Matching Threshold & Continuum for exclusive top pairs

Jürgen R. Reuter, DESY

in collaboration with: Fabian Bach, Bijan Chokoufé Nejad, Andre H. Hoang, Wolfgang Kilian, Thomas Teubner, Maximilian Stahlhofen, Christian Weiss

arXiv:1712.02220 [sent to JHEP]

Top Threshold/Continuum at lepton colliders

- LC top threshold scan best-known method to measure top quark mass, ΔM ~ 30-70 MeV
- LC continuum top production best-known method to measure top couplings

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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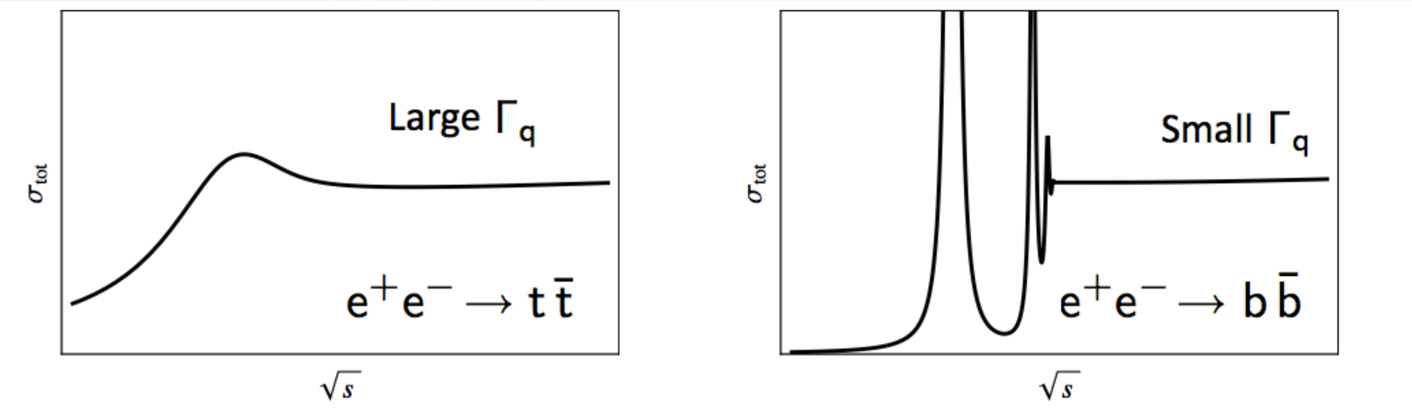
Heavy quark production at lepton colliders, qualitatively:



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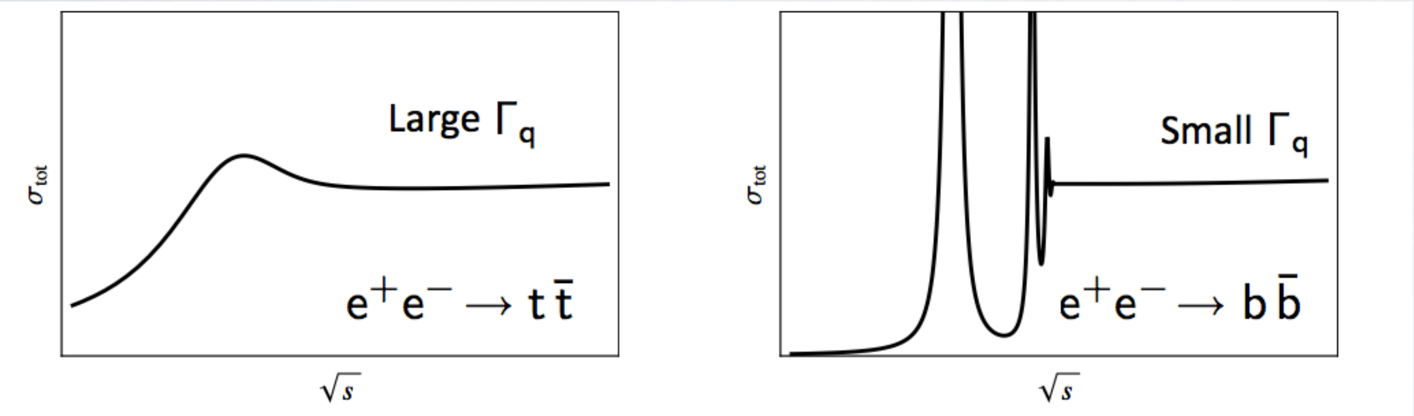

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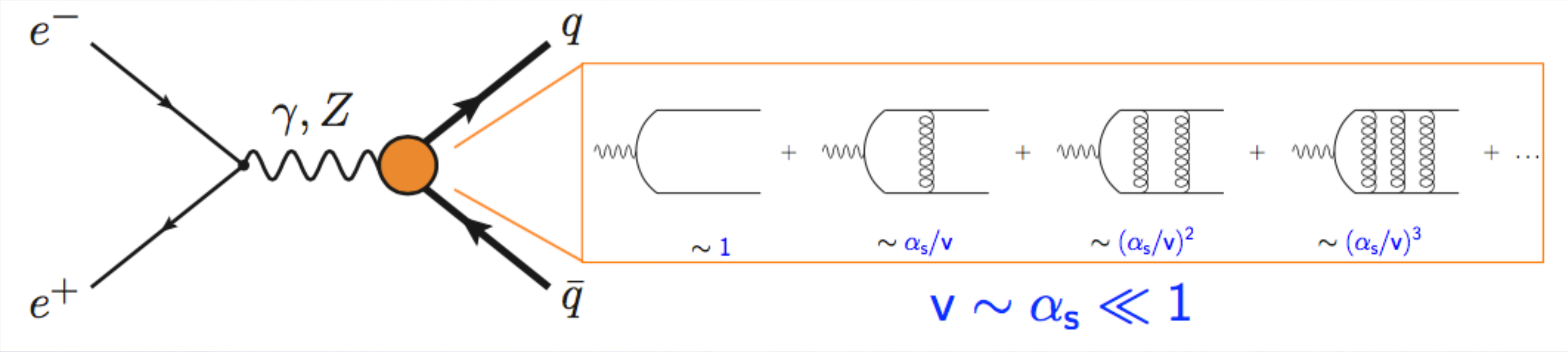
Threshold region: top velocity $v \sim \alpha_s \ll 1$ non-relativistic EFT: (v)NRQCD



Continuum region: "standard" fixed-order QCD

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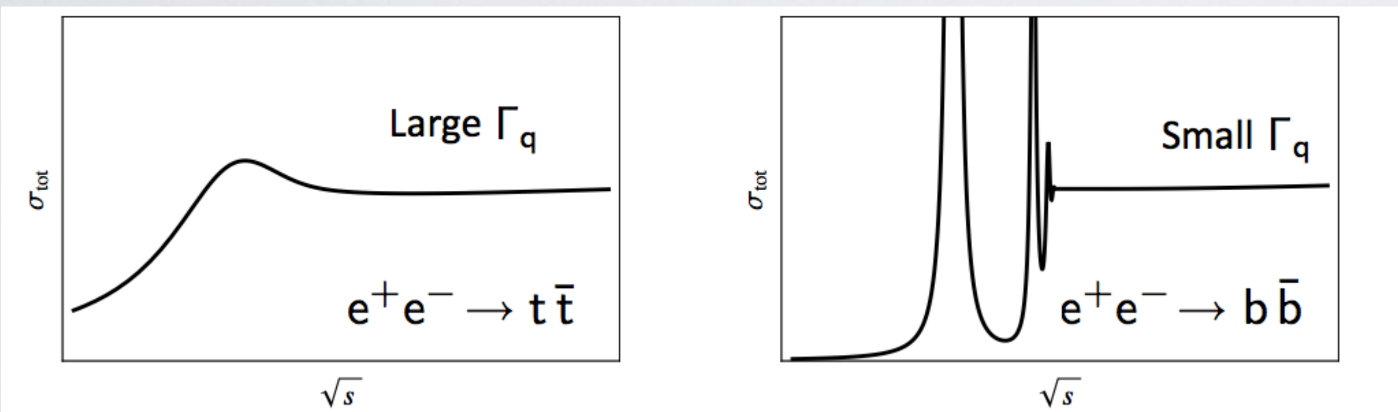

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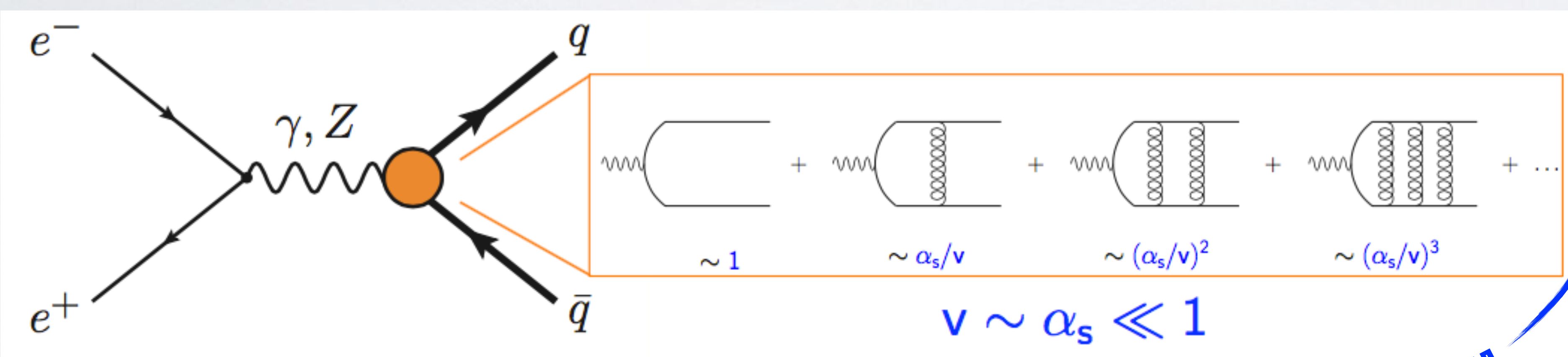


