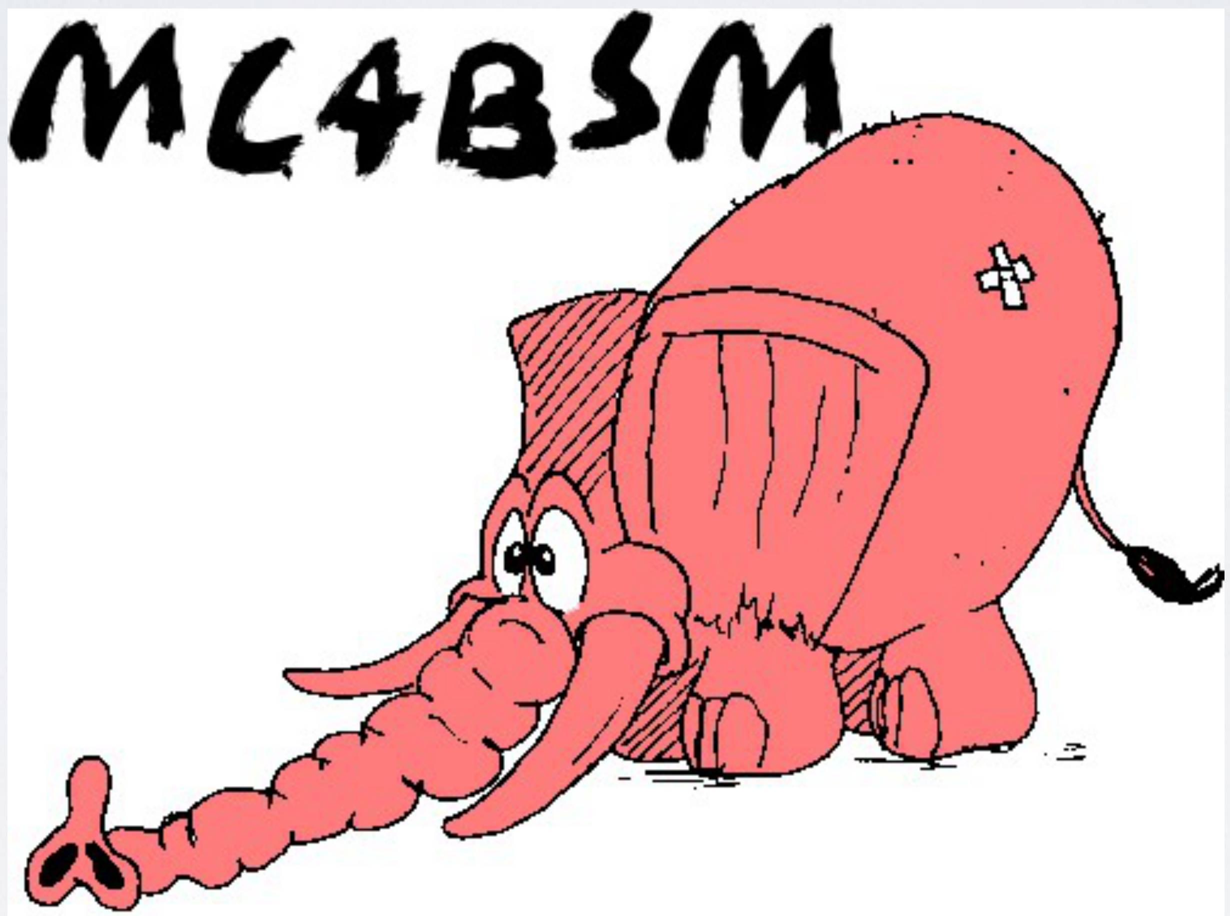
The Event Generator WHIZARD



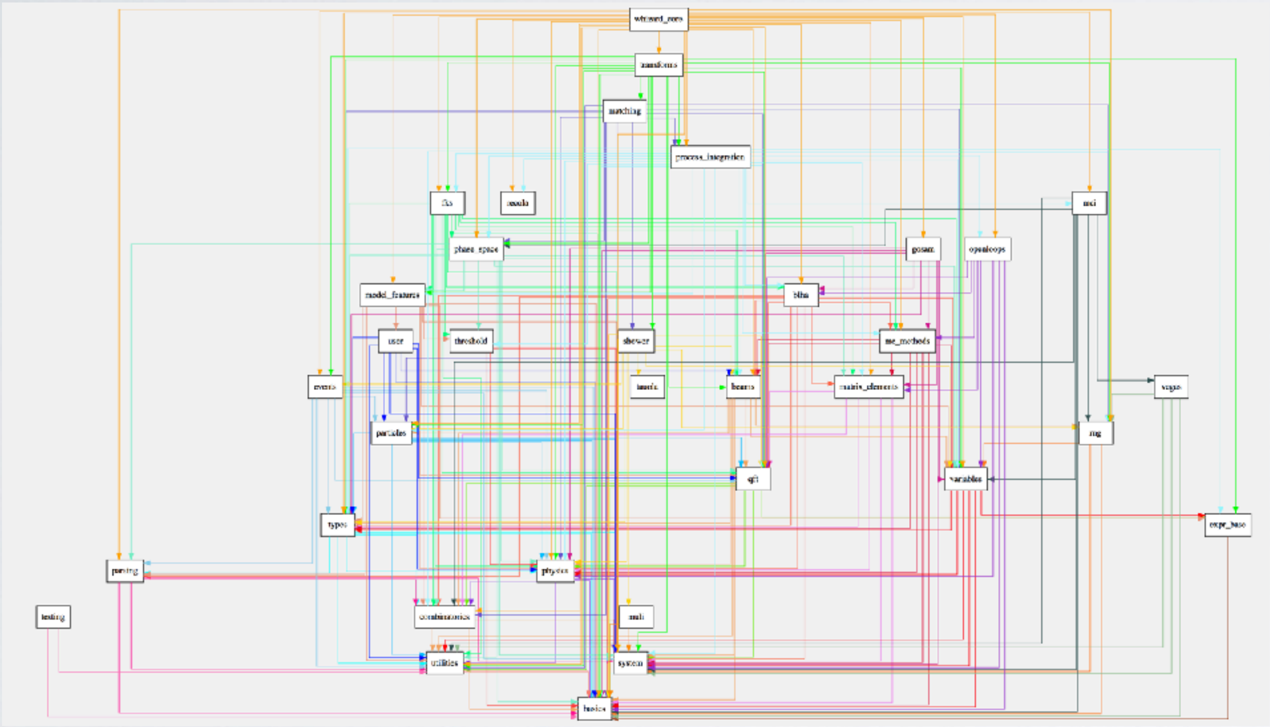
Jürgen R. Reuter, DESY

WHIZARD: Some (technical) facts

WHIZARD v2.6.3 (10.02.2018) http://whizard.hepforge.org <whizard@desy.de>

WHIZARD Team: *Wolfgang Kilian, Thorsten Ohl, JRR*

Simon Braß/Vincent Rothe/Christian Schwinn/Marco Sekulla/So Young Shim/Pascal Stienemeier/Zhijie Zhao + 2 Master



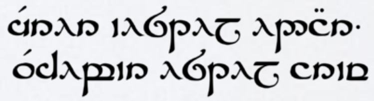
PUBLICATIONS

- General WHIZARD reference: EPJ C71 (2011) 1742, arXiv:0708.4241
- O'Mega (ME generator): LC-TOOL (2001) 040; arXiv:hep-ph/0102195
- VAMP (MC integrator): CPC 120 (1999) 13; arXiv:hep-ph/9806432
- CIRCE (beamstrahlung): CPC 101 (1997) 269; arXiv:hep-ph/9607454
- Parton shower: JHEP 1204 (2012) 013; arXiv:1112.1039
- Color flow formalism: JHEP 1210 (2012) 022; arXiv:1206.3700
- NLO capabilities: JHEP 1612 (2016) 075; arXiv: 1609.03390
- Parallelization of MEs: CPC 196 (2015) 58; arXiv:1411.3834
- POWHEG matching: EPS-HEP (2015) 317; arXiv: 1510.02739

- Programming Languanges: `Fortran08 (gfortran ≥4.8.4), OCaml (≥3.12.0)`
- Standard installation: `configure <FLAGS>, make, [make check], make install`
- Large self test suite, unit tests [module tests], regression testing
- Continous integration system (`gitlab CI` @ Siegen)

WHIZARD: Introduction / Technical Facts

- Universal event generator for lepton and hadron colliders
- Tree ME generator O'Mega optimized ME generator
- Generator/simulation tool for lepton collider beam spectra: CIRCE1/2
- Parton showering internal: analytic + k_T-ordered, hadronization: external
- Interfaces to external packages for Feynman rules, hadronization, tau decays, event formats, analysis, jet clustering etc. : FastJet, GoSam, GuineaPig(++), HepMC, HOPPET, LCIO, LHAPDF(5/6), LoopTools, OpenLoops, PYTHIA6 [internal], [PYTHIA8], Recola, StdHep [internal], Tauola [internal]
- Event formats: LHE, StdHEP, HepMC, LCIO + several ASCII
- Scattering processes and decays
- Factorized processes with spin correlations [variants: no correlations, definite helicity]
- Scripting language for the steering: SINDARIN



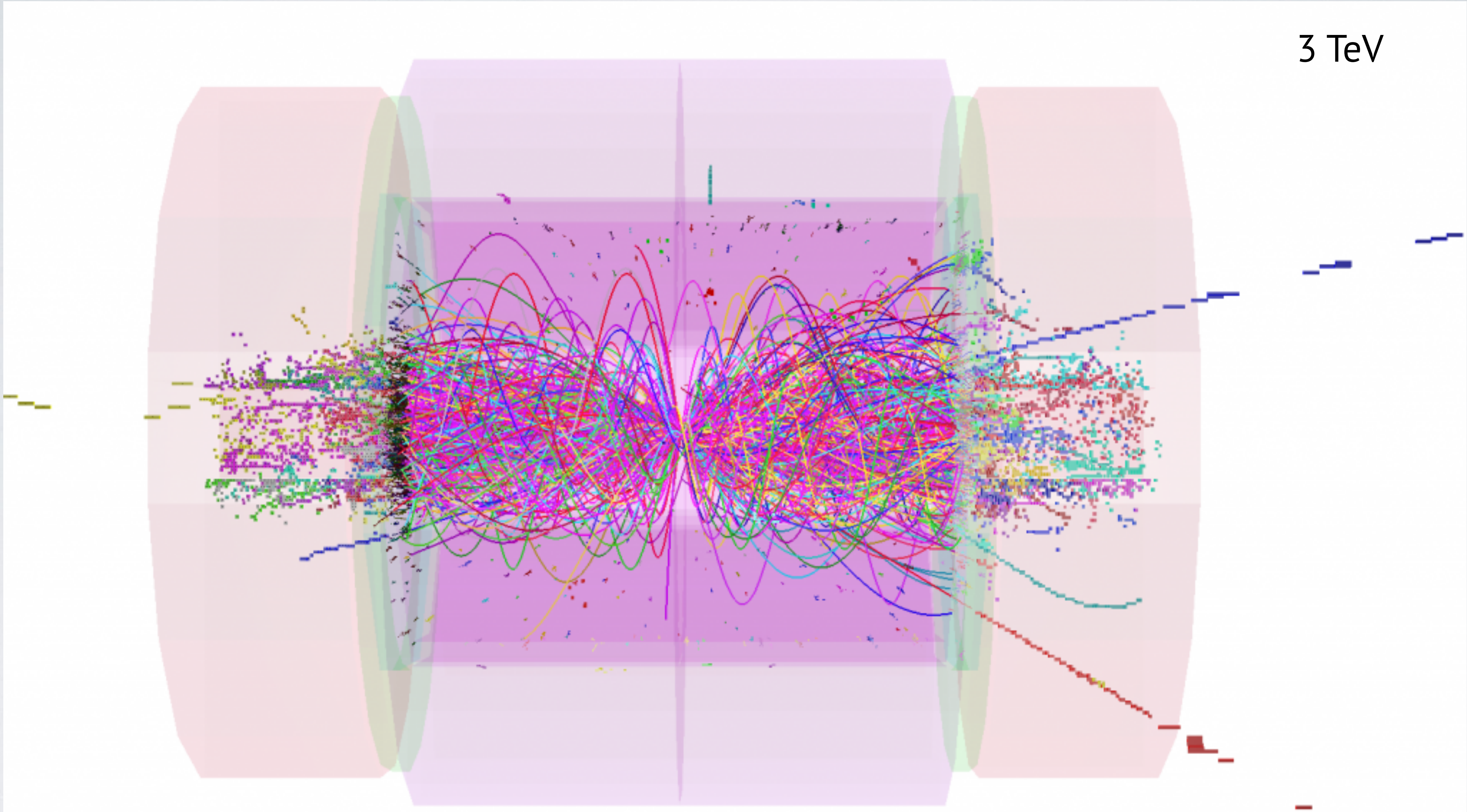
- Beam structure: polarization, asymmetric beams, crossing angle, structured beams, decays

```
beams = e1, E1
beams_pol_density = @(-1), @(+1)
beams_pol_fraction = 80%, 30%
```

```
beams = p, pbar => lhapdf
$lhapdf = "NNPDF3"
```

```
beams = e1, E1 => circe2 => isr => ewa
```

e^+e^- Beamspectra



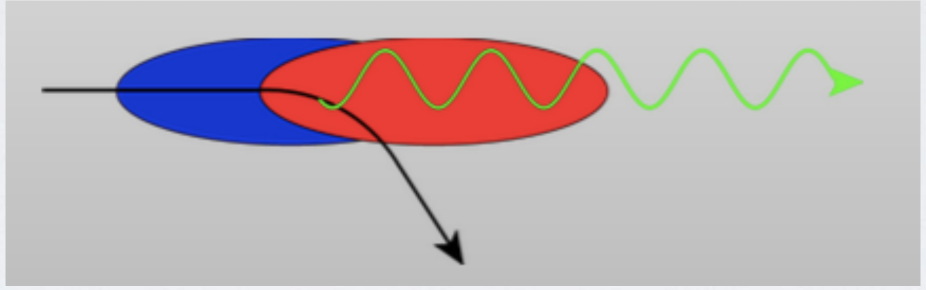
$$e^+e^- \to \tilde{\mu}^+\tilde{\mu}^-$$

Courtesy to Philipp Roloff

e^+e^- Beamspectra

- High-energy e+e- colliders need to achieve extreme luminosities
- Price for limited AC power: high bunch charges and tiny cross sections
- Dense beams generate strong EM fields: deflect particles in other bunch (beamstrahlung)

$$L \approx \frac{N}{4\pi\sigma_x\sigma_y}\frac{\eta P_{AC}}{E_{CM}}$$



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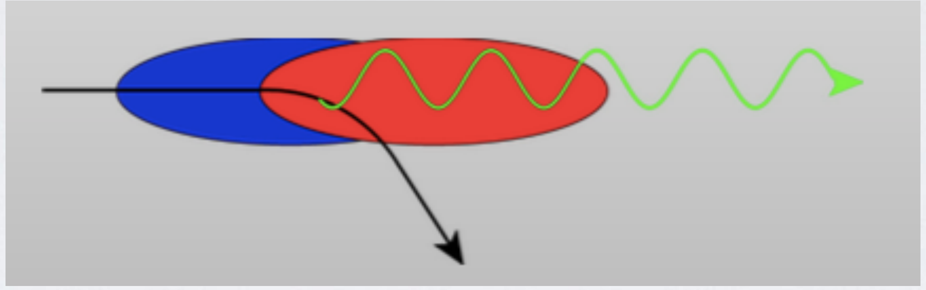

Index of /circe_files/CLIC

Name	Last modified	Size Des
Parent Directory		-
0.5TeVeeMapPB0.67E0.0Mi0.30.circe	06-Jul-2016 17:03	6.0M
0.5TeVegMapPB0.67E0.0Mi0.0.circe	06-Jul-2016 17:03	6.0M
0.5TeVgeMapPB0.67E0.0Mi0.0.circe	06-Jul-2016 17:03	6.0M
0.5TeVggMapPB0.67E0.0Mi0.0.circe	06-Jul-2016 17:03	3.9M
0.35TeVeeMapPB0.67E0.0Mi0.30.circe	06-Jul-2016 17:02	6.0M
0.35TeVegMapPB0.67E0.0Mi0.0.circe	06-Jul-2016 17:02	6.0M
0.35TeVgeMapPB0.67E0.0Mi0.0.circe	06-Jul-2016 17:03	6.0M
0.35TeVggMapPB0.67E0.0Mi0.0.circe	06-Jul-2016 17:03	3.9M
0.38TeVeeMapPB0.67E0.0Mi0.30.circe	23-Jun-2017 16:02	14M
0.38TeVegMapPB0.67E0.0Mi0.0.circe	23-Jun-2017 16:02	9.0M
0.38TeVgeMapPB0.67E0.0Mi0.0.circe	23-Jun-2017 16:02	9.0M
0.38TeVggMapPB0.67E0.0Mi0.0.circe	23-Jun-2017 16:02	3.9M
1.4TeVeeMapPB0.67E0.0Mi0.15.circe	06-Jul-2016 17:03	35M
1.4TeVegMapPB0.67E0.0Mi0.0.circe	06-Jul-2016 17:03	15M
1.4TeVgeMapPB0.67E0.0Mi0.0.circe	06-Jul-2016 17:04	7.8M
1.4TeVggMapPB0.67E0.0Mi0.0.circe	06-Jul-2016 17:04	15M
3TeVeeMapN100.circe	06-Jul-2016 17:04	1.0M
3TeVeeMapPB0.67E0.0Mi0.15.circe	06-Jul-2016 17:04	24M
3TeVegMapN100.circe	06-Jul-2016 17:04	521K
3TeVegMapPB0.67E0.0Mi0.0.circe	06-Jul-2016 17:04	12M
3TeVgeMapN100.circe	06-Jul-2016 17:04	1.0M
3TeVgeMapPB0.67E0.0Mi0.0.circe	06-Jul-2016 17:04	24M
3TeVggMapN100.circe	06-Jul-2016 17:05	273K
3TeVggMapPB0.67E0.0Mi0.0.circe	06-Jul-2016 17:05	6.1M

Index of /circe_files/TESLA

Name	Last modified	Size	Description
Parent Directory		-	
teslagg_500.circe	29-Jul-2016 13:20	1.1M	
teslagg_500_polavg.circe	29-Jul-2016 13:20	270K	

Index of /circe_files/ILC

Name	Last modified	Size	Description
Parent Directory		-	
ilc200ee_nobeamspread.circe	29-Jul-2016 13:20	1.0M	
ilc230ee_nobeamspread.circe	29-Jul-2016 13:20	1.0M	
ilc250ee_nobeamspread.circe	29-Jul-2016 13:20	1.0M	
ilc350ee_nobeamspread.circe	29-Jul-2016 13:20	1.0M	
ilc500ee_nobeamspread.circe	29-Jul-2016 13:20	1.0M	

Index of /circe_files/CEPC

Name	Last modified	Size	Description
Parent Directory		-	
cepc240.circe	29-Jul-2016 13:20	252K	
cepc250.circe	29-Jul-2016 13:20	252K	

Inclusive Lepton Collider ISR included

Soft exponentiation to all orders

$$\epsilon = \frac{\alpha}{\pi} q_e^2 \ln\left(\frac{s}{m^2}\right)$$

Gribov/Lipatov, 1971

$$f_0(x) = \epsilon \cdot (1-x)^{-1+\epsilon}$$

Hard-collinear photons up to 3rd QED order

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Hard-collinear photons up to 3rd QED order

Kuraev/Fadin, 1983; Skrzypek/Jadach, 1991

$$g_3(\epsilon) = 1 + \frac{3}{4}\epsilon + \frac{27-8\pi^2}{96}\epsilon^2 + \frac{27-24\pi^2+128\zeta(3)}{384}\epsilon^3$$

$$\begin{aligned} f_3(x) = {} & g_3(\epsilon)\, f_0(x) - \frac{\epsilon}{2}(1+x) \\ & - \frac{\epsilon^2}{8}\left(\frac{1+3x^2}{1-x}\ln x + 4(1+x)\ln(1-x) + 5 + x\right) \\ & - \frac{\epsilon^3}{48}\Bigg((1+x)\left[6\,\mathrm{Li}_2(x) + 12\ln^2(1-x) - 3\pi^2\right] + 6(x+5)\ln(1-x) \\ & \quad + \frac{1}{1-x}\Bigg[\frac{3}{2}(1+8x+3x^2)\ln x + 12(1+x^2)\ln x \ln(1-x) \\ & \quad - \frac{1}{2}(1+7x^2)\ln^2 x + \frac{1}{4}(39-24x-15x^2)\Bigg]\Bigg) \end{aligned}$$

$$\zeta(3) = 1.202056903159594285399738161511\ldots$$

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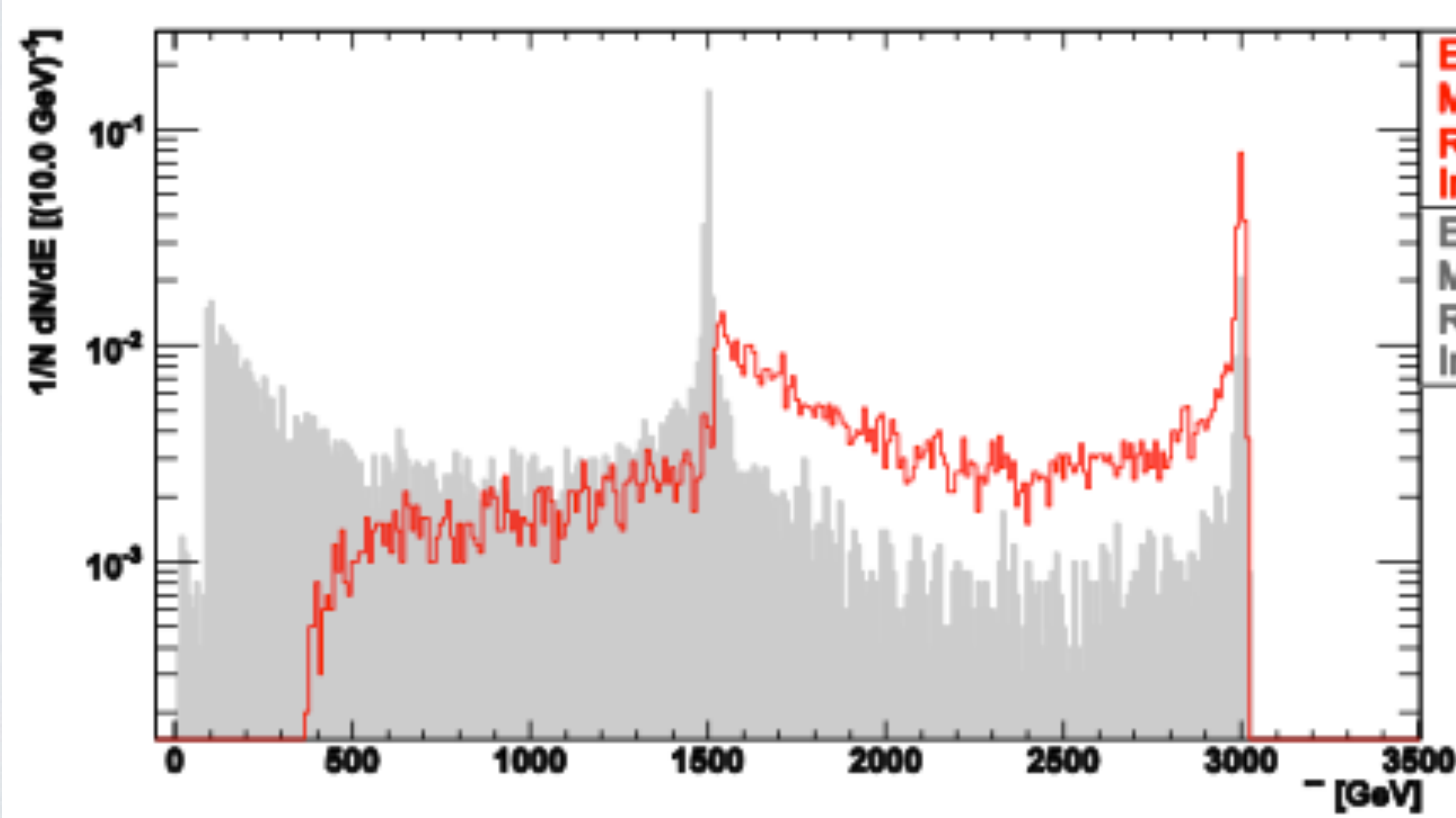


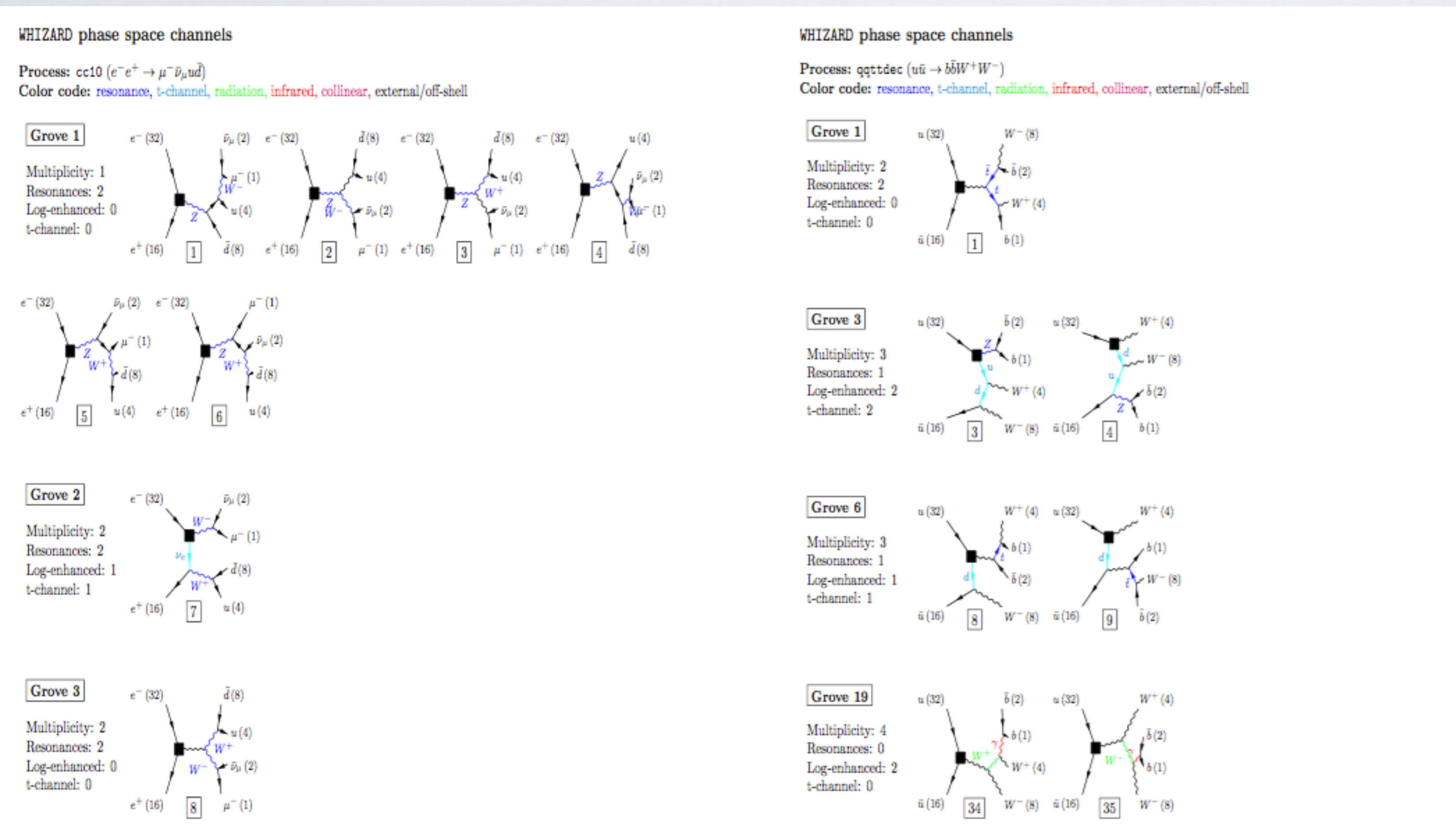
- $E = 3000$ GeV (luminosity spectrum peak)
- $E = 1500$ GeV (Z peak and lumi spectrum)
- $E = M_Z$ (Z resonance)
- $E \approx 30$ GeV (due to $e^+e^- \to \gamma^* \to b\bar{b}$)

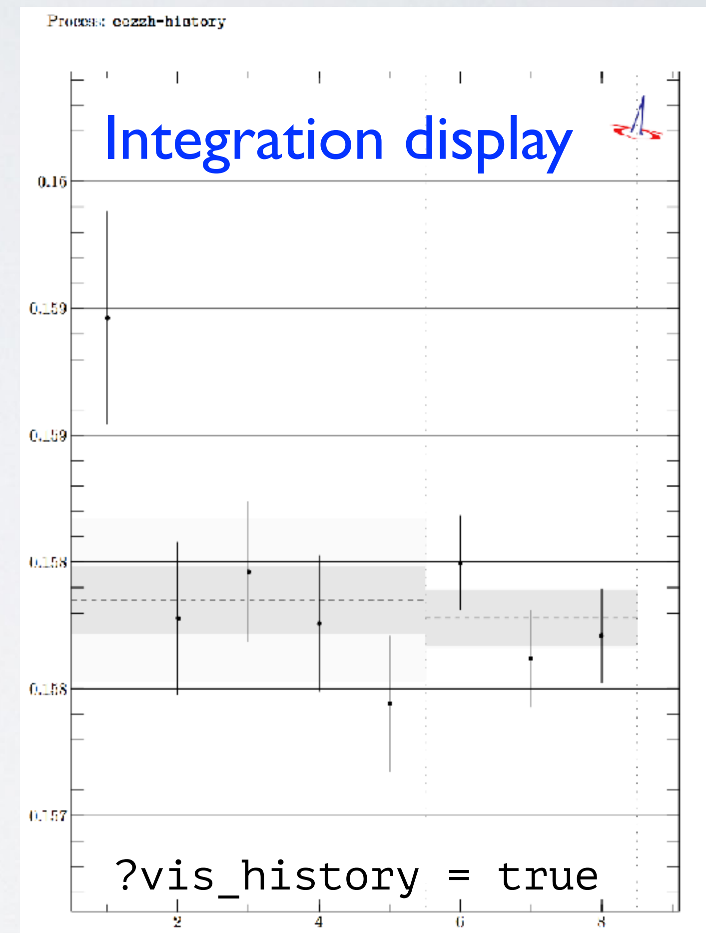
[from J.-J. Blaising]

Phase Space Integration

- VAMP: adaptive multi-channel Monte Carlo integrator
- VAMP2: fully MPI-parallelized version, using RNG stream generator

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



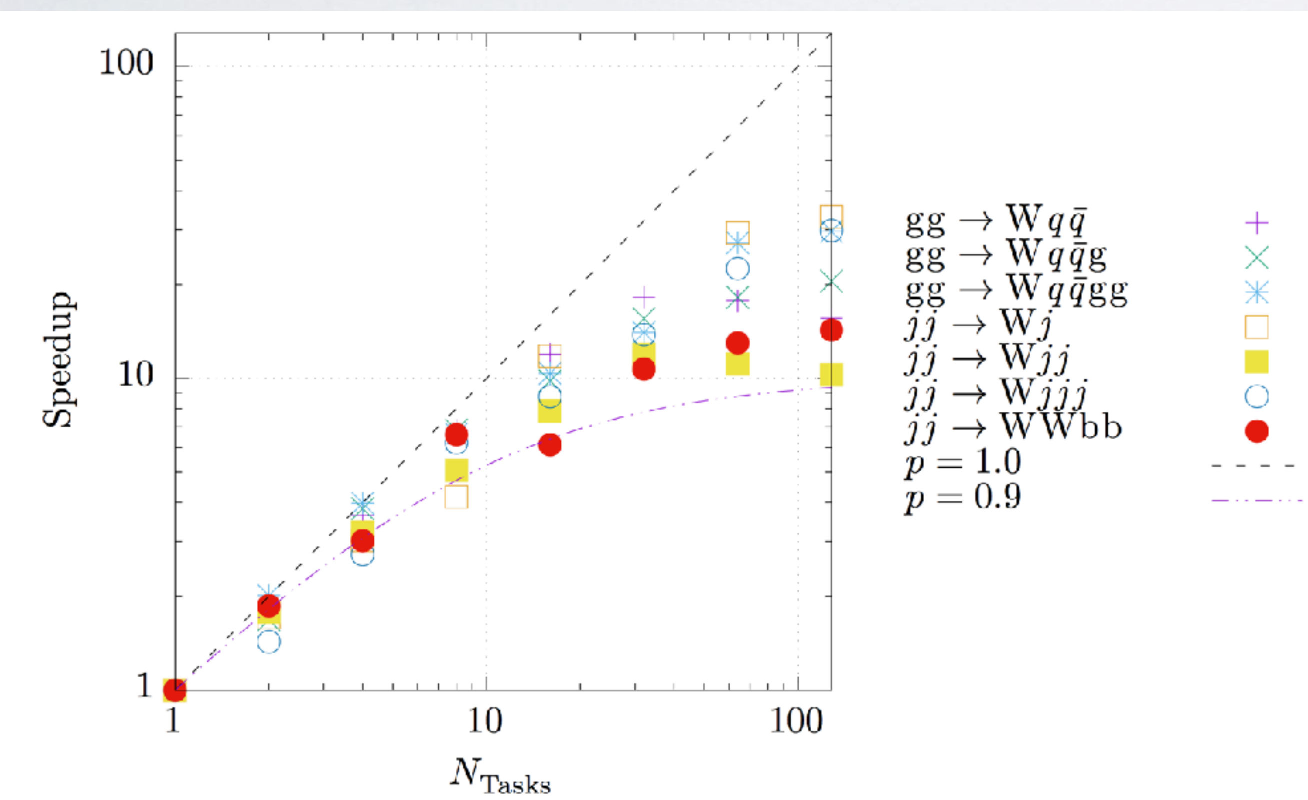


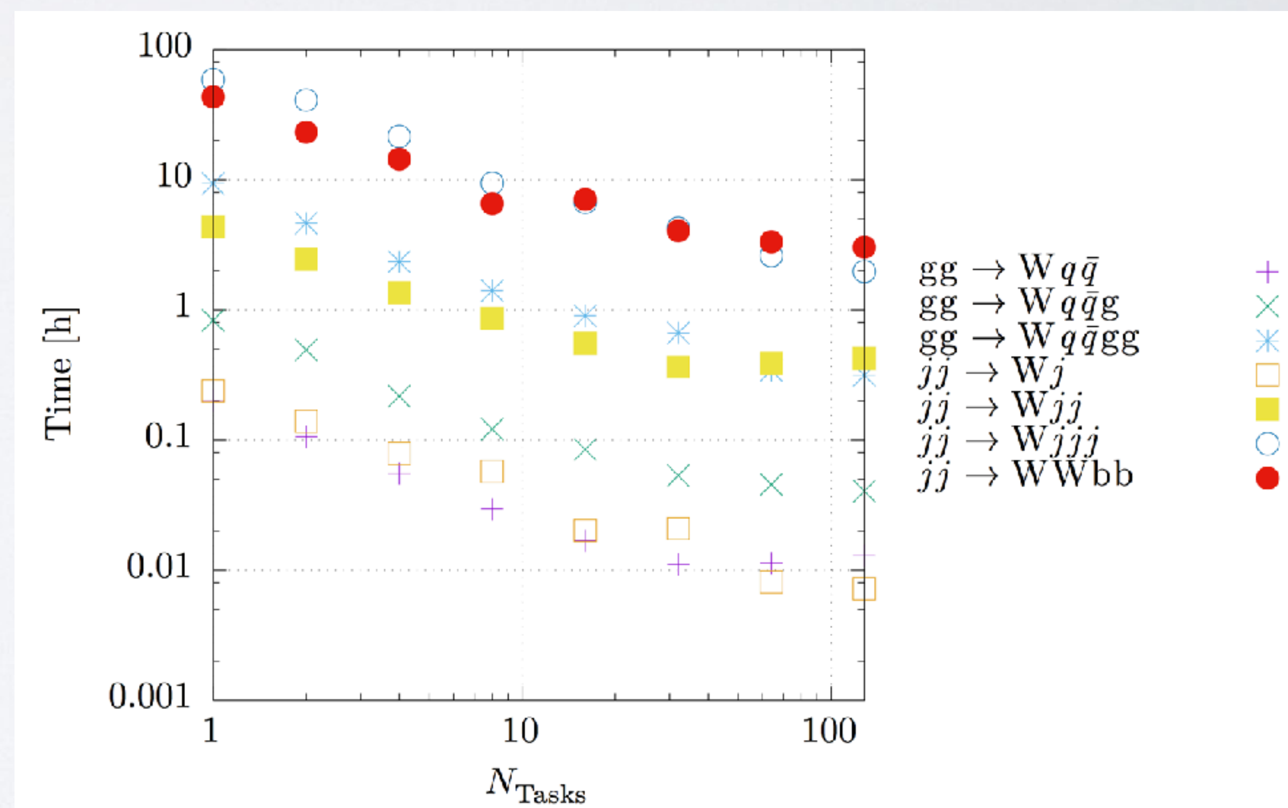
Complicated processes: factorization into production and decay with the `unstable` option

Resonance-aware factorization for NLO processes and parton showers (e.g. $e^+e^- \to jjjj$)

MPI Parallelization

- Event generation trivially parallelizable
- Major bottleneck: adaptive phase space integration (generation of grids)
- Parallelization of integration: OMP multi-threading for different helicities since long
- NEW (after v2.5.0/2.6.3): MPI parallelisation (using OpenMPI)
- Distributes workers over multiple cores, grid adaption needs non-trivial communication
- Amdahl's law: $s = \frac{1}{1-p+\frac{p}{N}}$
- Speedups of 10 to 30, saturation at O(100) tasks
- Integration times go down from weeks to hours!





