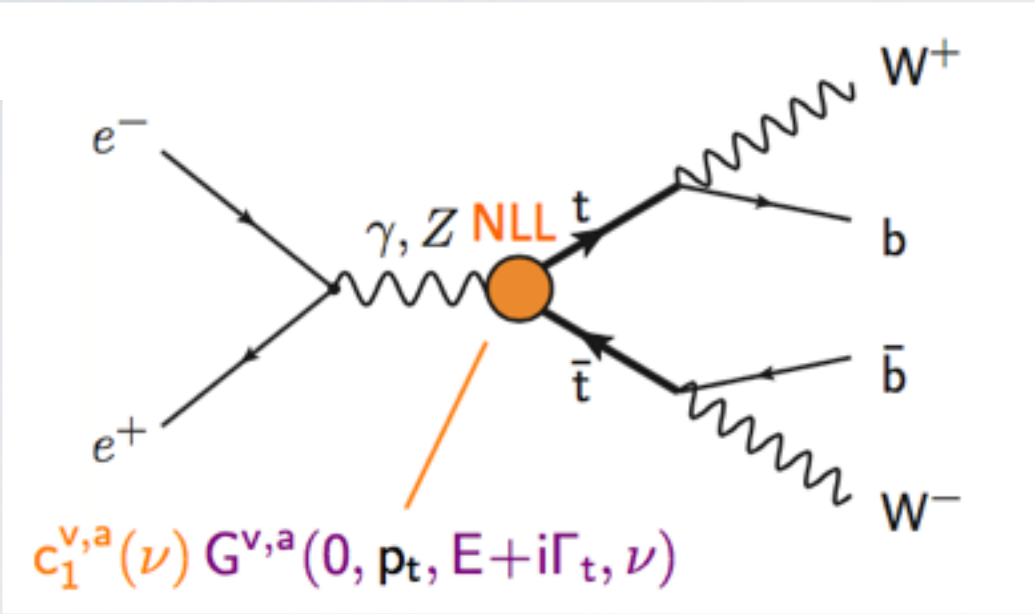

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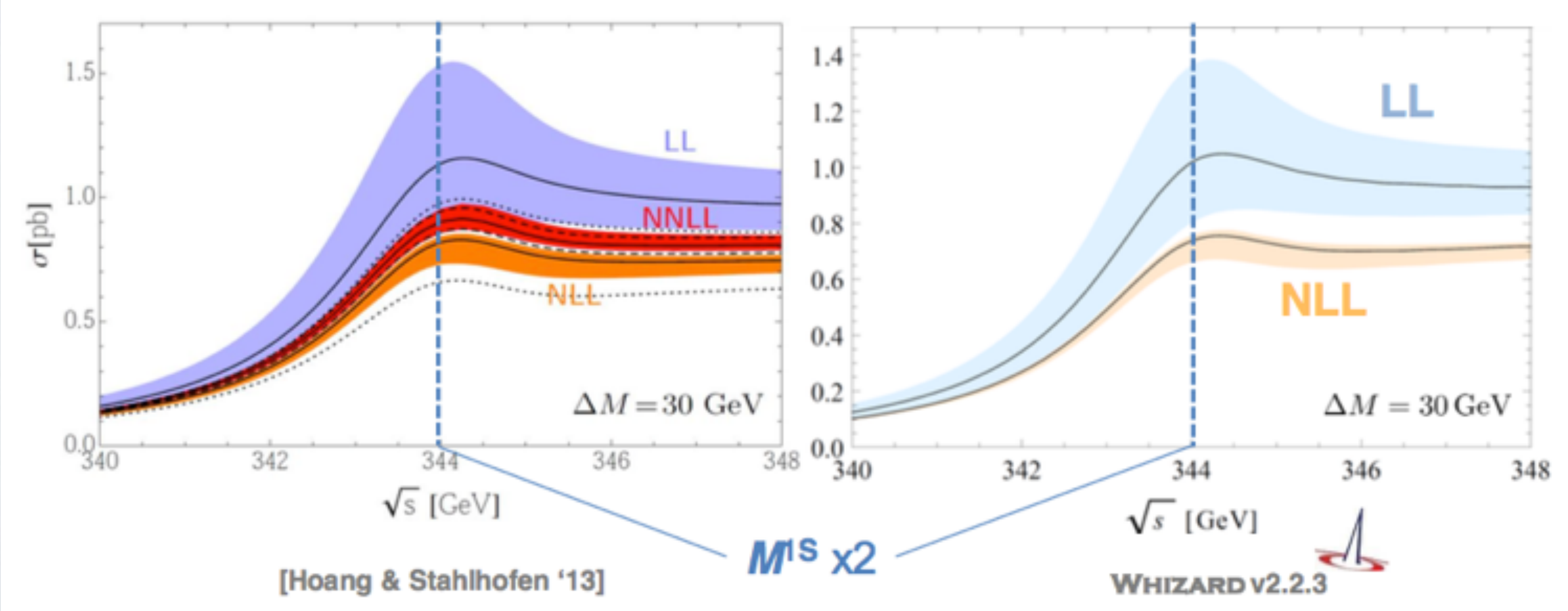
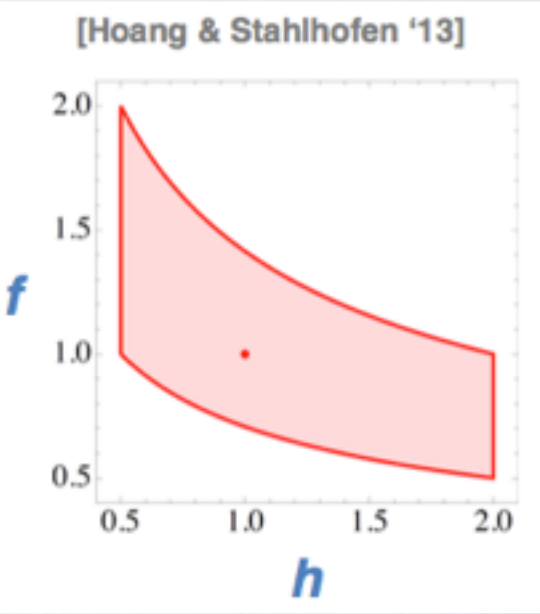
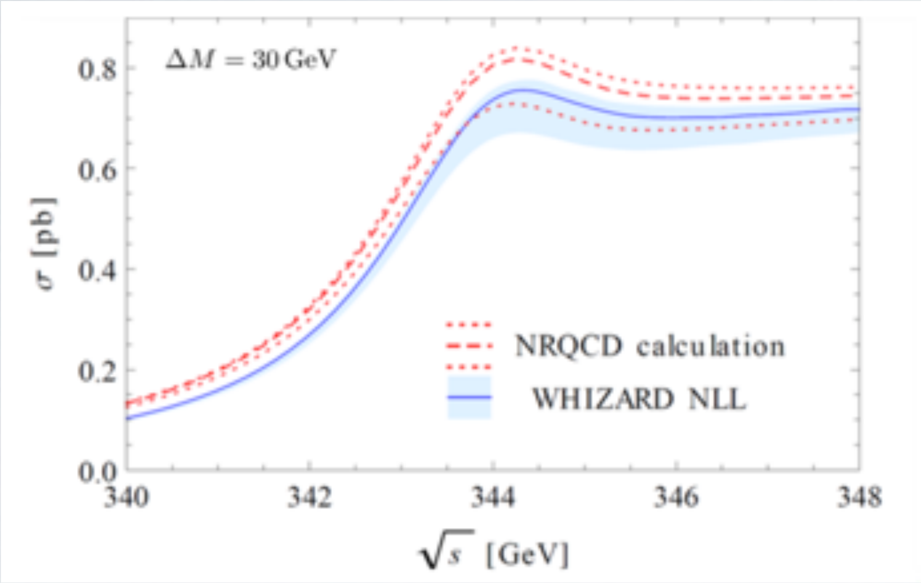
Theory uncertainties from scale variations: hard and soft scale