MATCH

Continuum region: "standard" fixed-order QCD

WHIZARD: our NLO MC framework

WHIZARD v2.6.2 (13.12.2017) 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/Florian Staub/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

```
alpha_power = 2
alphas_power = 0

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

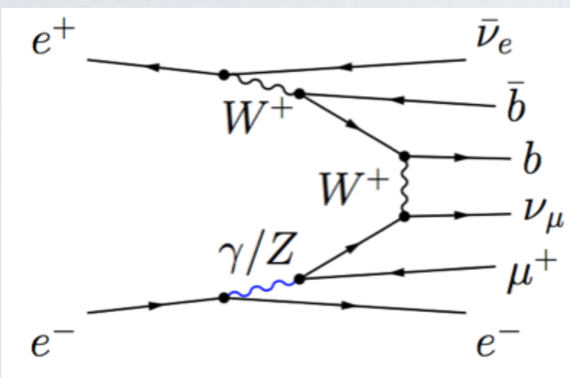
- FKS subtraction [Frixione/Kunszt/Signer, '95]
- Resonance-aware treatment [Ježo/Nason, 1509.09071]
- NLO QCD final validation phase
- NLO EW work in progress

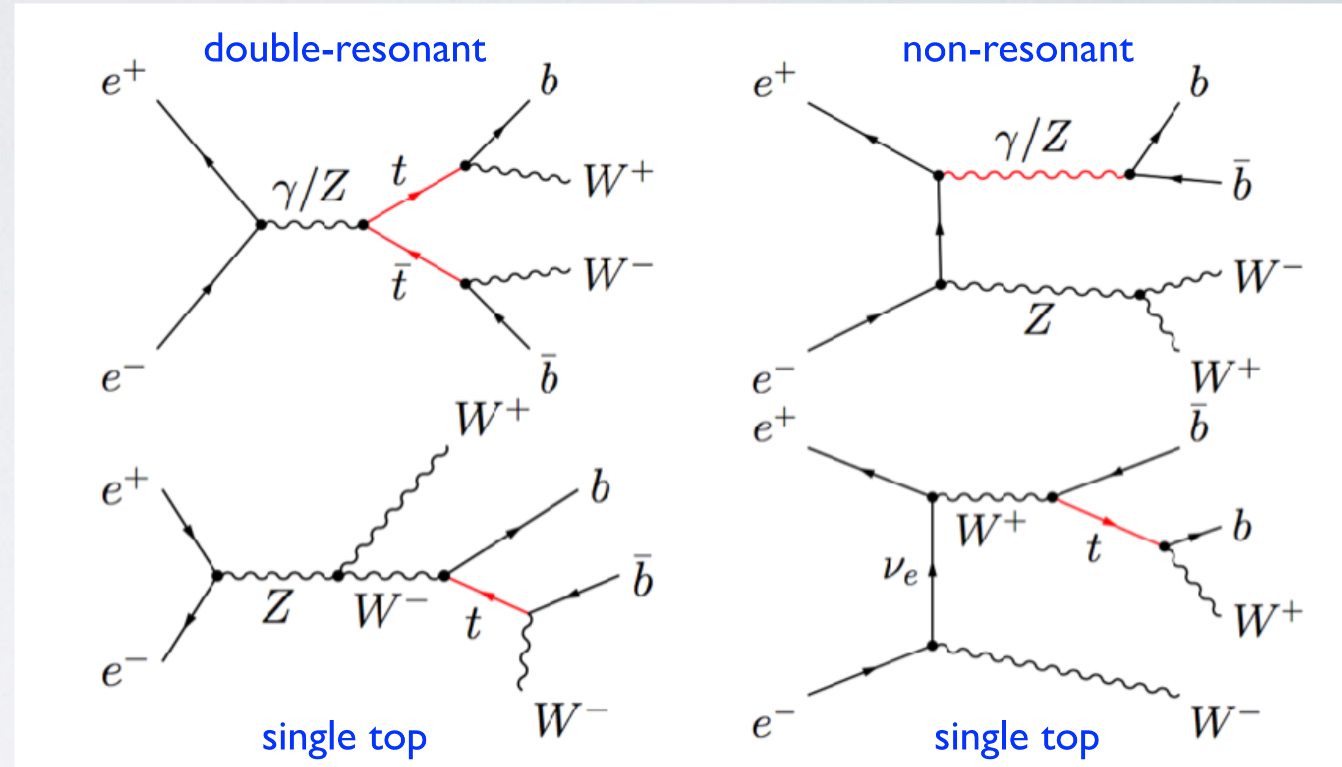
Working NLO interfaces to:

- ★ GoSam [N. Greiner, G. Heinrich… et al.]
- ★ **OpenLoops** [J. Lindert, P. Maierhöfer, S. Pozzorini et al.]
- ★ Recola [A. Denner, L. Hofer, J.-N. Lang, S. Uccirati]

$e^+e^- \to tt$ off-shell in the continuum

- Cross checks for $2 \to 2$ and $2 \to 4$ with `Sherpa` & `Munich`
- 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