Keep resonances in ME-PS merging

- Problem: $e^+e^- \to jjjj$ not dominated by highest α_s power,
  but by resonances $e^+e^- \to WW/ZZ \to (jj)(jj)$
- Solution: proper merging with resonant subprocesses by means of resonance histories
- `WHIZARD v2.6.0:` option to set resonance histories

```
?resonance_history = true
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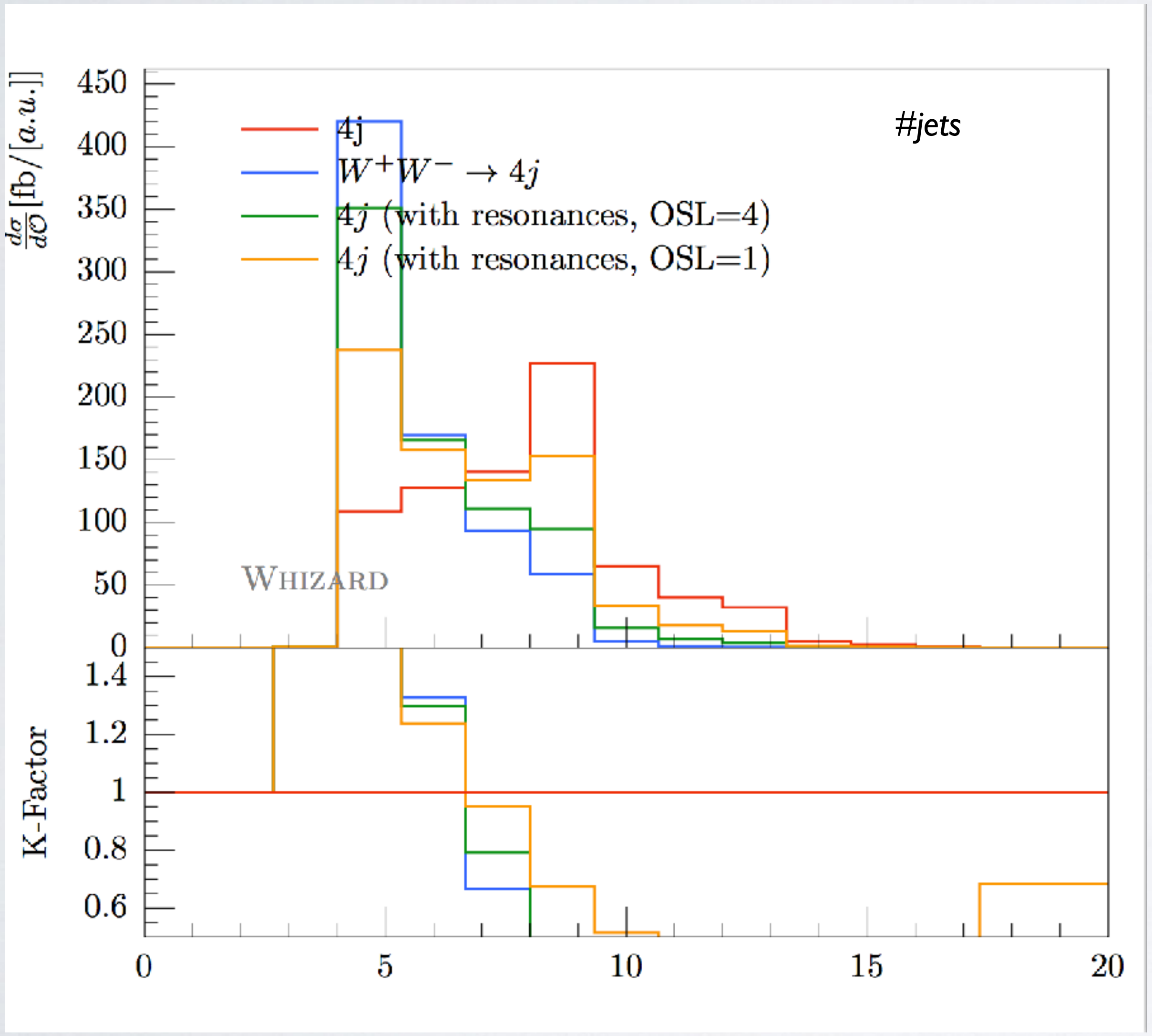

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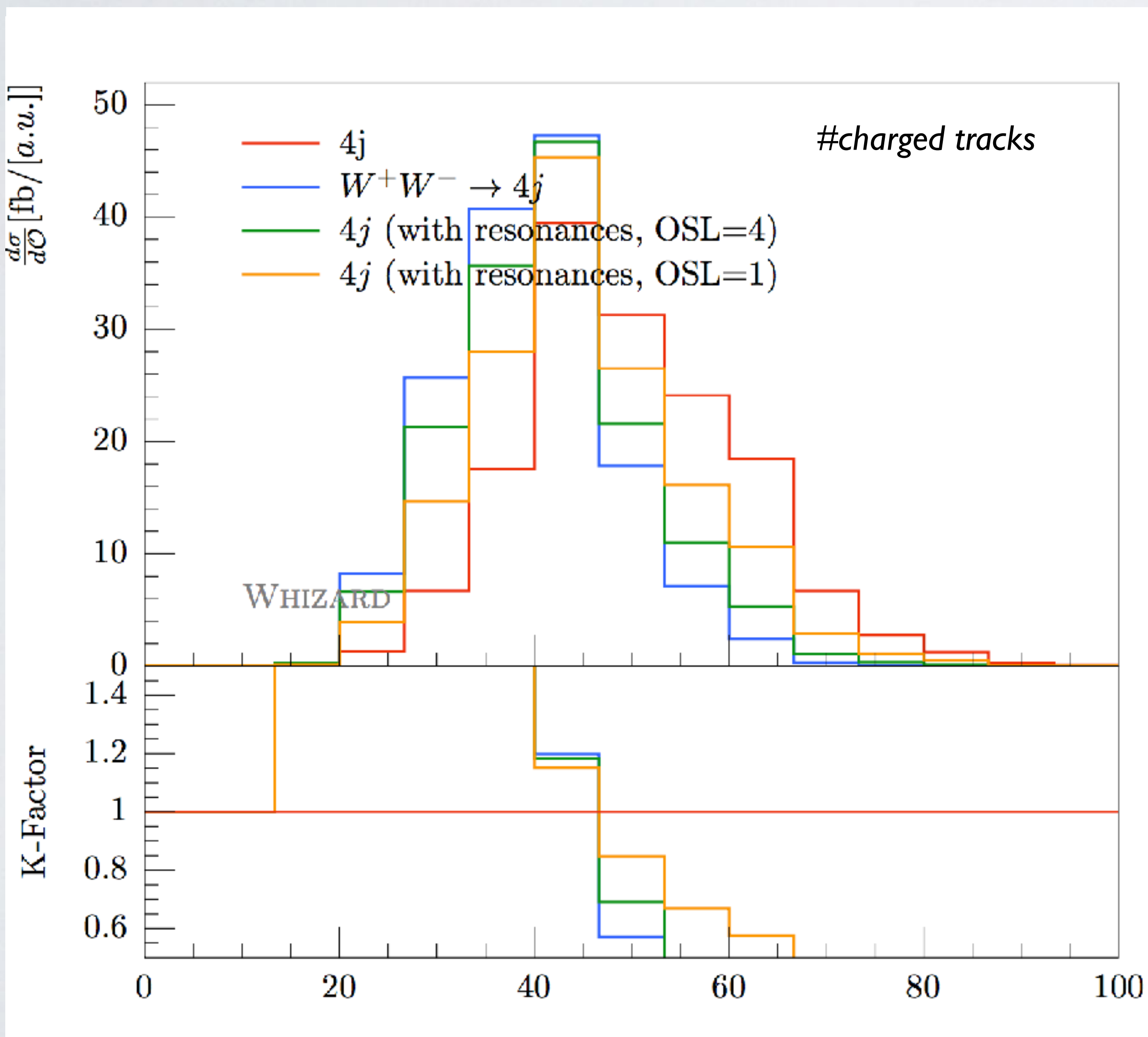

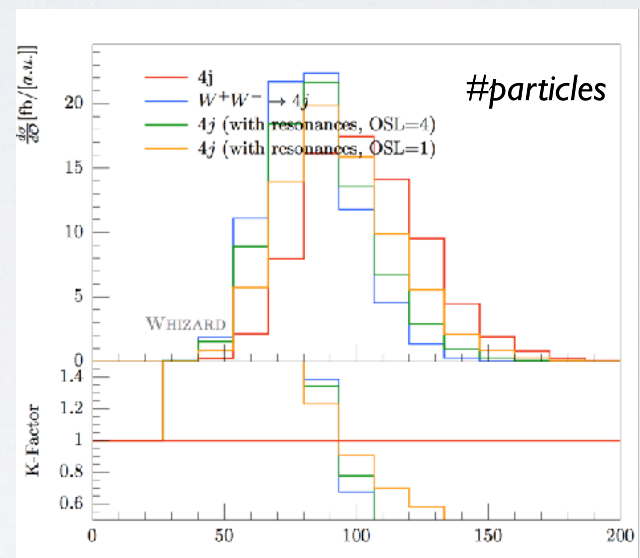

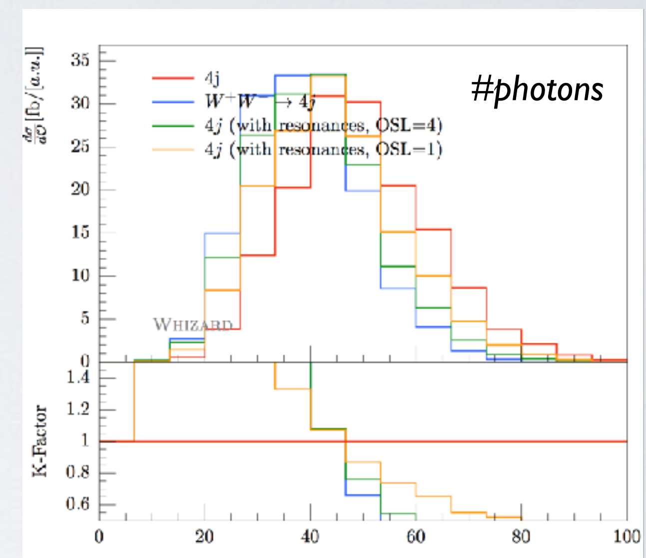

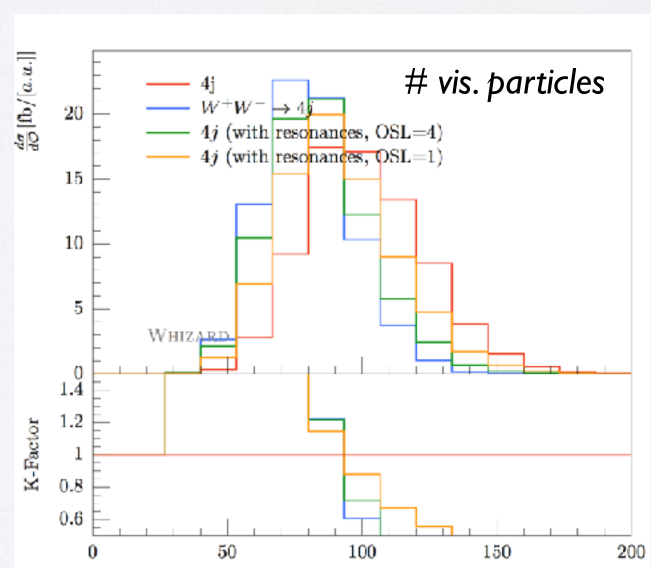

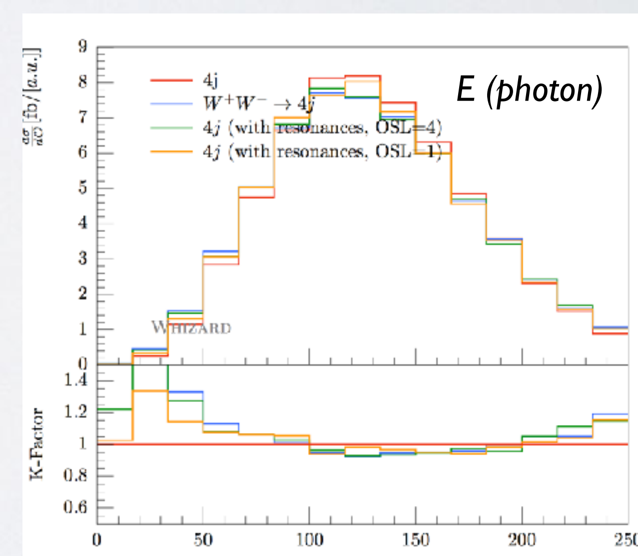

BSM Models in WHIZARD

MODEL TYPE	with CKM matrix	trivial CKM
Yukawa test model	---	Test
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 couplings	SM_ac_CKM	SM_ac
SM with Hgg, $H\gamma\gamma$, $H\mu\mu$, He^+e^-	SM_Higgs_CKM	SM_Higgs
SM with bosonic dim-6 operators	---	SM_dim6
SM with charge 4/3 top	---	SM_top
SM with anomalous top couplings	---	SM_top_anom
SM with anomalous Higgs couplings	---	SM_rx/NoH_rx/SM_ul
SM extensions for VV scattering	---	SSC/AltH/SSC_2/SSC_AltT
SM with Z'	---	Zprime
Two-Higgs Doublet Model	THDM_CKM	THDM
Higgs Singlet Extension	---	HSExt
MSSM	MSSM_CKM	MSSM
MSSM with gravitinos	---	MSSM_Grav
NMSSM	NMSSM_CKM	NMSSM
extended SUSY models	---	PSSSM
Littlest Higgs	---	Littlest
Littlest Higgs with ungauged $U(1)$	---	Littlest_Eta
Littlest Higgs with T parity	---	Littlest_Tpar
Simplest Little Higgs (anomaly-free)	---	Simplest
Simplest Little Higgs (universal)	---	Simplest_univ
SM with graviton	---	Xdim
UED	---	UED
"SQED" with gravitino	---	GravTest
Augmentable SM template	---	Template

- 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

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- Automated models: UFO interface [new WHIZARD/O'Mega model format]

Models from UFO Files in WHIZARD


```
model = SM  (ufo)
```

UFO file is assumed to be in working directory OR

```
model = SM  (ufo ("<my UFO path>"))
```

UFO file is in user-specified directory

```
|                              WHIZARD 2.5.1
|=============================================================================|
| Reading model file '/Users/reuter/local/share/whizard/models/SM.mdl'
| Preloaded model: SM
| Process library 'default_lib': initialized
| Preloaded library: default_lib
| Reading model file '/Users/reuter/local/share/whizard/models/SM_hadrons.mdl'
| Reading commands from file 'ufo_2.sin'
| Model: Generating model 'SM' from UFO sources
| Model: Searching for UFO sources in working directory
| Model: Found UFO sources for model 'SM'
| Model: Model file 'SM.ufo.mdl' generated
| Reading model file 'SM.ufo.mdl'
```