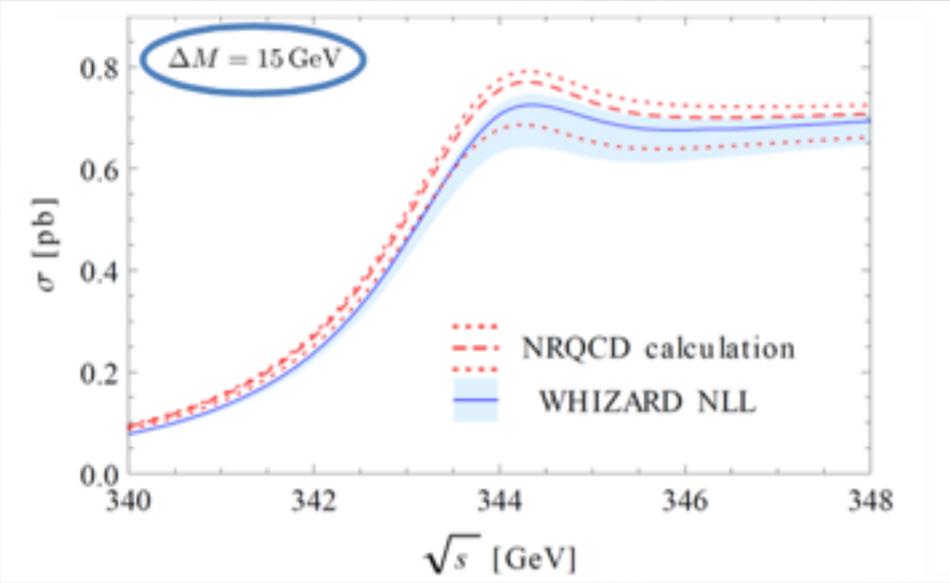
$$\mu_h = h \cdot m_t \qquad \mu_s = f \cdot m_t v$$





Sanity checks: correct limit for $\alpha_s \longrightarrow 0$, stable against variation of cutoff ΔM [15-30 GeV]





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  - Important effects: beamstrahlung; ISR; LO electroweak terms
  - More exclusive observables accessible