  Coulomb singularity:





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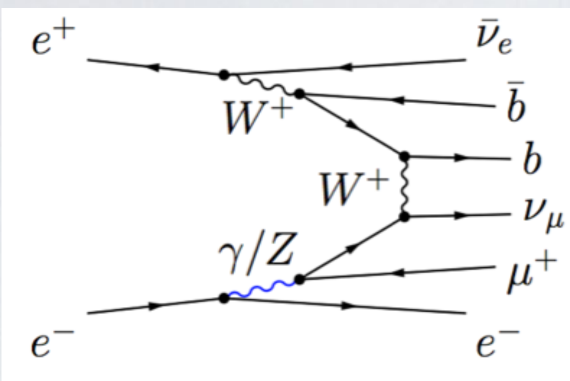

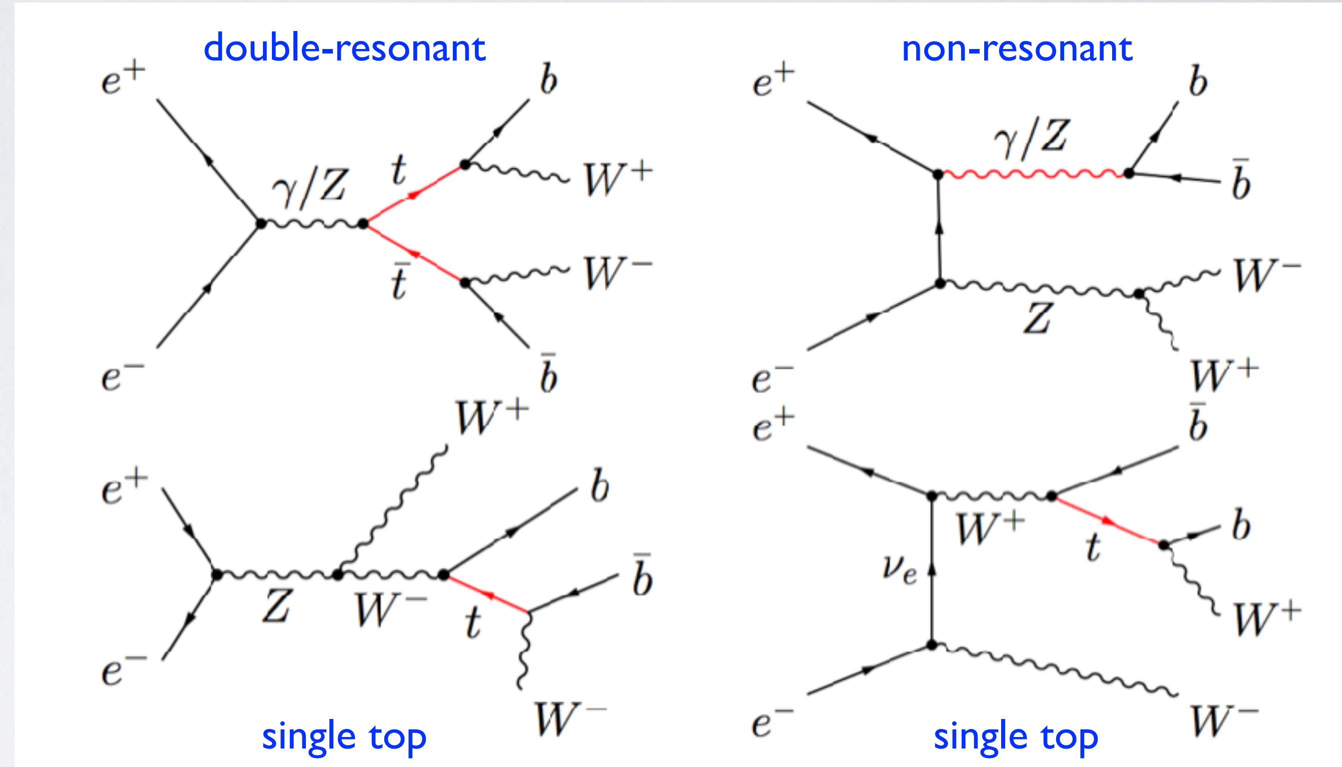

INPUT PARAMETERS:

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

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

$$m_H = 125\ \text{GeV} \quad \Gamma_H = 0.00431\ \text{GeV}$$

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

Complex Mass Scheme (CMS):

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

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

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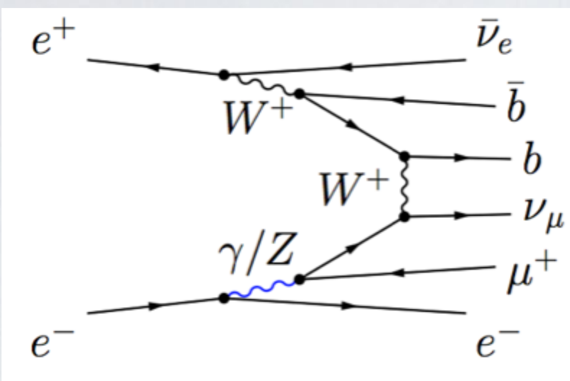

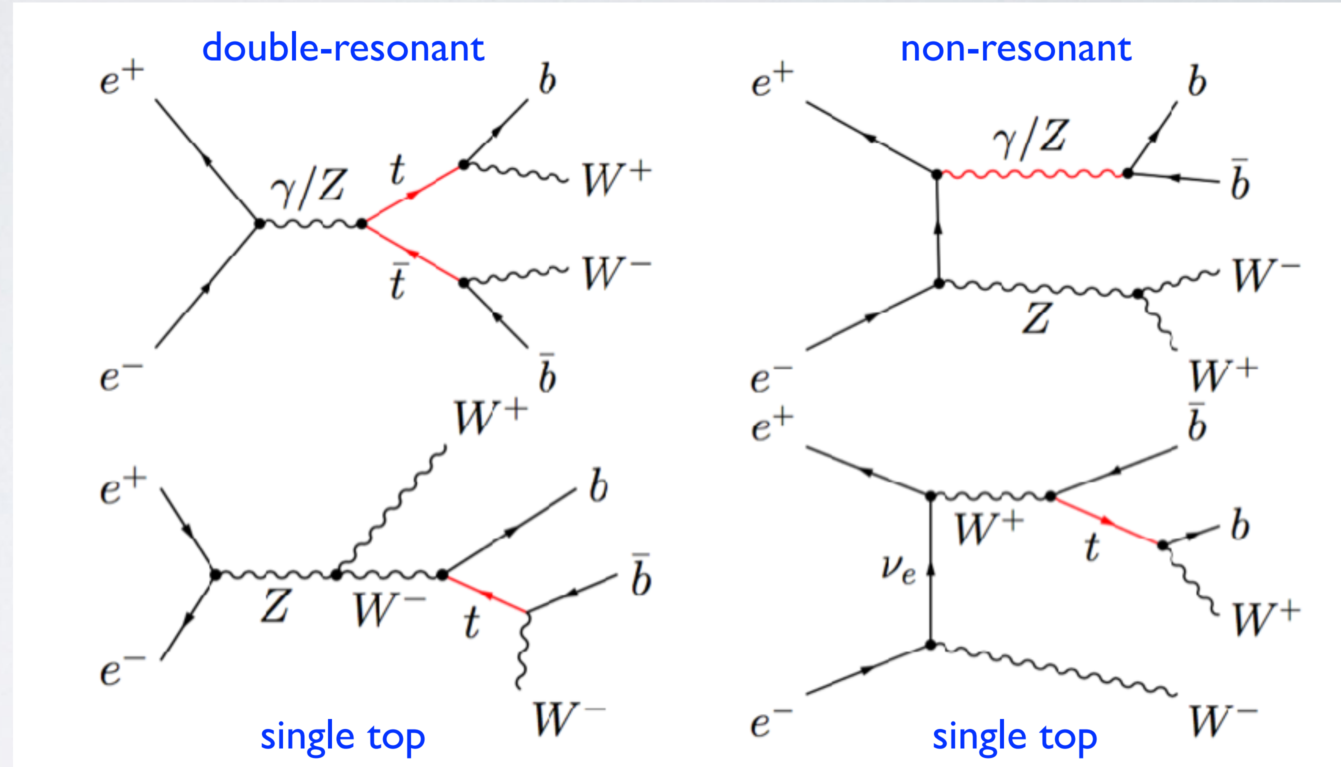

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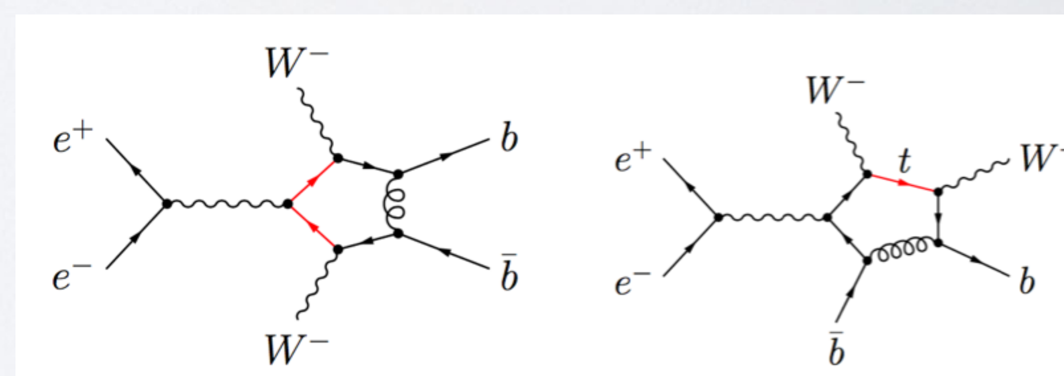
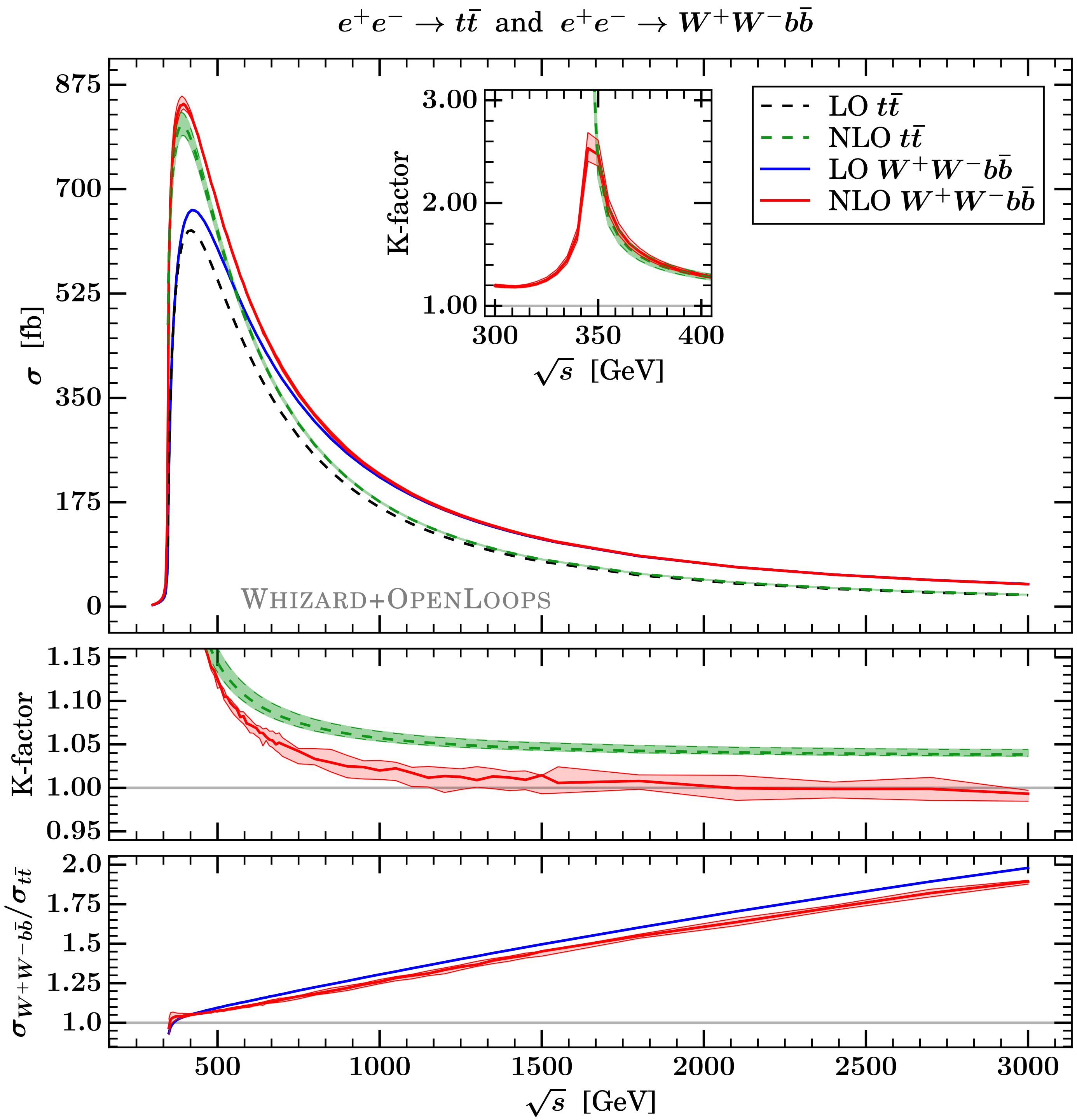
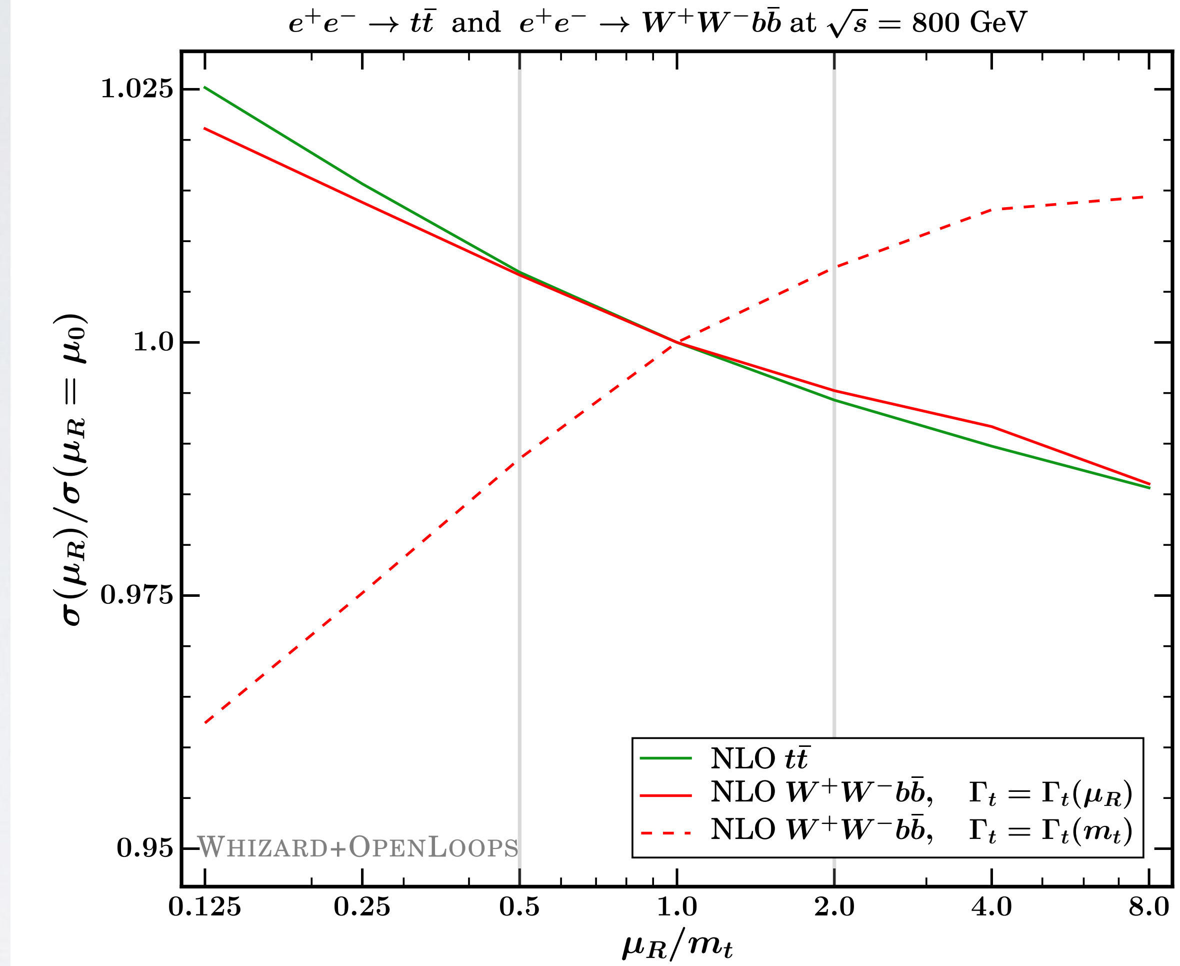
- Typical pentagons:



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