```
| Switching to model 'SM' (generated from UFO source)
```

NEW

All the setup works the same as for intrinsic models

Old FeynRules / SARAH interface will get deprecated

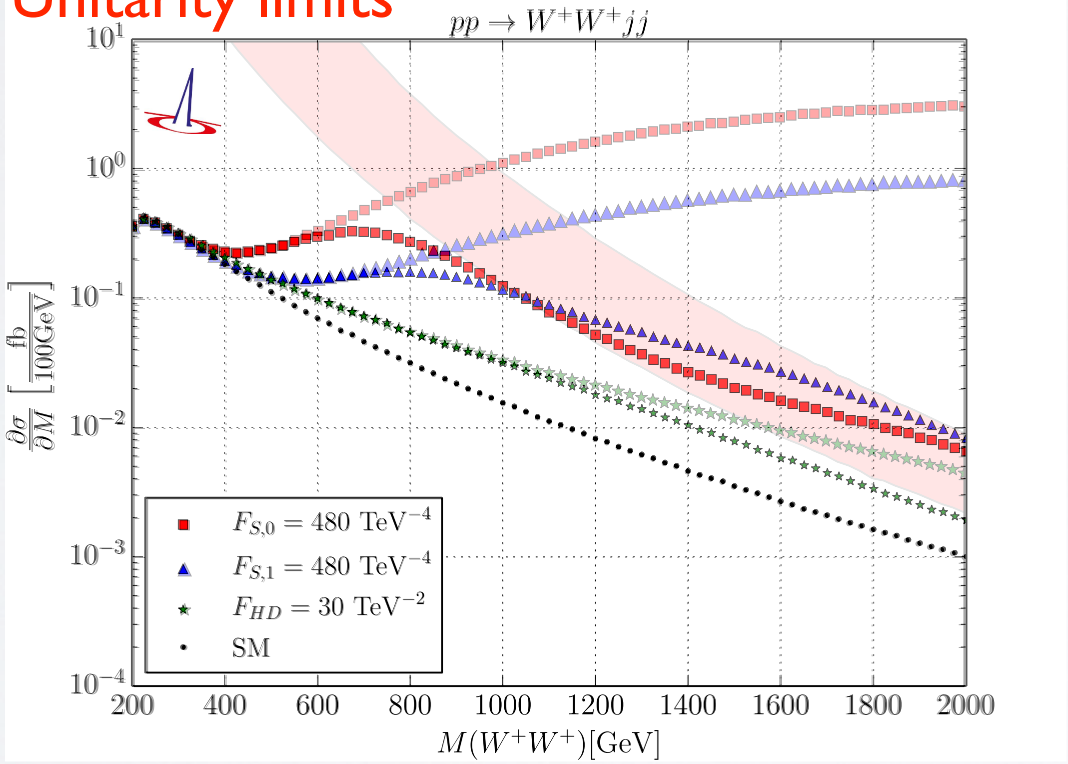
kept at the moment for user backwards compatibility

All SM-like models/scalar extensions already supported
Higher-dim. operators, general Lorentz/color structures is work in progress

New Physics in Vector Boson Scattering: LHC

- Vector Boson Scattering (VBS) major measurement of LHC runs II/III   Gianotti, 01/2014
- Light Higgs suppression makes VBS prime candidate for BSM searches
- Model-independent EFT: either weakly-coupled resonances in reach or strongly-coupled sectors   Alboteanu/Kilian/JRR, 0806.4145; Kilian/Ohl/JRR/Sekulla, 1408.6207
- Parameterize new physics by dim 6/dim 8 operators, calculate unitarity limits
- Dimension-8 operators for longitudinal/mixed/transverse modes   Fleper/Kilian/JRR/Sekulla, 2017
- T-matrix unitarization implemented in `WHIZARD` (both for operators and resonances)

Unitarity limits

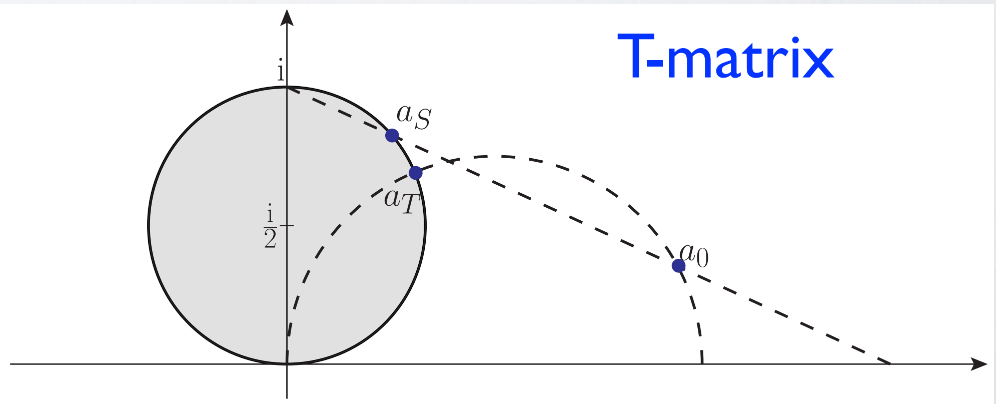


$$\mathcal{L}_{S,0} = F_{S,0}\text{Tr}[(\mathbf{D}_\mu\mathbf{H})^\dagger(\mathbf{D}_\nu\mathbf{H})]\ \text{Tr}[(\mathbf{D}^\mu\mathbf{H})^\dagger(\mathbf{D}^\nu\mathbf{H})]$$
$$\mathcal{L}_{S,1} = F_{S,1}\text{Tr}[(\mathbf{D}_\mu\mathbf{H})^\dagger(\mathbf{D}^\mu\mathbf{H})]\ \text{Tr}[(\mathbf{D}_\nu\mathbf{H})^\dagger(\mathbf{D}^\nu\mathbf{H})]$$

$$\mathcal{L}_{M,0} = -g^2 F_{M,0}\text{Tr}[(\mathbf{D}_\mu\mathbf{H})^\dagger(\mathbf{D}^\mu\mathbf{H})]\ \text{Tr}[\mathbf{W}_{\nu\rho}\mathbf{W}^{\nu\rho}]$$
$$\mathcal{L}_{M,1} = -g^2 F_{M,1}\text{Tr}[(\mathbf{D}_\mu\mathbf{H})^\dagger(\mathbf{D}^\rho\mathbf{H})]\ \text{Tr}[\mathbf{W}_{\nu\rho}\mathbf{W}^{\nu\mu}]$$

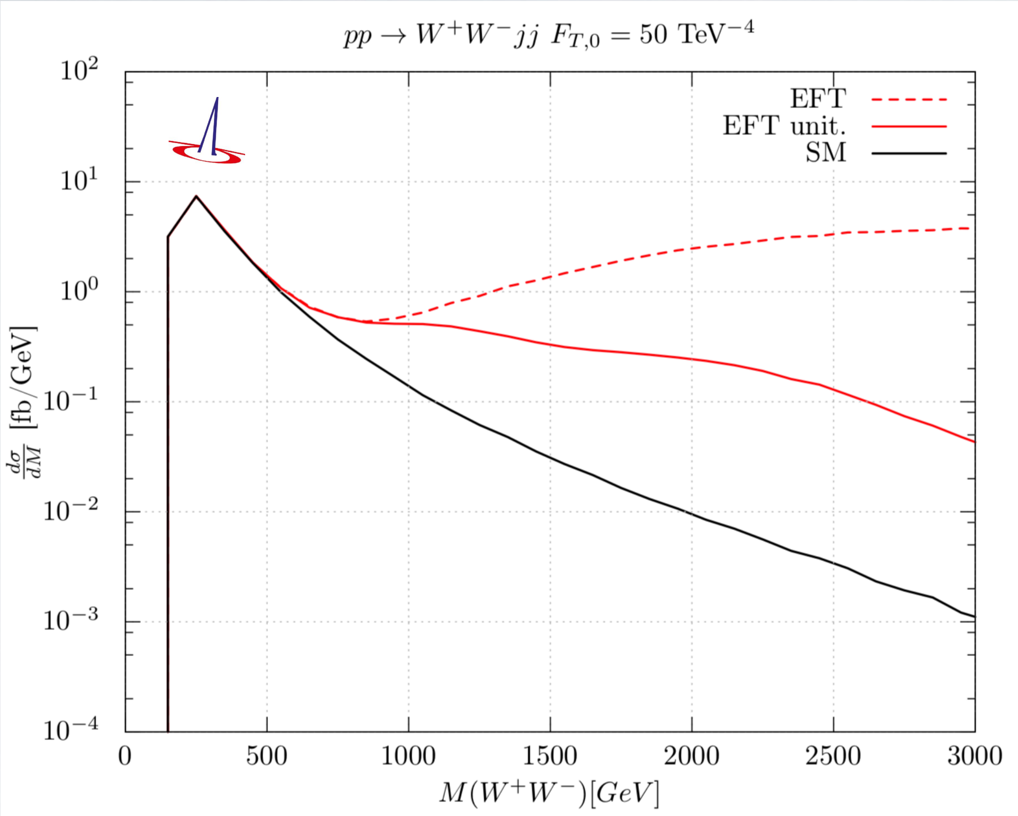
$$\mathcal{L}_{T,0} = g^4 F_{T,0}\text{Tr}[\mathbf{W}_{\mu\nu}\mathbf{W}^{\mu\nu}]\ \text{Tr}[\mathbf{W}_{\alpha\beta}\mathbf{W}^{\alpha\beta}]$$
$$\mathcal{L}_{T,1} = g^4 F_{T,1}\text{Tr}[\mathbf{W}_{\alpha\nu}\mathbf{W}^{\mu\beta}]\ \text{Tr}[\mathbf{W}_{\mu\beta}\mathbf{W}^{\alpha\nu}]$$
$$\mathcal{L}_{T,2} = g^4 F_{T,2}\text{Tr}[\mathbf{W}_{\alpha\mu}\mathbf{W}^{\mu\beta}]\ \text{Tr}[\mathbf{W}_{\beta\nu}\mathbf{W}^{\nu\alpha}]$$

T-matrix



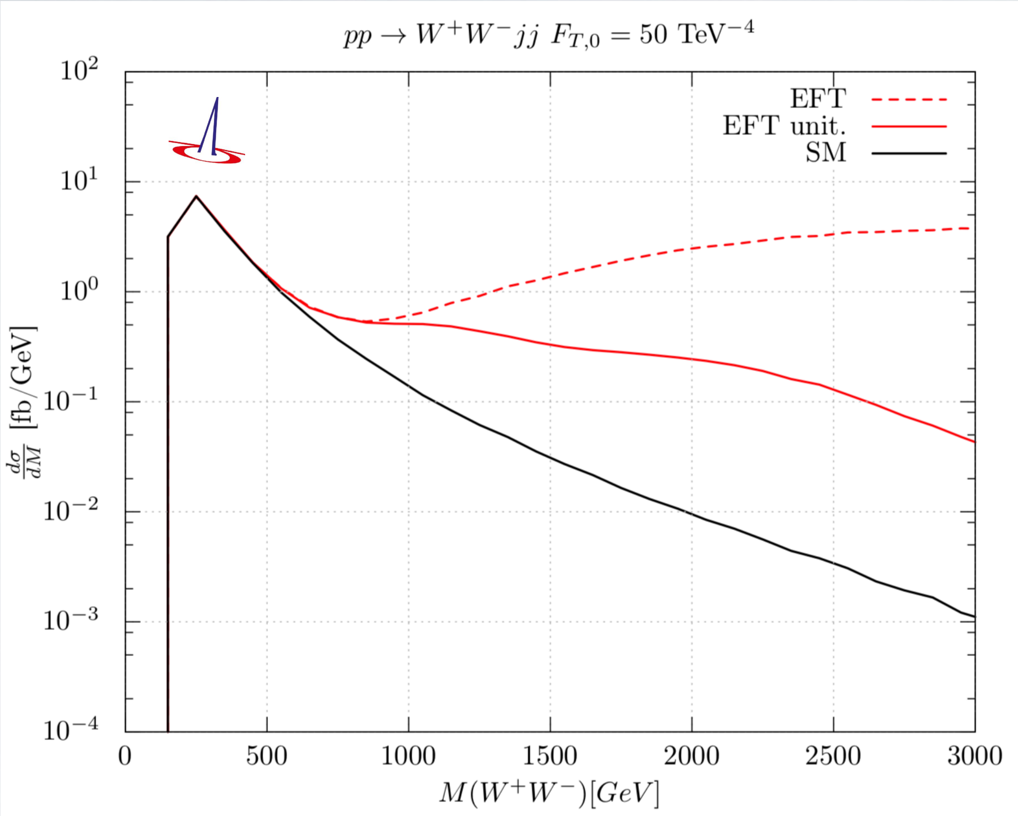
$$\left|a - \frac{a_K}{2}\right| = \frac{a_K}{2} \quad \Rightarrow \quad a = \frac{1}{\text{Re}\left(\frac{1}{a_0}\right) - \text{i}}$$

New Physics in VBS: LHC & Lepton Colliders



Braß/Kilian/JRR/Sekulla, 04-05/18

New Physics in VBS: LHC & Lepton Colliders

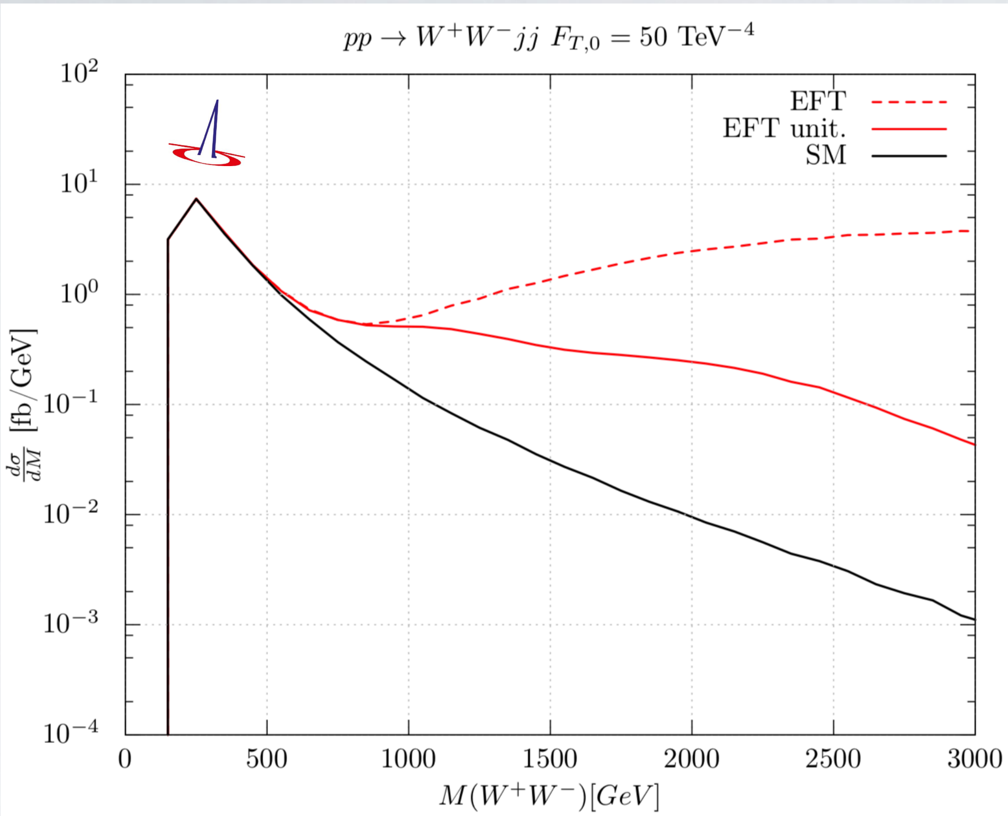


Braß/Kilian/JRR/Sekulla, 04-05/18

Transversal (&mixed) operators:

Much more room for new physics

New Physics in VBS: LHC & Lepton Colliders



Braß/Kilian/JRR/Sekulla, 04-05/18

Transversal (&mixed) operators:

Much more room for new physics

	isoscalar	isotensor
scalar	σ^0	$\phi_t^{--}, \phi_t^-, \phi_t^0, \phi_t^+, \phi_t^{++}$ $\phi_v^-, \phi_v^0, \phi_v^+$ ϕ_s^0
tensor	f^0	$\Big(X_t^{--}, X_t^-, X_t^0, X_t^+, X_t^{++}$ X_v^-, X_v^0, X_v^+ $X_s^0 \Big)$
...	...	...

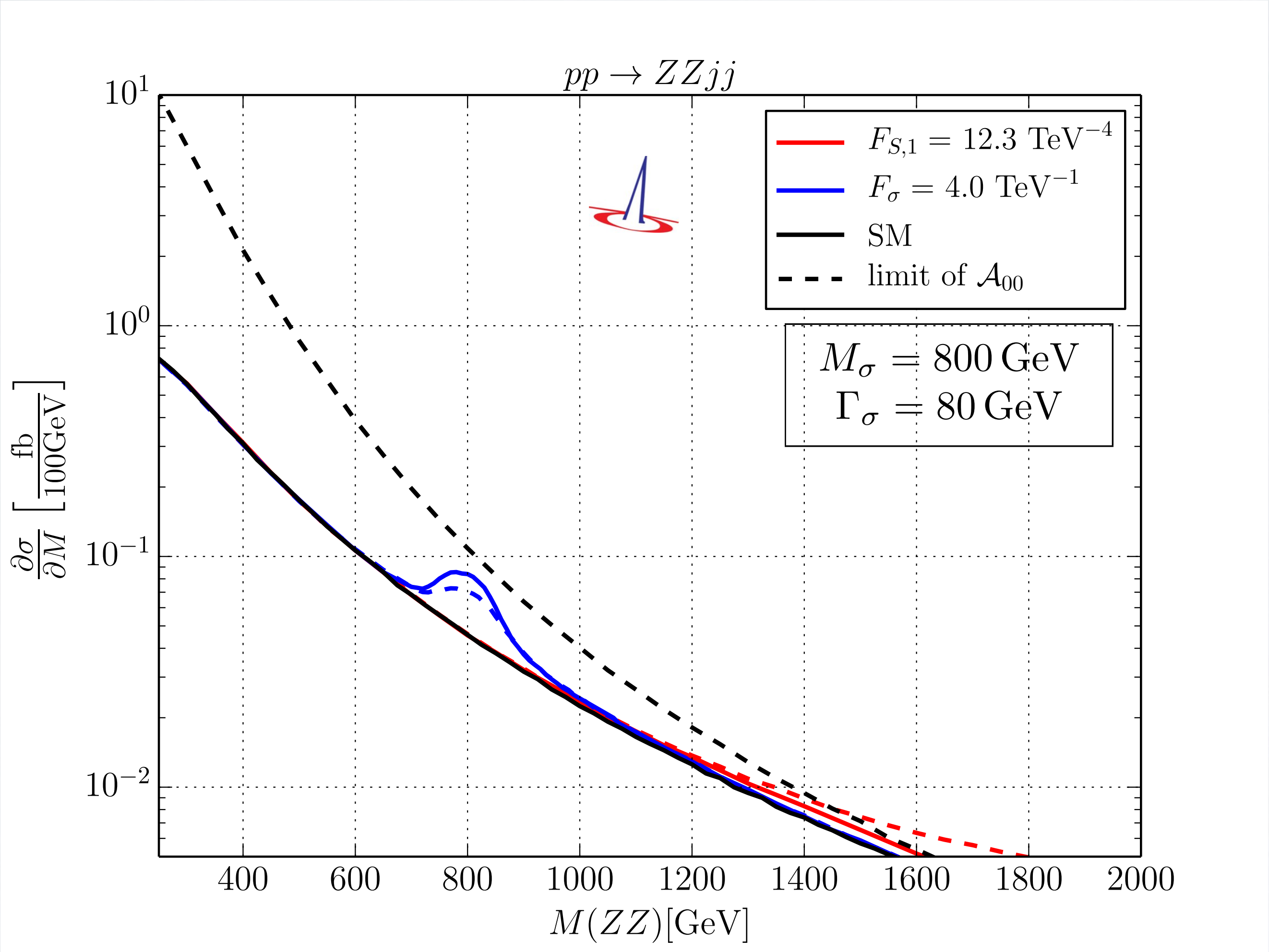
- Rise of amplitude: Taylor expansion below a resonance
- Resonances might be in direct reach of LHC
- EFT framework EW-restored regime: $SU(2)_L \times SU(2)_R$, $SU(2)_L \times U(1)_Y$ gauged
- Include EFT operators in addition (more resonances, continuum contribution)
- Apply *T*-matrix unitarization beyond resonance ("UV-incomplete" model)

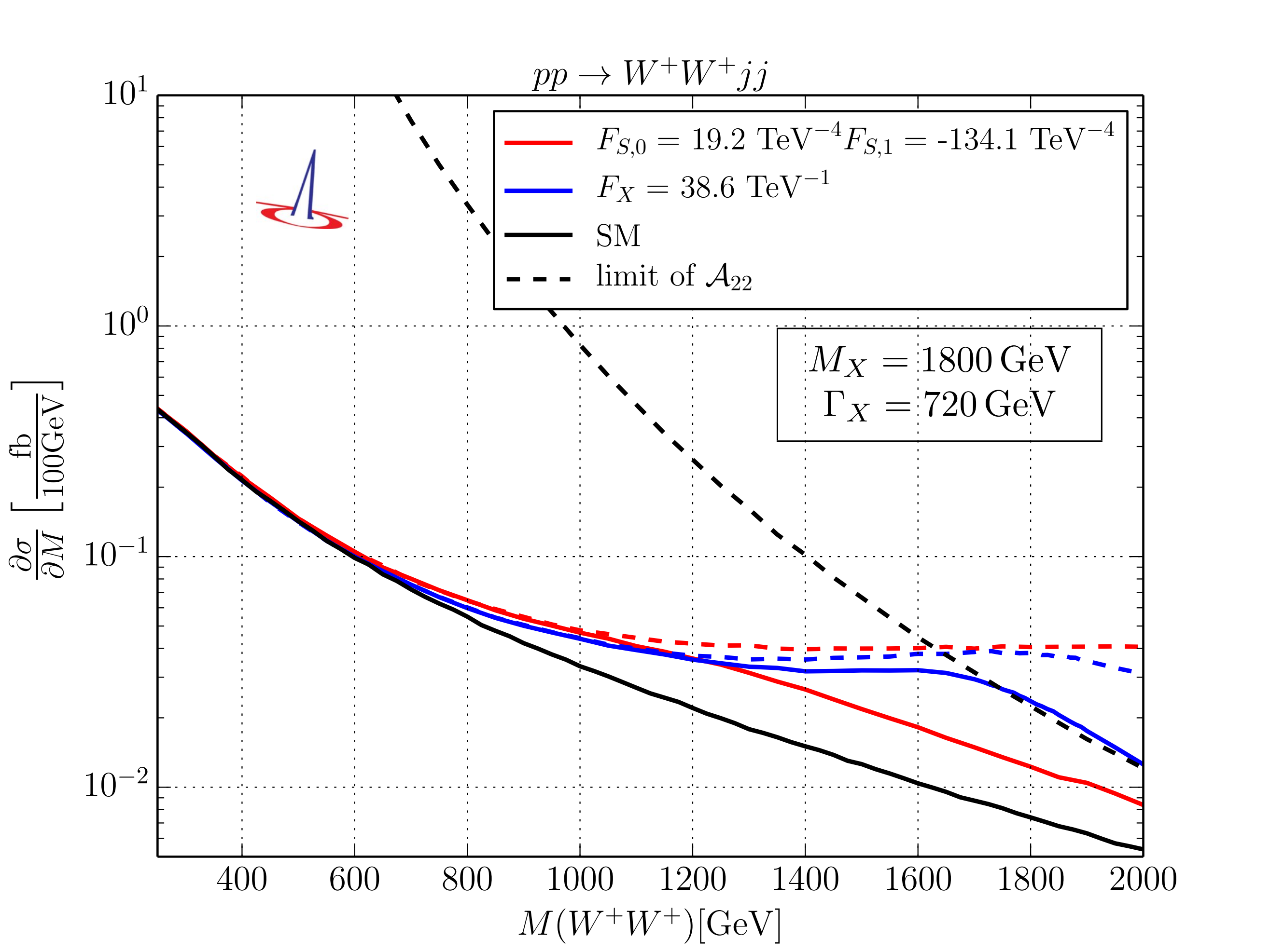
Spins 0, 2 considered, Spin 1 has different physics (mixing with *W*/*Z*)

Comparison: Simplified Models & EFT

Kilian/Ohl/JRR/Sekulla: 1511.00022

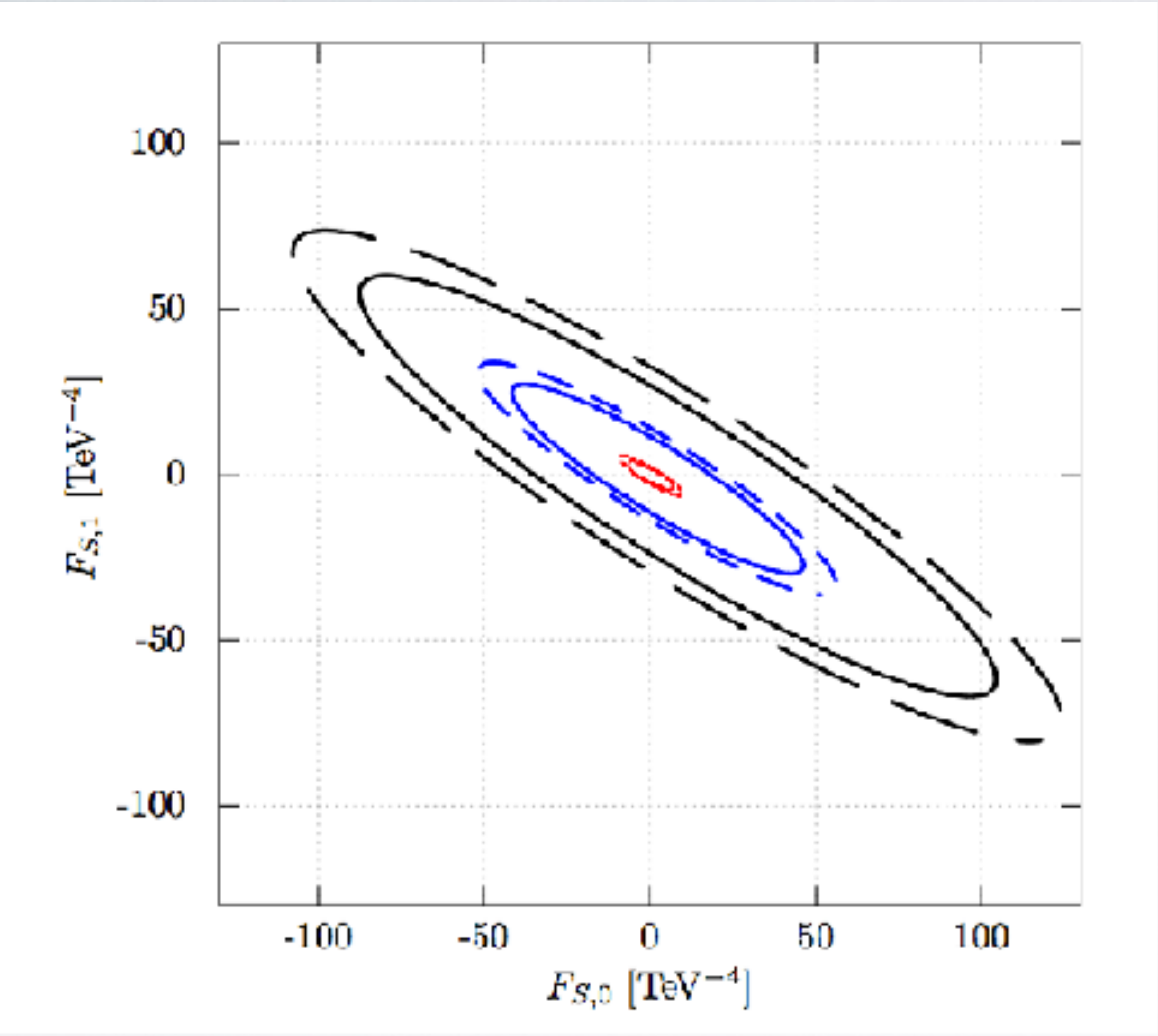
Black dashed line:
saturation of $\mathcal{A}_{22}(W^+W^+)/\mathcal{A}_{00}(ZZ)$

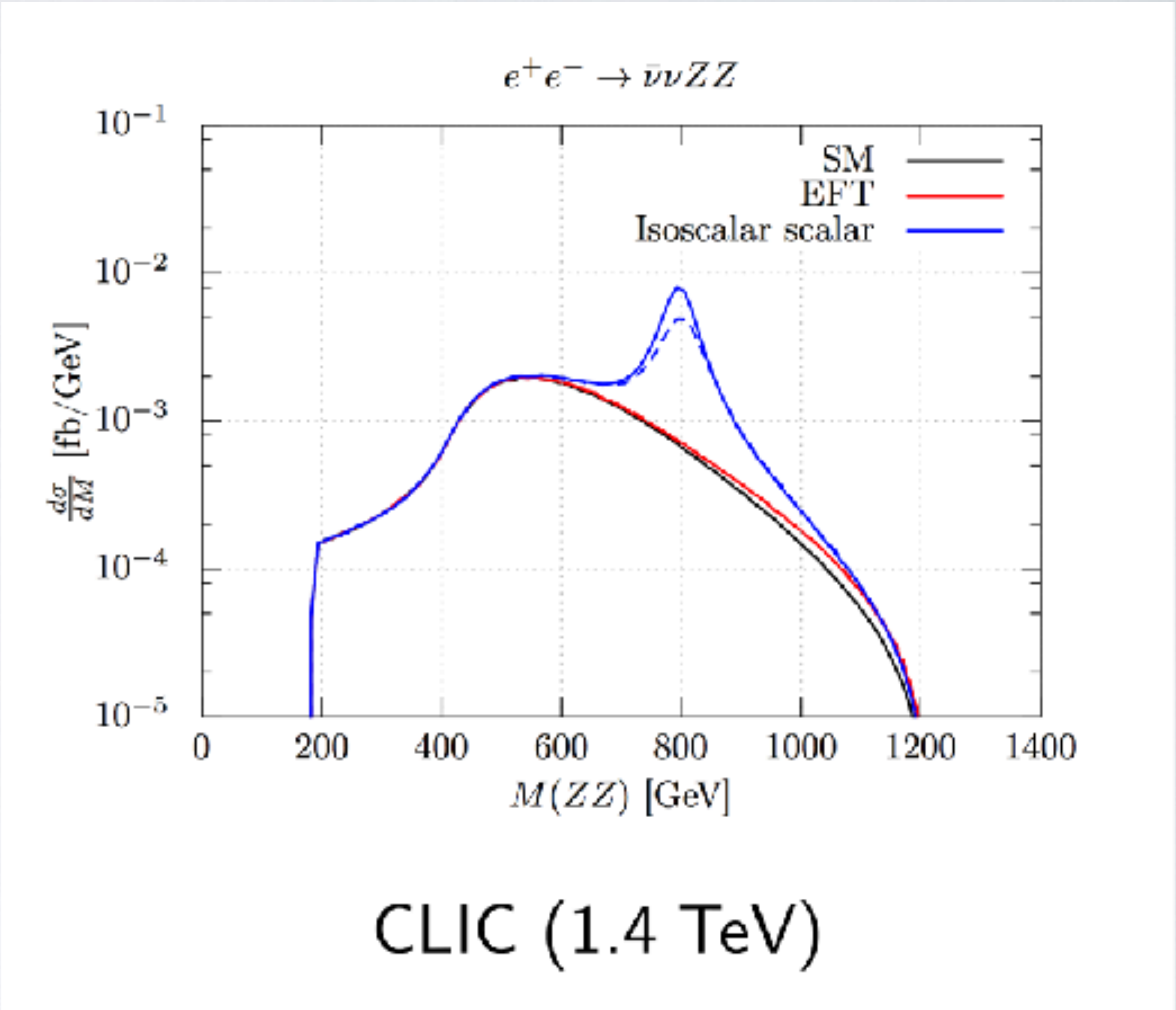




$M_{jj} > 500\,\text{GeV};\ \Delta\eta_{jj} > 2.4;\ \ p_T^j > 20\,\text{GeV};\ \ |\Delta\eta_j| < 4.5$

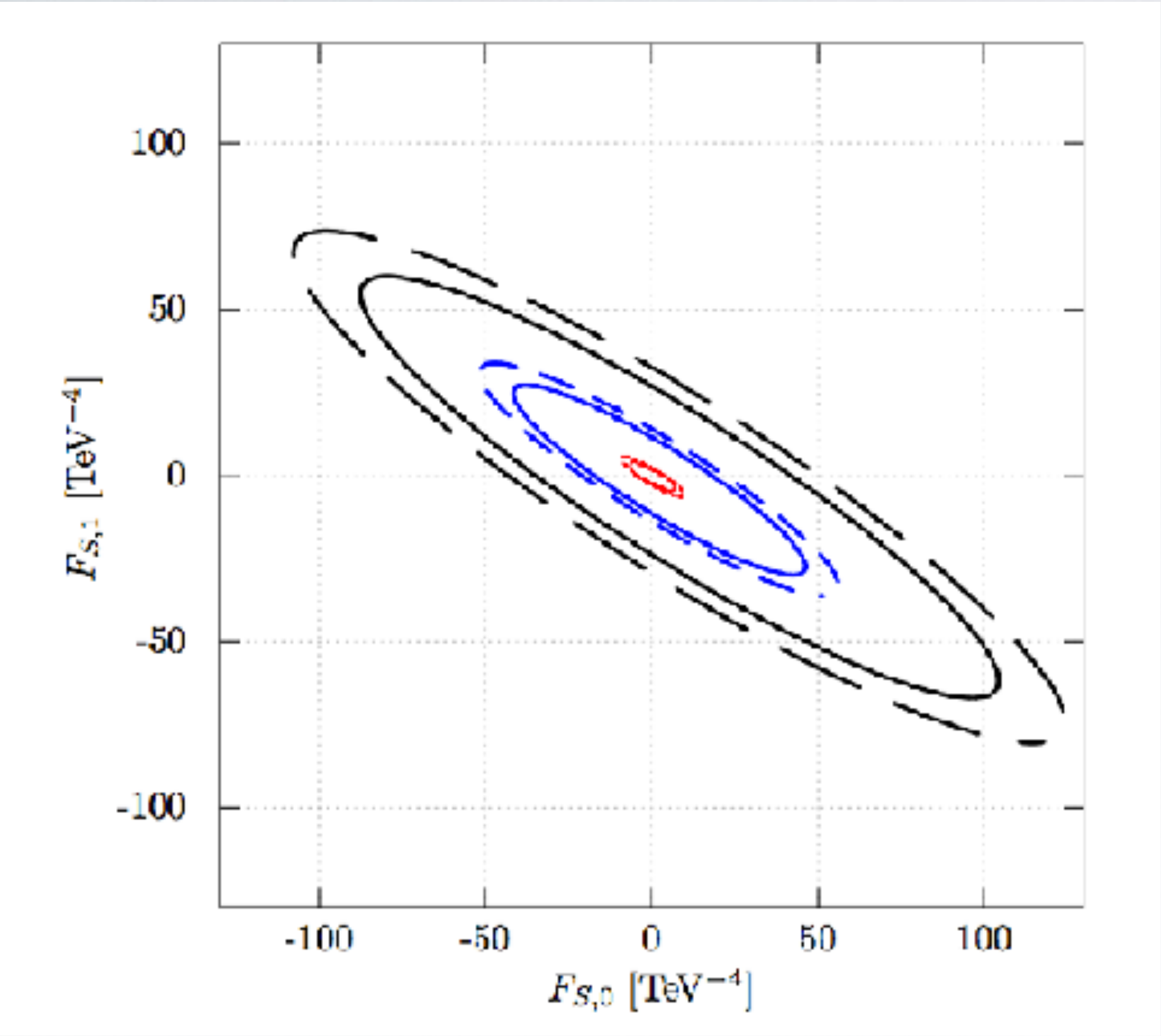
Comparison: Simplified Models & EFT

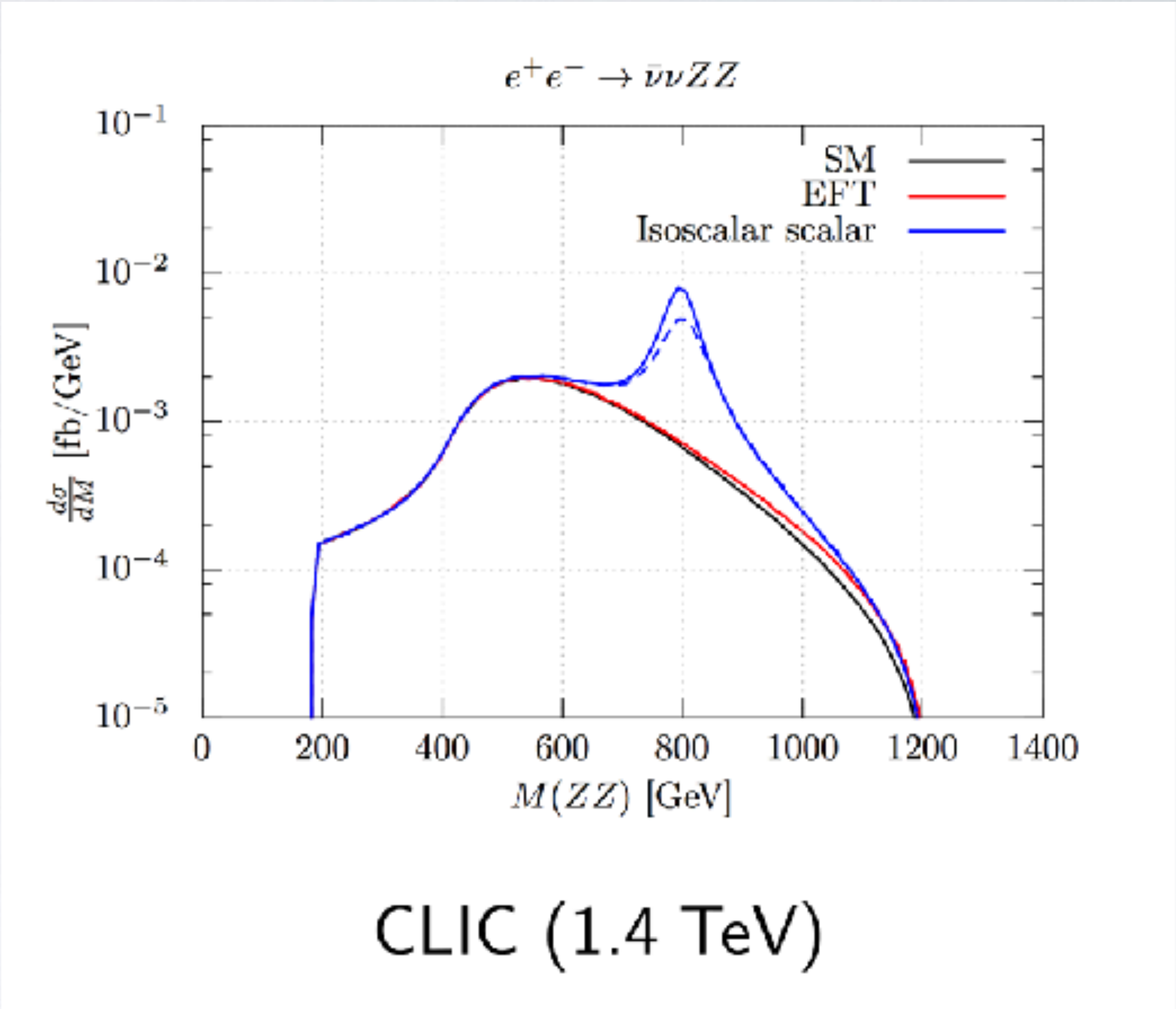




Fleper/Kilian/JRR/Sekulla: 1607.03030

Comparison: Simplified Models & EFT





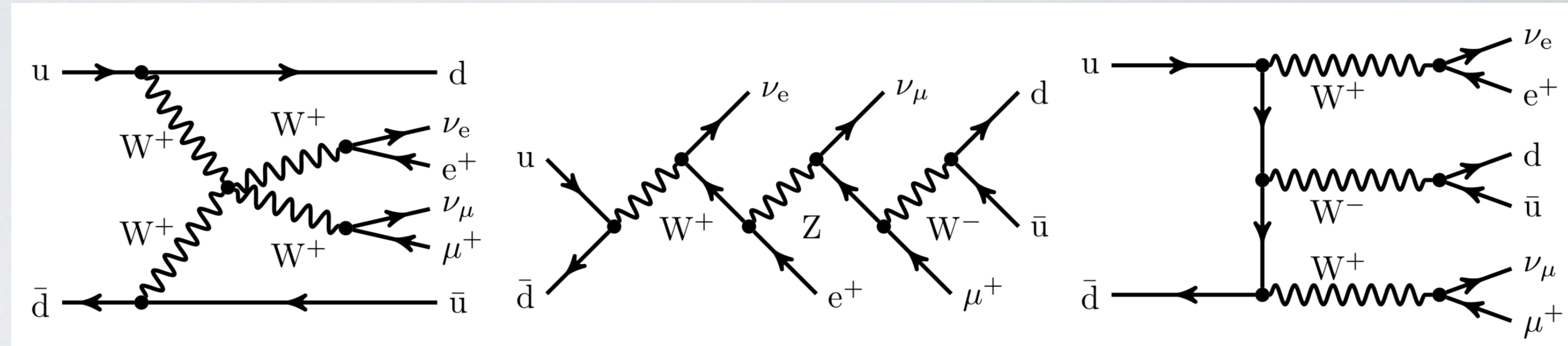
Fleper/Kilian/JRR/Sekulla: 1607.03030

WIP: Unitarity limits for $pp \to VVV$ Brass/Kilian/JRR/Sekulla: 1805.xxxxx

VBS & SM: Comparison LO/NLO (+PS)

Ballestrero *et al.*, 1803.07943

Order	$\mathcal{O}(\alpha^6)$	$\mathcal{O}(\alpha_s^2\alpha^4)$	$\mathcal{O}(\alpha_s\alpha^5)$
σ[fb]	2.292 ± 0.002	1.477 ± 0.001	0.223 ± 0.003



Code	σ[fb]
BONSAY	1.43636 ± 0.00002
MG5_AMC	1.4304 ± 0.0007
MOCANLO+RECOLA	1.43476 ± 0.00009
PHANTOM	1.4374 ± 0.0006
POWHEG-BOX	1.44092 ± 0.00009
VBFNLO	1.43796 ± 0.00005
WHIZARD	1.4381 ± 0.0002

LO

$p_{T,\ell} > 20$ GeV $\quad |y_\ell| < 2.5 \quad \Delta R_{\ell\ell} > 0.3$

$p_{T,\text{miss}} > 40$ GeV

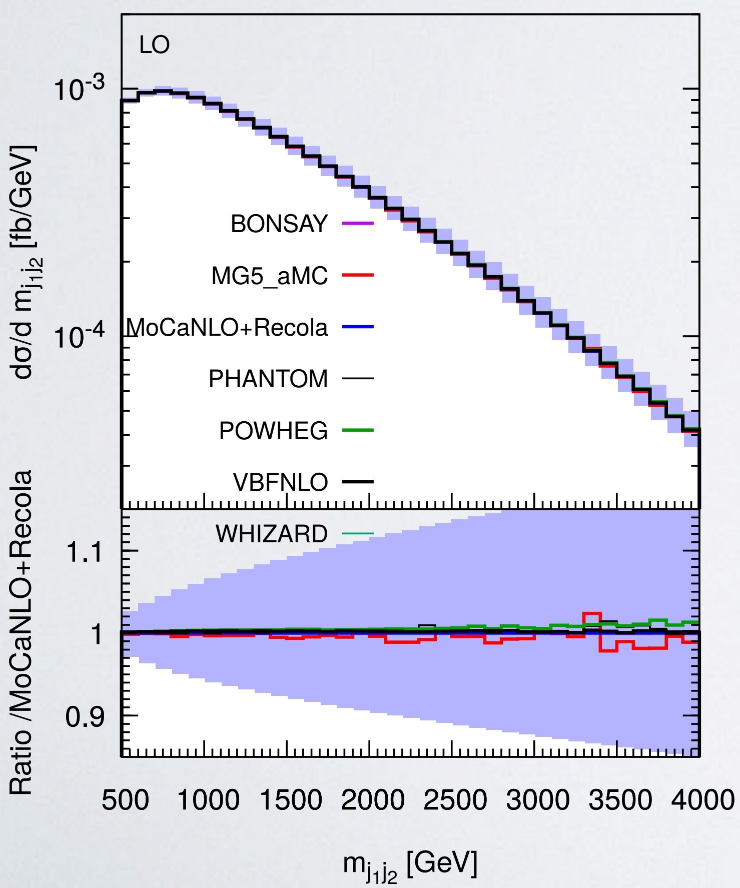
Anti-k_T jets with $R = 0.4$:

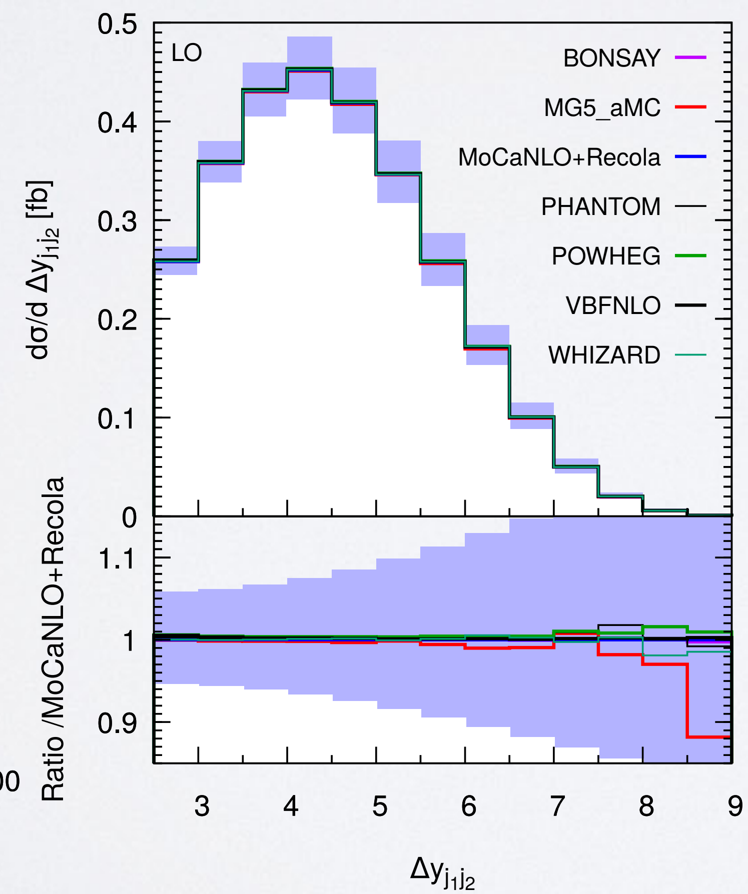
$p_{T,j} > 30$ GeV $\quad |y_j| < 4.5 \quad \Delta R_{\ell j} > 0.3$

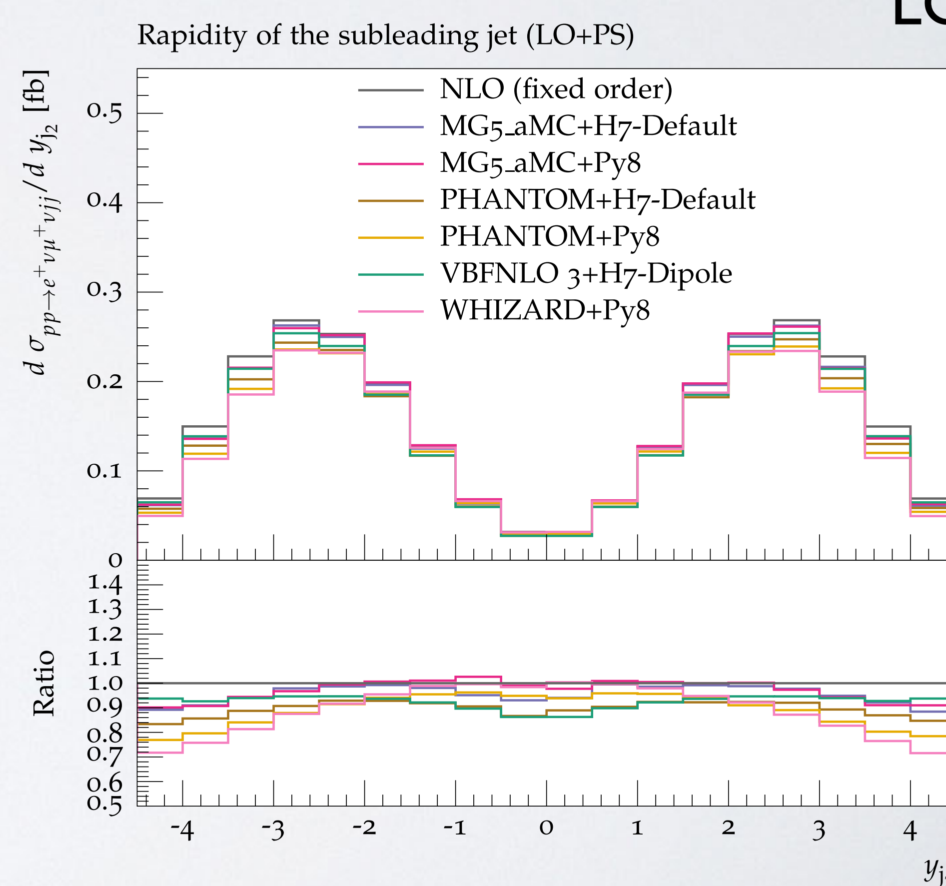
$m_{jj} > 500$ GeV $\quad |\Delta y_{jj}| > 2.5$

Code	σ[fb]
MG5_AMC+PYTHIA8	1.352 ± 0.003
MG5_AMC+HERWIG7	1.342 ± 0.003
MG5_AMC+PYTHIA8, Γ_{resc}	1.275 ± 0.003
MG5_AMC+HERWIG7, Γ_{resc}	1.266 ± 0.003
PHANTOM+PYTHIA8	1.235 ± 0.001
PHANTOM+HERWIG7	1.258 ± 0.001
VBFNLO+HERWIG7-DIPOLE	1.3001 ± 0.0002
WHIZARD+PYTHIA8	1.229 ± 0.001

LO+PS







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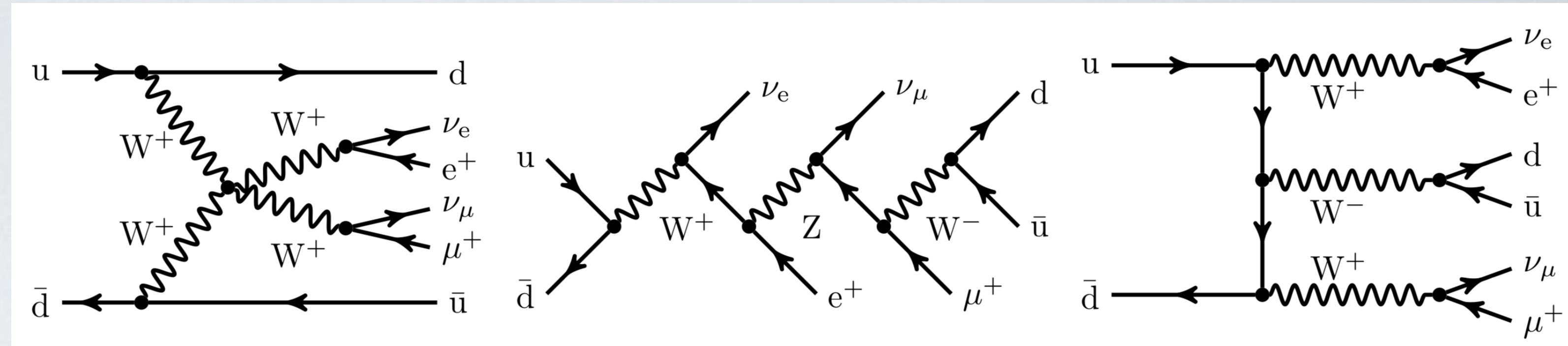

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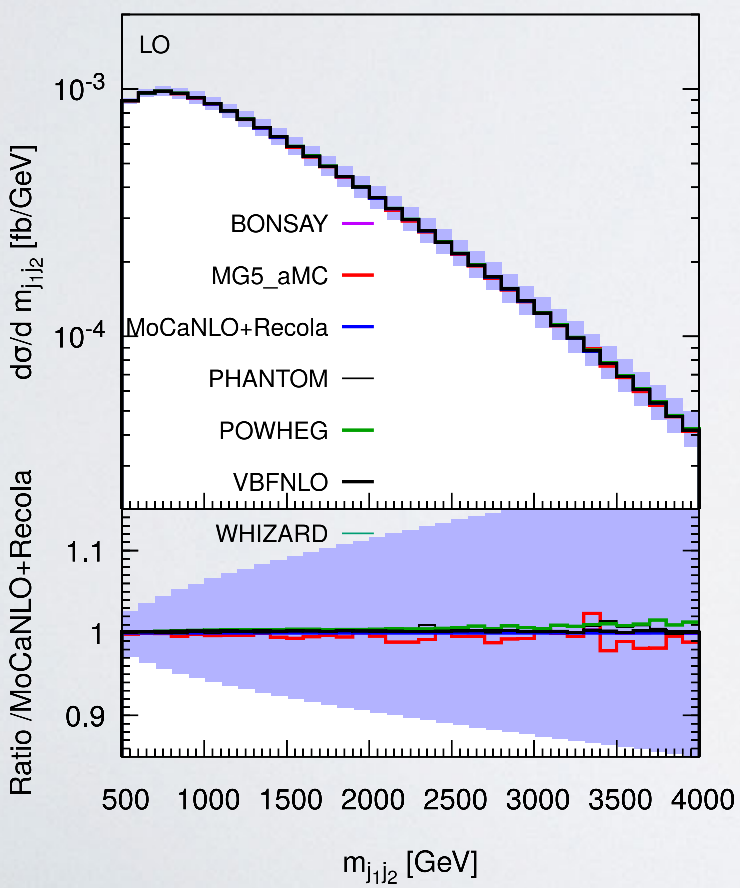
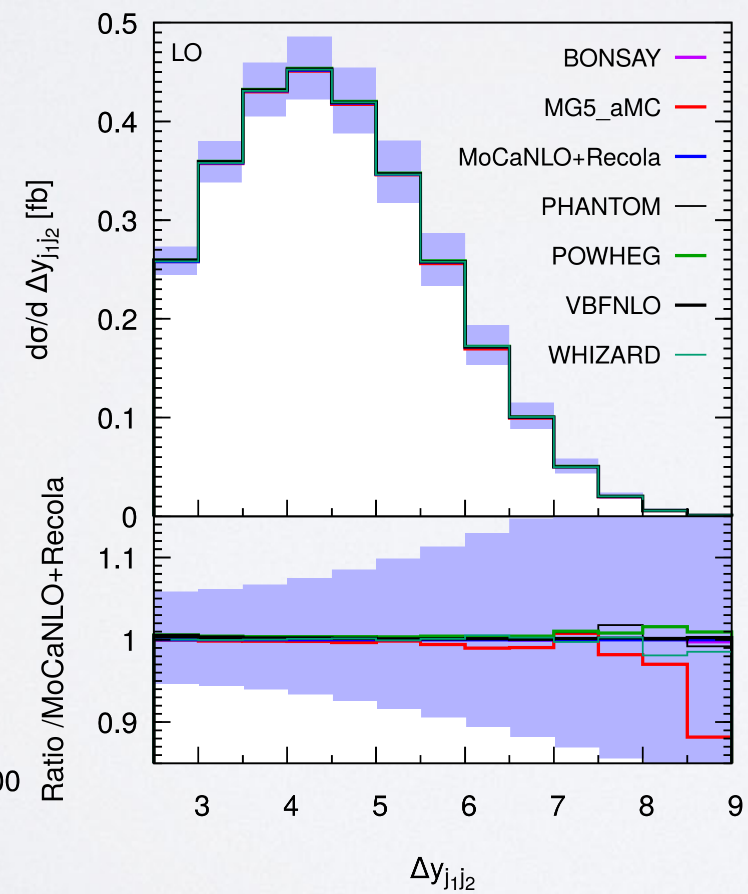
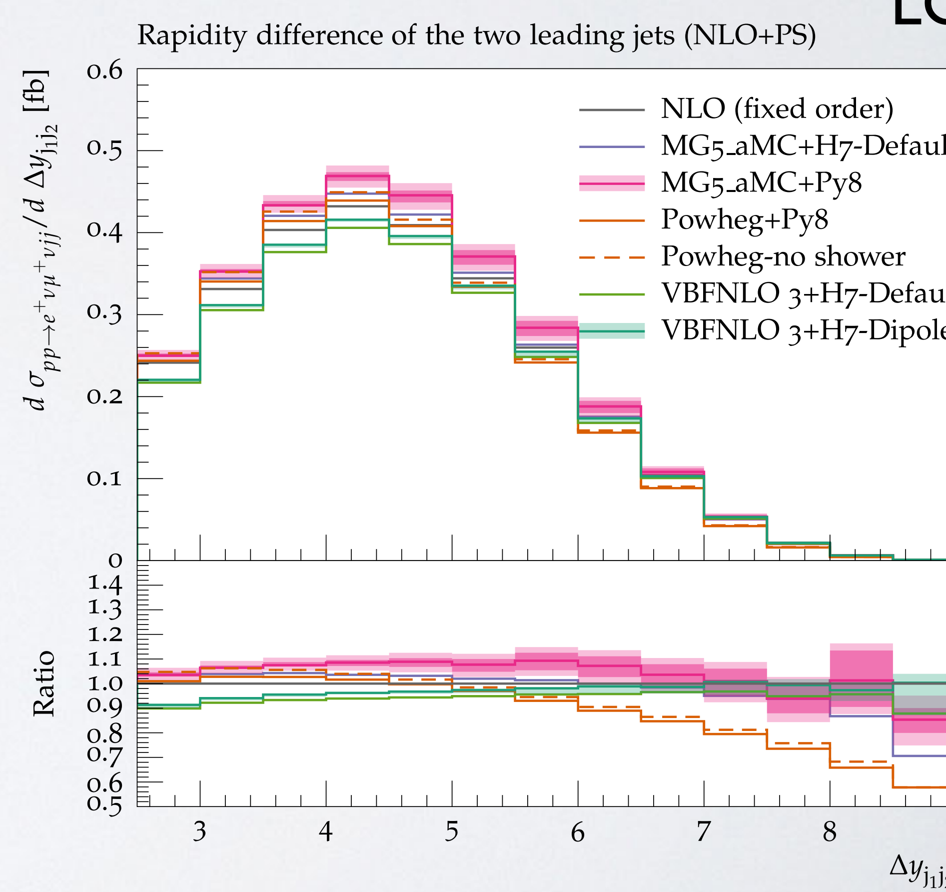
LO+PS







NLO Automation in WHIZARD

Working NLO interfaces to:

- ★ GoSam [N. Greiner, G. Heinrich, J. v. Soden-Fraunhofen et al.]
- ★ OpenLoops [F. Cascioli, J. Lindert, P. Maierhöfer, S. Pozzorini]
- ★ Recola [A. Denner, L. Hofer, J.-N. Lang, S. Uccirati]

NLO QCD (massless & massive) fully supported

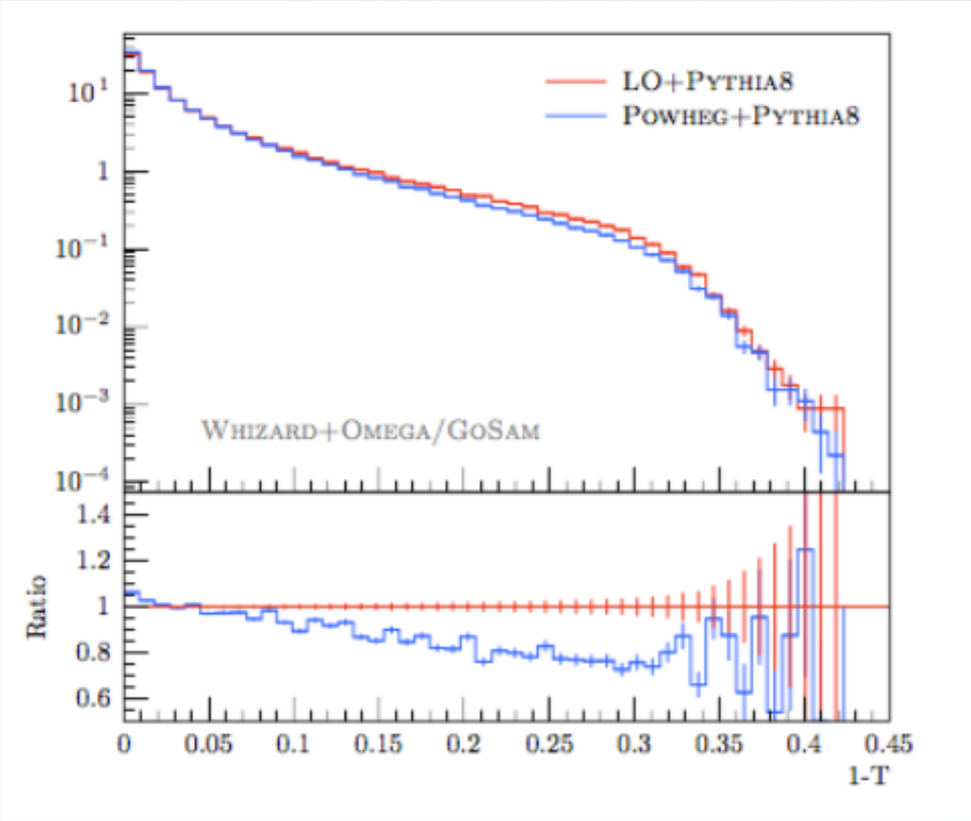
```
alpha_power = 2
alphas_power = 0