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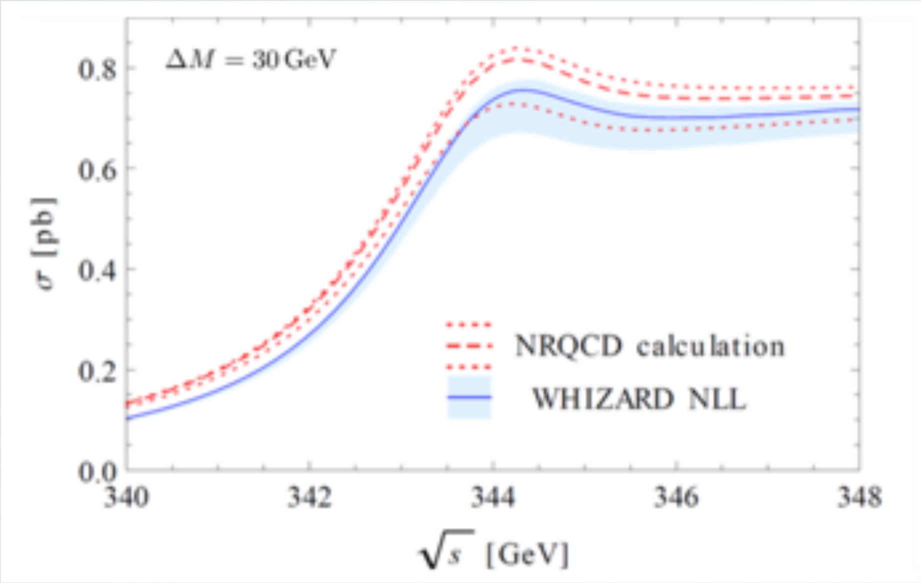