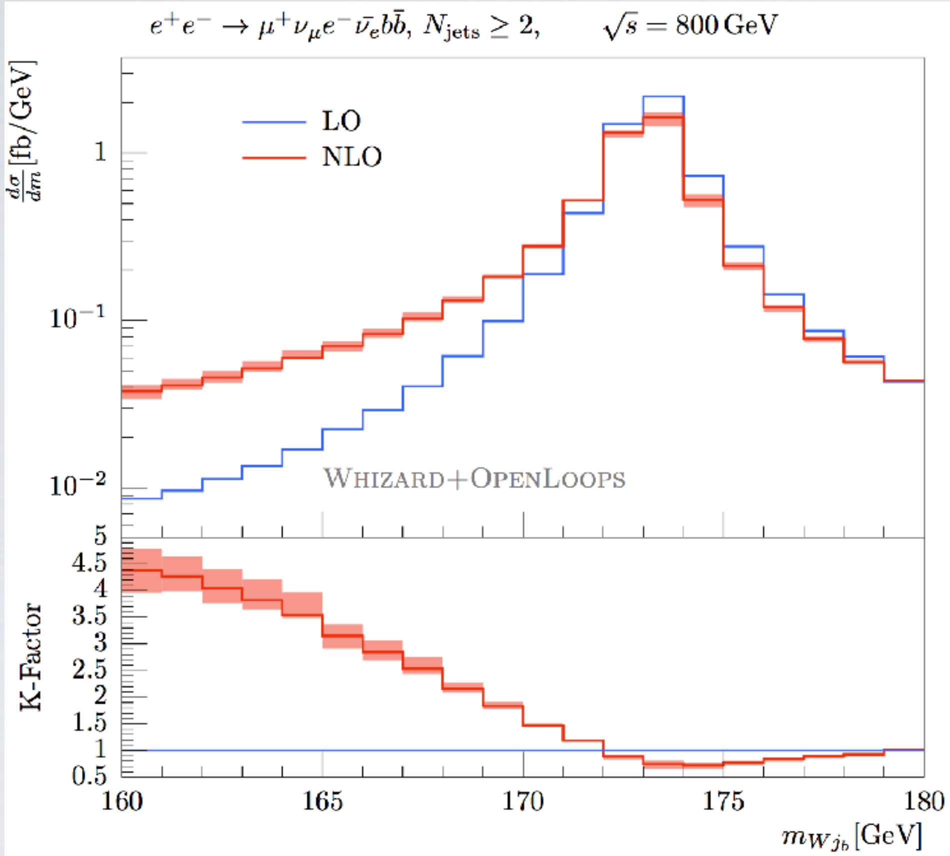


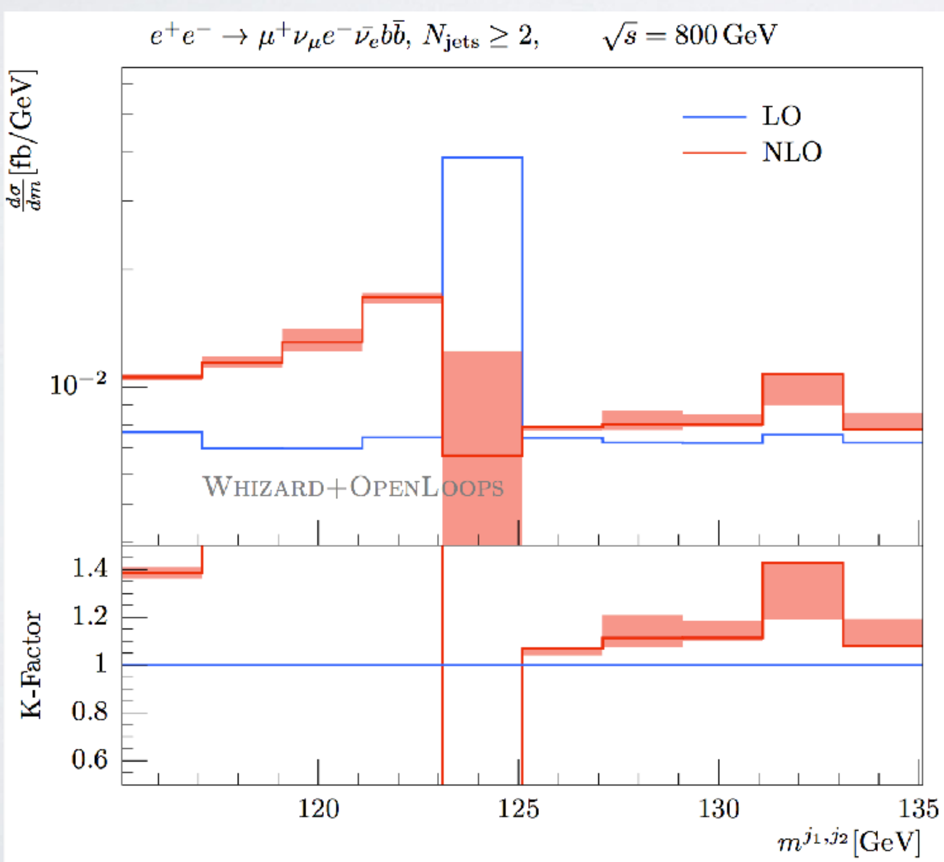


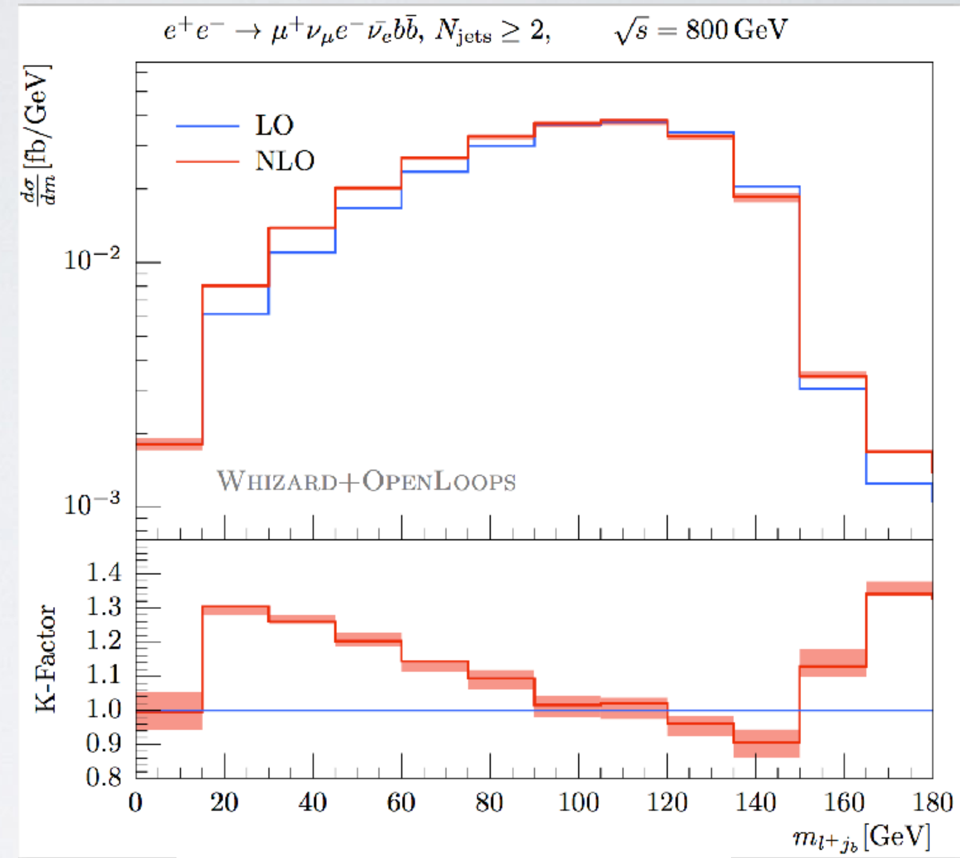
	$e^+e^- \to t\bar{t}$			$e^+e^- \to W^+W^-b\bar{b}$		
$\sqrt{s}$ [GeV]	$\sigma^{\rm LO}$[fb]	$\sigma^{\rm NLO}$[fb]	K-factor	$\sigma^{\rm LO}$[fb]	$\sigma^{\rm NLO}$[fb]	K-factor
500	548.4	$627.4^{+1.4\%}_{-0.9\%}$	1.14	600.7	$675.1^{+0.4\%}_{-0.8\%}$	1.12
800	253.1	$270.9^{+0.8\%}_{-0.4\%}$	1.07	310.2	$320.7^{+1.1\%}_{-0.7\%}$	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

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







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

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

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 et al. '99-'01; Beneke et al., '13-'14

Phase space of two massive particles

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

(p/v)NRQCD EFT w/ RG improvement