process eett = e1,E1 => t, tbar
     { nlo_calculation = “full” }
```

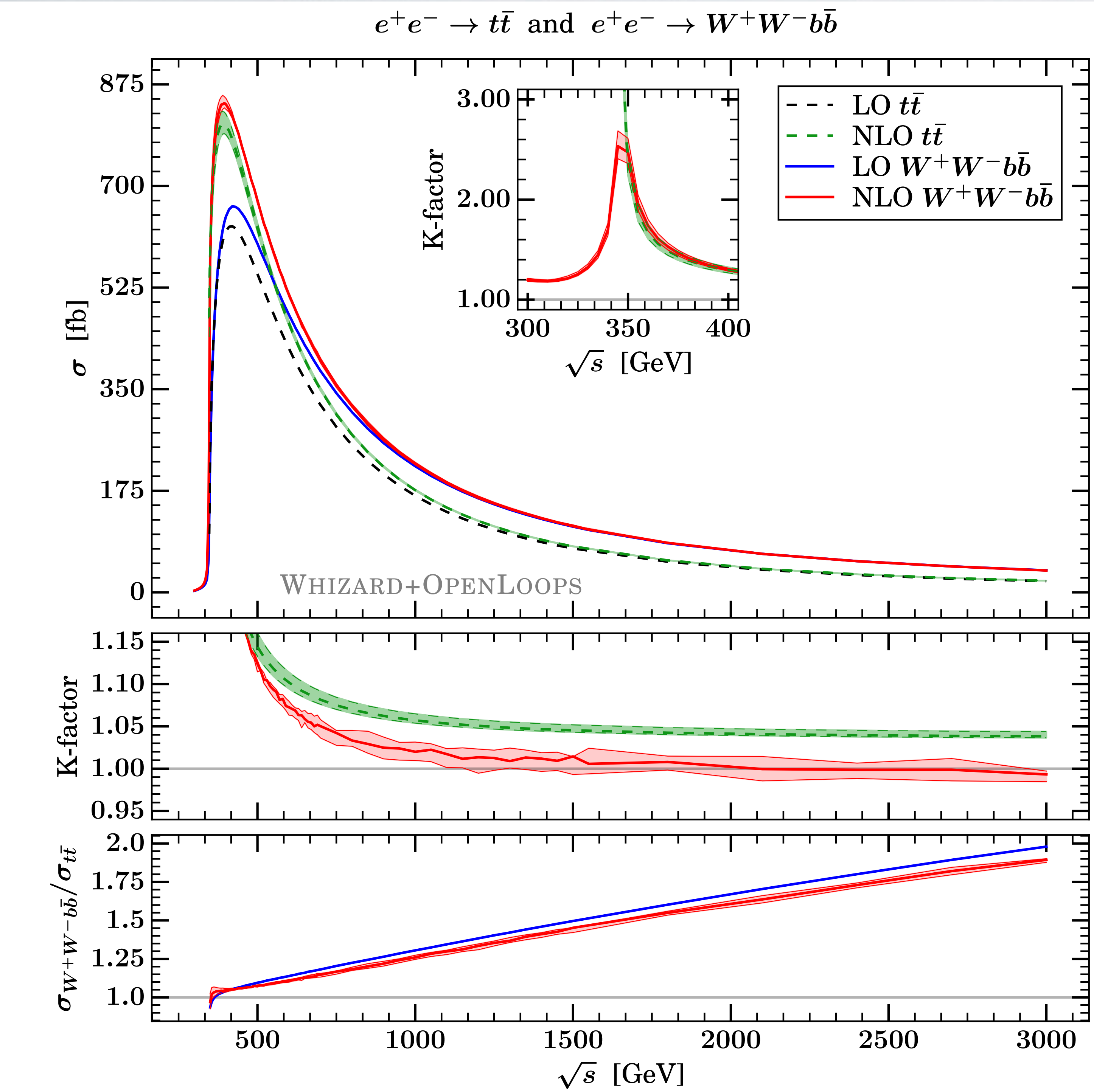
List of validated NLO QCD processes

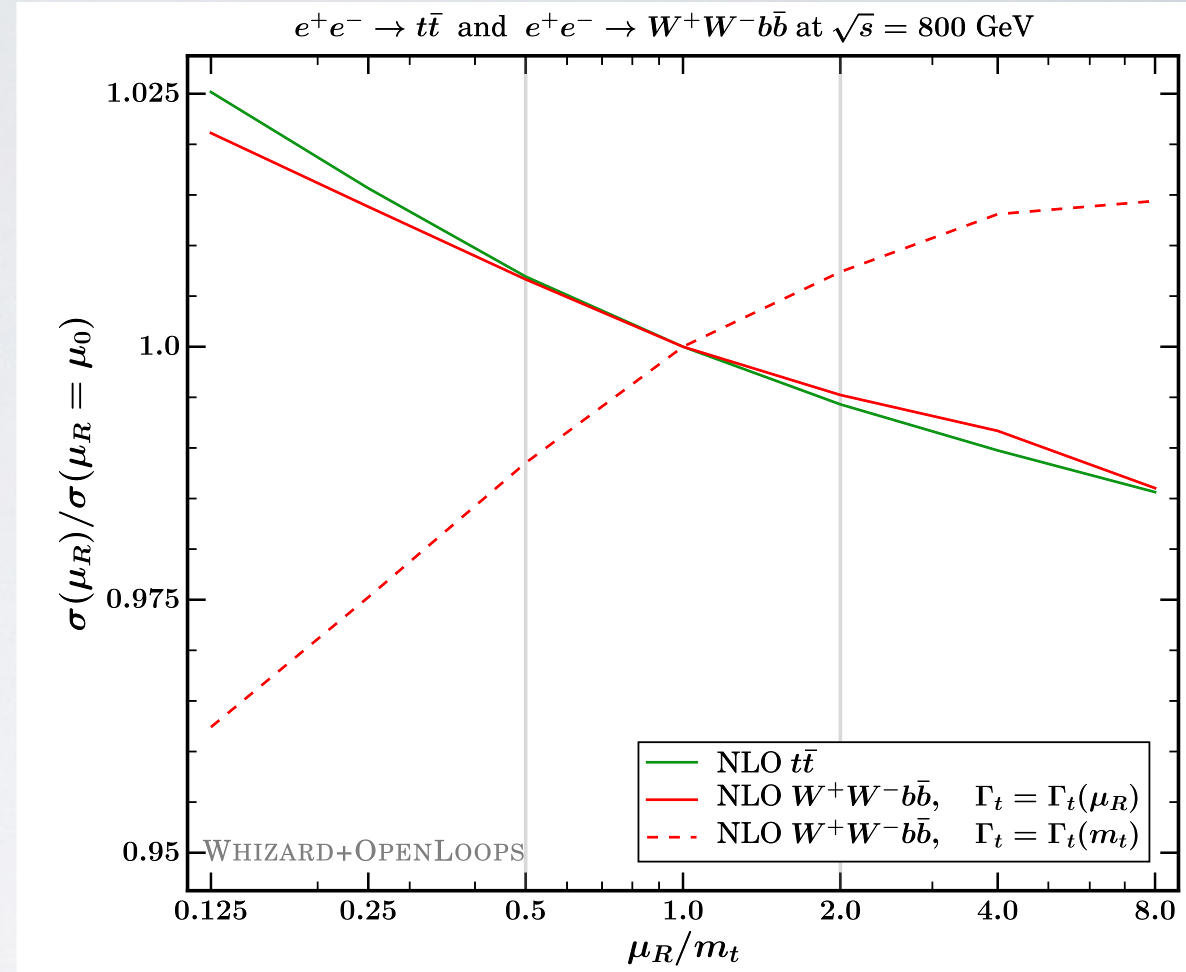
- $e^+e^- \to jj$
- $e^+e^- \to jjj$
- $e^+e^- \to \ell^+\ell^- jj$
- $e^+e^- \to \ell^+\nu_\ell jj$
- $e^+e^- \to t\bar{t}$
- $e^+e^- \to t\bar{t}t\bar{t}$
- $e^+e^- \to t\bar{t}W^+jj$
- $e^+e^- \to tW^-b$
- $e^+e^- \to W^+W^-b\bar{b}, \quad \ell^+\ell^-\nu_\ell\bar{\nu}_\ell b\bar{b}$
- $e^+e^- \to b\bar{b}\ell^+\ell^-$
- $e^+e^- \to t\bar{t}H$
- $e^+e^- \to W^+W^-b\bar{b}H, \quad \ell^+\ell^-\nu_\ell\bar{\nu}_\ell b\bar{b}H$
- $pp \to \ell^+\ell^-$
- $pp \to \ell\nu$
- $pp \to ZZ$

- FKS subtraction [Frixione/Kunszt/Signer, hep-ph/9512328]
- Resonance-aware treatment [Ježo/Nason, 1509.09071]
- Virtual MEs external
- Real and virtual subtraction terms internal
- NLO decays available for the NLO processes
- Fixed order events for plotting (weighted)
- Automated POWHEG damping and matching



NLO QCD Results for off-shell $e^+e^- \to tt$

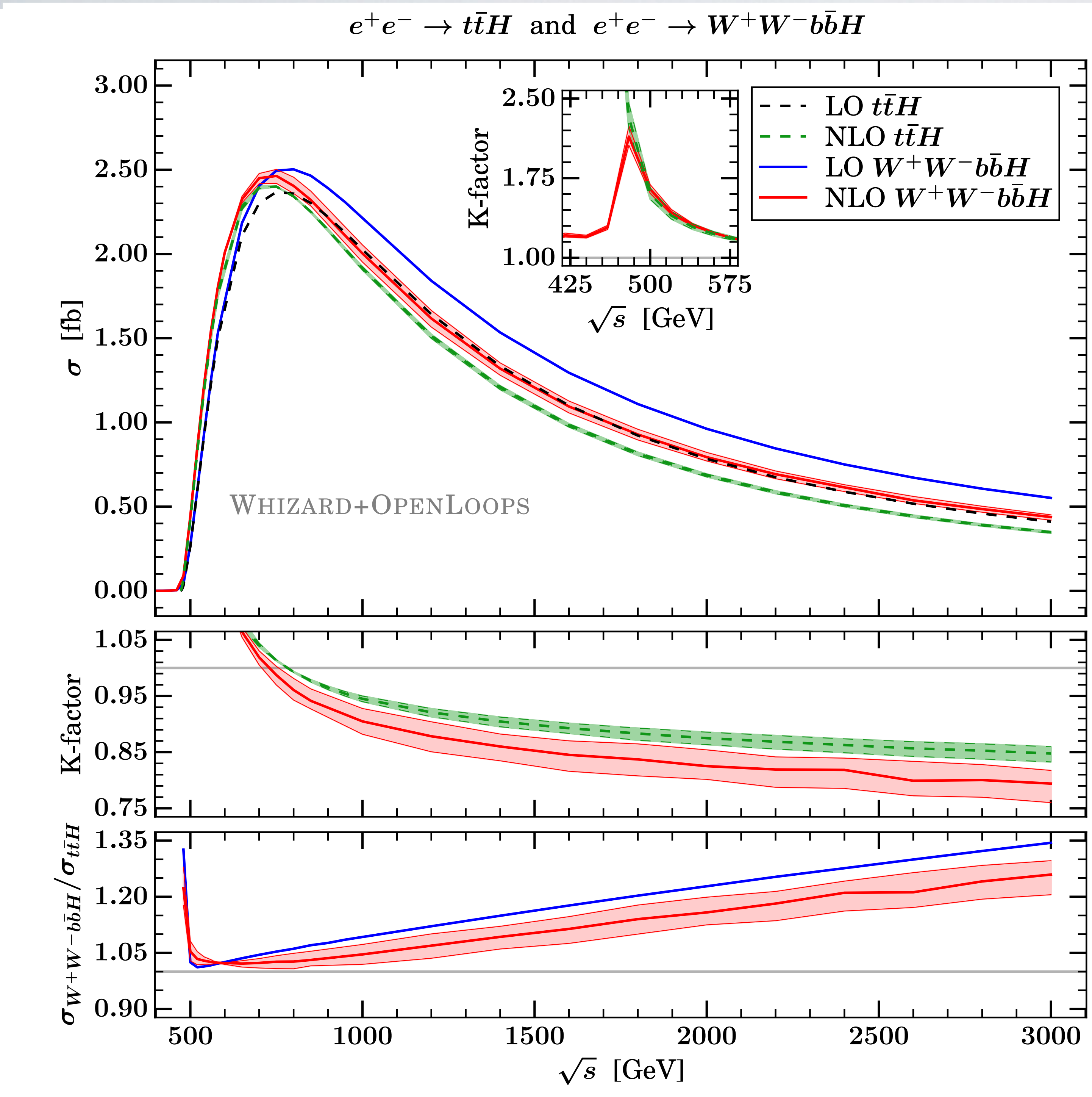


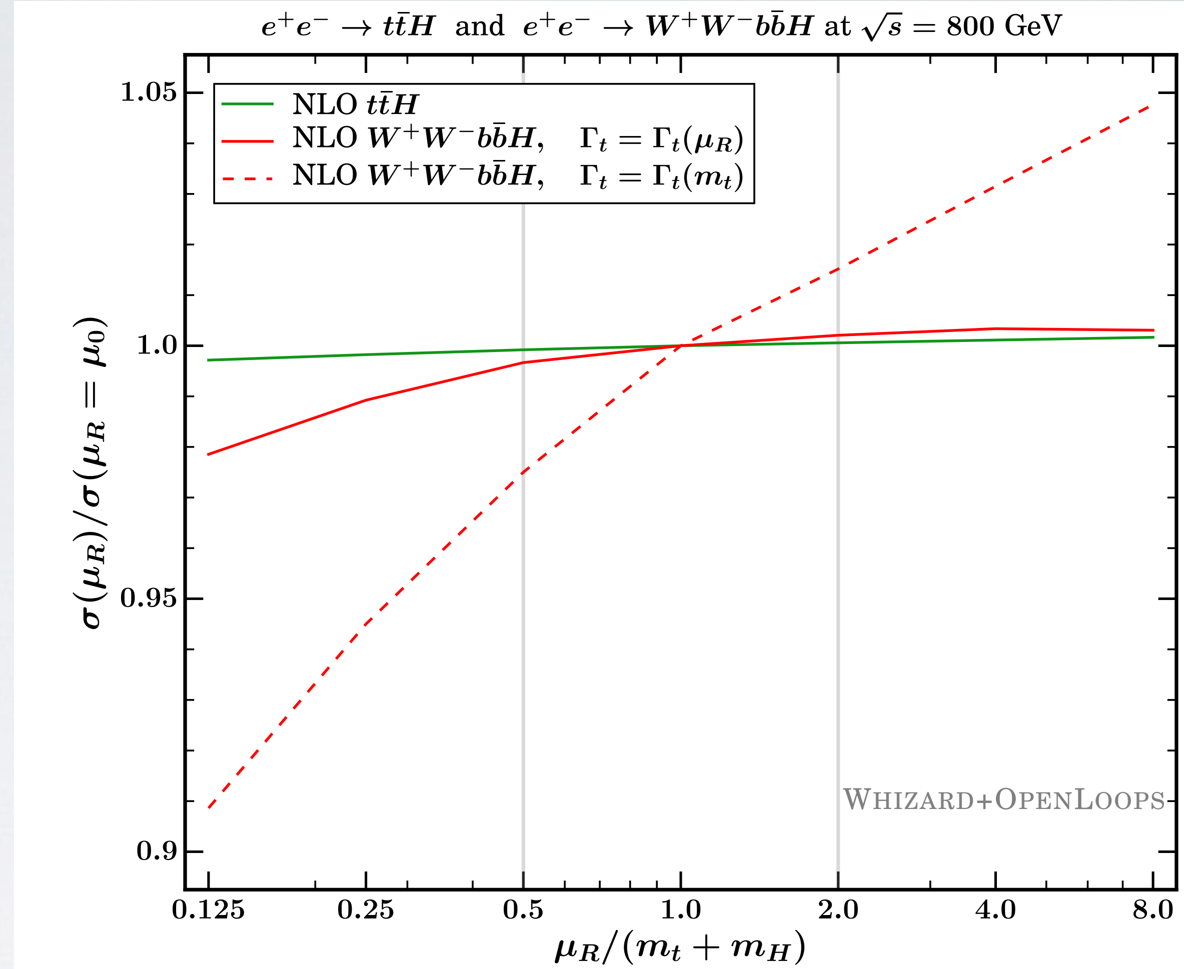


	$e^+e^- \to t\bar{t}$			$e^+e^- \to W^+W^-b\bar{b}$		
$\sqrt{s}$ [GeV]	$\sigma^{\rm LO}$[fb]	$\sigma^{\rm NLO}$[fb]	K-factor	$\sigma^{\rm LO}$[fb]	$\sigma^{\rm NLO}$[fb]	K-factor
500	548.4	$627.4^{+1.4\%}_{-0.9\%}$	1.14	600.7	$675.1^{+0.4\%}_{-0.8\%}$	1.12
800	253.1	$270.9^{+0.8\%}_{-0.4\%}$	1.07	310.2	$320.7^{+1.1\%}_{-0.7\%}$	1.03
1000	166.4	$175.9^{+0.7\%}_{-0.3\%}$	1.06	217.2	$221.6^{+1.1\%}_{-1.0\%}$	1.02
1400	86.62	$90.66^{+0.6\%}_{-0.2\%}$	1.05	126.4	$127.9^{+0.7\%}_{-1.5\%}$	1.01
3000	19.14	$19.87^{+0.5\%}_{-0.2\%}$	1.04	37.89	$37.63^{+0.4\%}_{-0.9\%}$	0.993

Chokoufé/Kilian/Lindert/Pozzorini/JRR/Weiss, 1609.03390

NLO QCD Results for off-shell $e^+e^- \to ttH$

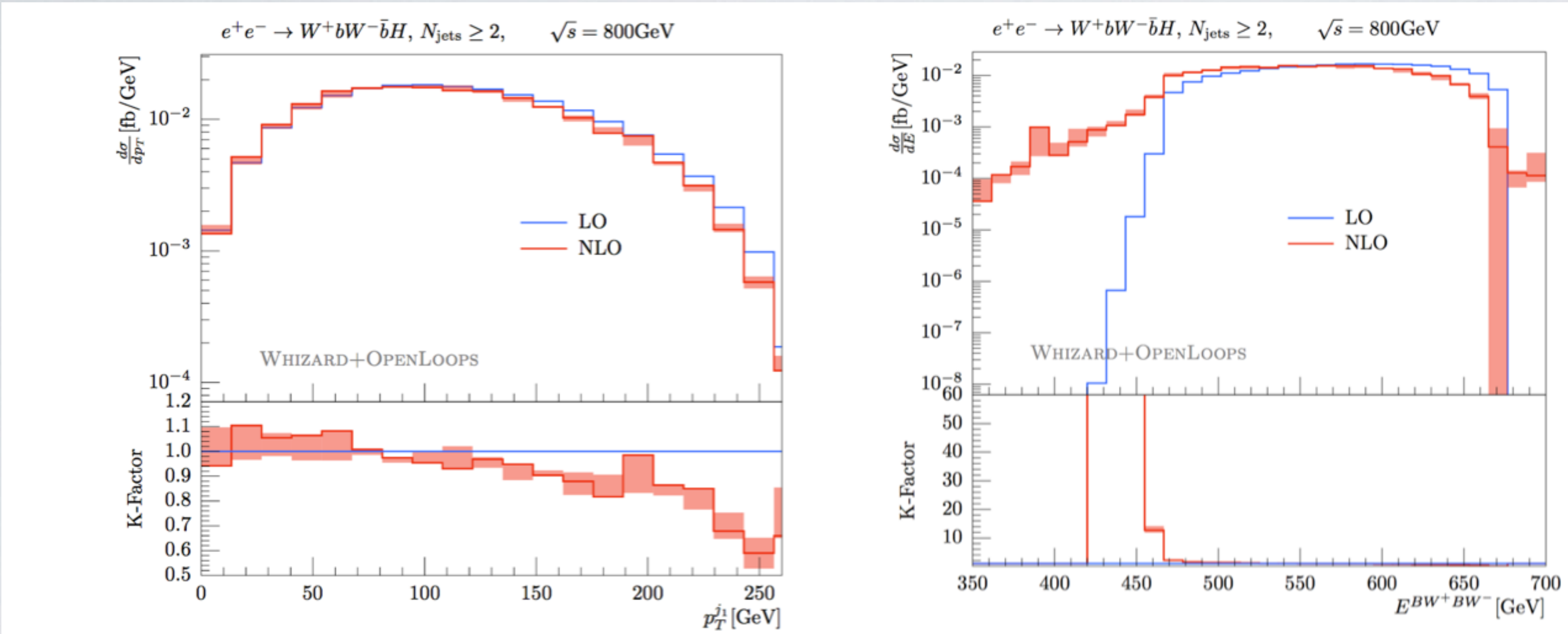


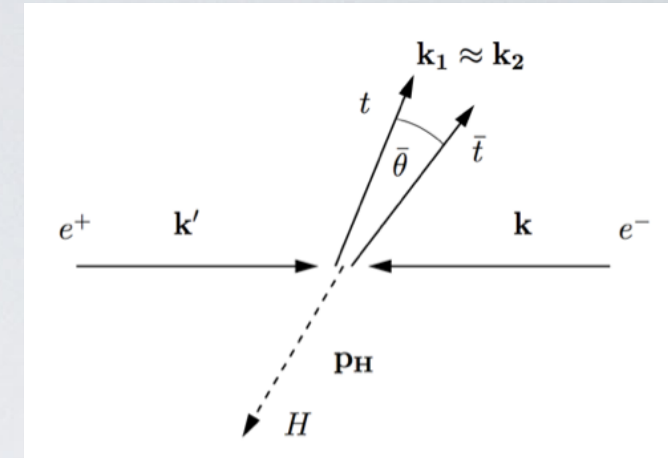


	$e^+e^- \to t\bar{t}H$			$e^+e^- \to W^+W^-b\bar{b}H$		
$\sqrt{s}$ [GeV]	$\sigma^{\rm LO}$[fb]	$\sigma^{\rm NLO}$[fb]	K-factor	$\sigma^{\rm LO}$[fb]	$\sigma^{\rm NLO}$[fb]	K-factor
500	0.26	$0.42^{+3.6\%}_{-3.1\%}$	1.60	0.27	$0.44^{+2.6\%}_{-2.4\%}$	1.63
800	2.36	$2.34^{+0.1\%}_{-0.1\%}$	0.99	2.50	$2.40^{+2.1\%}_{-1.9\%}$	0.96
1000	2.02	$1.91^{+0.5\%}_{-0.5\%}$	0.95	2.21	$2.00^{+2.5\%}_{-2.5\%}$	0.90
1400	1.33	$1.21^{+0.9\%}_{-1.0\%}$	0.90	1.53	$1.32^{+2.6\%}_{-3.0\%}$	0.86
3000	0.41	$0.35^{+1.4\%}_{-1.8\%}$	0.84	0.55	$0.44^{+2.9\%}_{-4.3\%}$	0.79

Chokoufé/Kilian/Lindert/Pozzorini/JRR/Weiss, 1609.03390

Differential Results for off-shell ttH

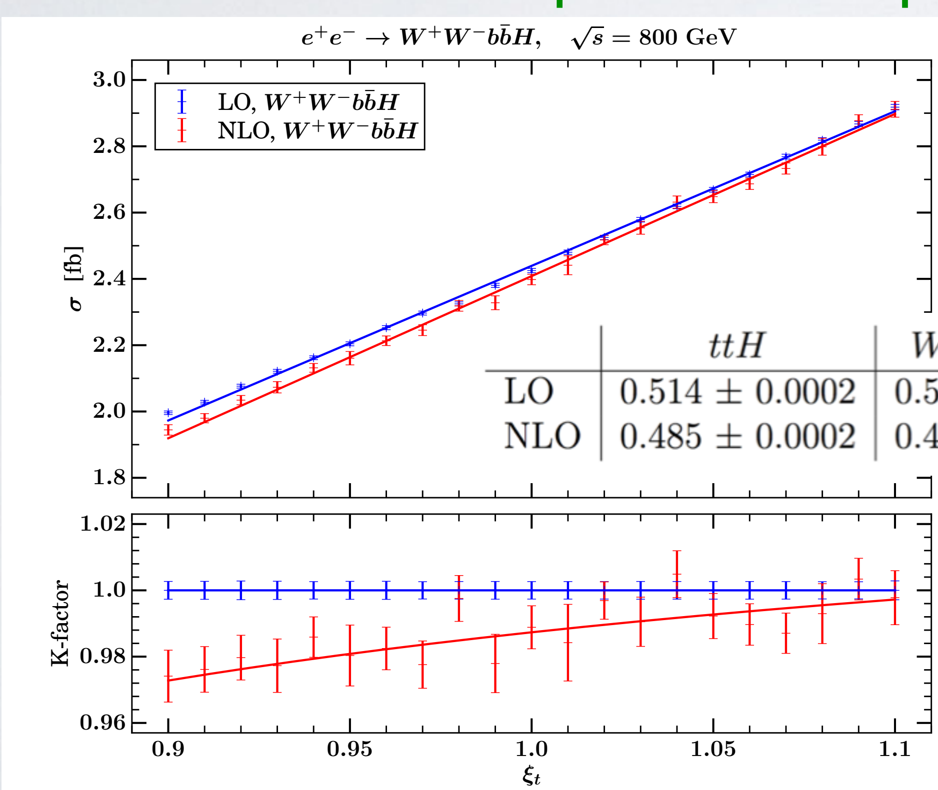




$$E_h = \frac{1}{2\sqrt{s}}\left[s + M_h^2 - (k_1 + k_2)^2\right]$$