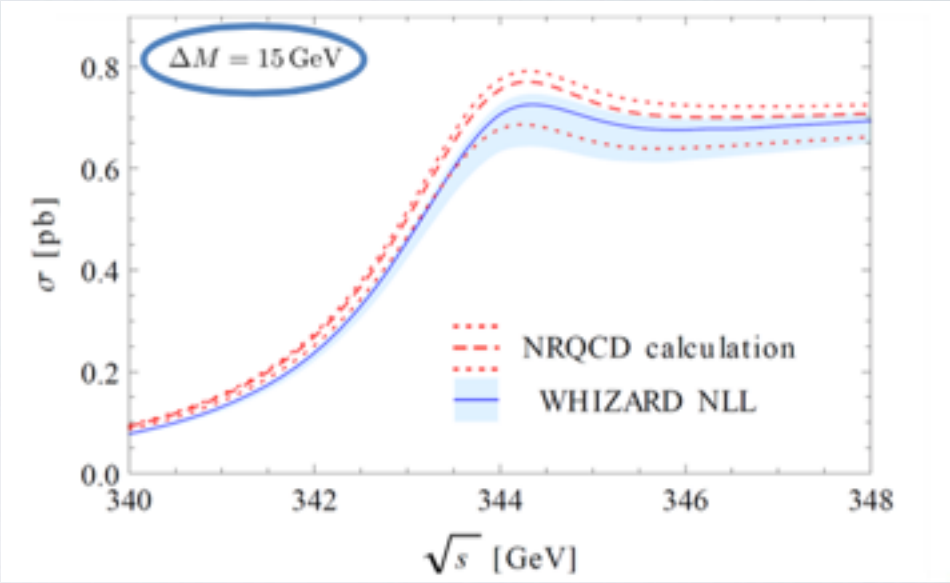

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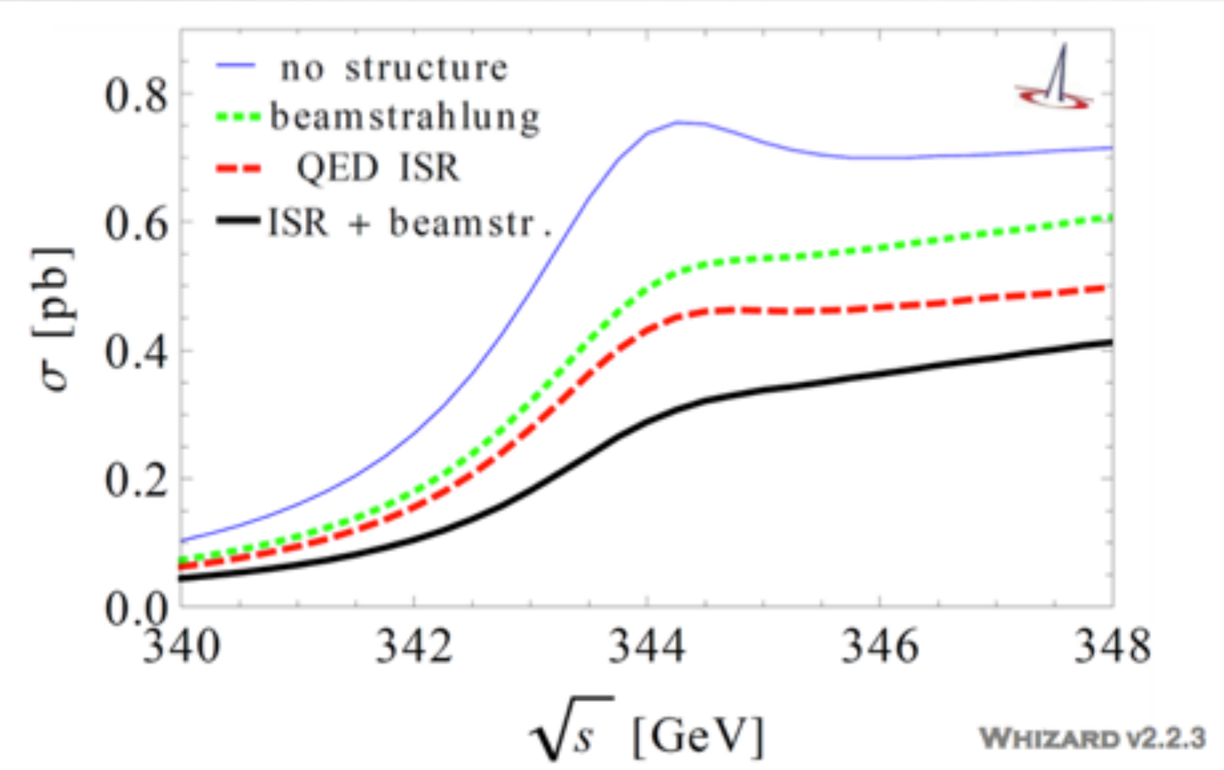

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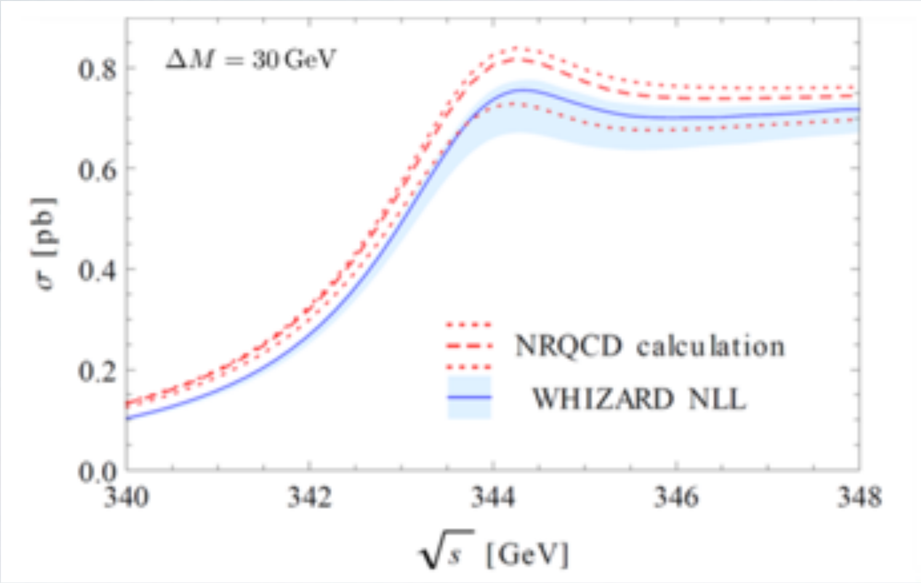