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

but contributes
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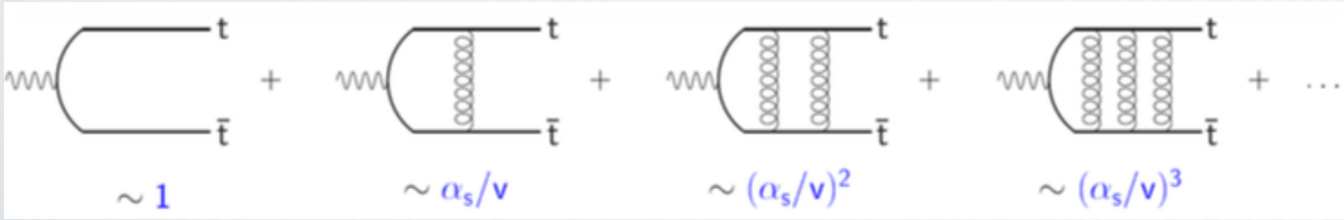
Coulomb potential gluon ladder resummation



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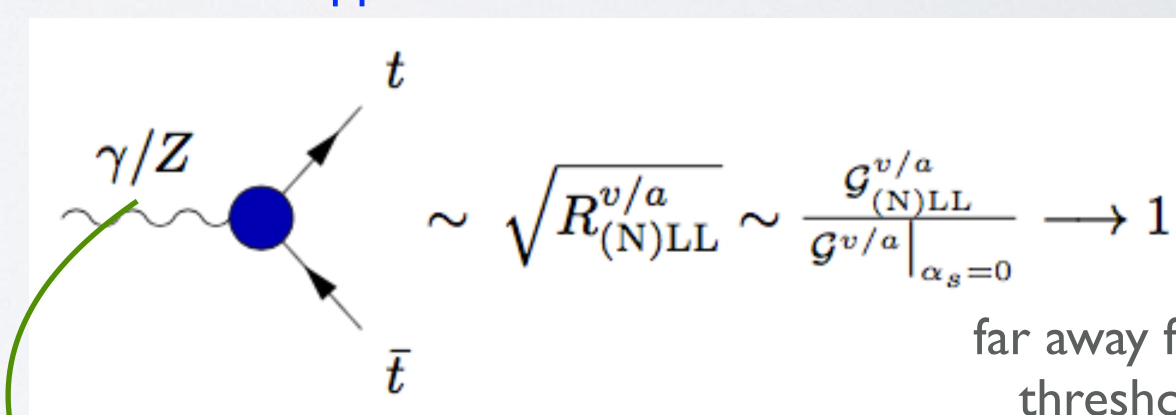
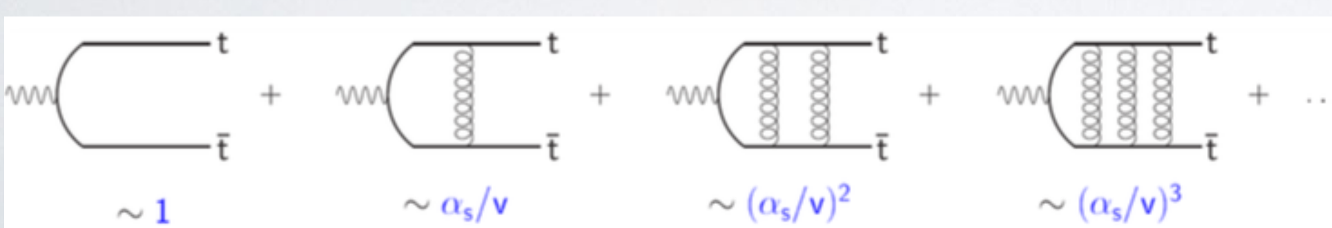
can be mapped onto effective *ttV* vertex



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

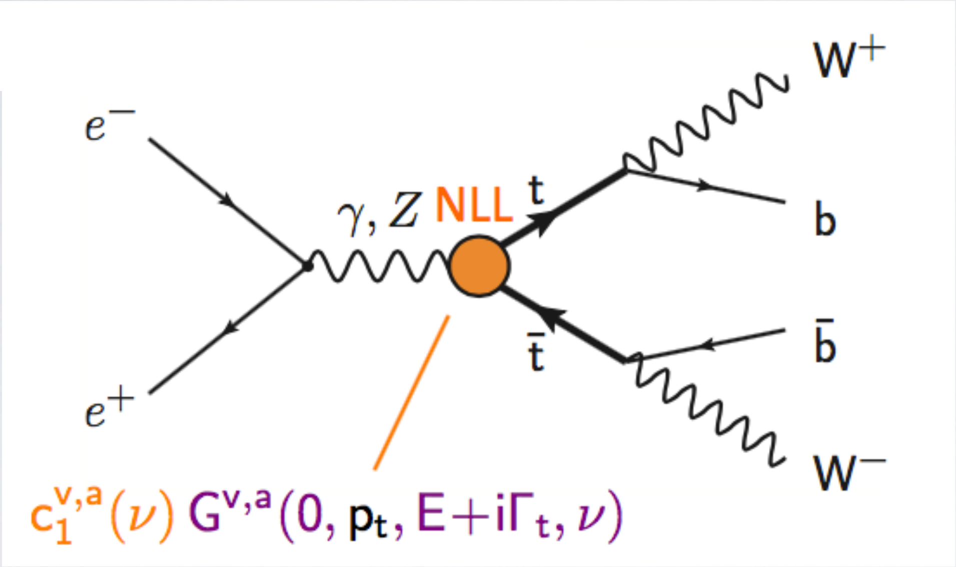
differential in off-shell *tt* phase space

Coulomb potential gluon ladder resummation



Top Threshold in WHIZARD

- 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

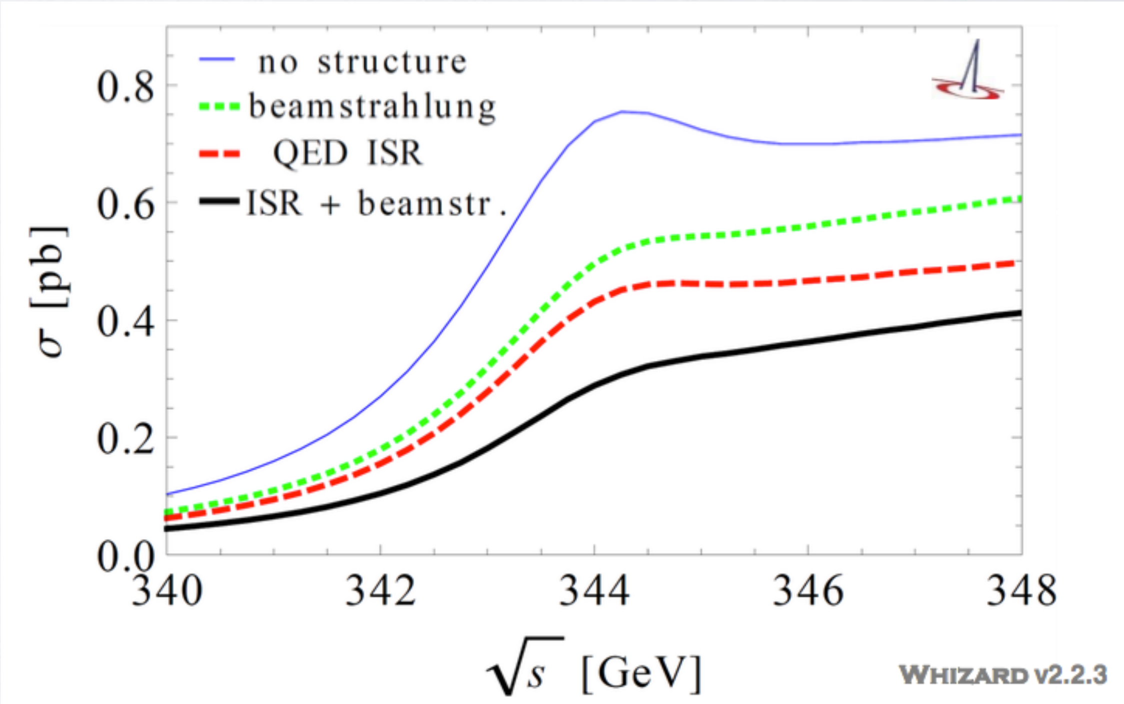


- Default parameters:

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

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

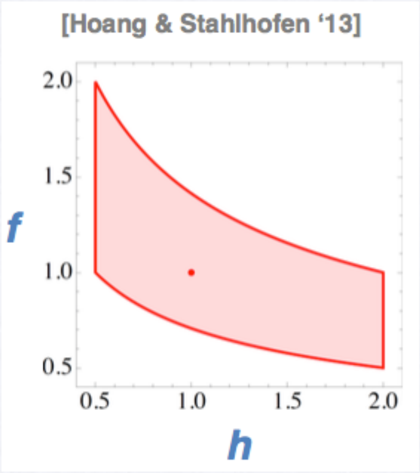
- Important effects: beamstrahlung; ISR; LO EW terms