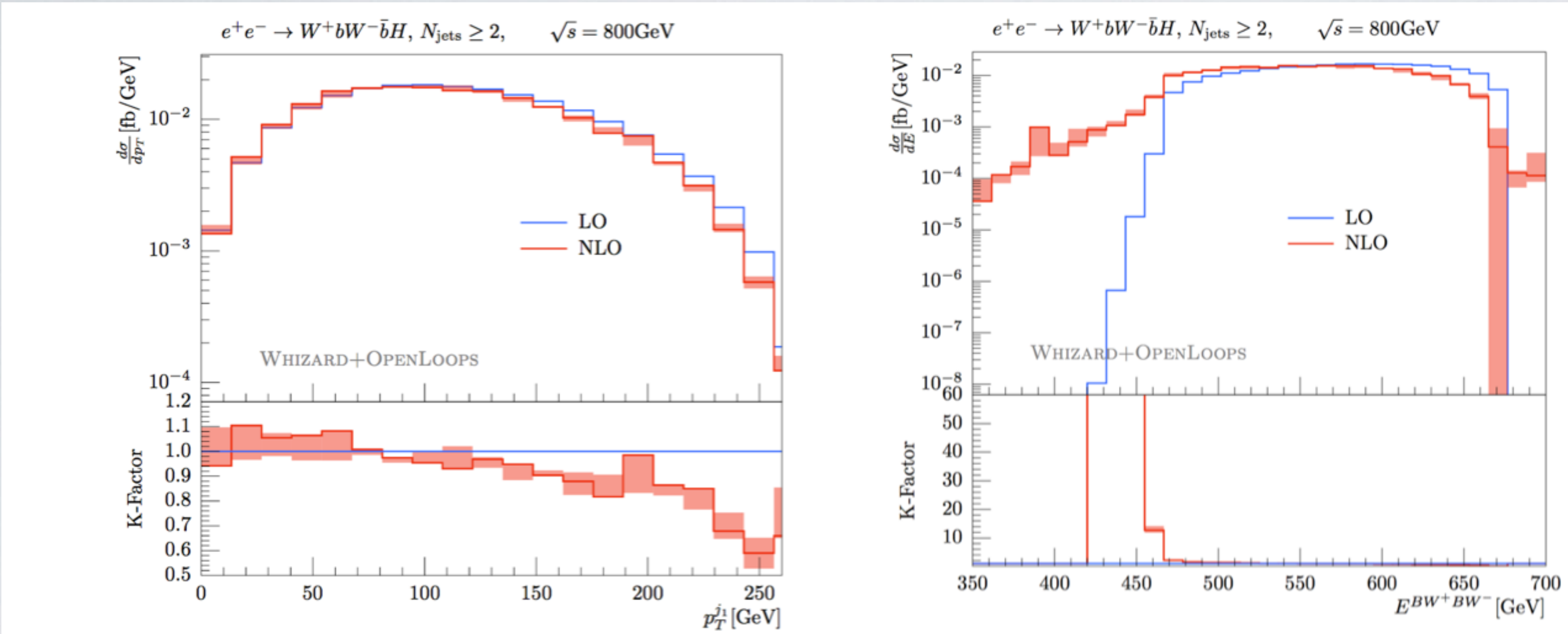
Chokoufé/Kilian/Lindert/Pozzorini/JRR/Weiss, 1609.03390

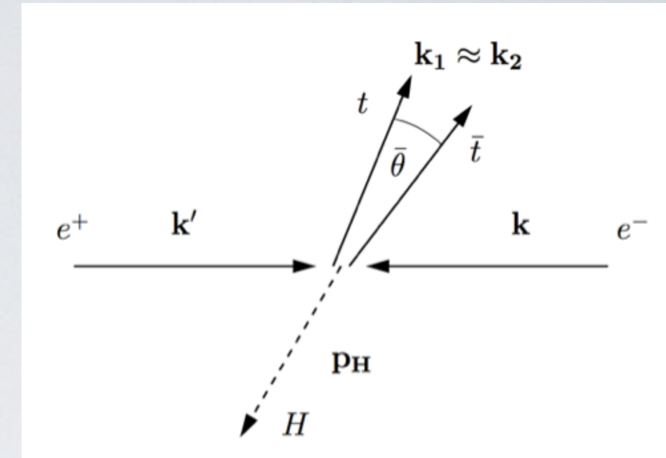
Determination of top Yukawa coupling (ttH)



	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

Differential Results for off-shell *ttH*





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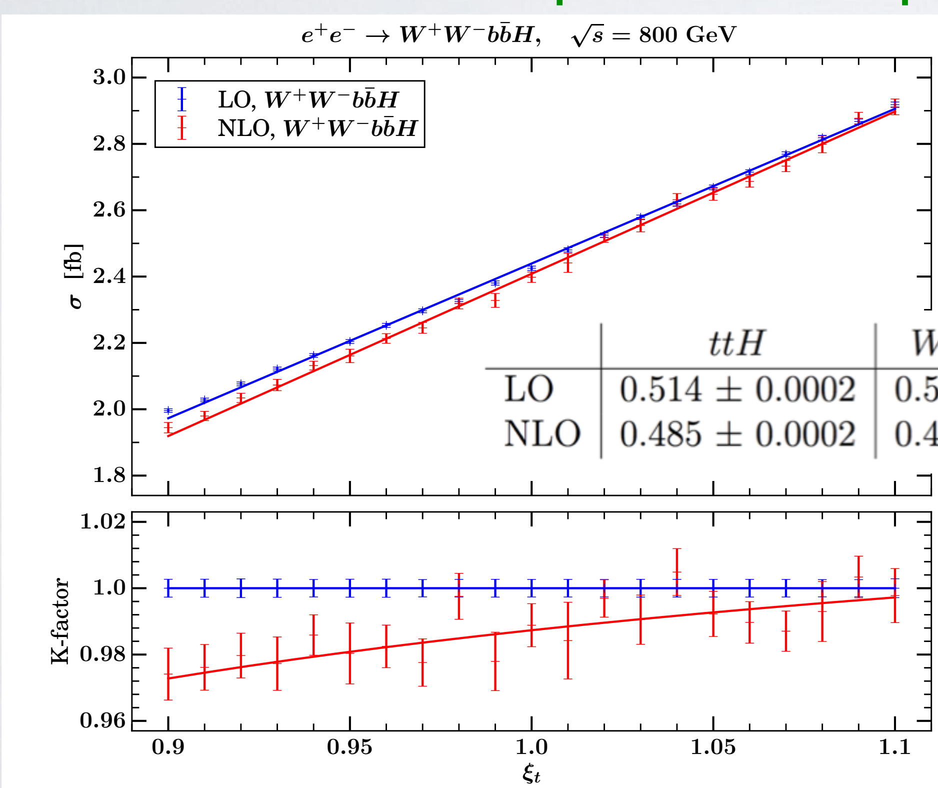


	ttH	$W^+W^-b\bar{b}H$
LO	0.514 ± 0.0002	0.520 ± 0.001
NLO	0.485 ± 0.0002	0.497 ± 0.002

Polarized Results (*tt*)

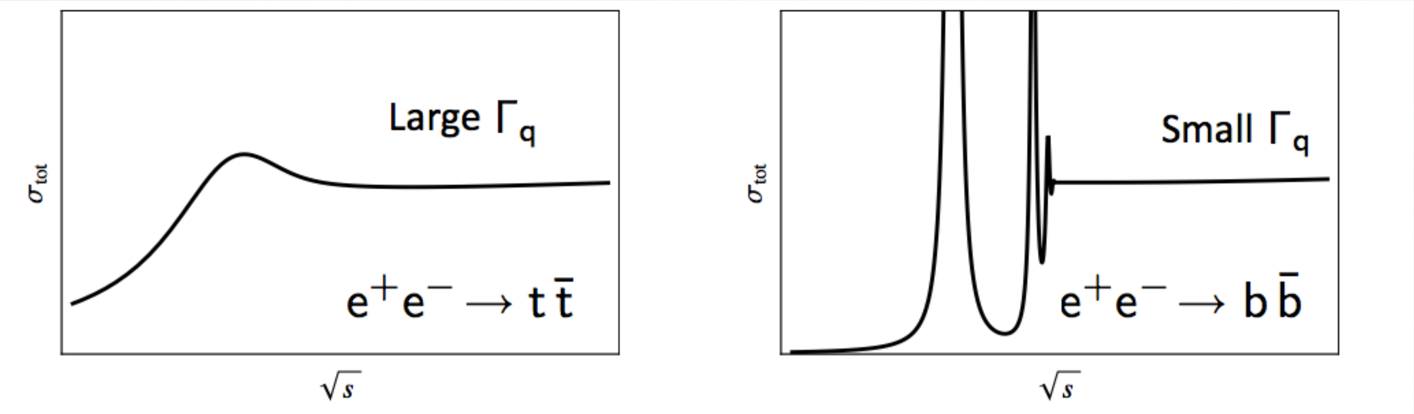
- ILC will always run polarized
- Polarized 1-loop amplitudes beyond BLHA

		$\sqrt{s} = 800$ GeV			$\sqrt{s} = 1500$ GeV		
$P(e^-)$	$P(e^+)$	$\sigma^{\rm LO}$[fb]	$\sigma^{\rm NLO}$[fb]	K-factor	$\sigma^{\rm LO}$[fb]	$\sigma^{\rm NLO}$[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

Top Threshold/Continuum at lepton colliders

- LC top threshold scan best-known method to measure top quark mass, $\Delta M \sim$ 30-70 MeV
- LC continuum top production best-known method to measure top couplings

Heavy quark production at lepton colliders, qualitatively:



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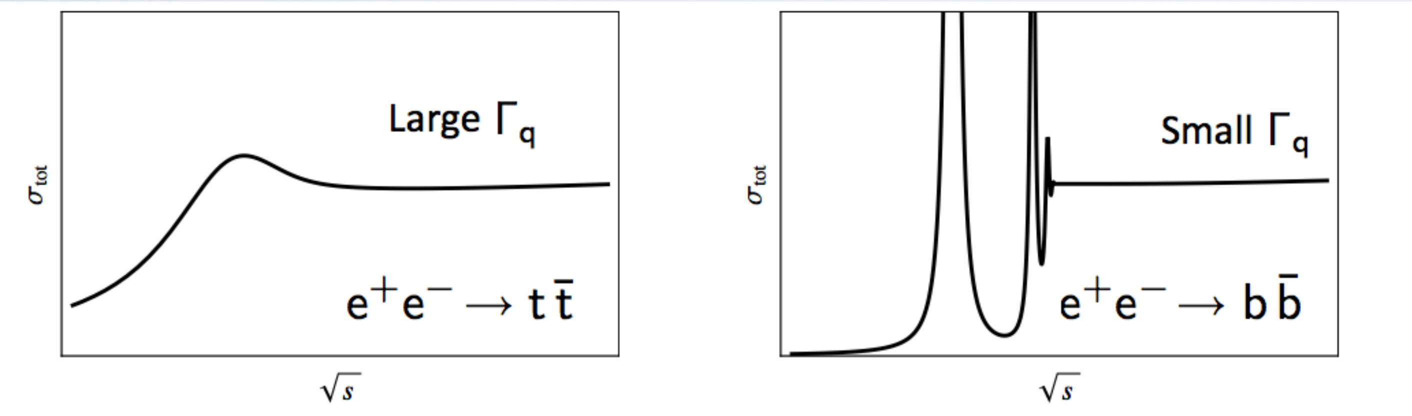

error source	Δm_t^{PS} [MeV]
stat. error (200 fb^{-1})	13
theory (NNNLO scale variations, PS scheme)	40
parametric (α_s, current WA)	35
non-resonant contributions (such as single top)	< 40
residual background / selection efficiency	10 – 20
luminosity spectrum uncertainty	< 10
beam energy uncertainty	< 17
combined theory & parametric	30 – 50
combined experimental & backgrounds	25 - 50
total (stat. + syst.)	40 – 75

from 1702.05333

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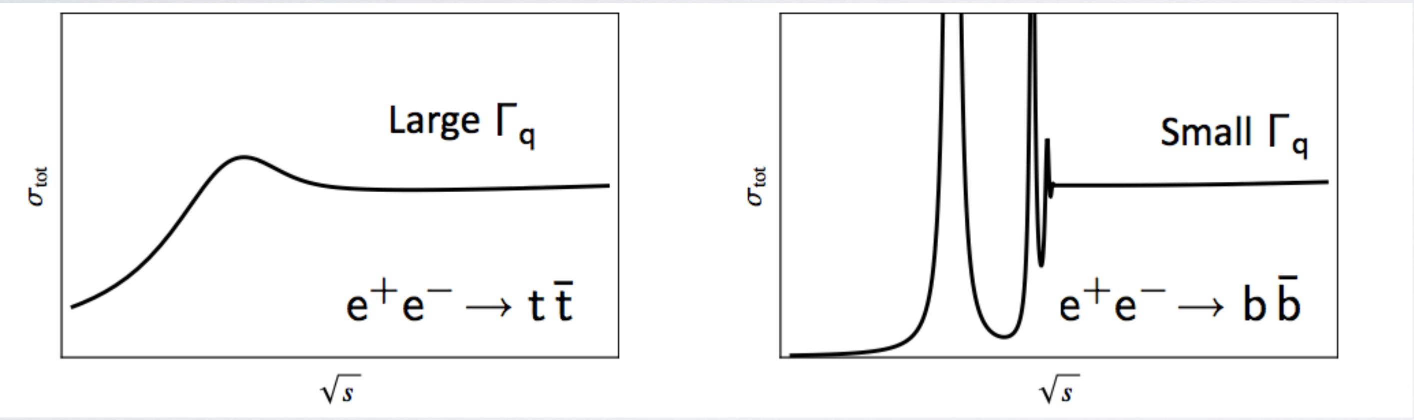

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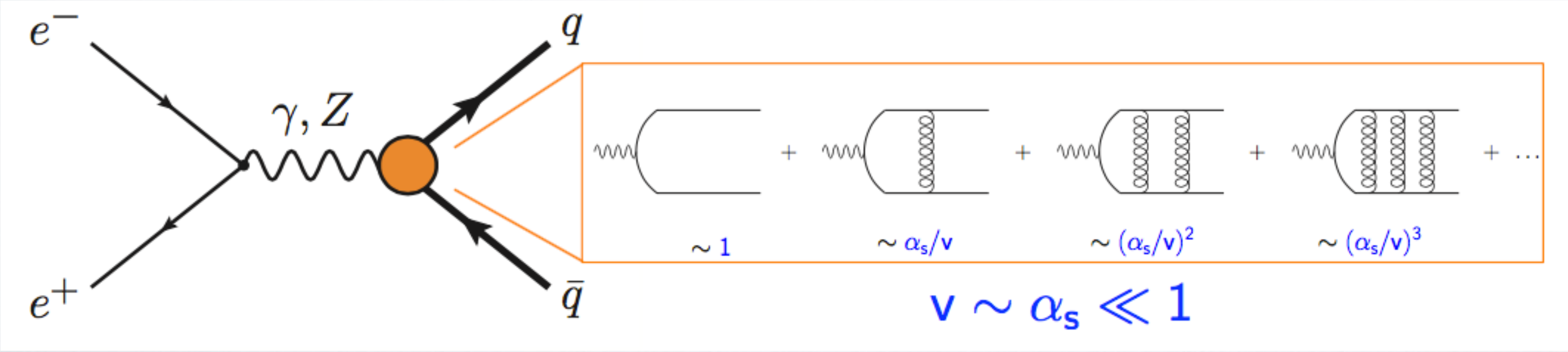
from 1702.05333

Threshold region: top velocity $v \sim \alpha_s \ll 1$ non-relativistic EFT: (v)NRQCD



Continuum region: "standard" fixed-order QCD

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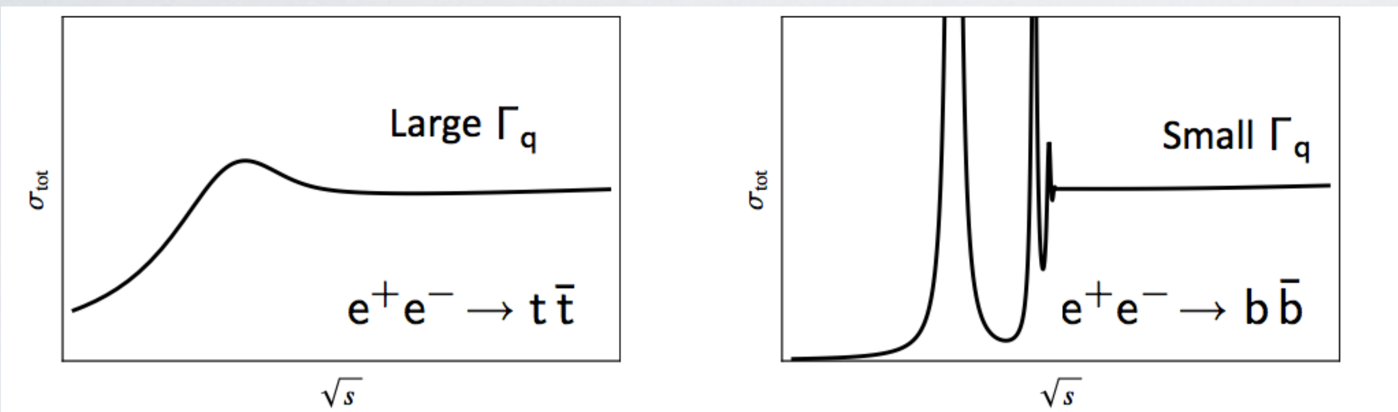

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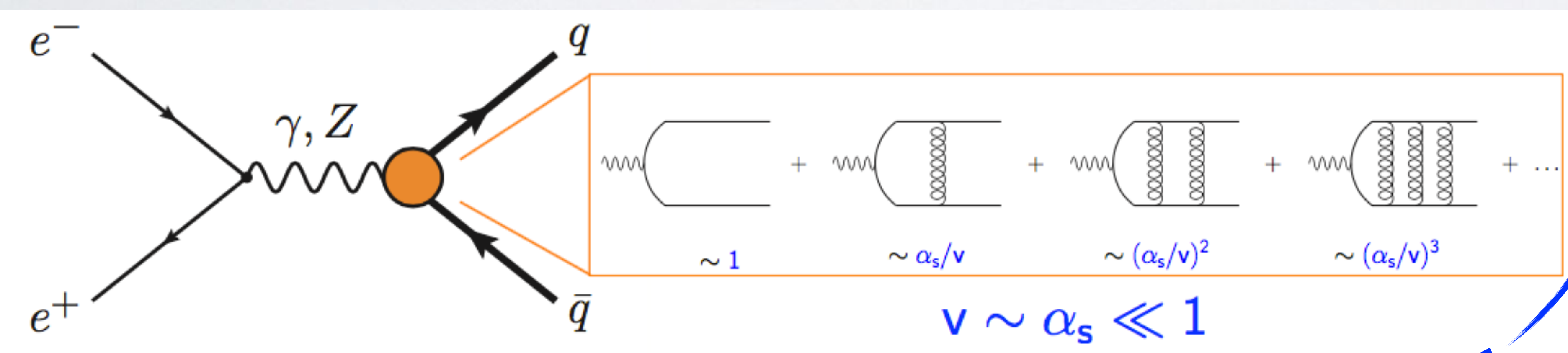
from 1702.05333

Threshold region: top velocity $v \sim \alpha_s \ll 1$ non-relativistic EFT: (v)NRQCD

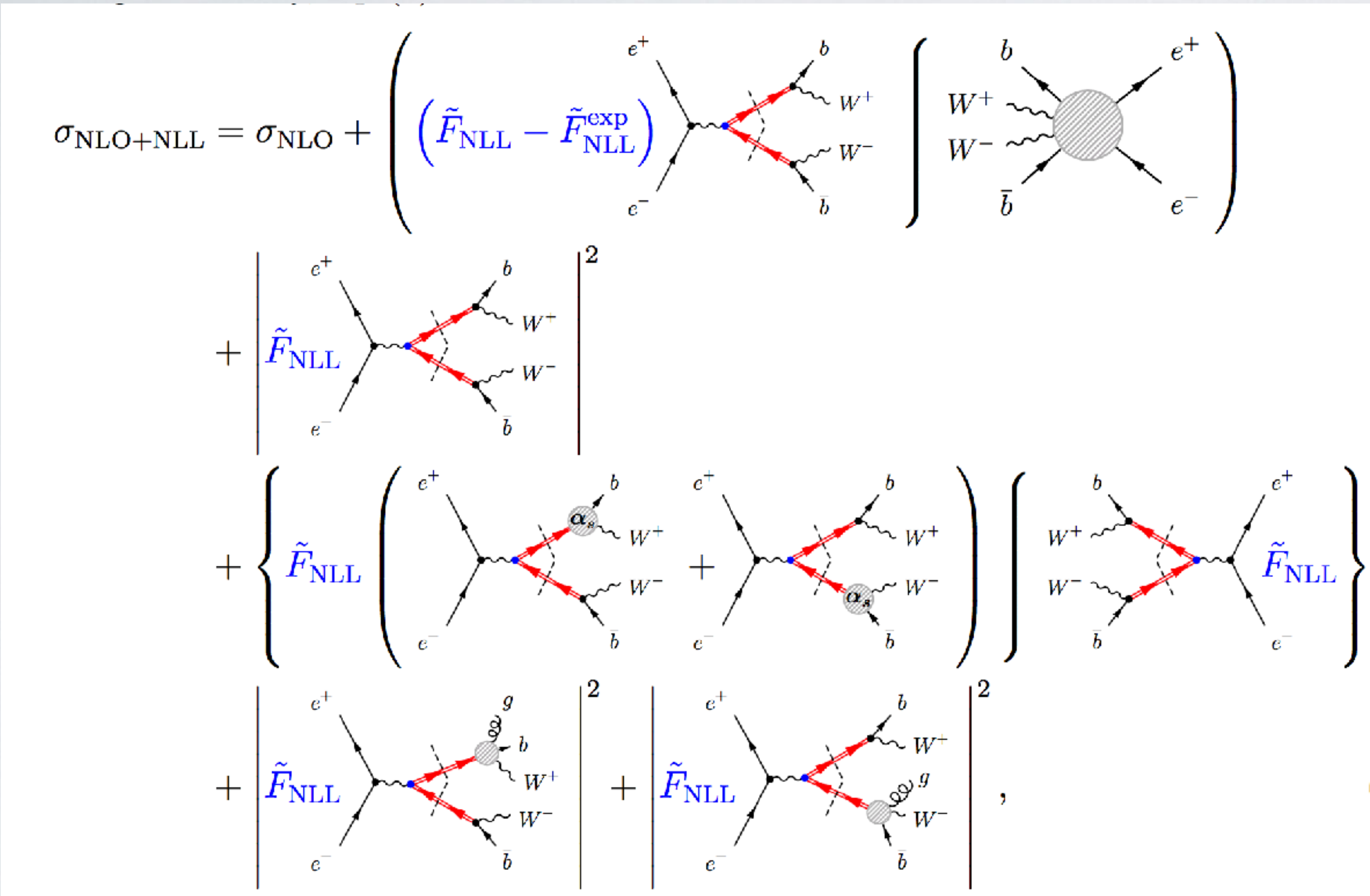


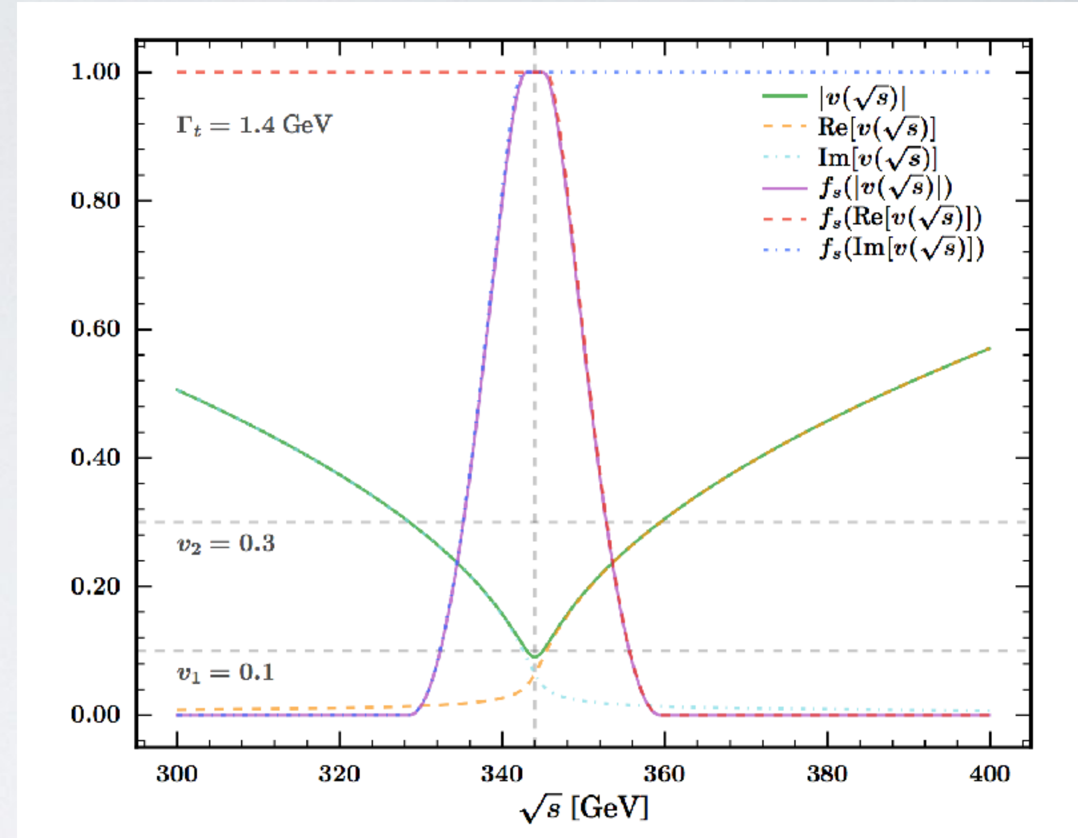
MATCH

Continuum region: "standard" fixed-order QCD

Top threshold: validation and matching

- Transition region between relativistic and resummation effects





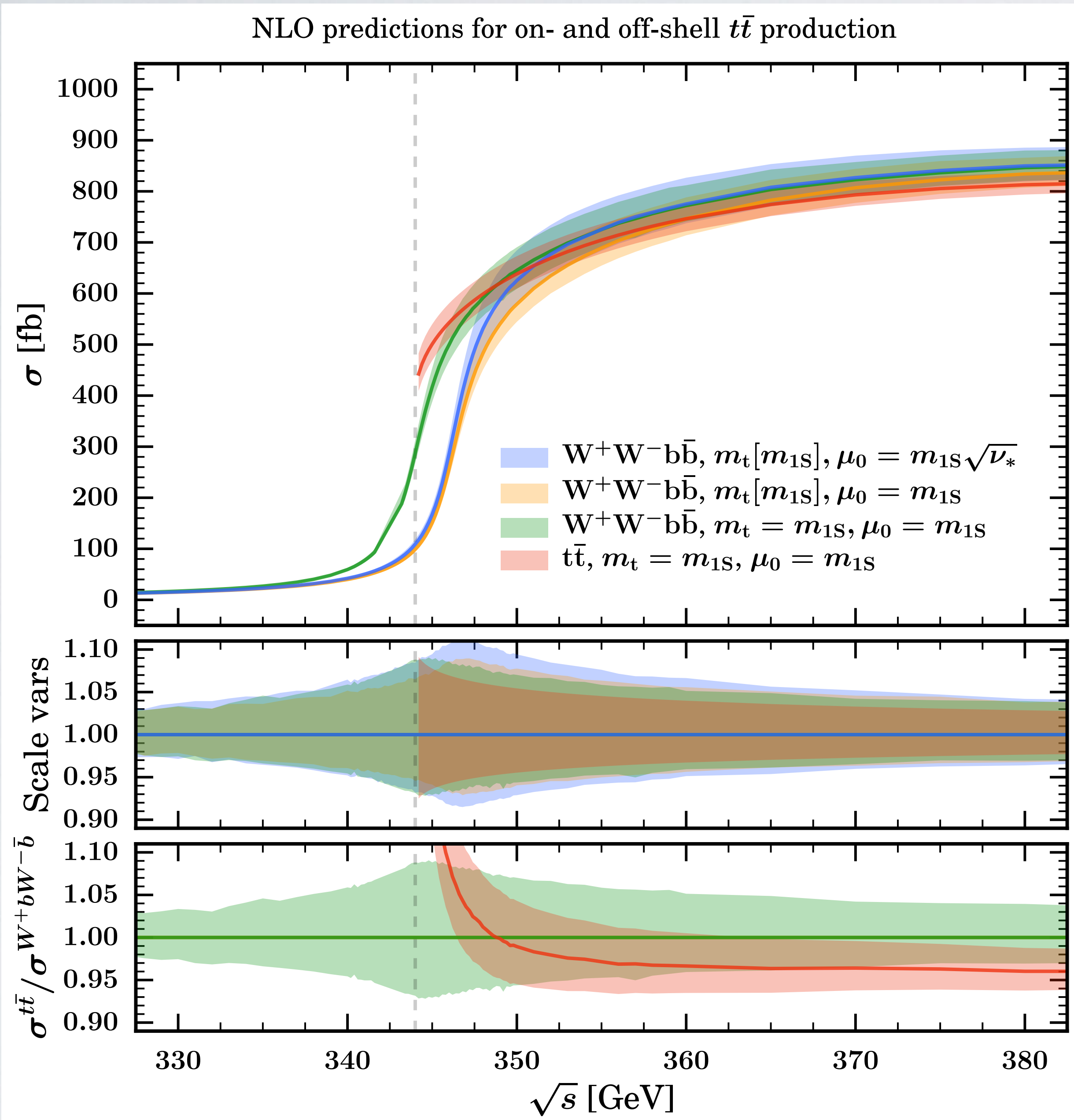