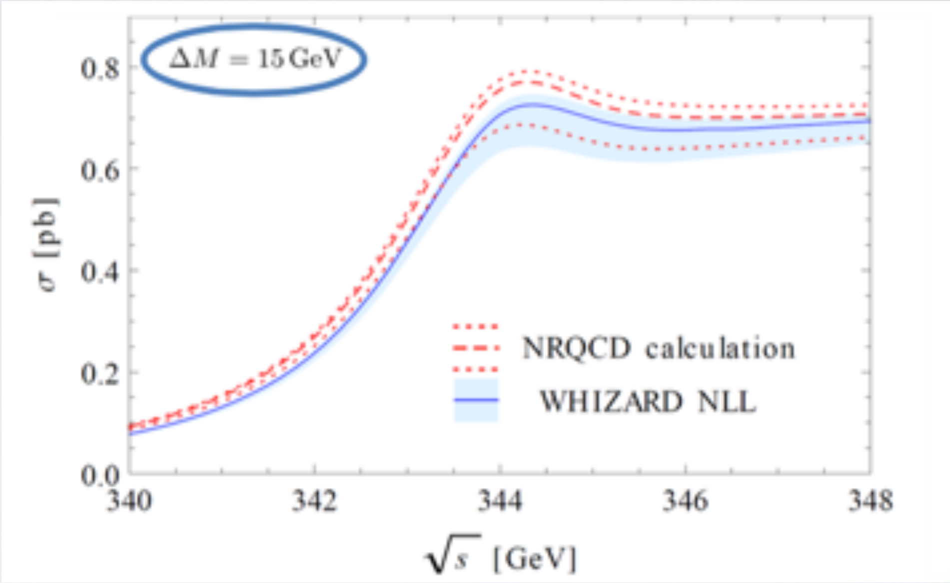

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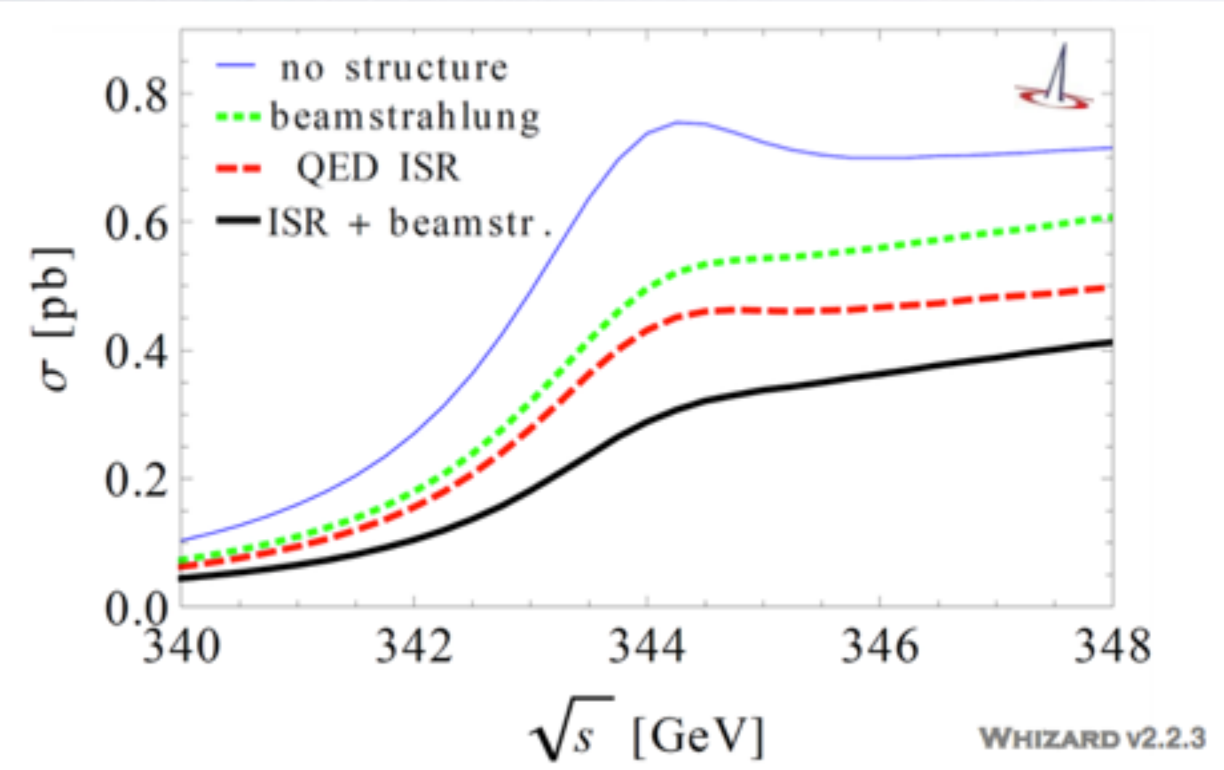
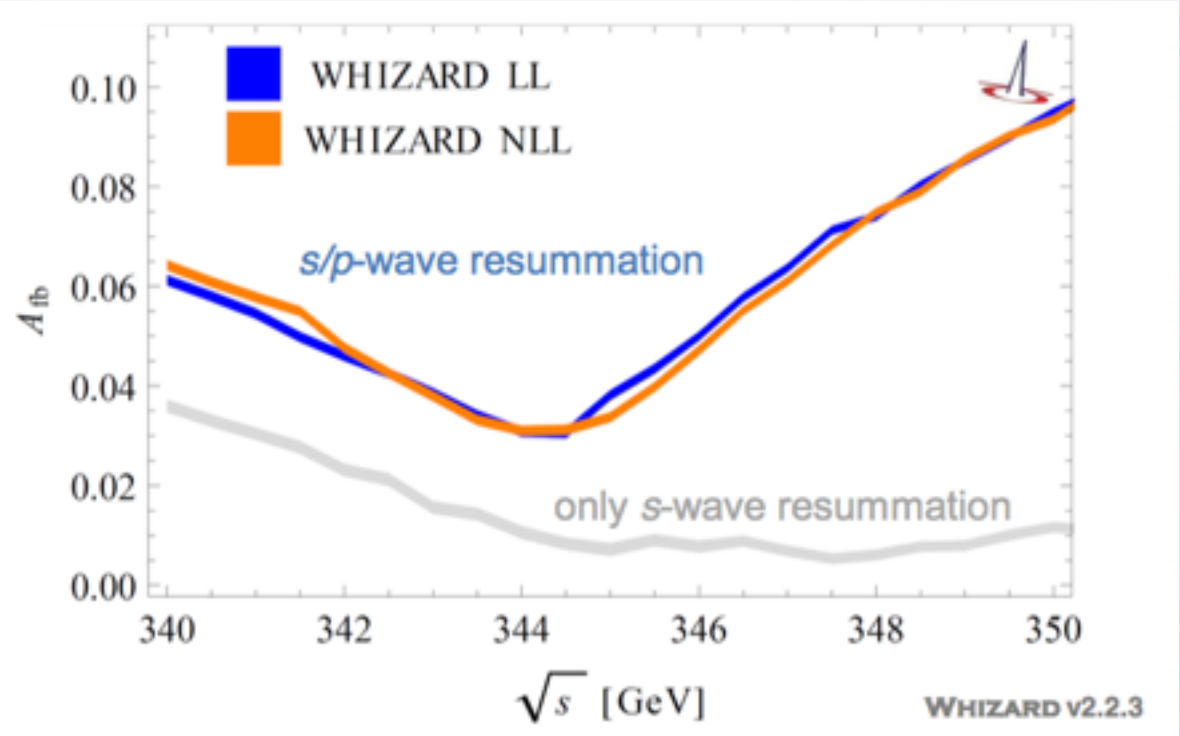
Forward-backward asymmetry (norm. ⇒ good shape stability)