- Exclusive observables accessible



cf. Frank Simon's talk

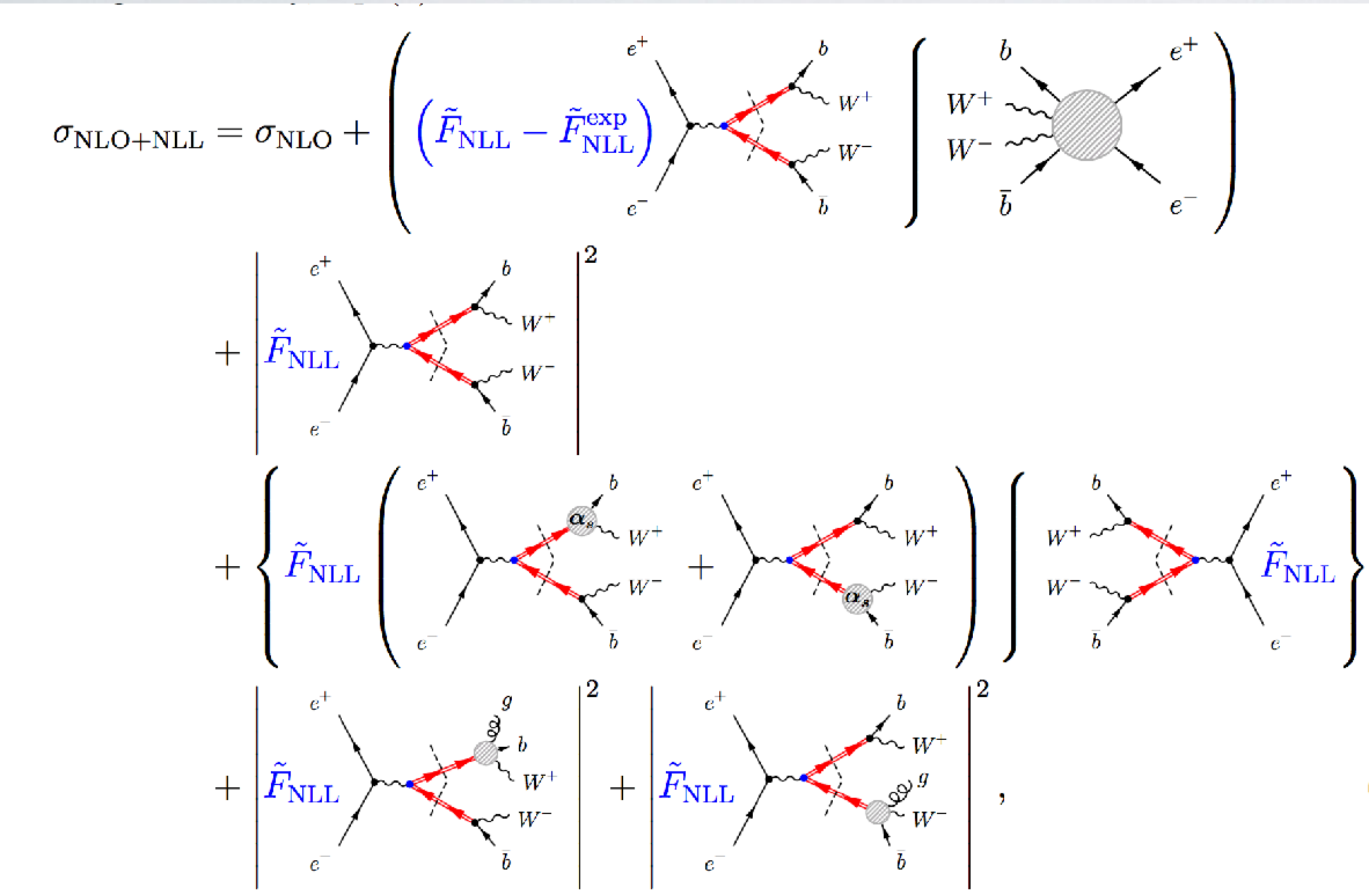
Theory uncertainties from scale variations: hard and soft scale

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



Top threshold: validation and matching

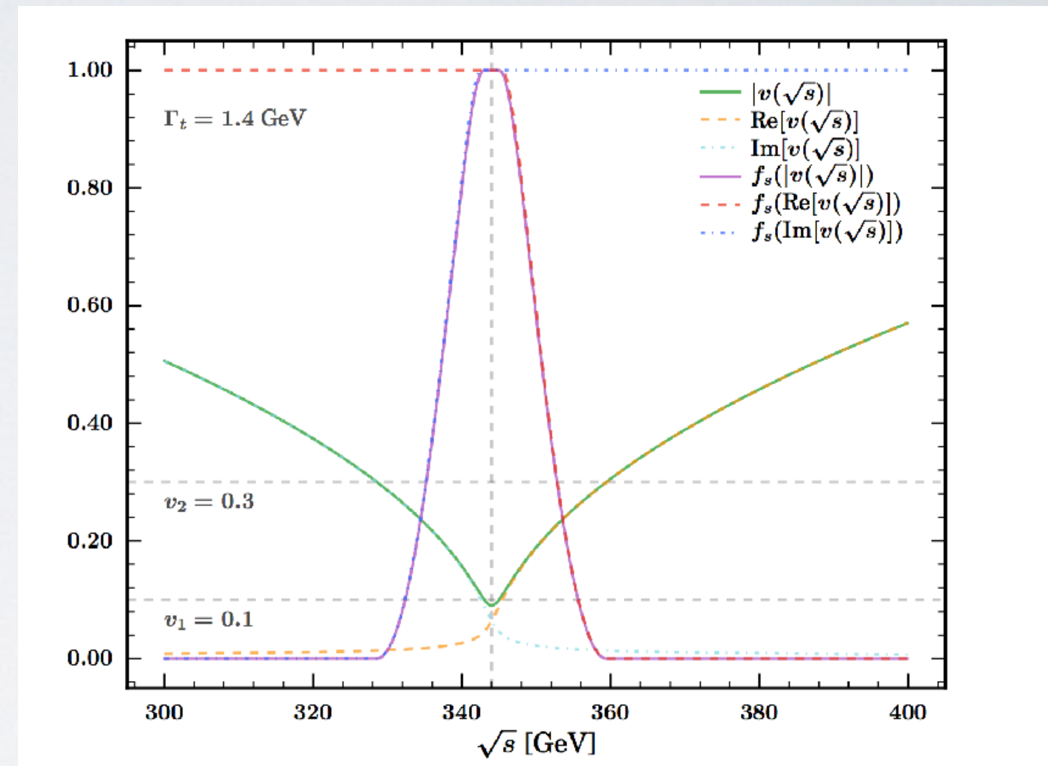
- Transition region between relativistic and resummation effects



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

$$\alpha_{\text{H}} = \alpha_s\left[\mu_{\text{H}} = hM_t^{1\text{S}}\right]\ , \qquad \alpha_{\text{F}} = \alpha_s\left[\mu_{\text{F}} = hM_t^{1\text{S}}\sqrt{\nu_*}\right]\ ,$$

$$\alpha_{\text{S}} = \alpha_s\left[\mu_{\text{S}} = hM_t^{1\text{S}} f\nu_*\right]\ , \qquad \alpha_{\text{U}} = \alpha_s\left[\mu_{\text{US}} = hM_t^{1\text{S}}(f\nu_*)^2\right]$$



Smoothstep matching function:

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