$$\sigma_{\rm matched} = \sigma_{\rm FO}\left[\alpha_{\rm H}\right] + \sigma^{\rm full}_{\rm NRQCD}\left[f_s\,\alpha_{\rm H},\; f_s\,\alpha_{\rm S},\; f_s\,\alpha_{\rm US}\right] - \sigma^{\rm expanded}_{\rm NRQCD}\left[f_s\,\alpha_{\rm H},\; f_s\,\alpha_{\rm H}\right]\,,$$

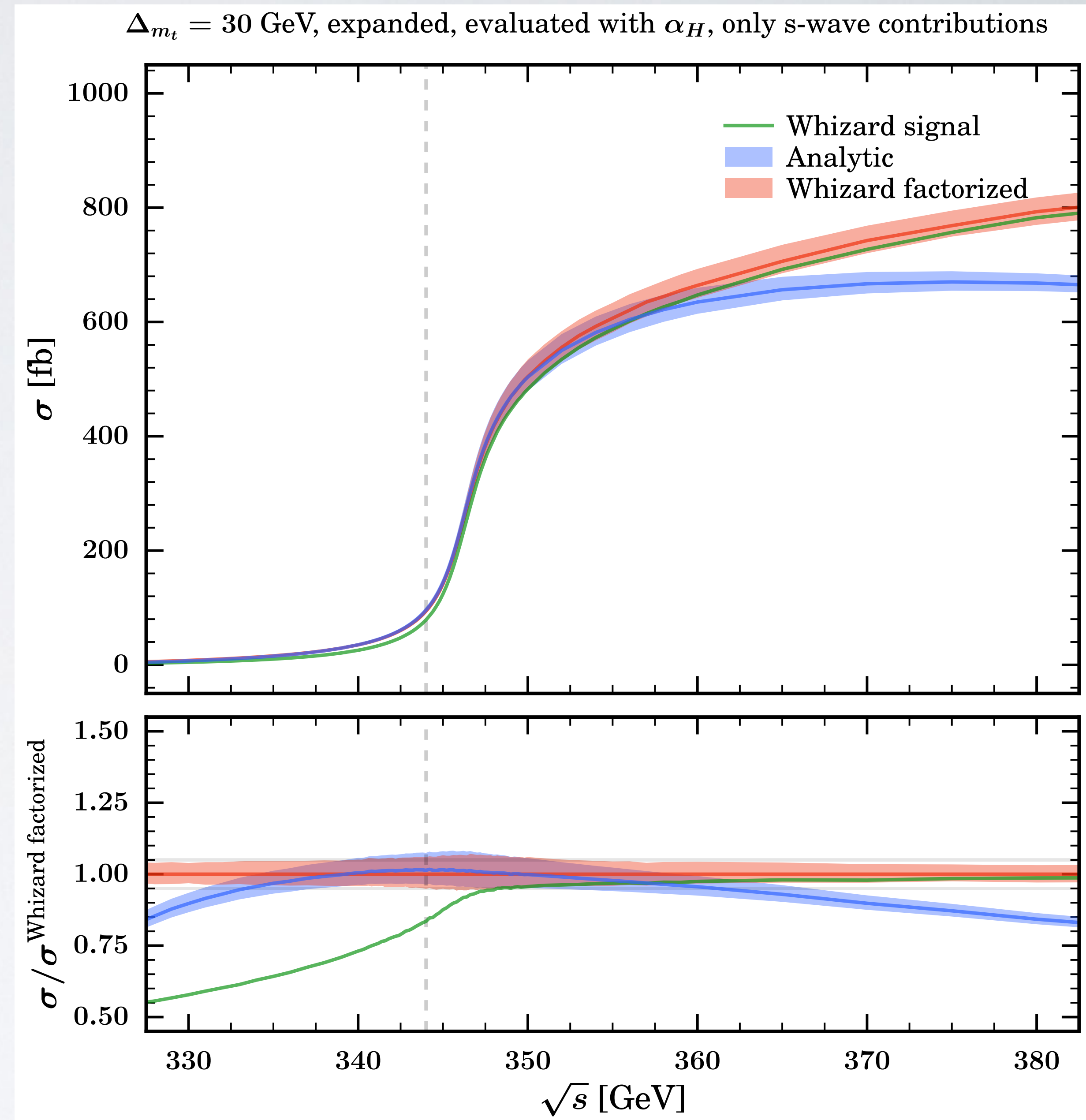
Smoothstep matching function:

$$f_s(v) = \begin{cases} 1 & v < v_1 \\ 1 - 3\left(\frac{v-v_1}{v_2-v_1}\right)^2 - 2\left(\frac{v-v_1}{v_2-v_1}\right)^3 & v_1 \le v \le v_2 \\ 0 & v > v_2 \end{cases}$$

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

Top threshold: validation and matching





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

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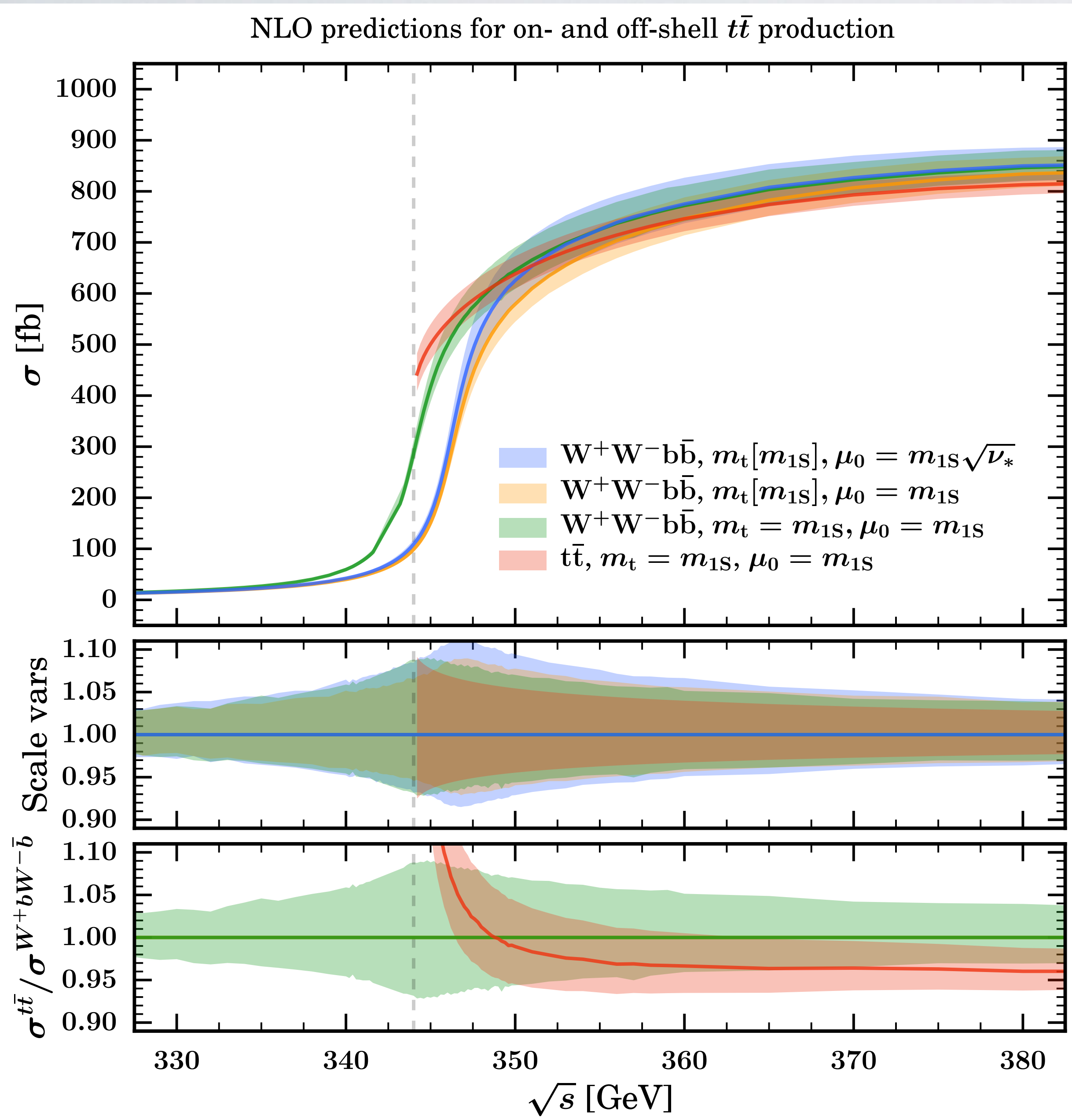

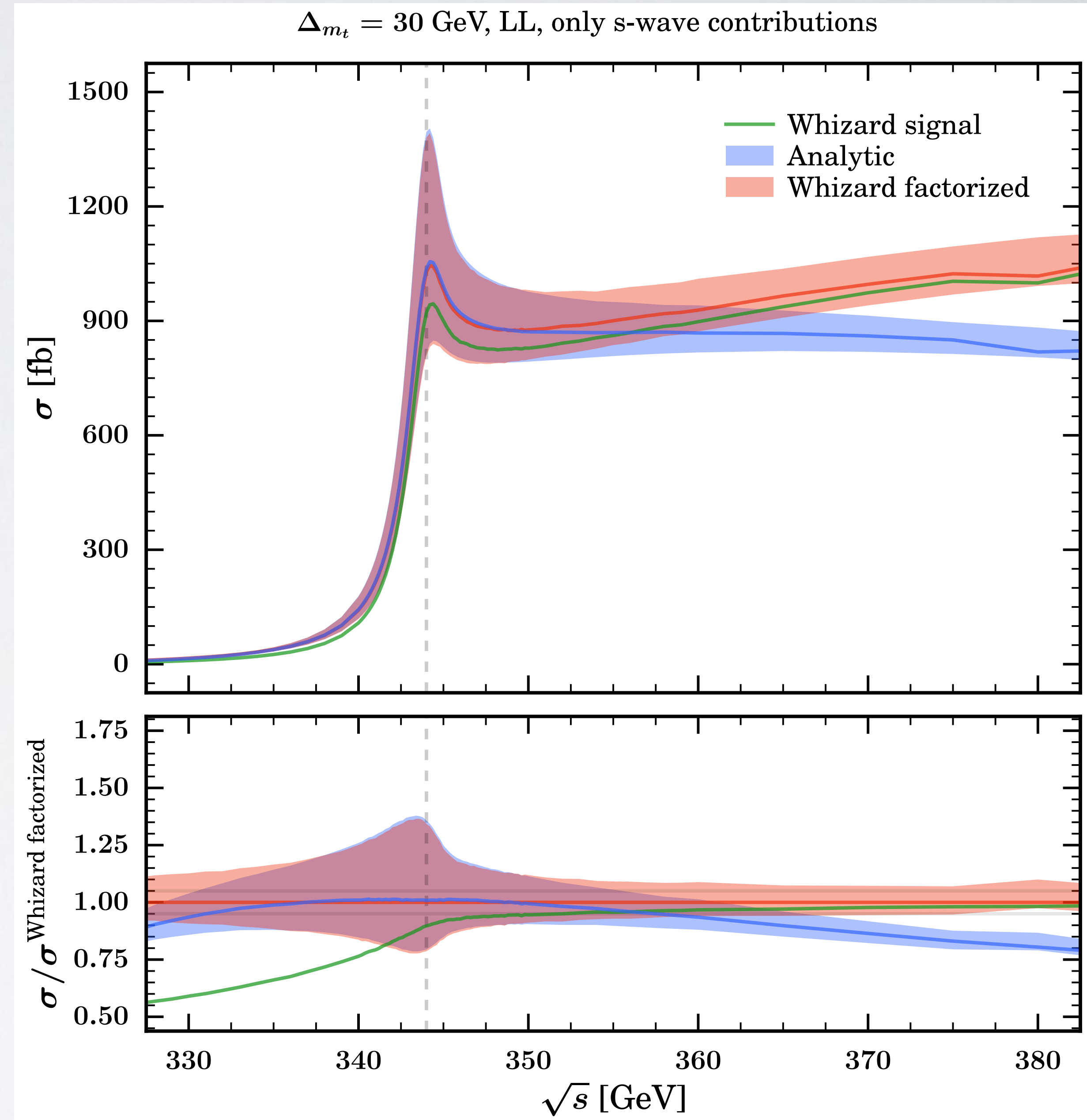

Bach/Chokoufé/Hoang/Kilian/JRR/Stahlhofen/Teubner/Weiss, 1712.02220

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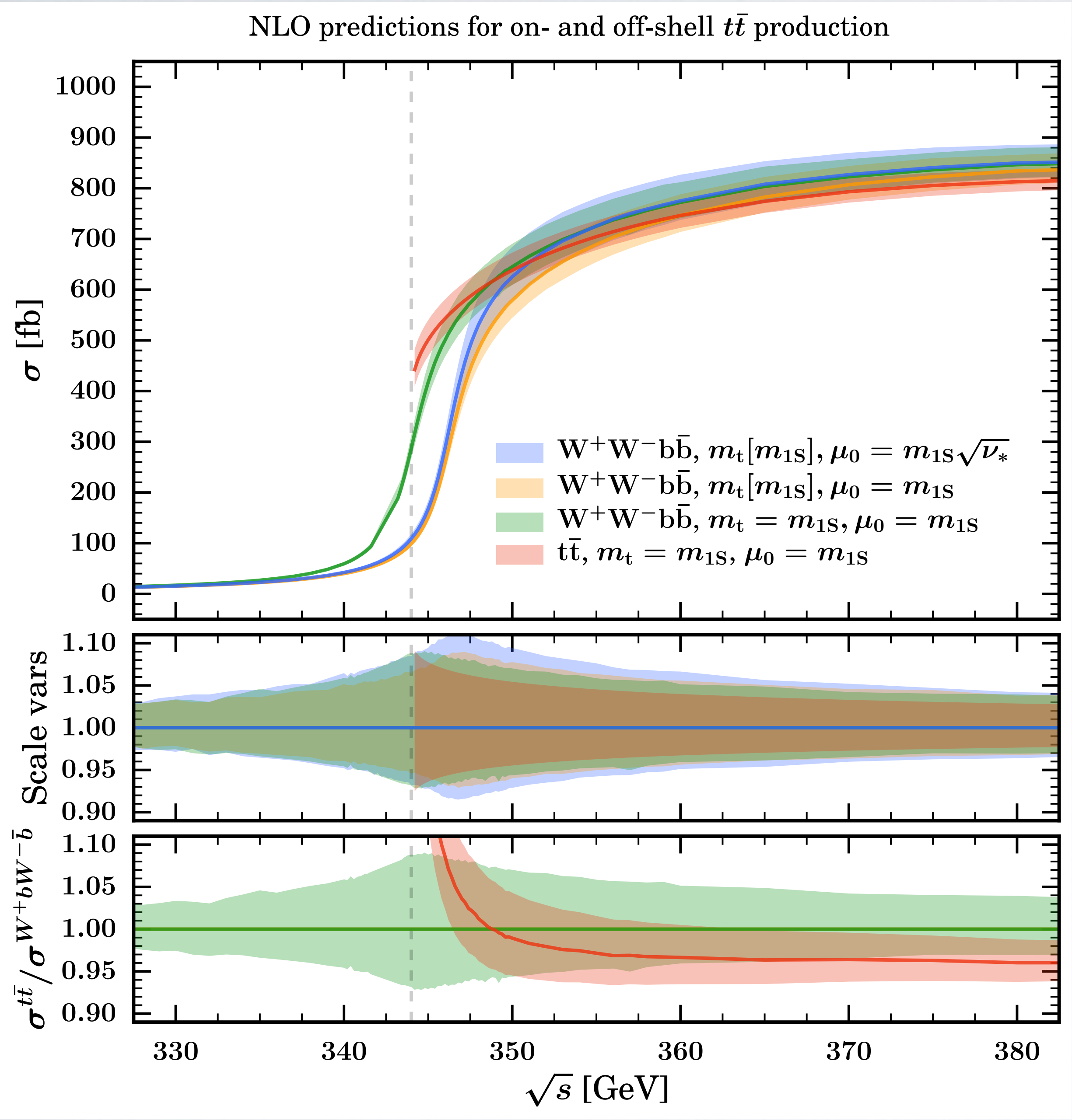
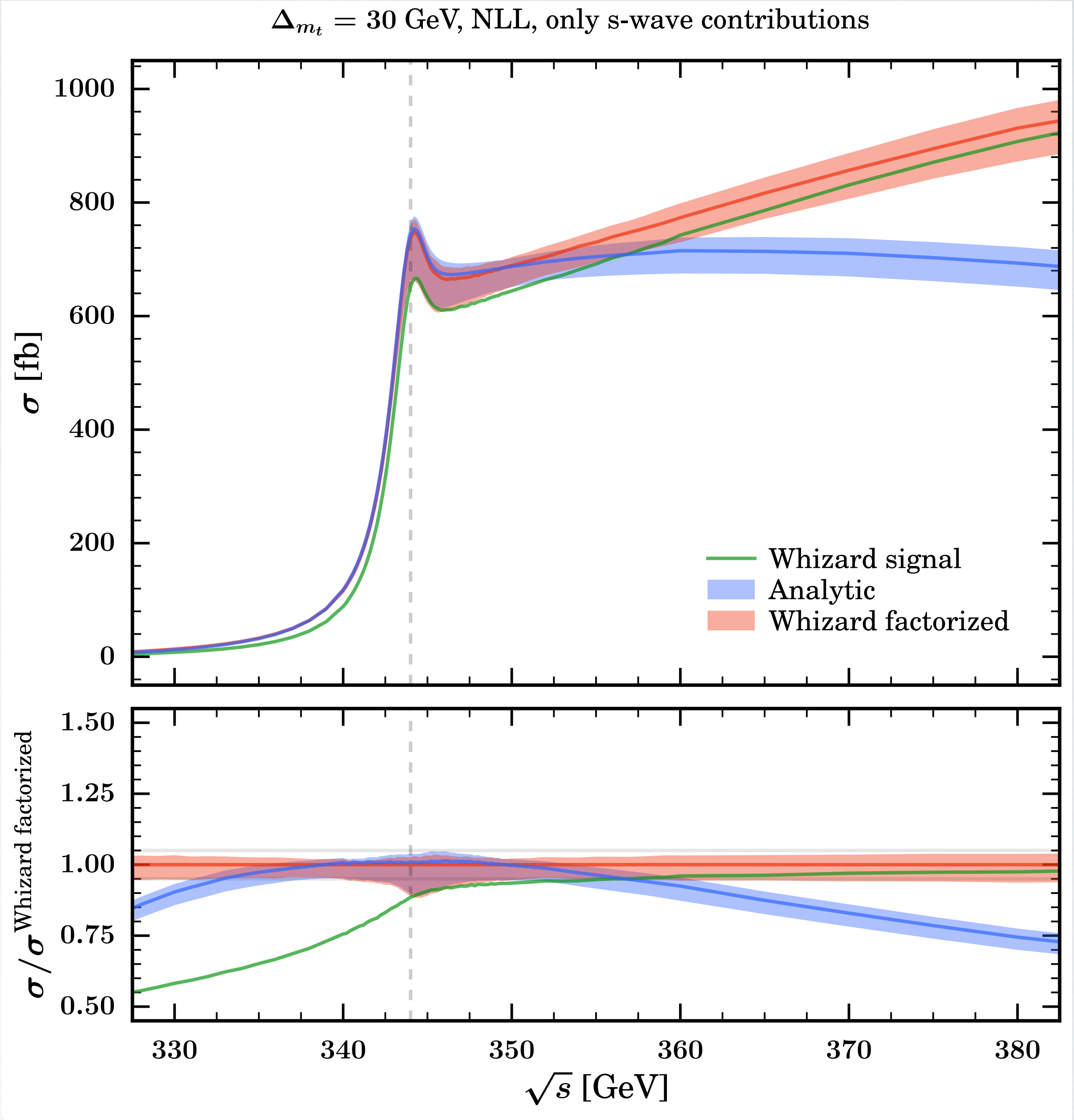
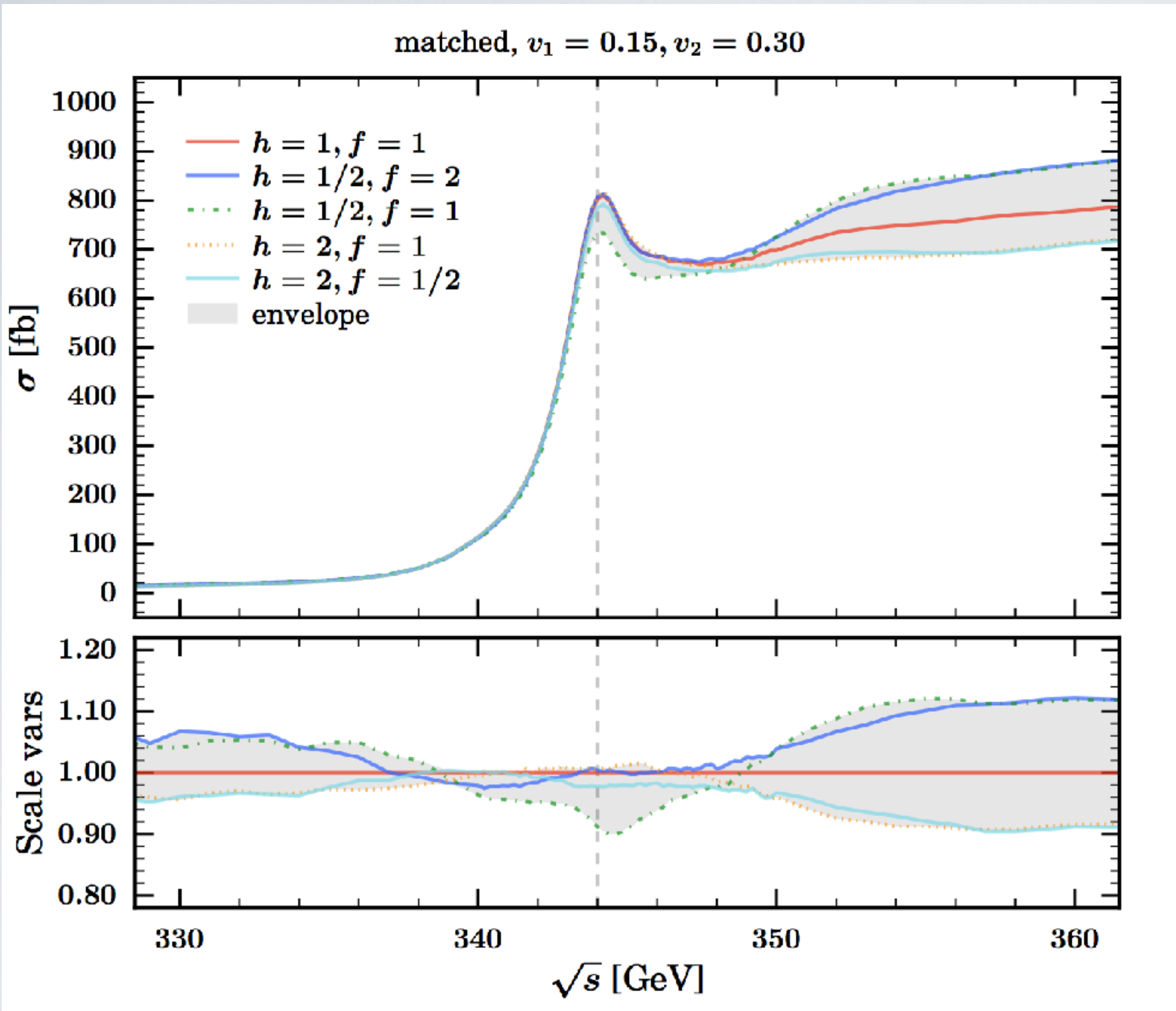
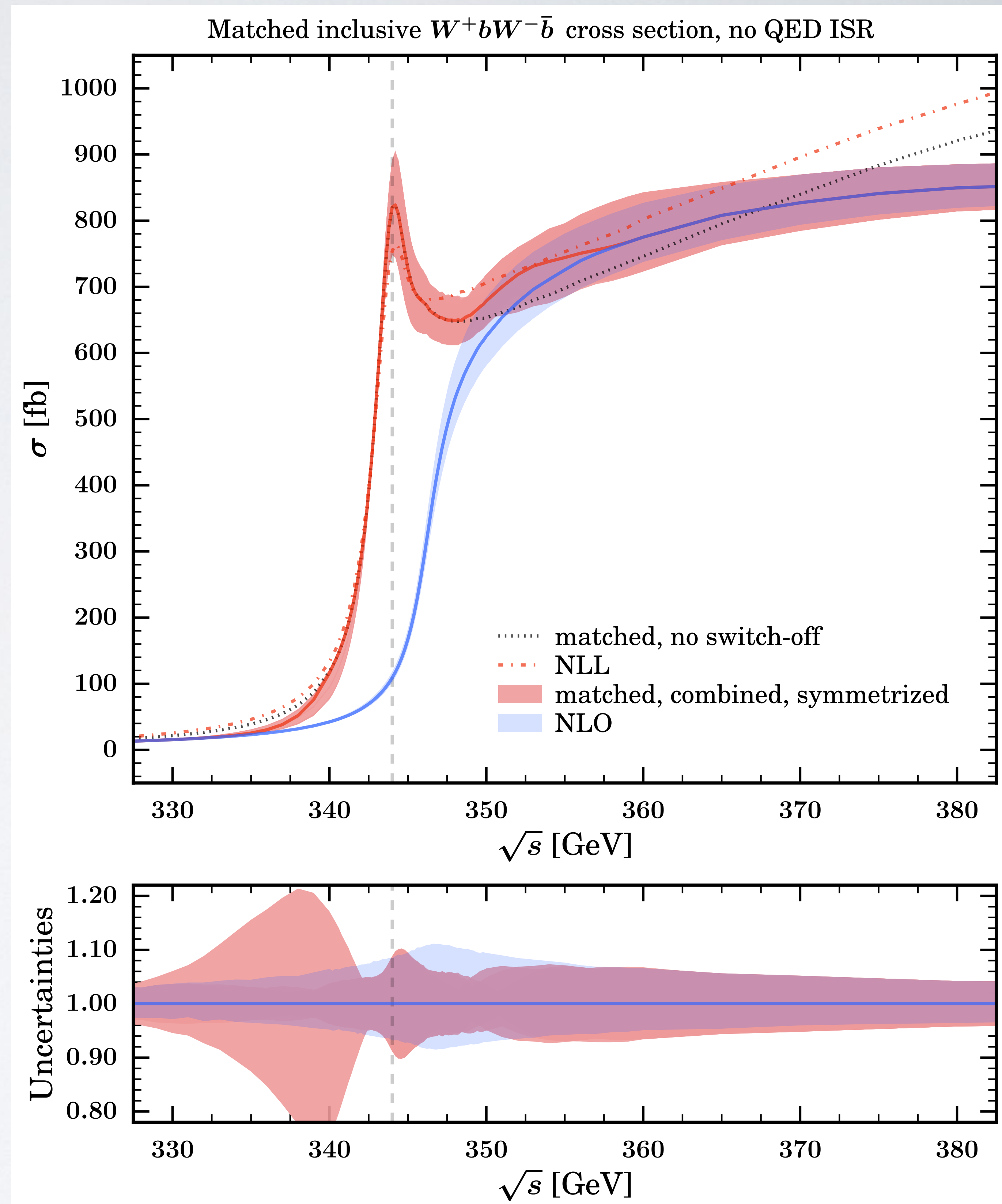




Bach/Chokoufé/Hoang/Kilian/JRR/Stahlhofen/Teubner/Weiss, 1712.02220

Matching threshold NLL to continuum NLO





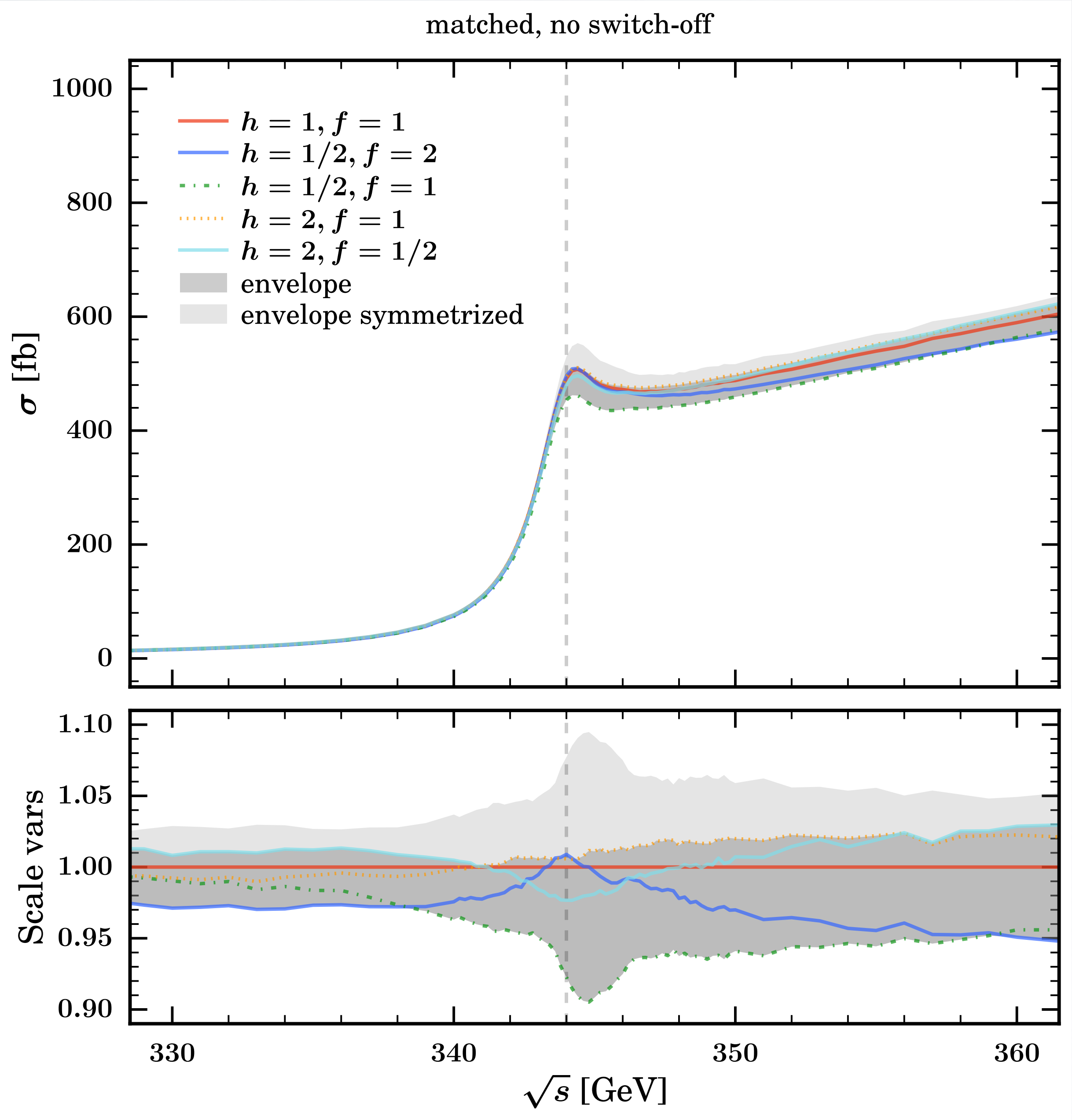
Total uncertainty: *h-f* variation band and matching [switch-off function]

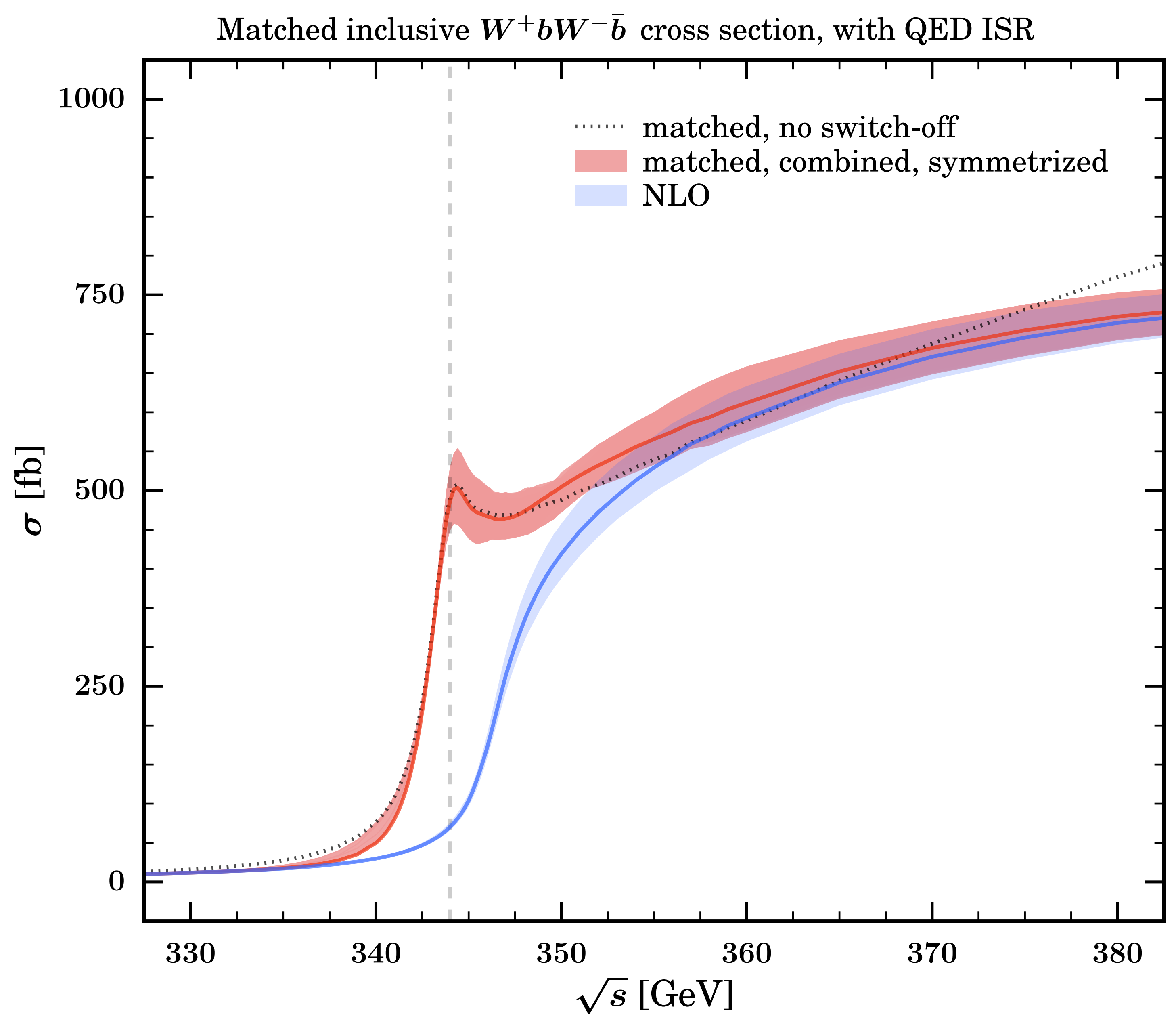
Symmetrization of error bands:

$$\sigma_{\max} = \max\left[\max_{i\in\mathrm{HF}} \sigma_i \;,\; \sigma_0 + (\sigma_0 - \min_{i\in\mathrm{HF}} \sigma_i)\right]$$

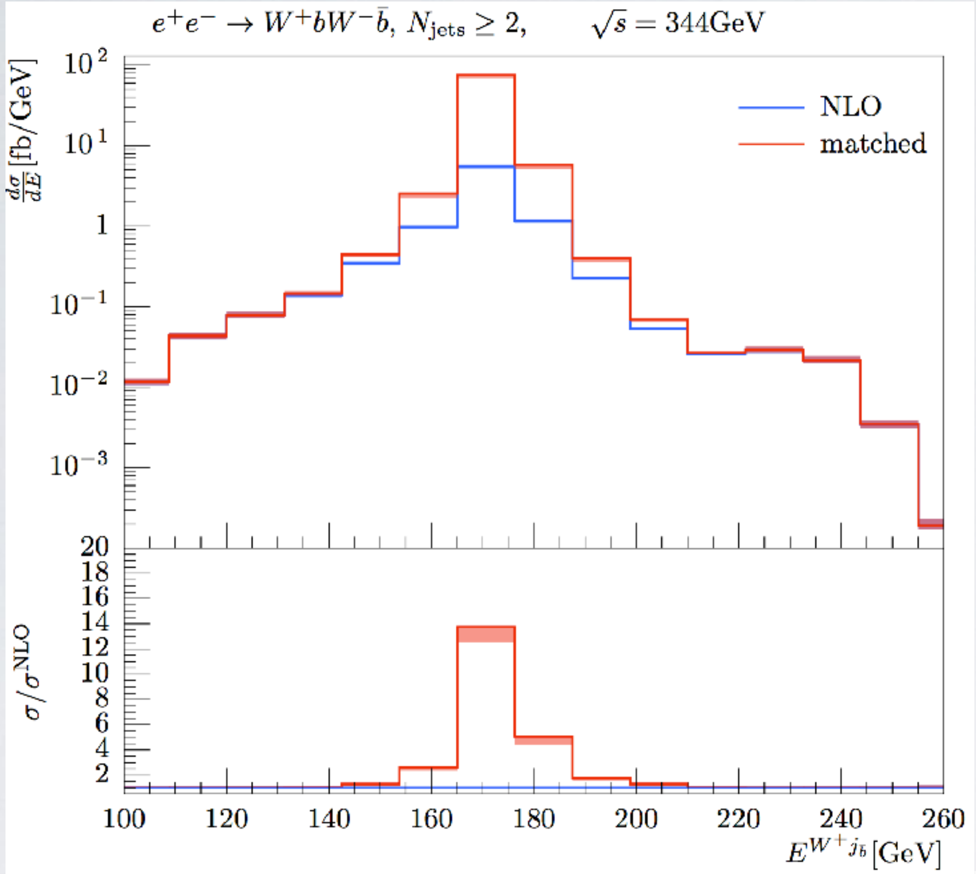
$$\sigma_{\min} = \min\left[\min_{i\in\mathrm{HF}} \sigma_i \;,\; \sigma_0 - (\max_{i\in\mathrm{HF}} \sigma_i - \sigma_0)\right]$$

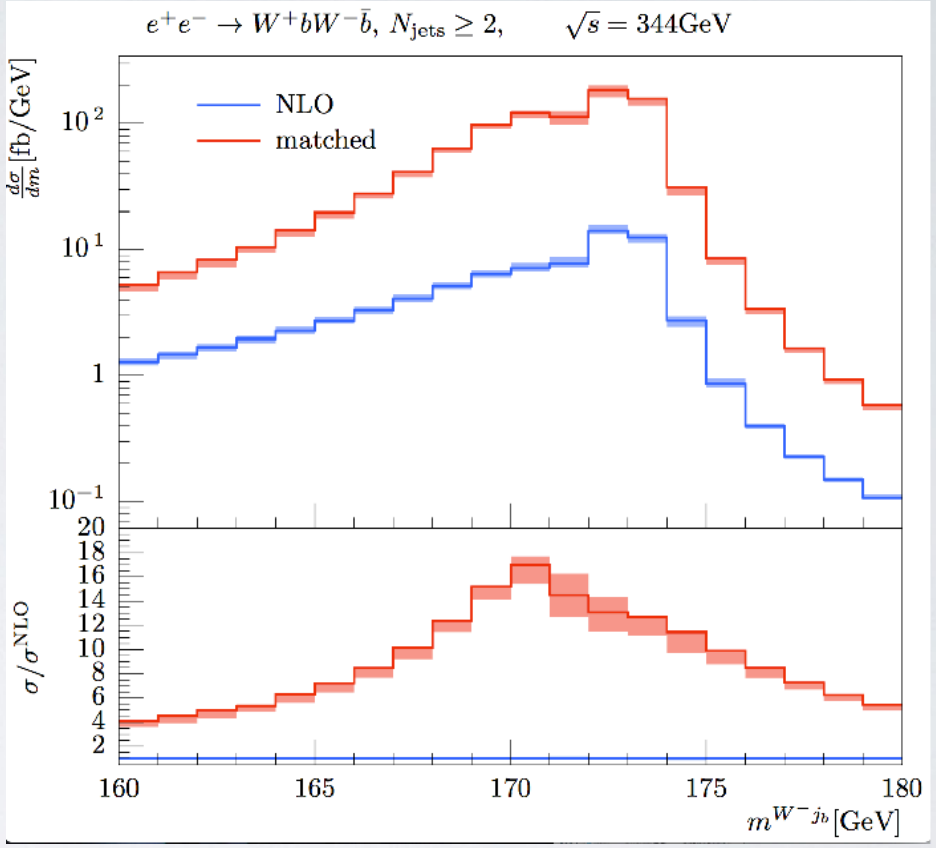
Threshold matching with QED ISR

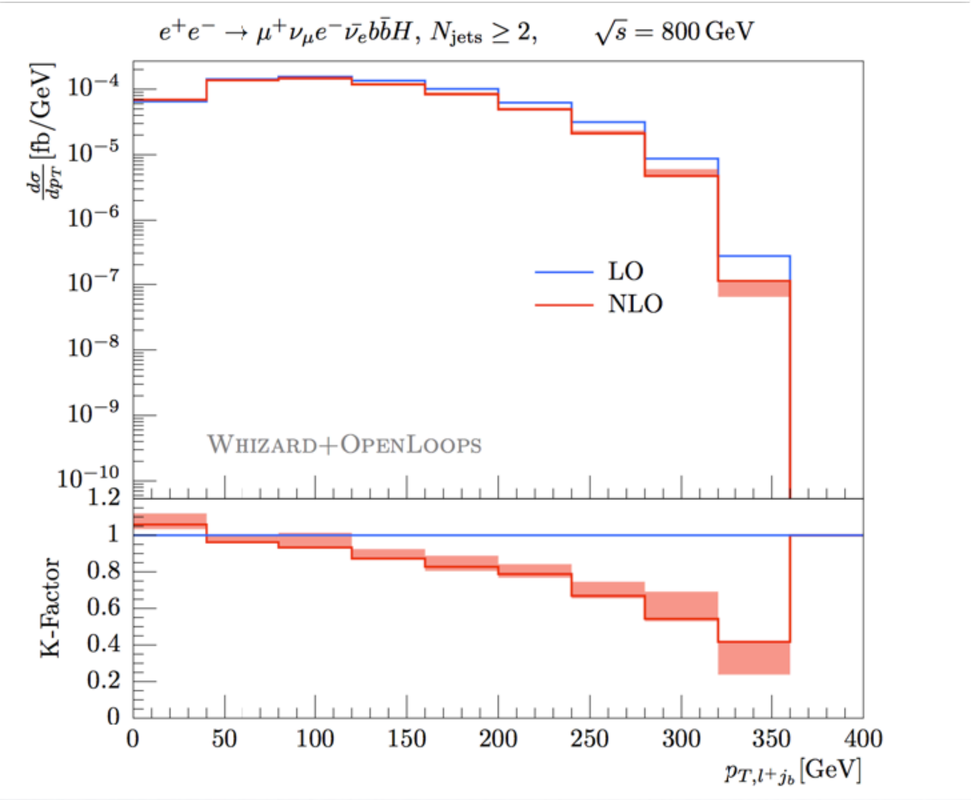


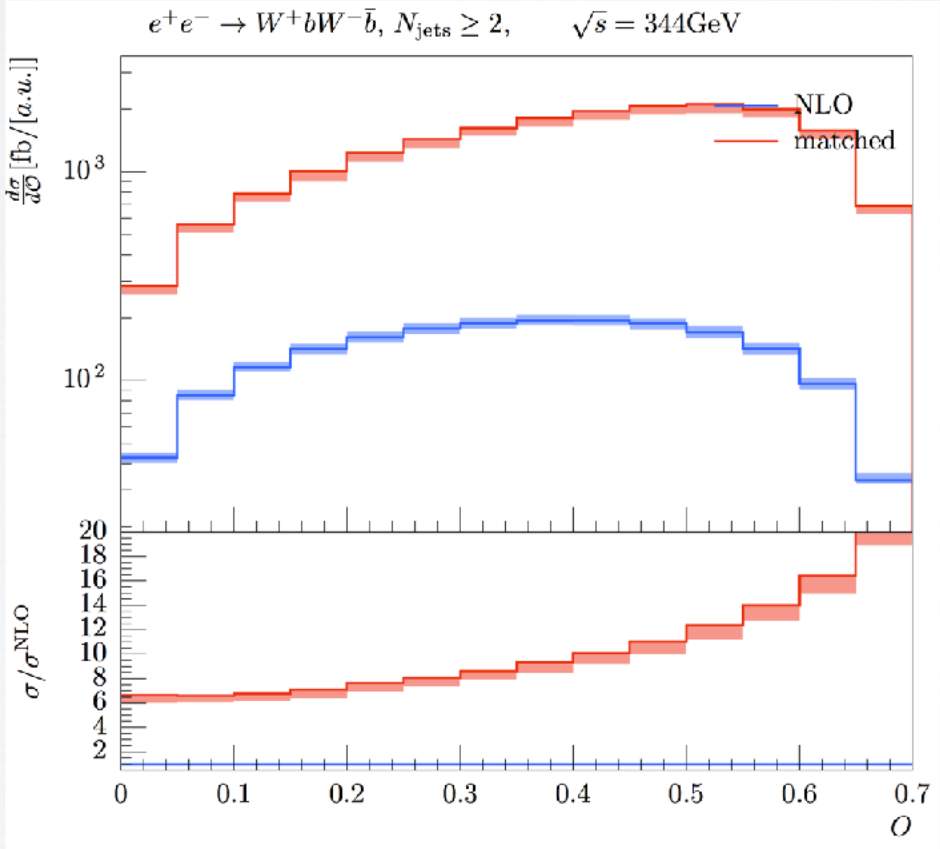


Matched threshold differential distributions





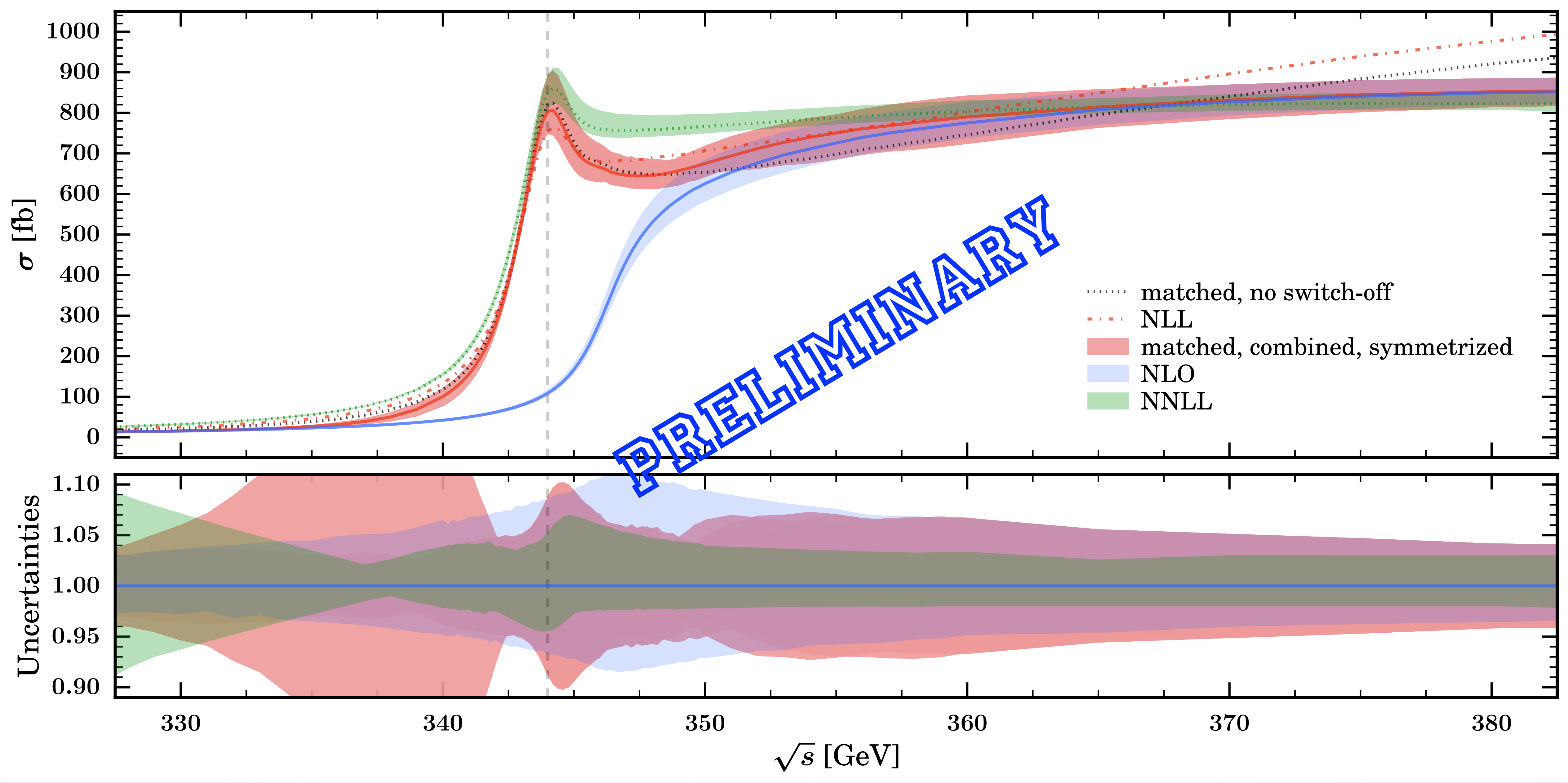




Summary & Outlook

Next steps: higher QCD order, EW corrections (ISR matching!!), soft gluons … … …

$e^+e^- \to W^+bW^-\bar{b}$

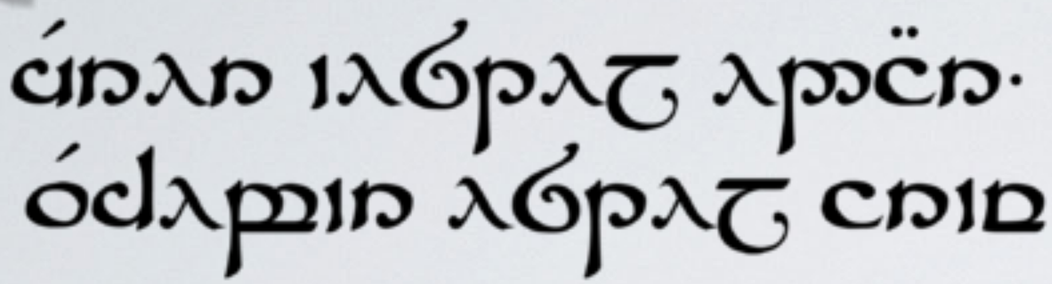


Conclusions & Outlook

- WHIZARD 2.6 event generator for collider physics (ee, pp, ep)
- Allows to simulate all possible BSM models
- High-multiplicity SM hard processes (2→10 etc.)
- Focus on e^+e^- physics: beam spectra, e^+e^- ISR, LCIO, polarizations
- NLO automation: reals/subtraction terms (FKS) [+ virtuals externally]
- NLO QCD (almost) done → WHIZARD 3.0 [EW validation started]
- Automated POWHEG matching
- Top threshold in e^+e^-: NLL NRQCD threshold / NLO continuum matching
- NEW: UFO models, MPI parallel integration, Resonance matching to shower

BACKUP

General structure of SINDARIN input