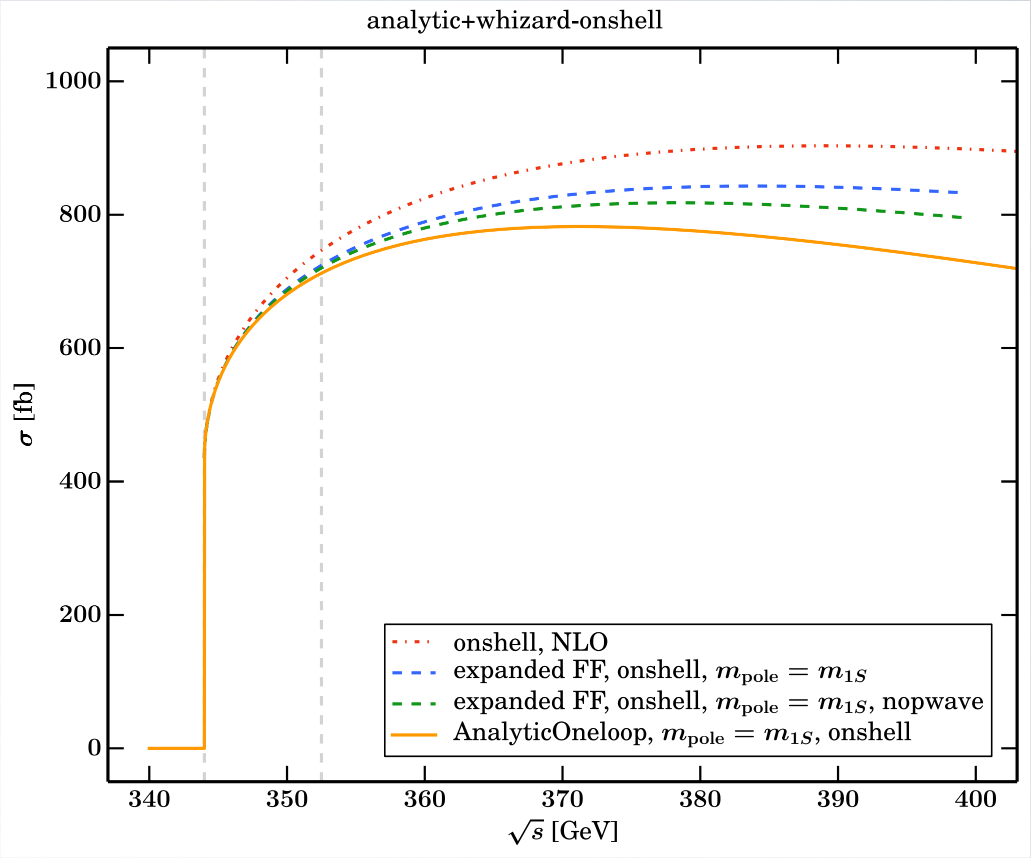
$$A_{fb} := \frac{\sigma(p_z^t > 0) - \sigma(p_z^t) < 0)}{\sigma(p_z^t > 0) + \sigma(p_z^t < 0)}$$





Matching to continuum at (LO and) NLO

- Transition region between relativistic and resummation effects
- CLIC benchmark energies:
  0.38 TeV, 1.4 TeV, 3.0 TeV
- Remove double-counting NLO / (N)LL