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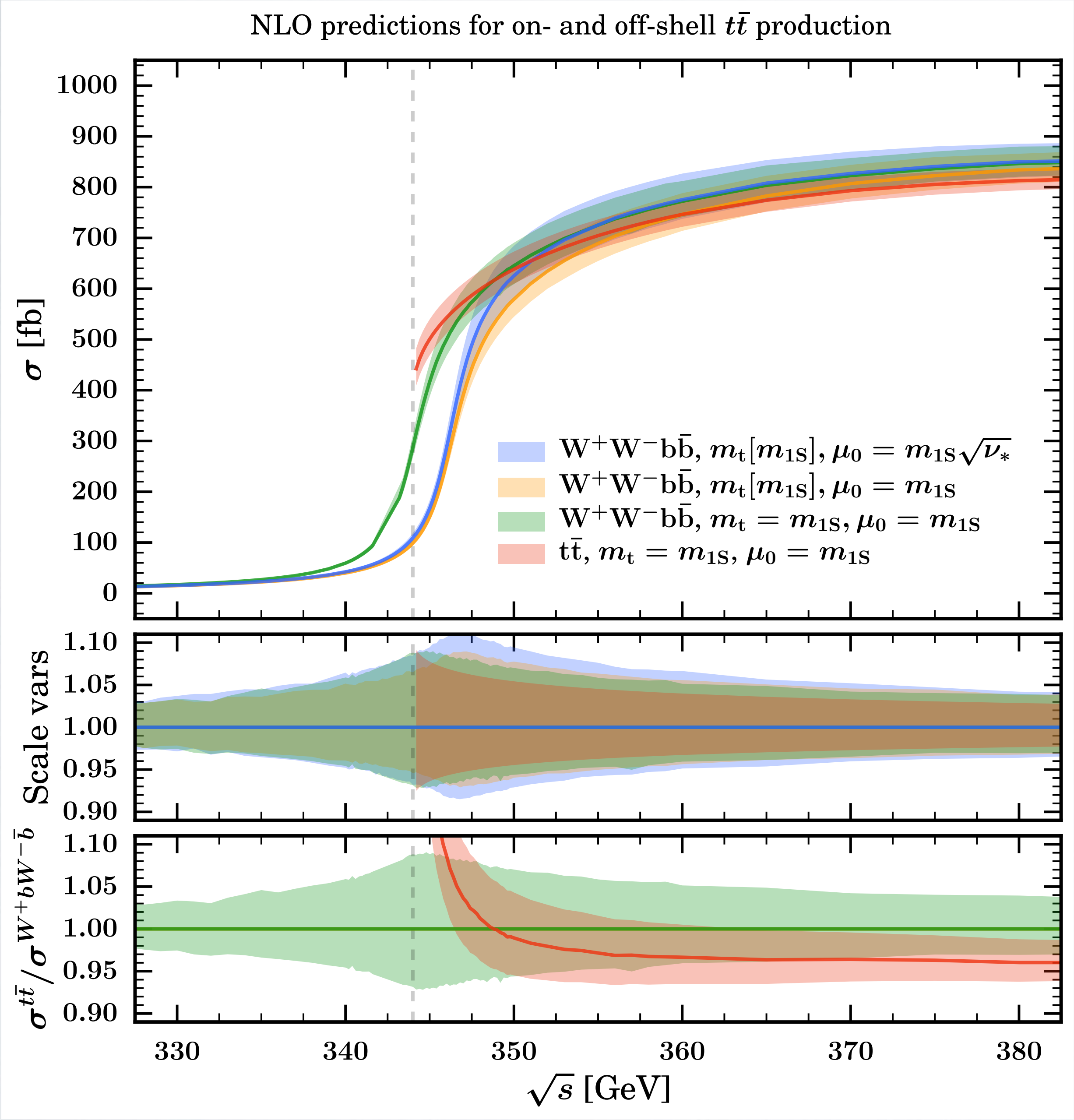

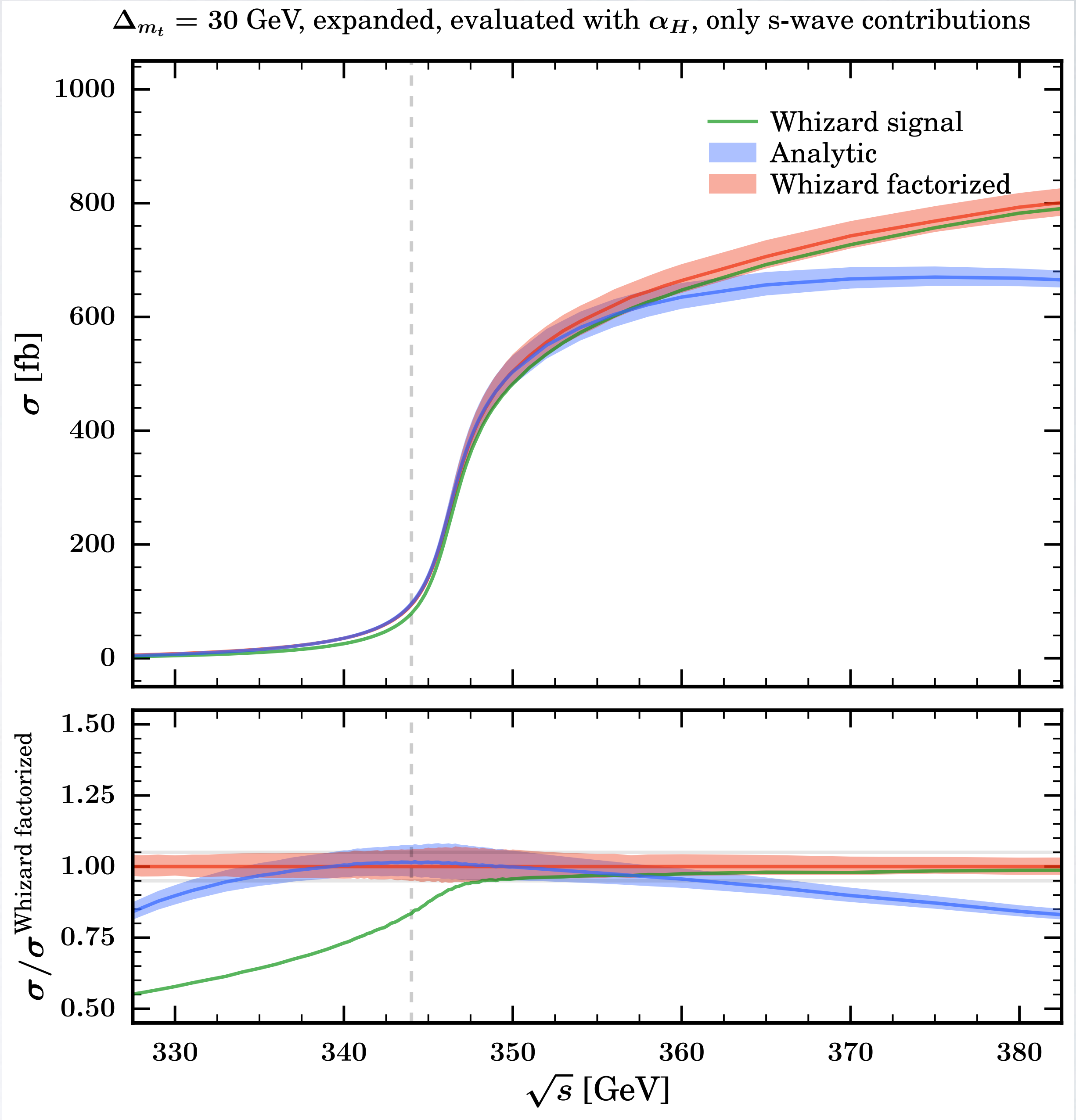

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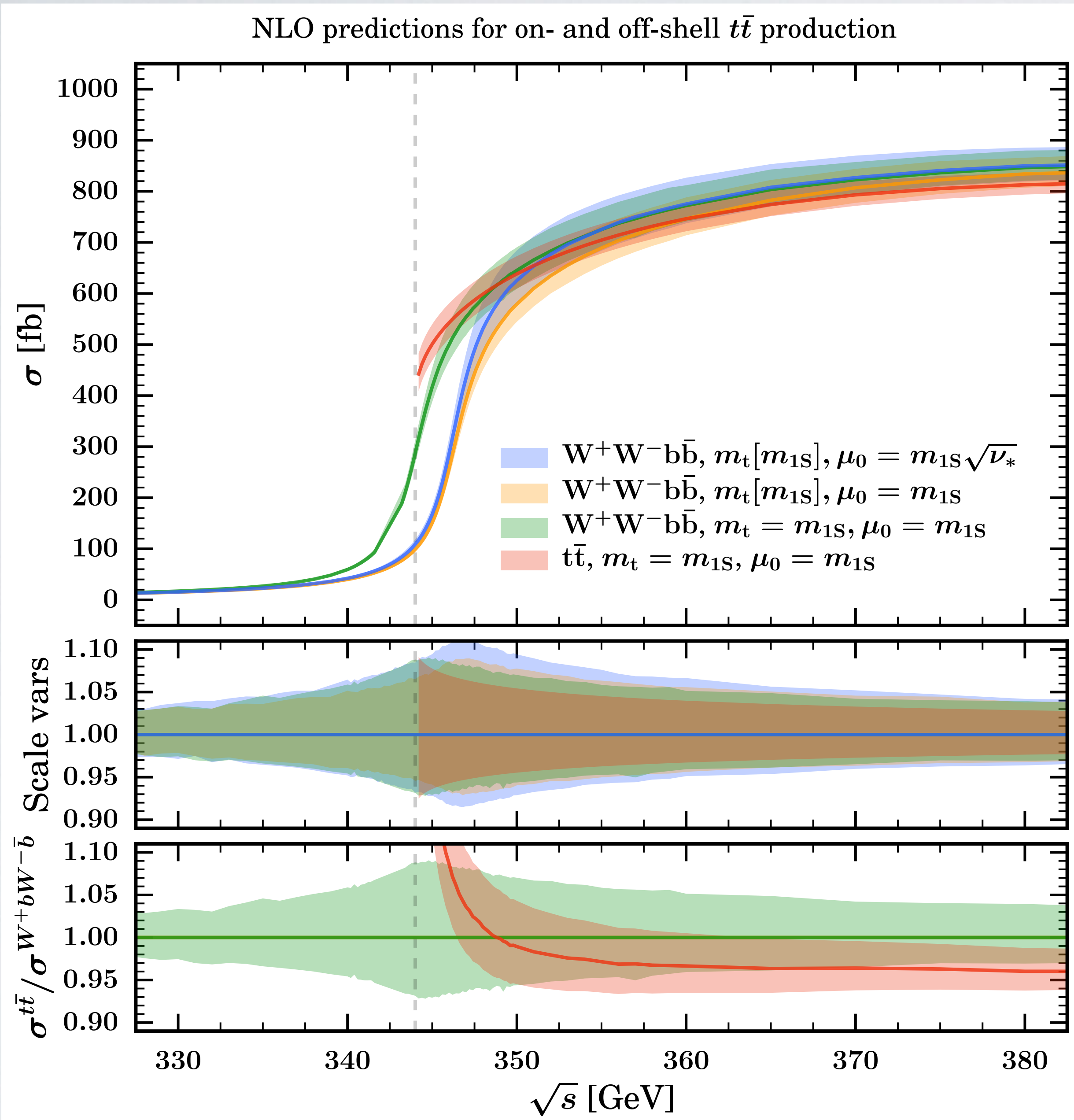
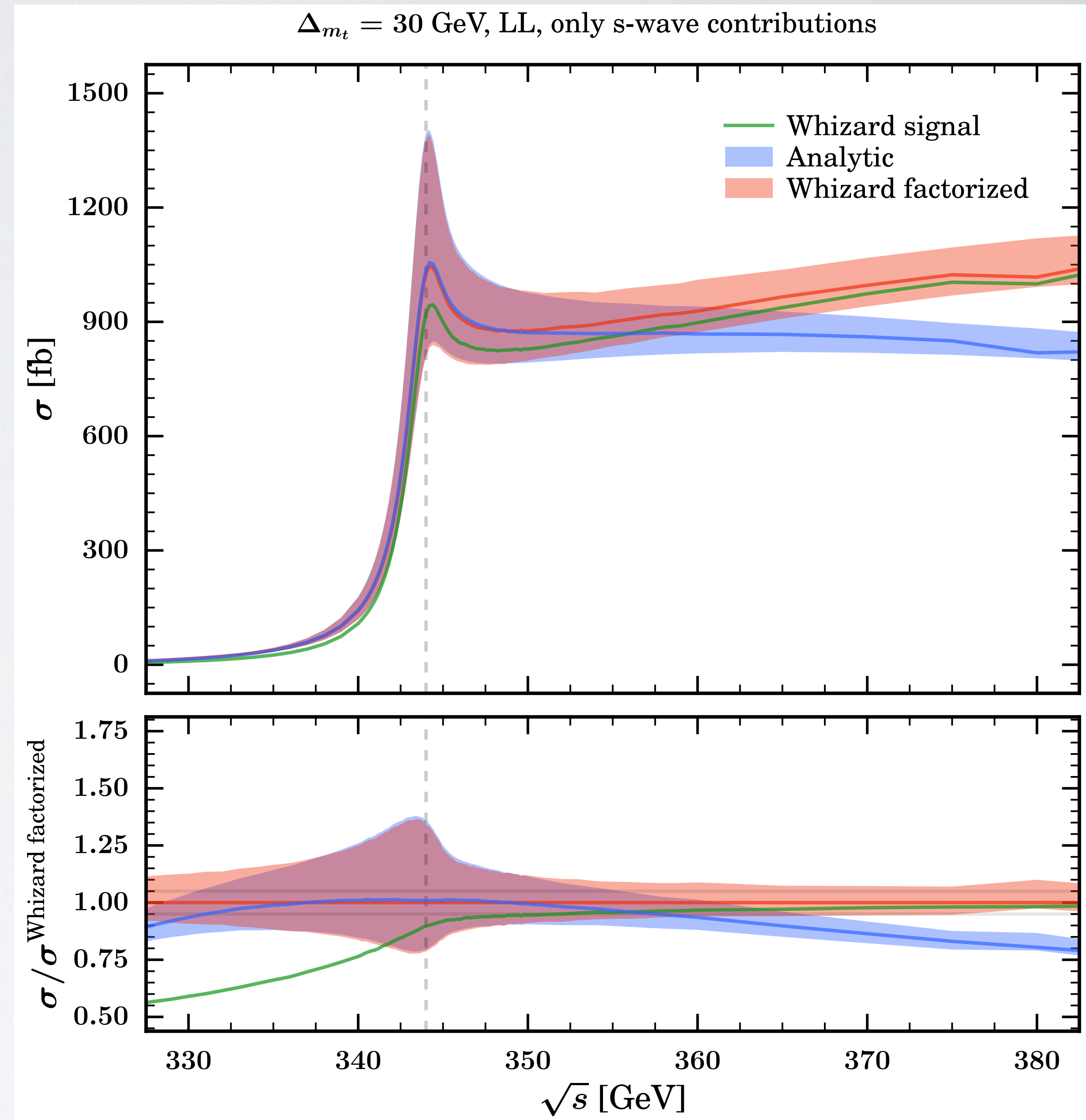
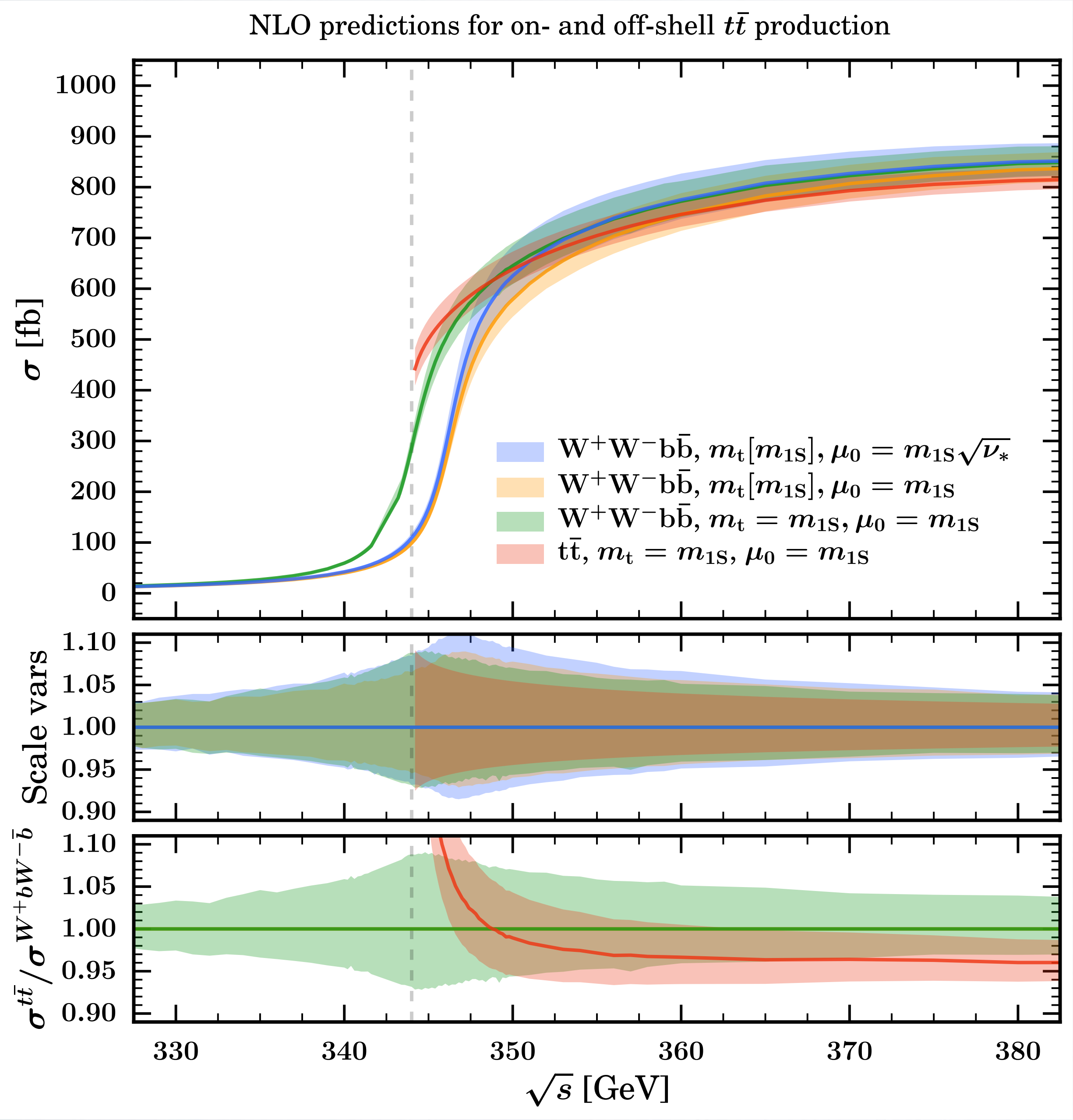
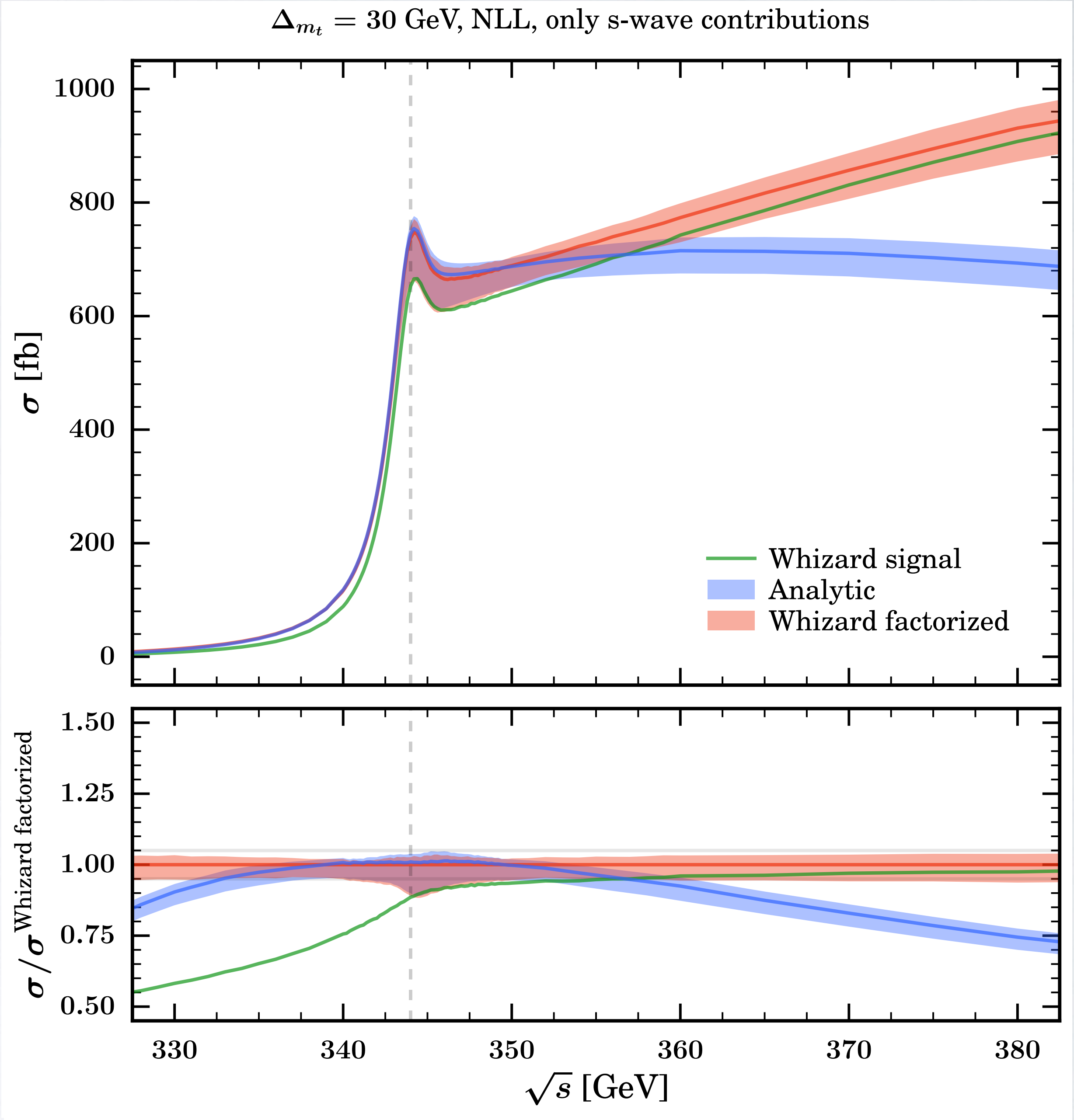


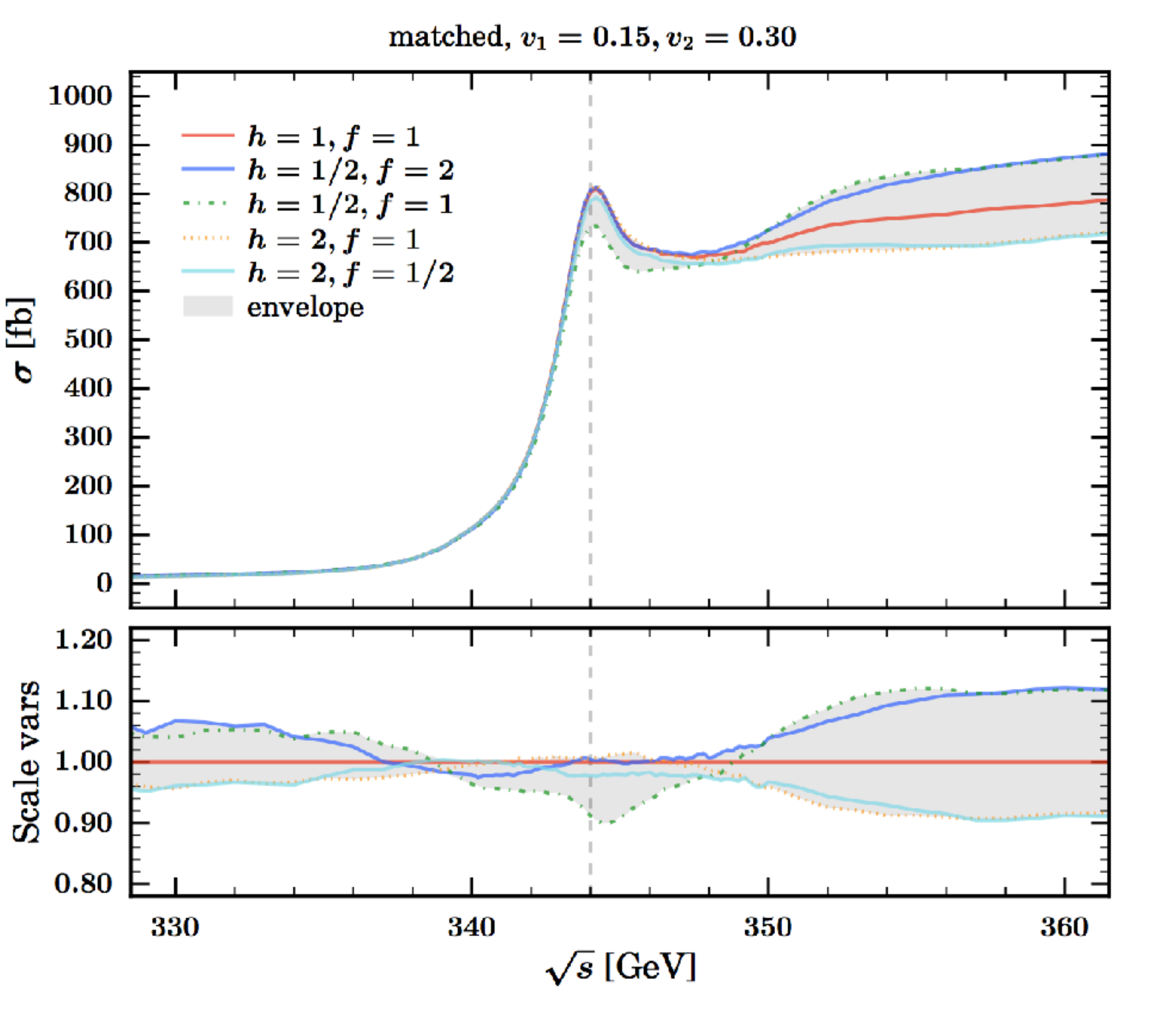


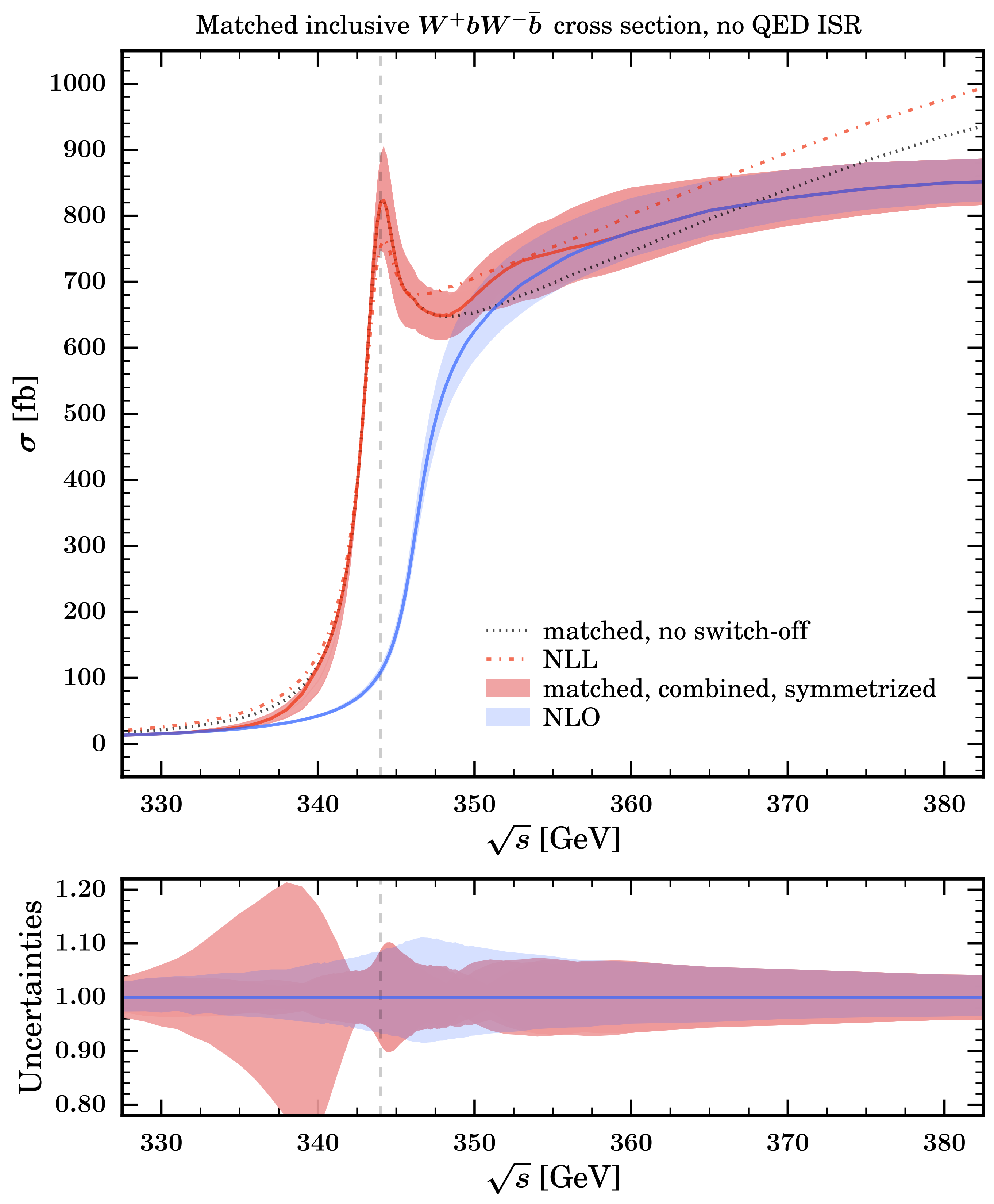
Top threshold: validation and matching





Matching threshold NLL to continuum NLO





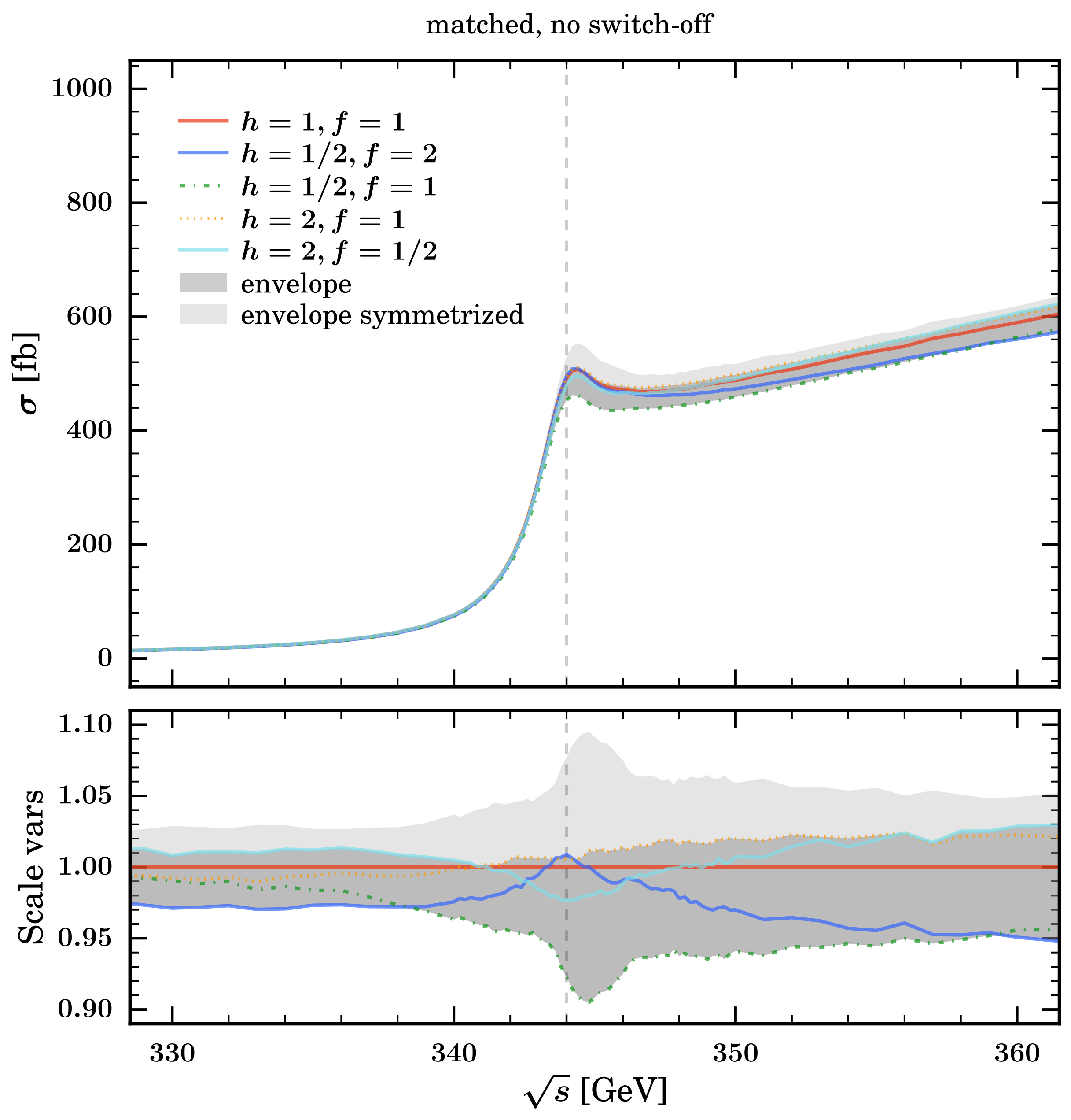
Total uncertainty: *h-f* variation band and matching [switch-off function]

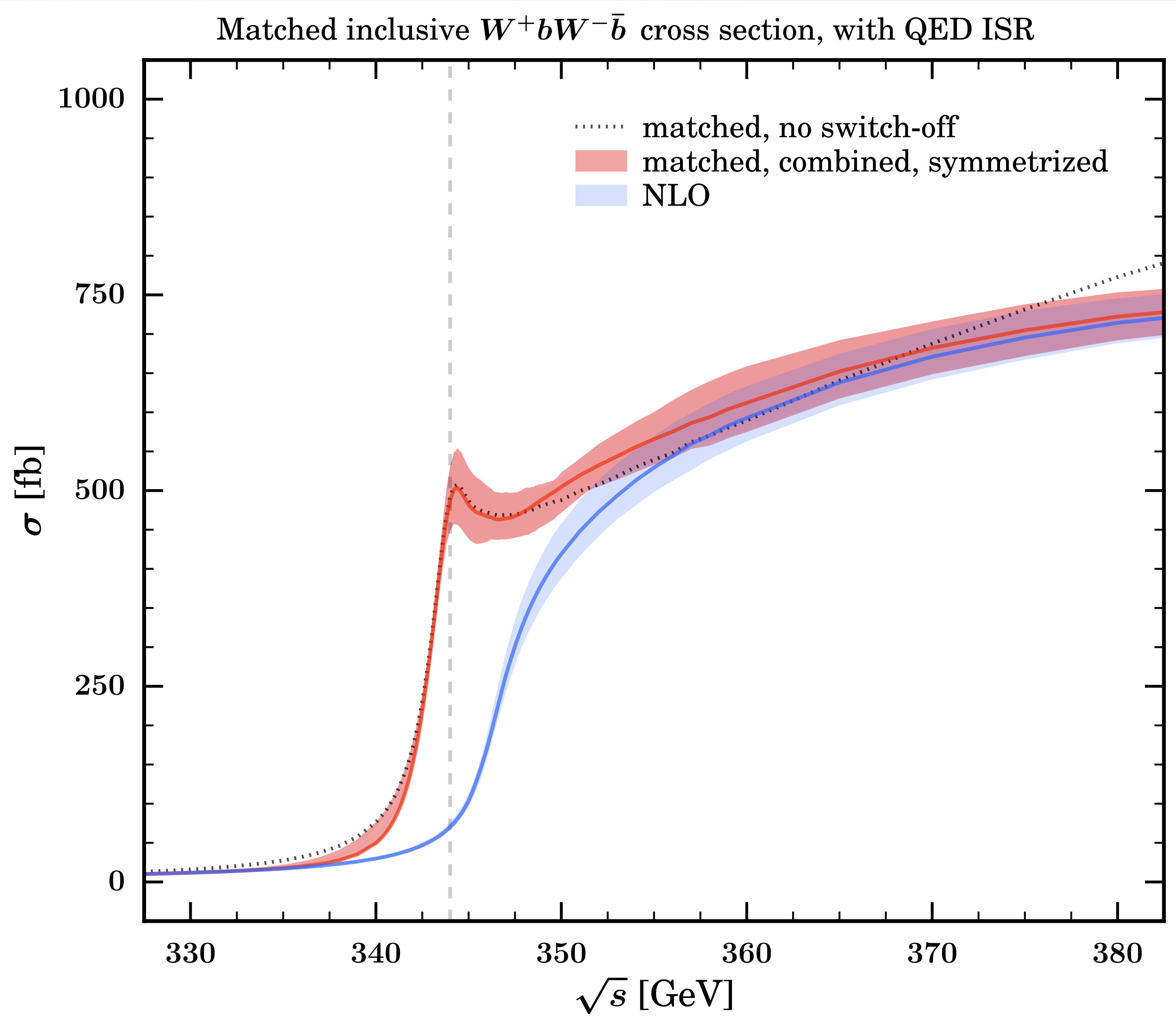
Symmetrization of error bands:

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

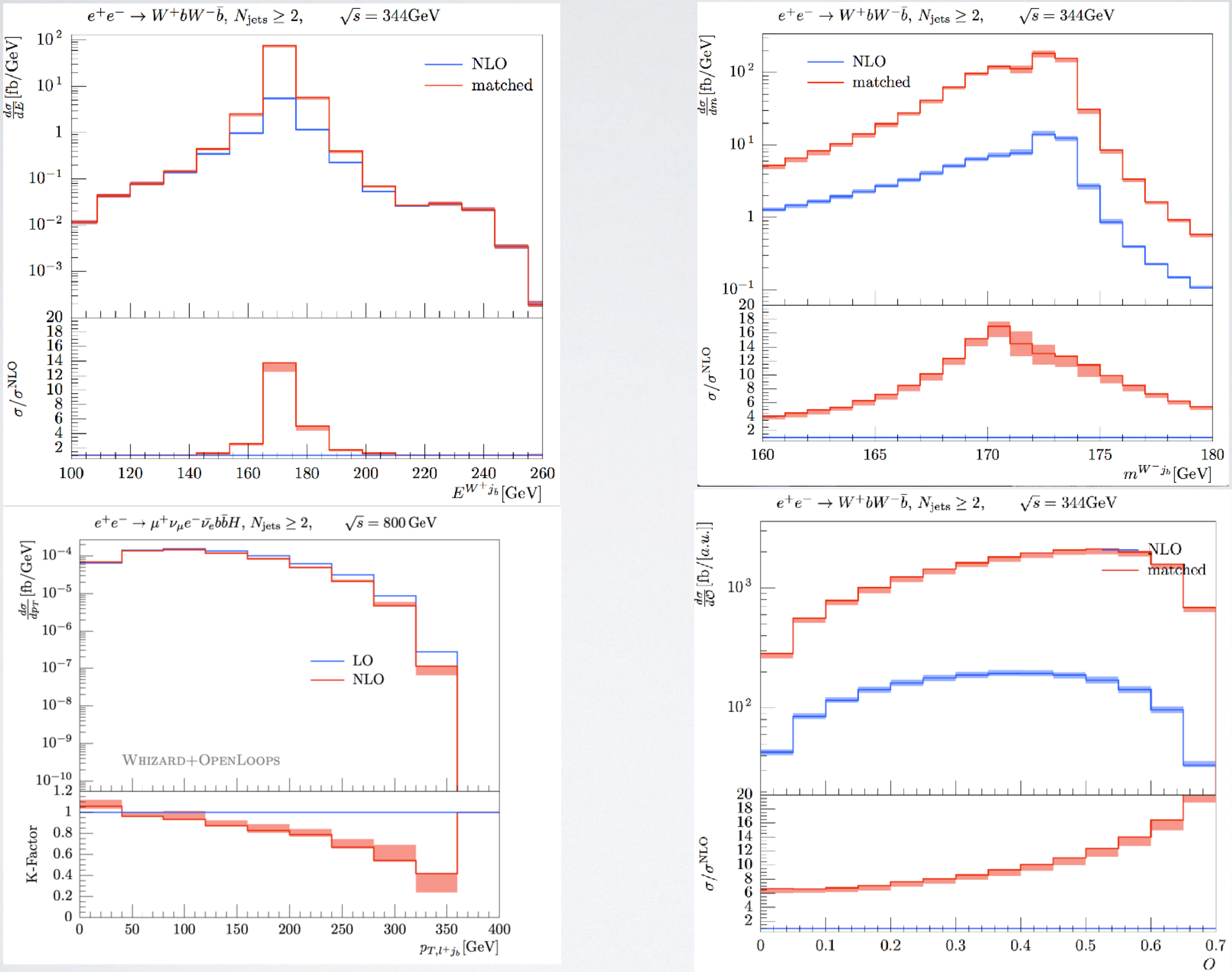
$$\sigma_{\min} = \min\left[\min_{i\in\mathrm{HF}} \sigma_i \ , \ \sigma_0 - (\max_{i\in\mathrm{HF}} \sigma_i - \sigma_0)\right]$$

Threshold matching with QED ISR