```
model = NMSSM

alias ll = “e-“:”e+”:”mu+”:”mu-“
alias parton = u:U:d:D:s:S:g
alias jet = parton
alias stop = st1:st2:ST1:ST2

process susyprod = parton, parton =>
    stop,stop + gg,gg + gg,stop



sqrts = 13000 GeV
beams = p, p => lhapdf

integrate (susyprod)
     { iterations = 15:500000, 5:1000000 }

n_events = 10000


sample_format = lhef, stdhep, hepmc
sample = “susydata”

simulate (susyprod)
```

Standard cut expression:

```
cuts = all Pt > 100 GeV [lepton]
```

Cuts on tensor products:

```
cuts = all Dist > 2 [e1:E1, e2:E2]
```

Selection cuts:

```
cuts = any PDG == 13 [lepton]
```

```
cuts = any M > 100 GeV [combine if cos(Theta) > 0.5
                          [lepton,neutrino]
```

Sorting and selecting:

```
cuts = any E > 2*mW [extract index 2
                 [sort by -Pt [lepton]]
```

Clustering:

[FastJet: Cacciari/Salam/Soyez]

```
jet_algorithm = antikt_algorithm
jet_r = 0.7
?keep_flavors_when_clustering = true
```

Subevents and jet counts:

```
cuts = let subevt @clustered_jets = cluster [jet] in
       let subevt @pt_selected =
          select if Pt > 30 GeV [@clustered_jets] in
```

Beam structure: special beams

Beam polarization, ILC-like setup

```
beams = e1, E1
beams_pol_density = @(-1), @(+1)
beams_pol_fraction = 80%, 30%
```

Polarized decays: longitudinal *Z*

```
process zee = Z => e1, E1
beams = Z
beams_pol_density = @(0)
```

Scan over polarizations

```
scan int h1 = (-1,1) {
  scan int h2 = (-1,1) {
    beams_pol_density = @(h1), @(h2)
    integrate (proc)
  }
}
```

Asymmetric beams

```
beams = e1, E1
beams_momentum = 100 GeV, 900 GeV
```

Beams with crossing angle

```
beams_momentum = 250 GeV, 250 GeV
beams_theta = 0, 10 degree
```

Beams with rotated crossing angle

```
beams_momentum = 250 GeV, 250 GeV
beams_theta = 0, 10 degree
beams_phi   = 0, 45 degree
```

Structure functions (also concatenated)

```
beams = p, p => pdf_builtin
$pdf_builtin_set = “mmht2014lo”
```

```
beams = p, pbar => lhapdf
```

```
beams = e, p => none, pdf_builtin
```

```
beams = e1, E1 => circe1
$circe1_acc = “TESLA”
?circe1_generate = false
circe1_mapping_slope = 2
```

```
beams = e1, E1 => circe2 => isr => ewa
```

```
beams = e1, E1 => beam_events
$beam_events_file = “uniform_spread_2.5%.dat”
```

Beam structure: beam polarization

Beam polarization

```
beams_pol_density = @([<spin entries>]), @([<spin entries>])
beams_pol_fraction = <degree beam 1>, <degree beam 2>
```

Spin j	Particle type	possible m values
0	Scalar boson	0
1/2	Spinor	+1, -1
1	(Massive) Vector boson	+1, (0), -1
3/2	(Massive) Vectorspinor	+2, (+1), (-1), -2
2	(Massive) Tensor	+2, (+1), (0), (-1), -2

$|m| = 2$ massless

$|m| = 2j+1$ massive

Different density matrices

```
beams_pol_density = @()
```

Unpolarized beams $\rho = \frac{1}{|m|}\mathbb{I}$

```
beams_pol_density = @(±j)
beams_pol_fraction = f
```

Circular polarization $\rho = \mathrm{diag}\left(\frac{1\pm f}{2}, 0, \ldots, 0, \frac{1\mp f}{2}\right)$

```
beams_pol_density = @(0)
beams_pol_fraction = f
```

Longitudinal polarization (massive) $\rho = \mathrm{diag}\left(\frac{1-f}{|m|}, \ldots, \frac{1-f}{|m|}, \frac{1+f\,(|m|-1)}{|m|}, \frac{1-f}{|m|}, \ldots, \frac{1-f}{|m|}\right)$

```
beams_pol_density = @(j, -j, j:-j:exp(-I*phi))
beams_pol_fraction = f
```

Transversal polarization (along an axis)

$$\rho = \begin{pmatrix} 1 & 0 & \cdots & \cdots & \frac{f}{2}\,e^{-i\phi} \\ 0 & 0 & \ddots & & 0 \\ \vdots & \ddots & \ddots & \ddots & \vdots \\ 0 & & \ddots & 0 & 0 \\ \frac{f}{2}\,e^{i\phi} & \cdots & \cdots & 0 & 1 \end{pmatrix}$$

```
beams_pol_density = @(j:j:1-cos(theta),
          j:-j:sin(theta)*exp(-I*phi), -j:-j:1+cos(theta))
beams_pol_fraction = f
```

Polarization along arbitrary axis (θ,Φ)

$$\rho = \frac{1}{2}\cdot\begin{pmatrix} 1-f\cos\theta & 0 & \cdots & \cdots & f\sin\theta\,e^{-i\phi} \\ 0 & 0 & \ddots & & 0 \\ \vdots & \ddots & \ddots & \ddots & \vdots \\ 0 & & \ddots & 0 & 0 \\ f\sin\theta\,e^{i\phi} & \cdots & \cdots & 0 & 1+f\cos\theta \end{pmatrix}$$

```
beams_pol_density = @(j:j:h_j, j-1:j-1:h_{j-1}, …, -j:-j:h_{-j})
```

```
beams_pol_density = @({m:m':x_{m,m'}})
```

Diagonal / arbitrary density matrices

Decay processes / auto decays

WHIZARD cannot only do scattering processes, but also decays

Example Energy distribution electron in muon decay:

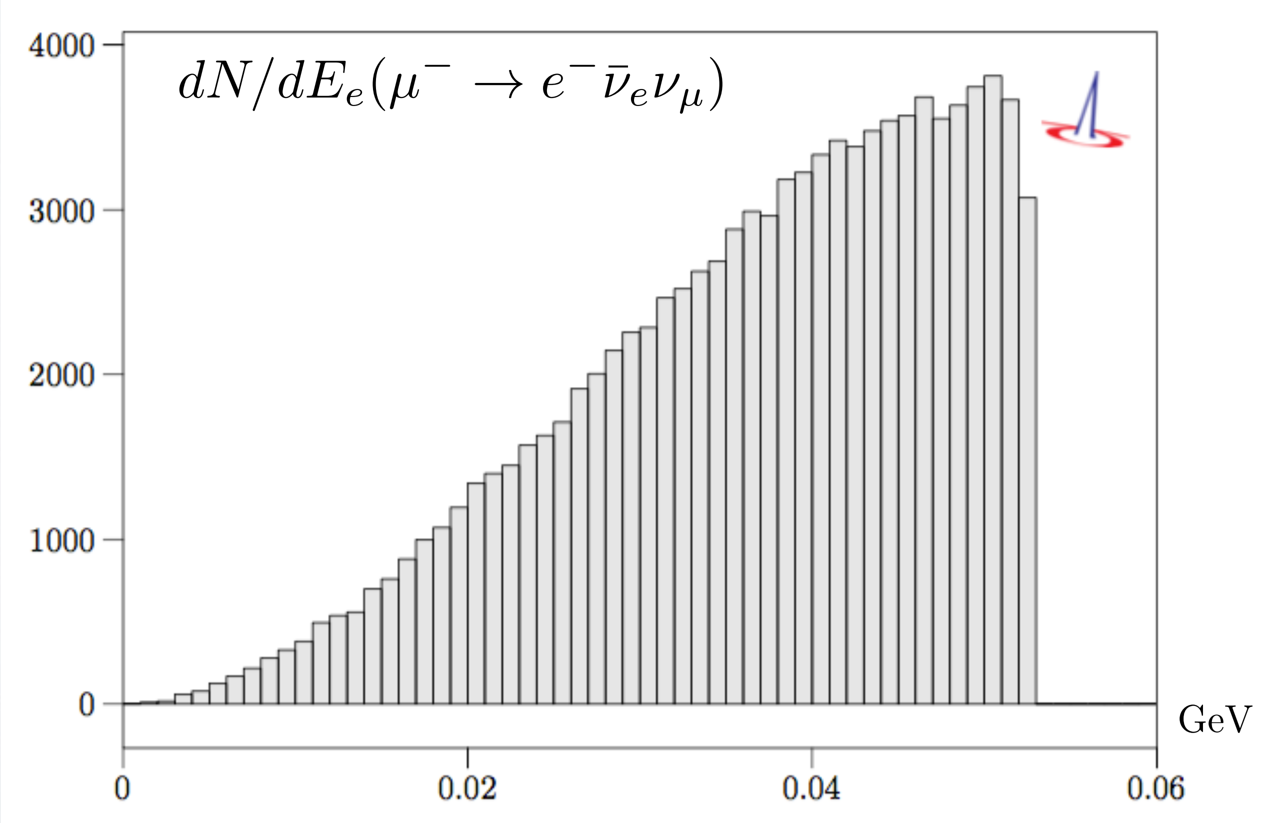
```
model = SM
process mudec = e2 => e1, N1, n2
integrate (mudec)

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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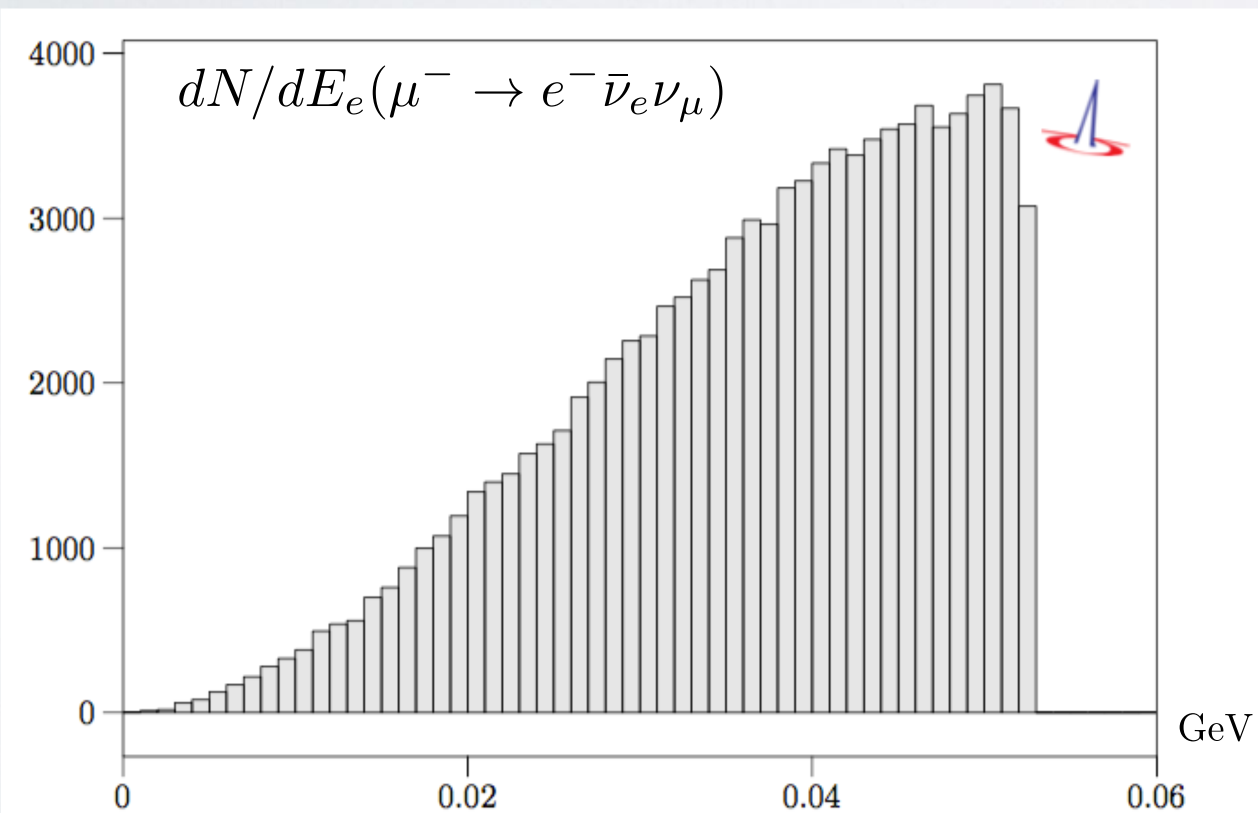