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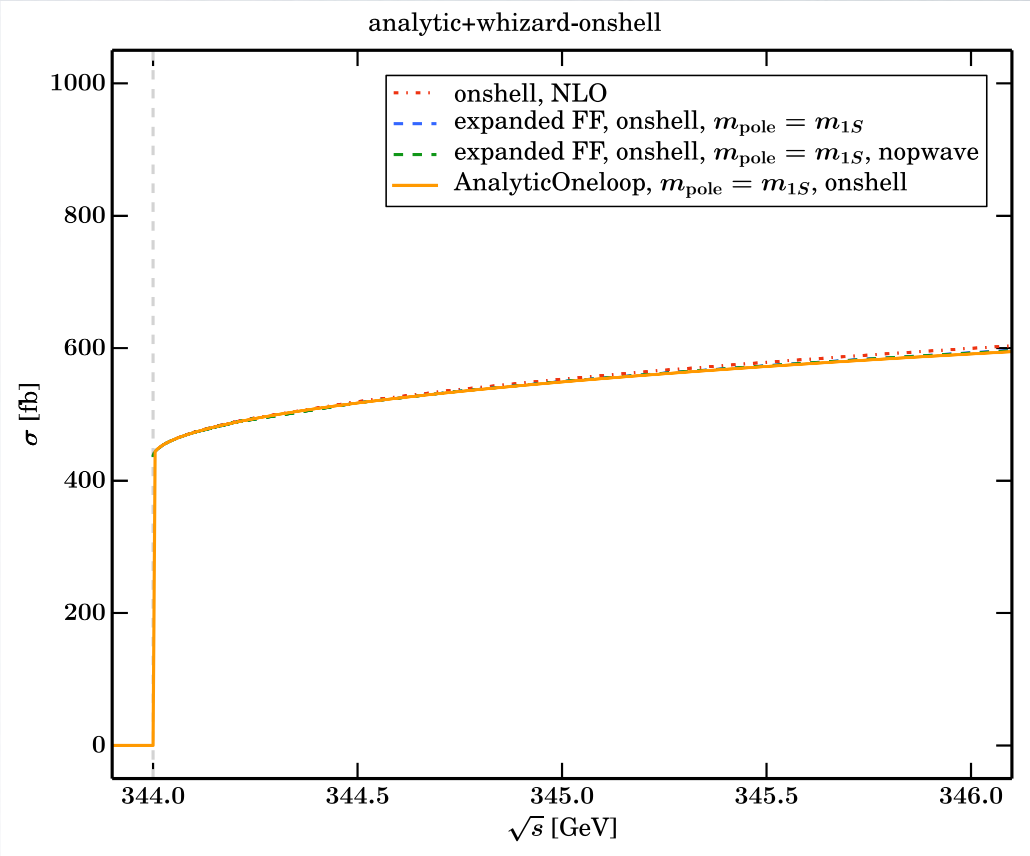

Resummed formfactor, expanded to $\mathcal{O}(\alpha_s)$

$$\nu = \sqrt{\frac{\sqrt{s} - 2m_t + \mathrm{i}\Gamma_t}{m}} \qquad p = |\vec{p}| \qquad p_0 = E_t - m_t$$

$$F^{\text{expanded}}\left[\alpha_{\text{H}},\, \alpha_{\text{S}}\right] = \alpha_{\text{H}} \left(-\frac{2C_F}{\pi} \right) + \alpha_{\text{S}} \left(\frac{\mathrm{i} C_F m \log \frac{mv+p}{mv-p}}{2p} \right)$$

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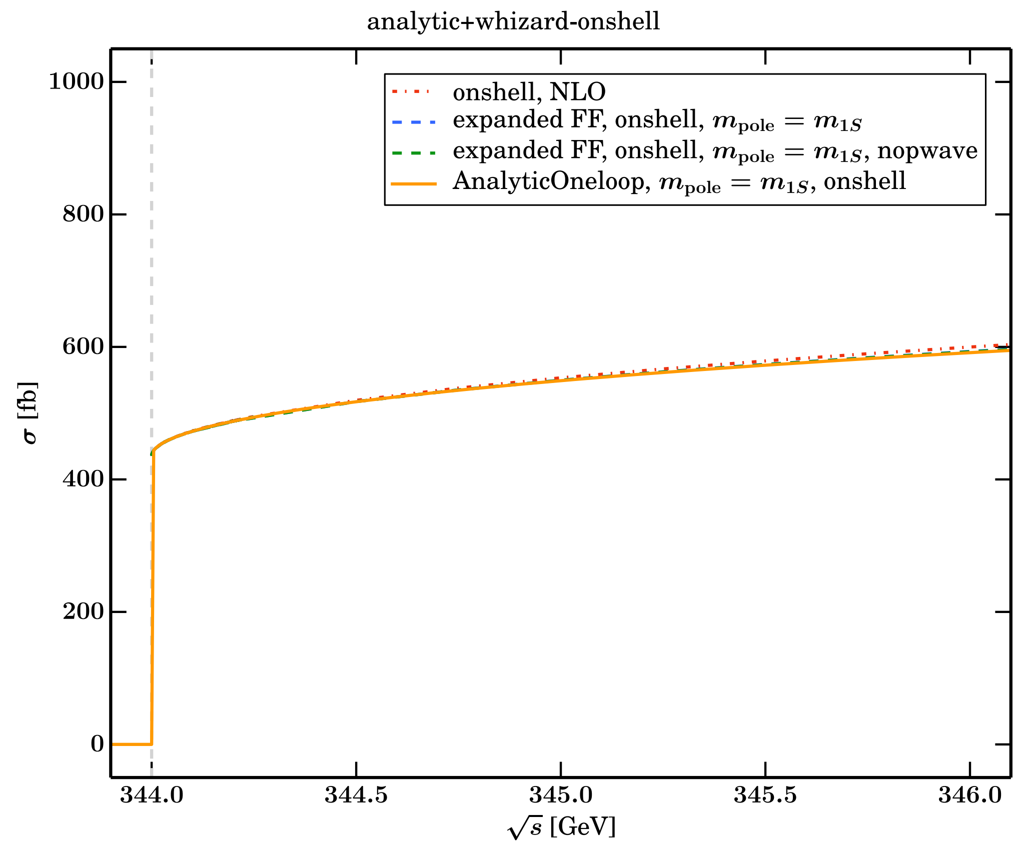