Automatic integration of particle decays

```
auto_decays_multiplicity = 2
?auto_decays_radiative = false

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

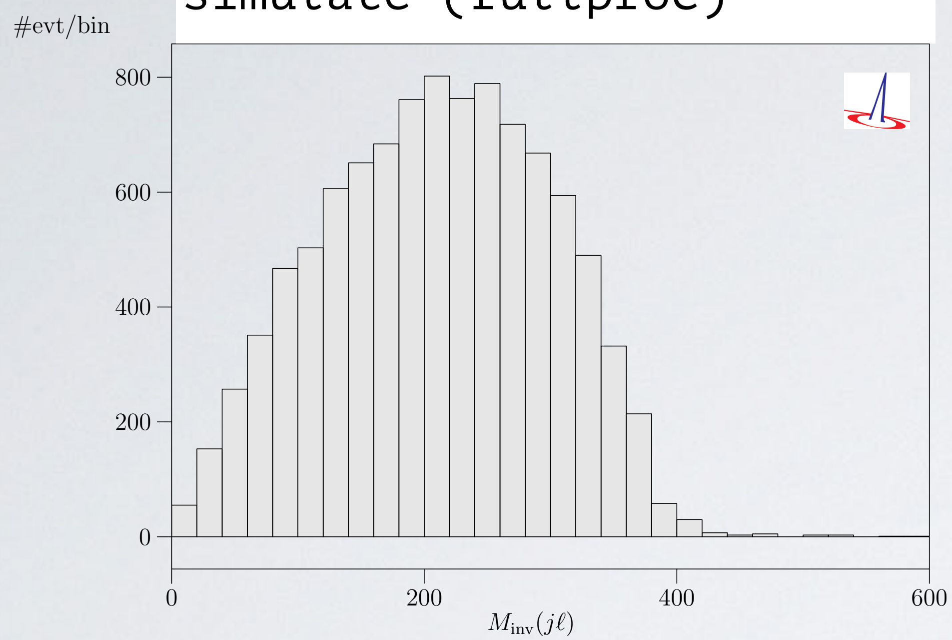
```
|==========================================================================
| It      Calls  Integral[GeV]  Error[GeV]   Err[%]    Acc
|==========================================================================
   1        100  2.2756406E-01  0.00E+00     0.00     0.00*
|--------------------------------------------------------------------------
   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
```

Spin Correlation and Polarization in Cascades

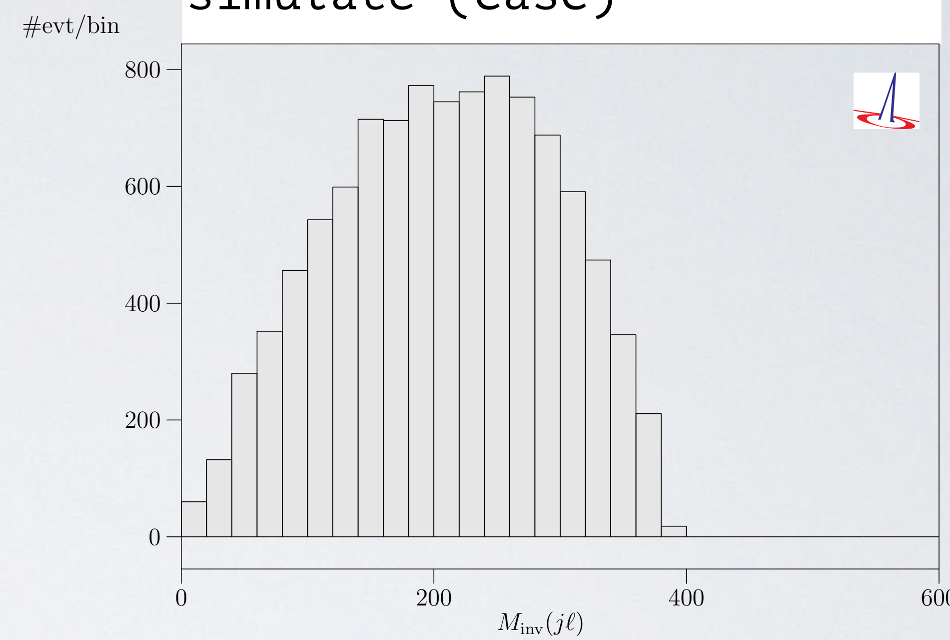
Cascade decay, factorize production and decay

$$p + p \to \tilde{u}^* + \tilde{u} \to \tilde{u}^* + u + \tilde{e}^+ + e^-$$

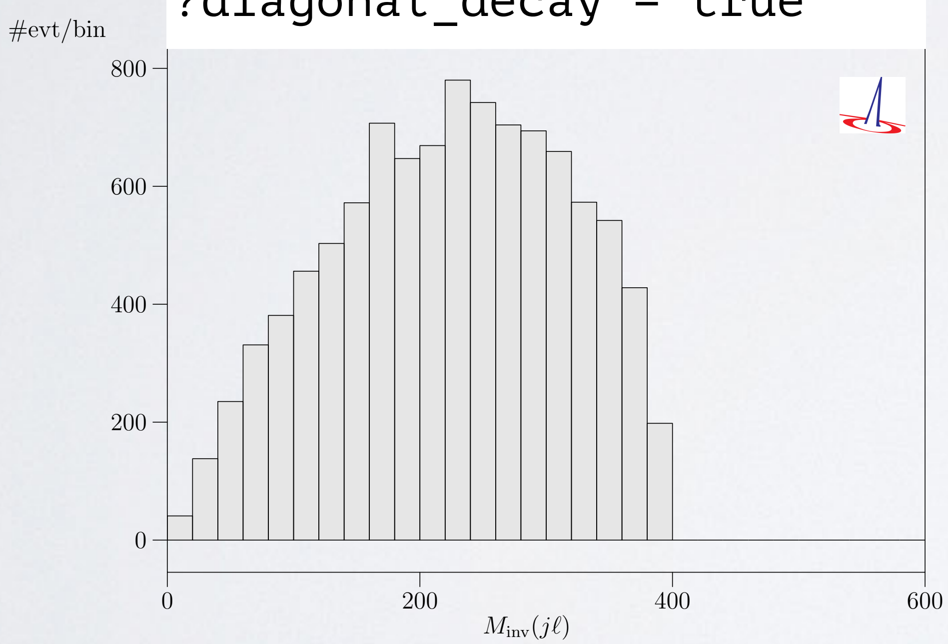
`simulate (fullproc)`



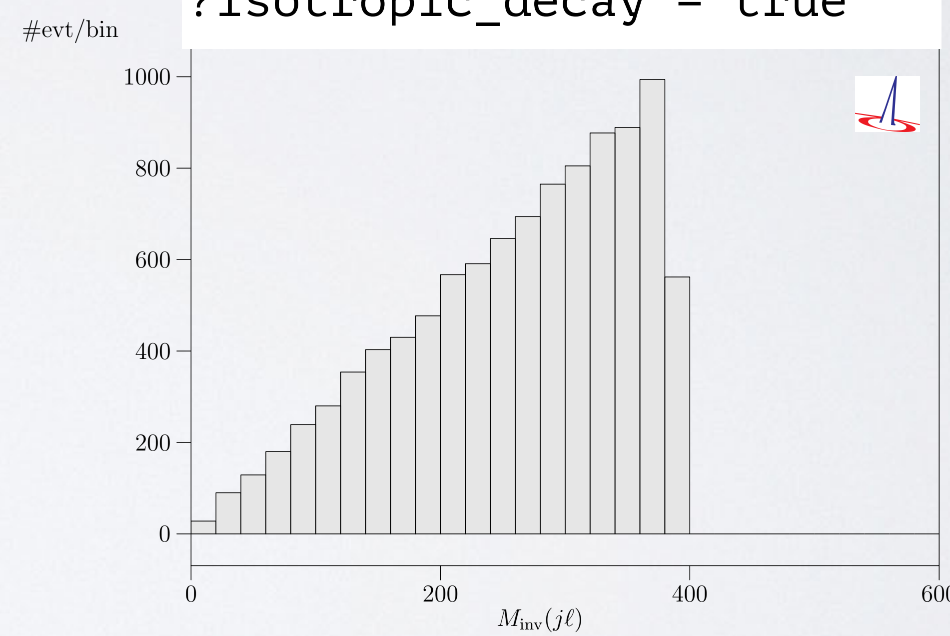
`simulate (casc)`



`?diagonal_decay = true`



`?isotropic_decay = true`



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```
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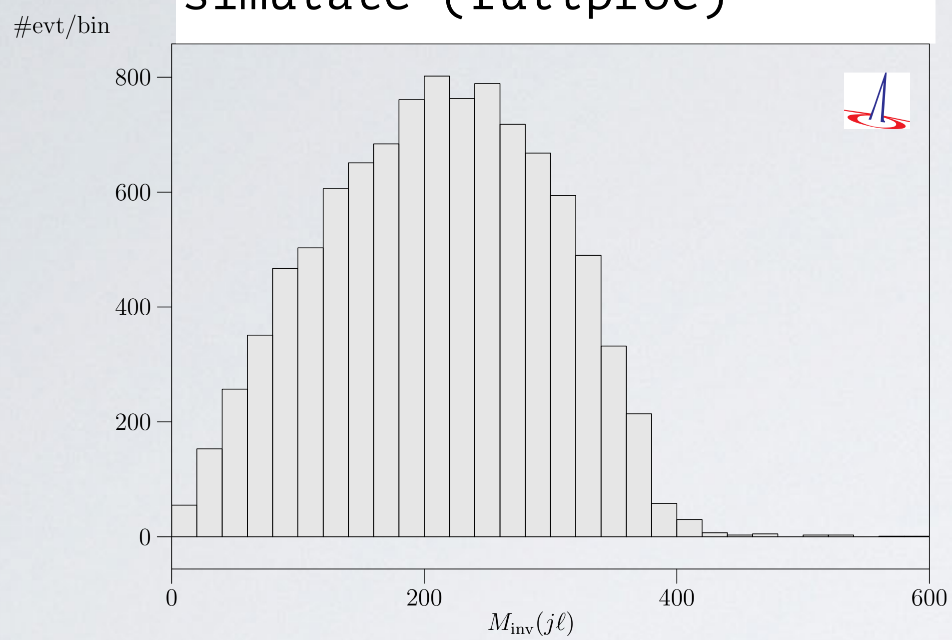


```
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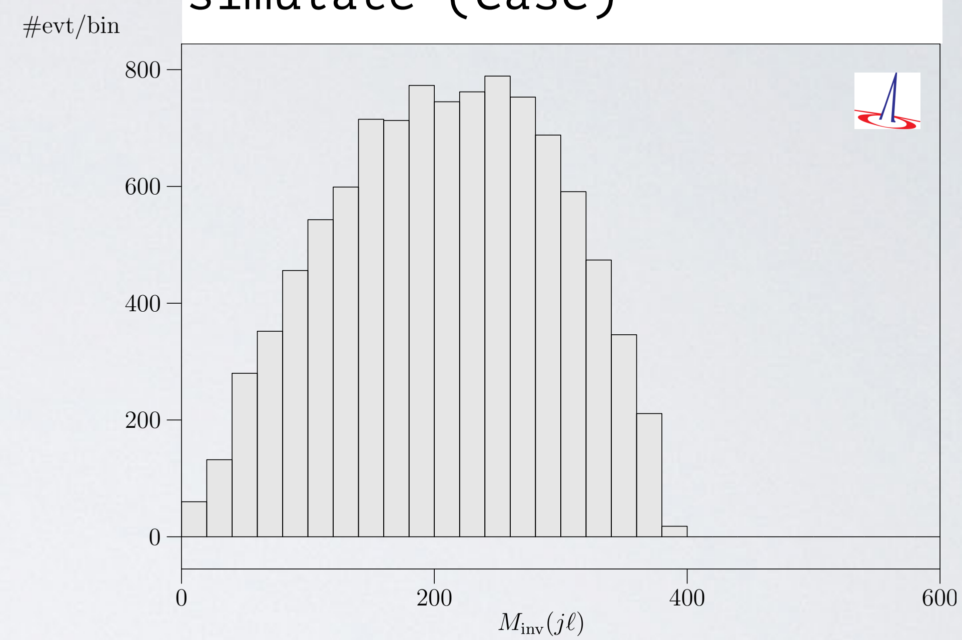
```

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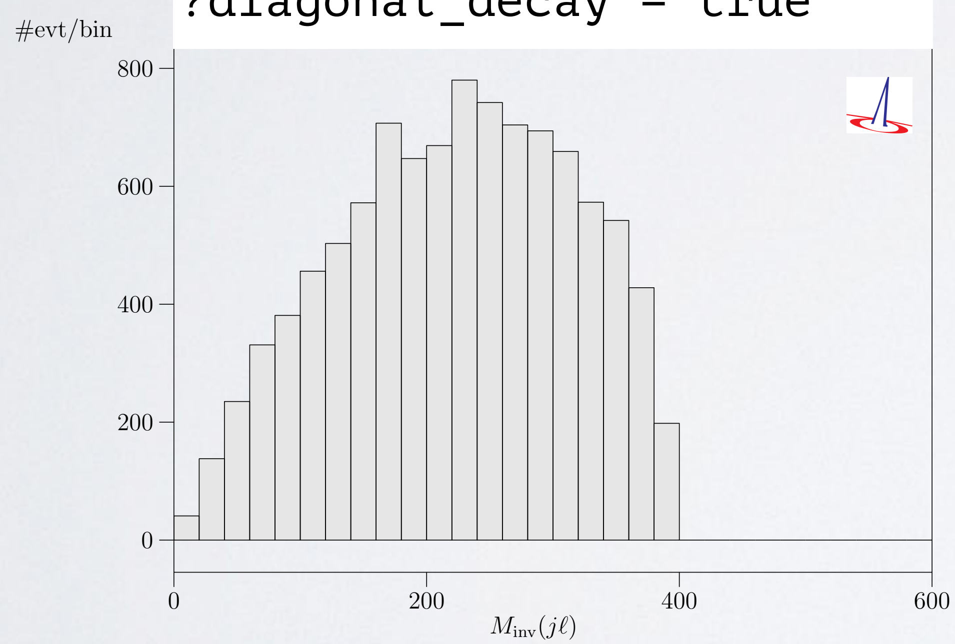


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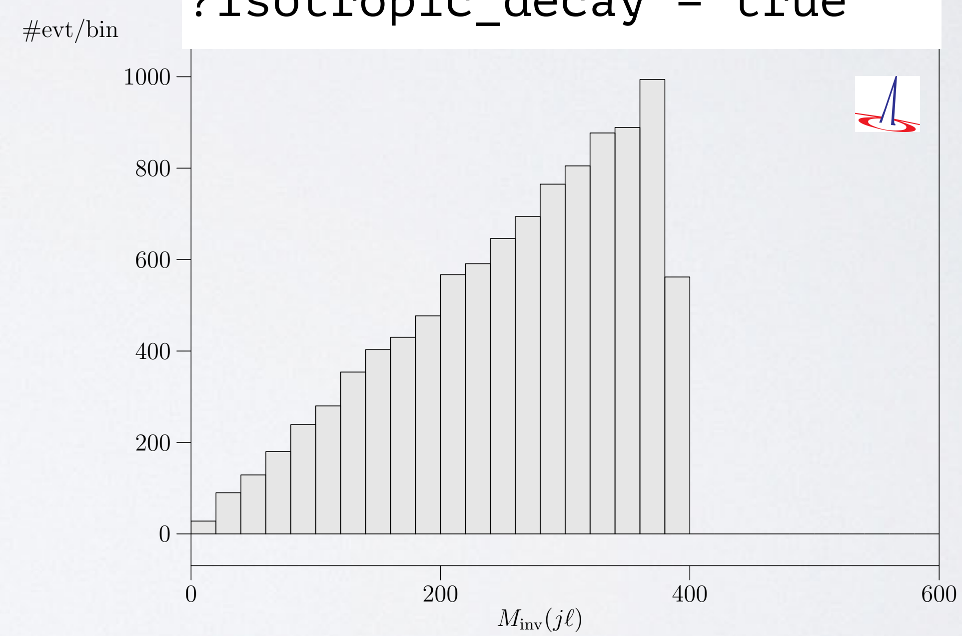
```



Possibility to select specific helicity in decays!

```
unstable “W+” { decay_helicity = 0 }
```

Resonance mappings for NLO processes

- 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

- Algorithm to include resonance histories [Ježo/Nason, 1509.09071]
- Avoids double logarithms in the resonances' width
- Most important for narrow resonances ($H \to bb$)
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  soft mismatch [, collinear mismatch]

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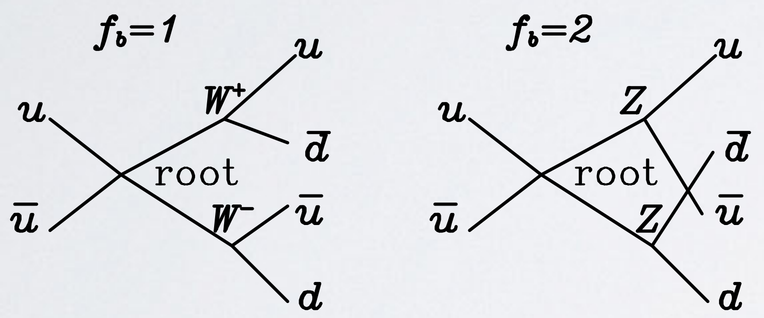

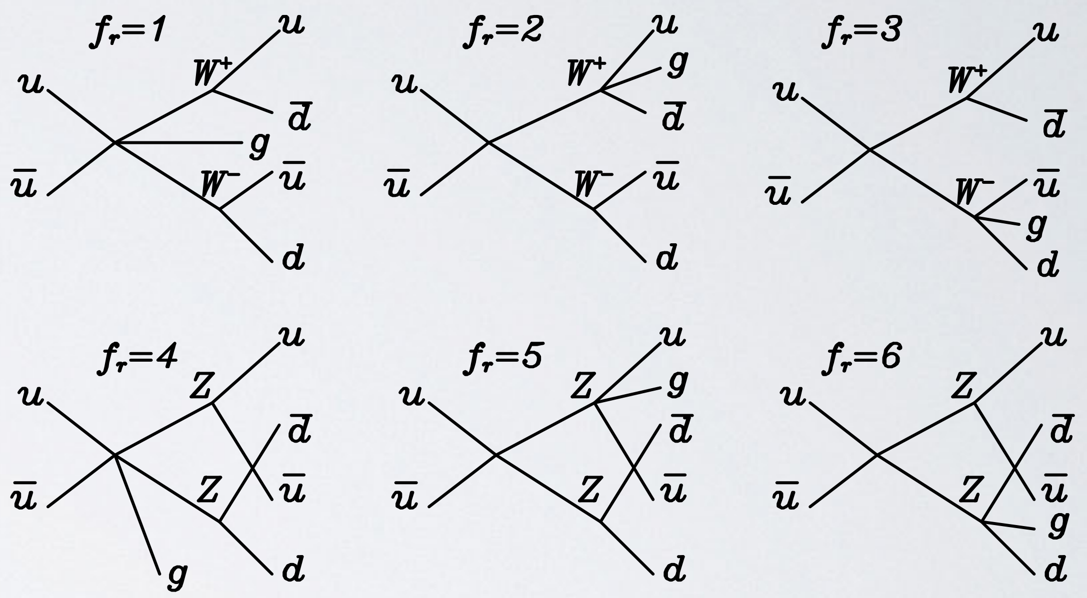

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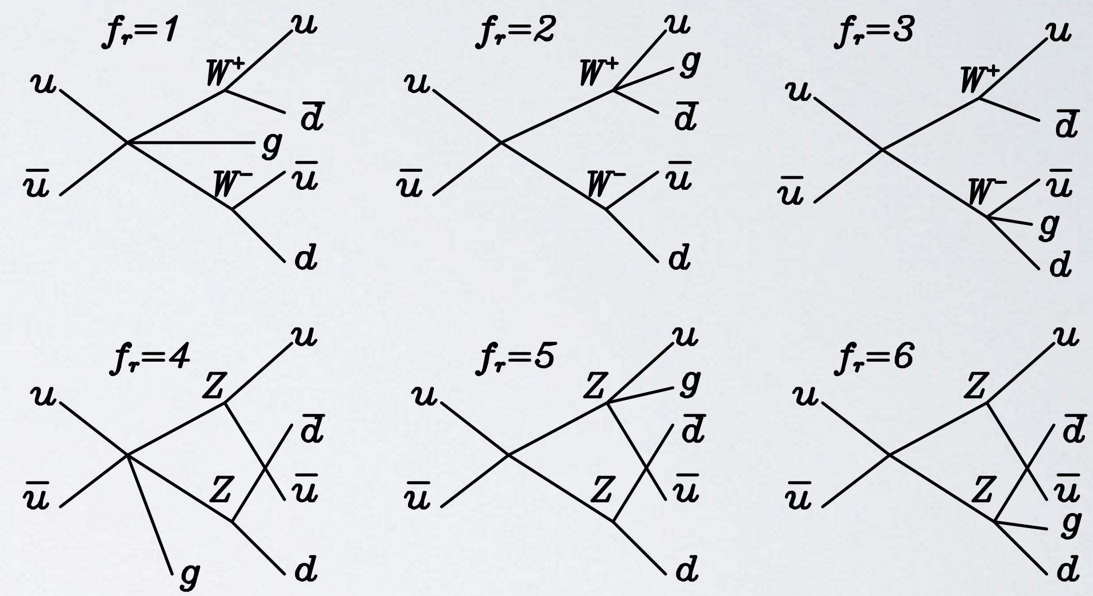

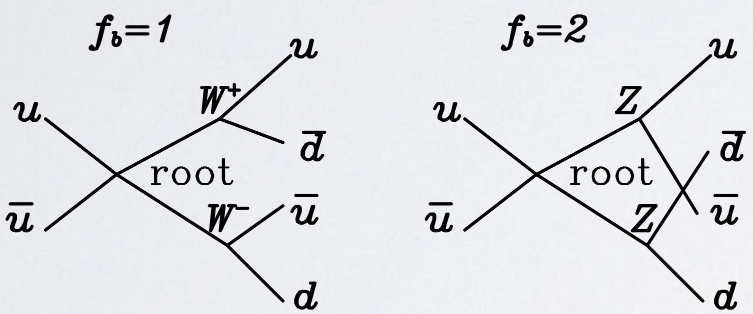

- WHIZARD complete automatic implementation: example $e^+ e^- \to \mu\mu bb$ (ZZ, ZH histories)

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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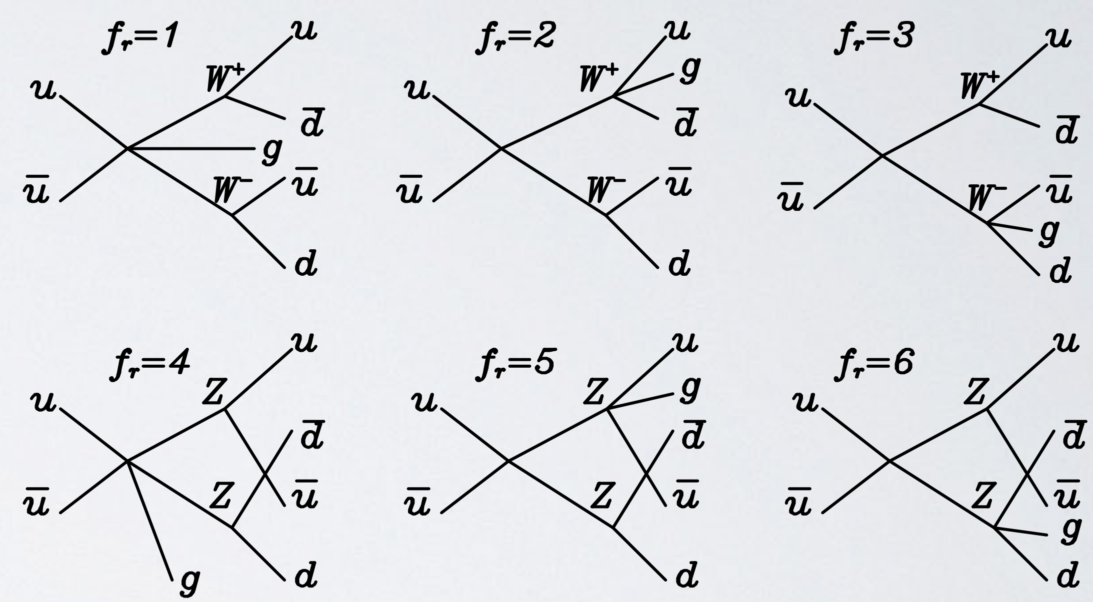

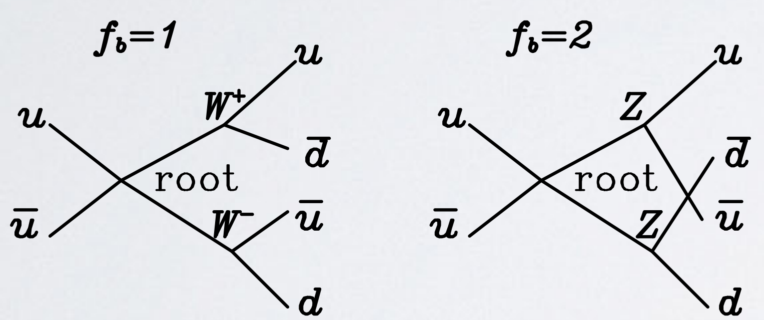

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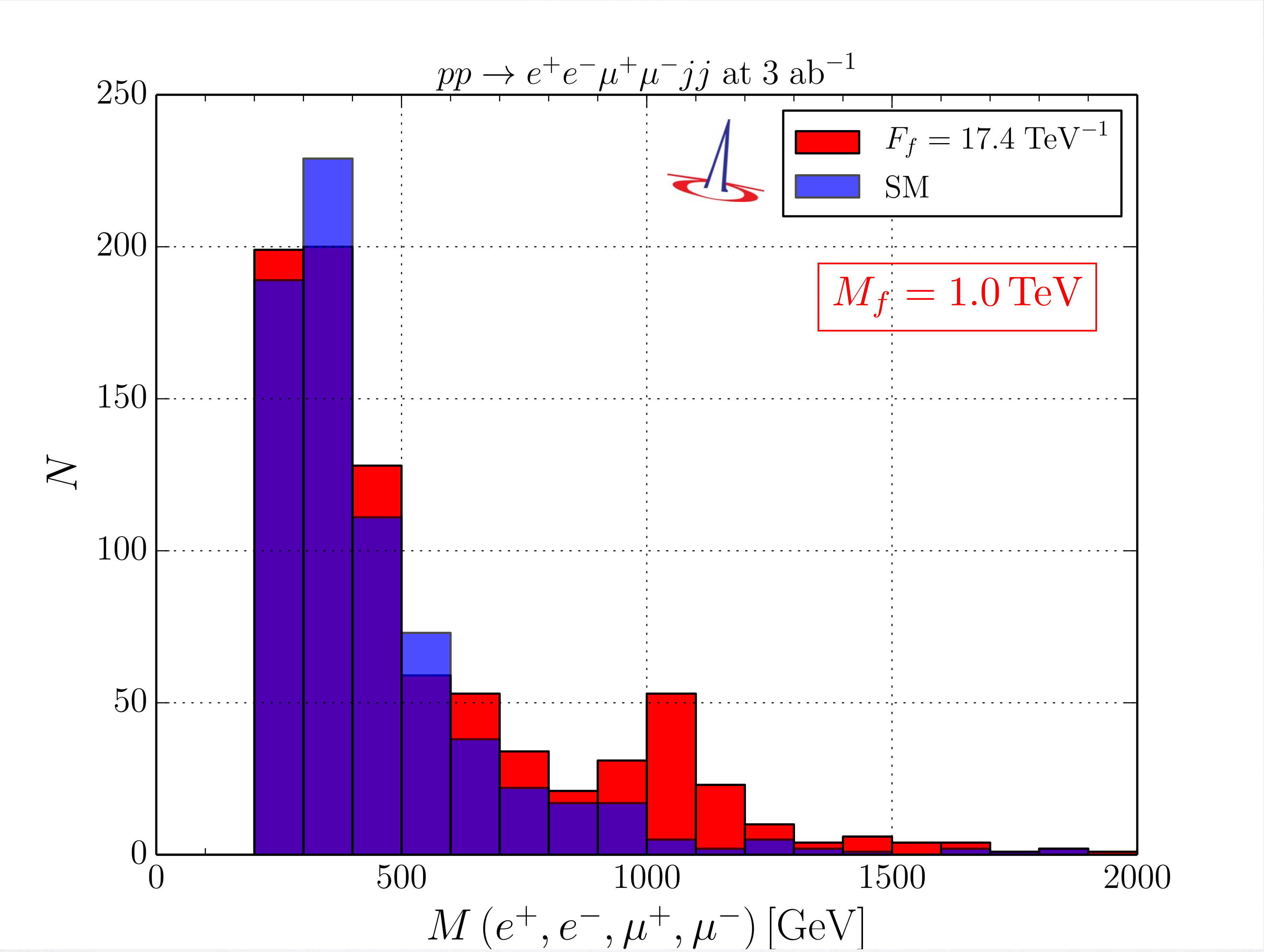
It	Calls	Integral[fb]	Error[fb]	Err[%]	Acc	Eff[%]	Chi2	N[It]
1	11988	9.6811847E+00	6.42E+00	66.30	72.60*	0.65		
2	11959	2.8539703E+00	2.35E-01	8.25	9.02*	0.69		
3	11936	2.4907574E+00	6.54E-01	26.25	28.68	0.35		
4	11908	2.7695559E+00	9.67E-01	34.91	38.09	0.30		
5	11874	2.4346151E+00	4.82E-01	19.80	21.57*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

standard FKS

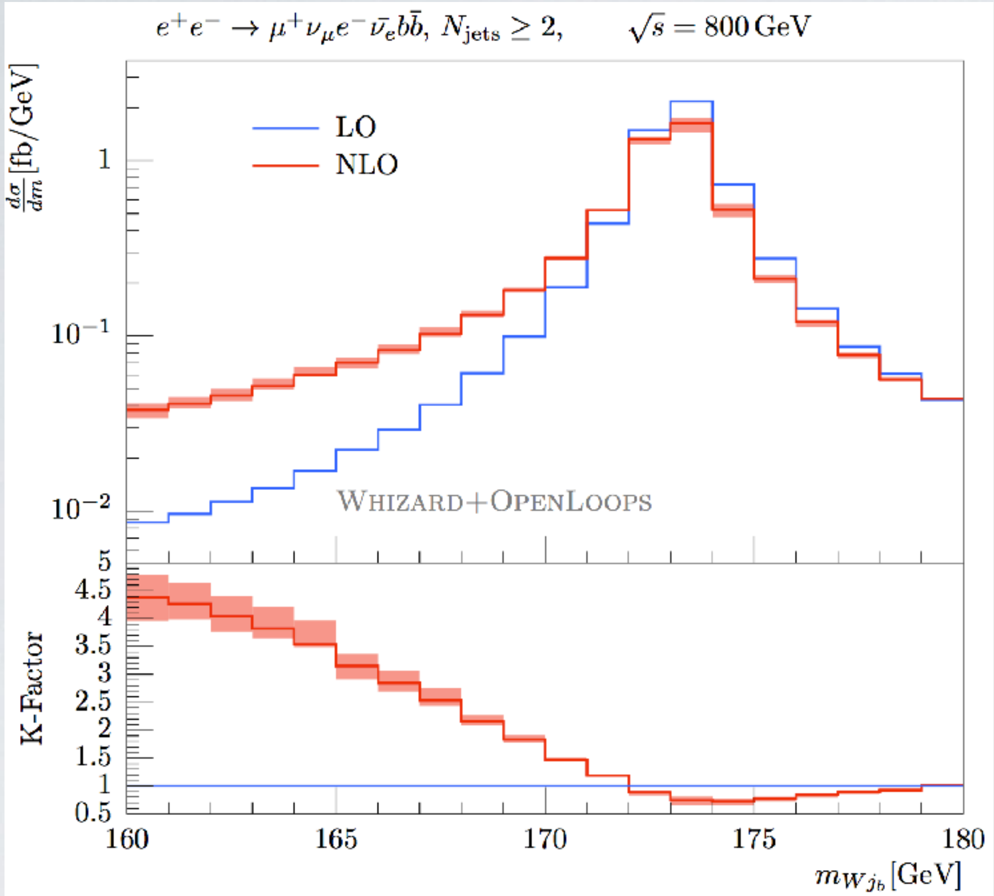
It	Calls	Integral[fb]	Error[fb]	Err[%]	Acc	Eff[%]	Chi2	N[It]
1	11988	2.9057032E+00	8.35E-02	2.87	3.15*	7.90		
2	11962	2.8591952E+00	5.20E-02	1.82	1.99*	10.91		
3	11936	2.9277880E+00	4.09E-02	1.40	1.52*	14.48		
4	11902	2.8512337E+00	3.98E-02	1.40	1.52*	13.70		
5	11874	2.8855399E+00	3.87E-02	1.34	1.46*	17.15		
5	59662	2.8842006E+00	2.04E-02	0.71	1.72	17.15	0.53	5

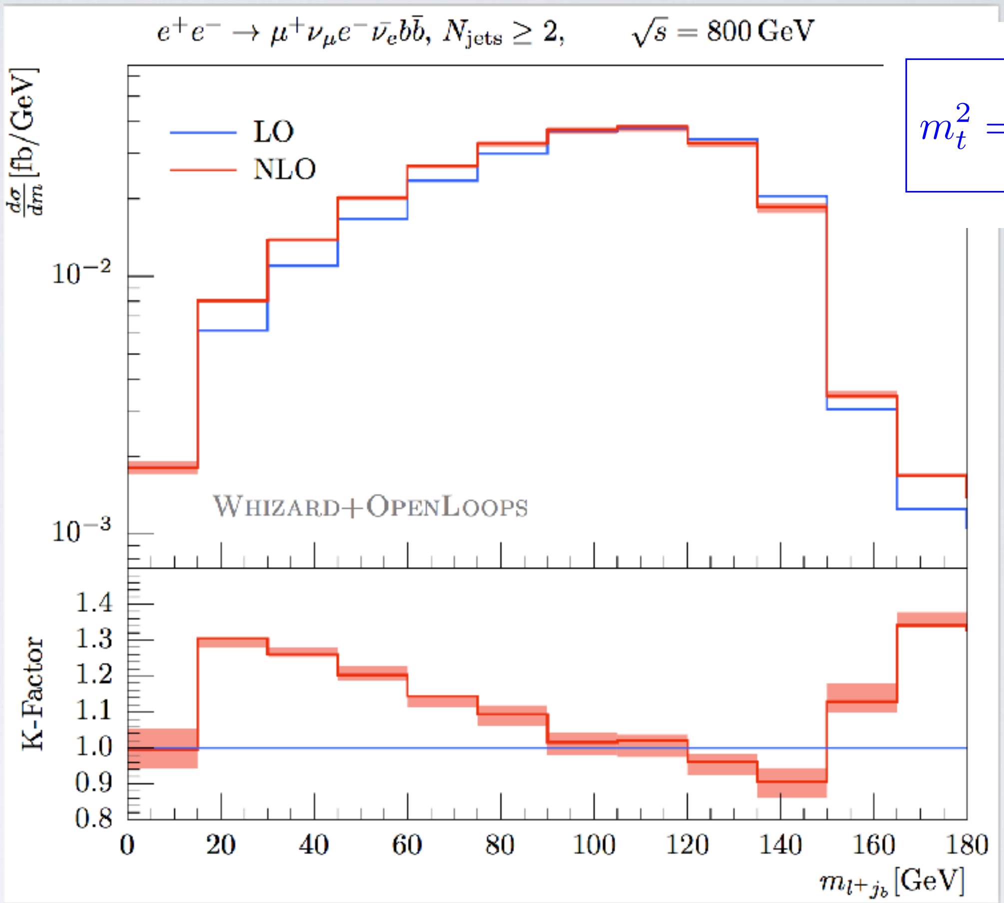
FKS with resonance mappings

Complete LHC process at 14 TeV



Differential Results for off-shell $e^+e^- \to tt$





$$m_t^2 = m_W^2 + \frac{2\langle m^2_{\ell j_b}\rangle}{1 - \langle \cos\theta_{\ell j_b}\rangle}$$