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Matching formula

$$\begin{aligned}\sigma_{\text{matched}} = {} & \sigma_{\text{QCD}}\left[\alpha_{\text{H}}\right] - \sigma^{\text{expanded}}_{\text{NRQCD}}\left[\alpha_{\text{H}},\, \alpha_{\text{H}}\right] \\ & + \sigma^{\text{expanded}}_{\text{NRQCD}}\left[\alpha_{\text{H}},\, f_s\,\alpha_{\text{S}} + (1-f_s)\,\alpha_{\text{H}}\right] \\ & + \sigma^{\text{full}}_{\text{NRQCD}}\left[f_s\,\alpha_{\text{H}},\, f_s\,\alpha_{\text{S}},\, f_s\,\alpha_{\text{US}}\right] - \sigma^{\text{expanded}}_{\text{NRQCD}}\left[f_s\,\alpha_{\text{H}},\, f_s\,\alpha_{\text{S}}\right]\end{aligned}$$

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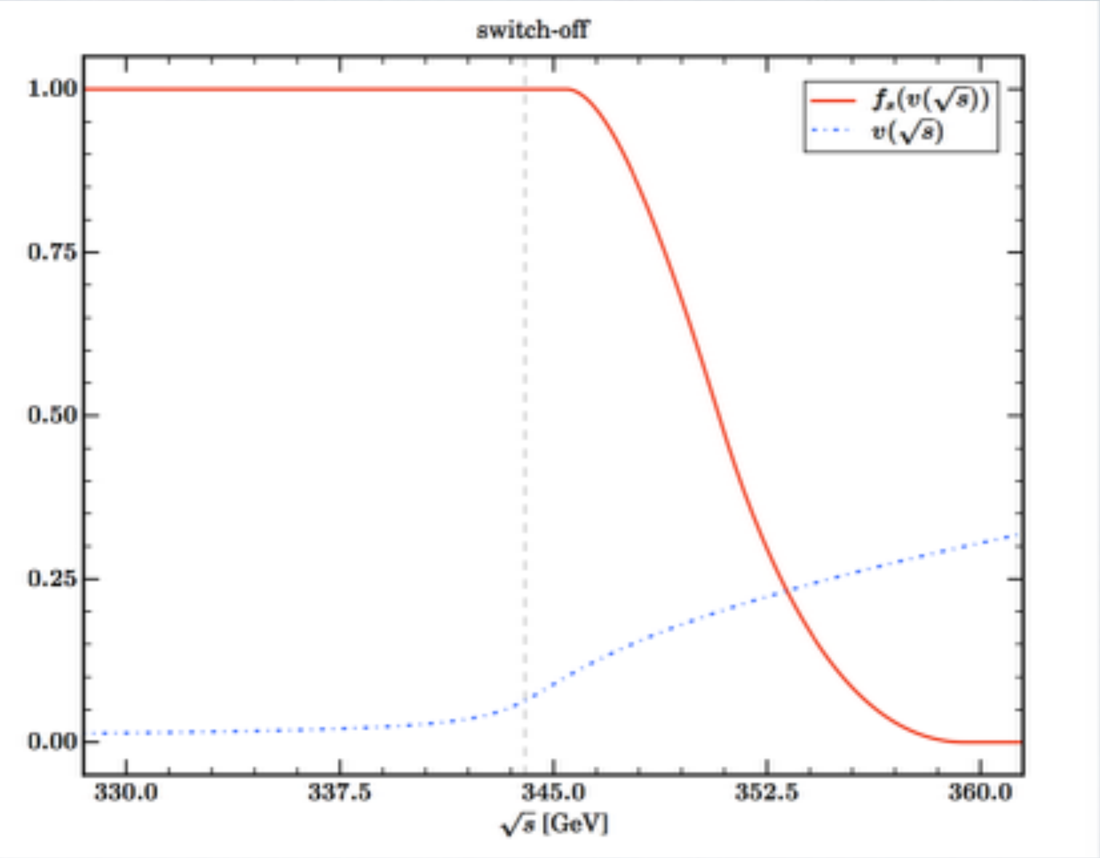

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Switch-off function

$$f_s(v) = \begin{cases} 1 & v < v_1 \\ 1 - 2\frac{(v-v_1)^2}{(v_2-v_1)^2} & v_1 < v < \frac{v_1+v_2}{2} \\ 2\frac{(v-v_2)^2}{(v_2-v_1)^2} & \frac{v_1+v_2}{2} < v < v_2 \\ 0 & v > v_2 \end{cases}$$