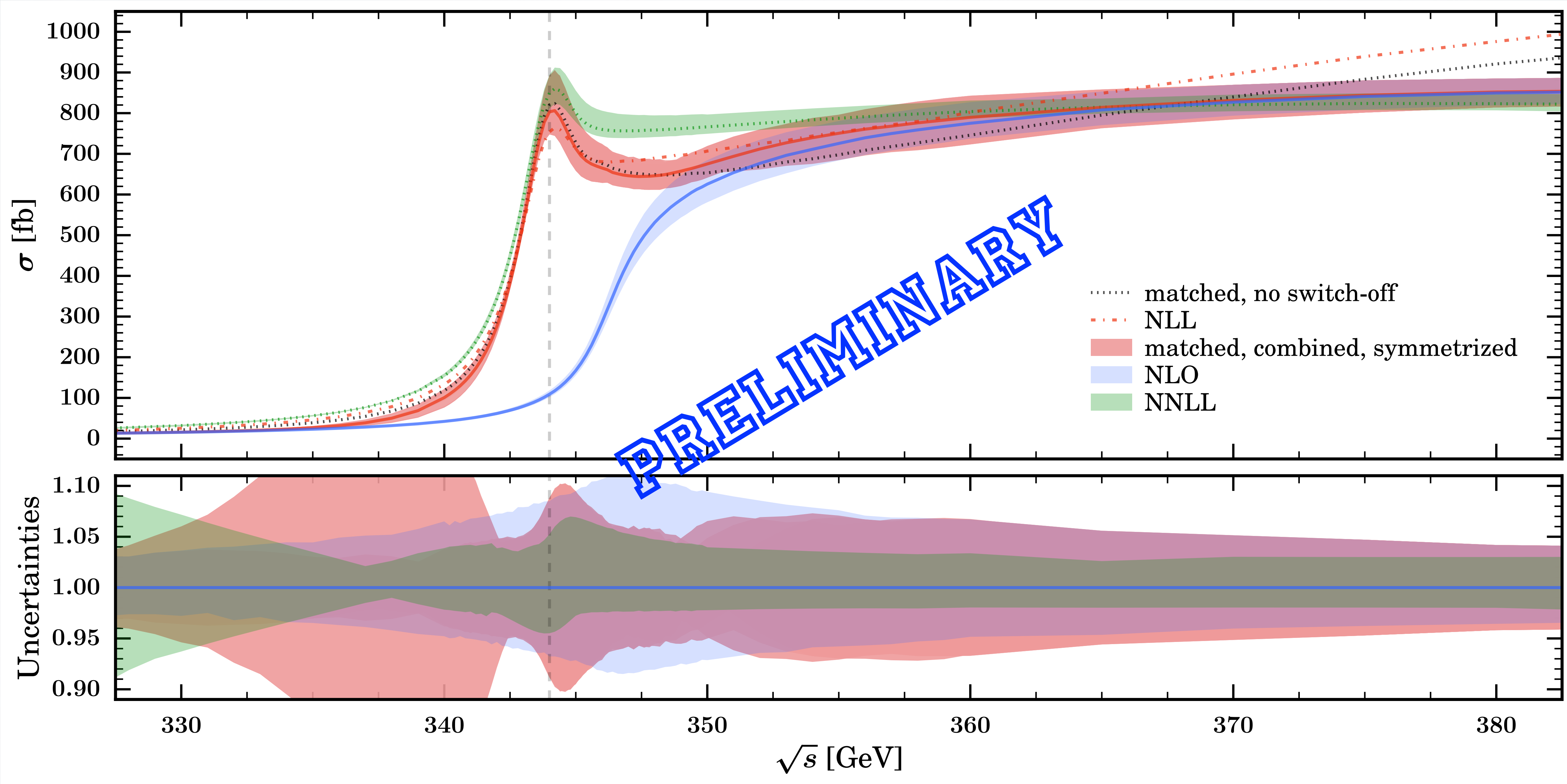
Matched threshold differential distributions



Summary & Outlook

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

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



Summary & Outlook

- Top physics is cornerstone of future lepton collider program
- Leptonic top fully off-shell at NLO QCD
- Inclusive processes: off-shell background grows with energy

- Complete vNRQCD threshold / QCD-NLO continuum matching
- Offers framework for new differential top mass measurements
- Can in principle be reweighted to NNNLO QCD accuracy at threshold
- Next steps: EW corrections, semi-leptonic/hadronic top decays,
  ttH threshold matching, top threshold matched with EWcorrections

- `WHIZARD 2.6` framework for automated (QCD) NLO
- NLO QCD (almost) done → `WHIZARD 3.0` [EW in validation]

Outlook to PDG 203x:

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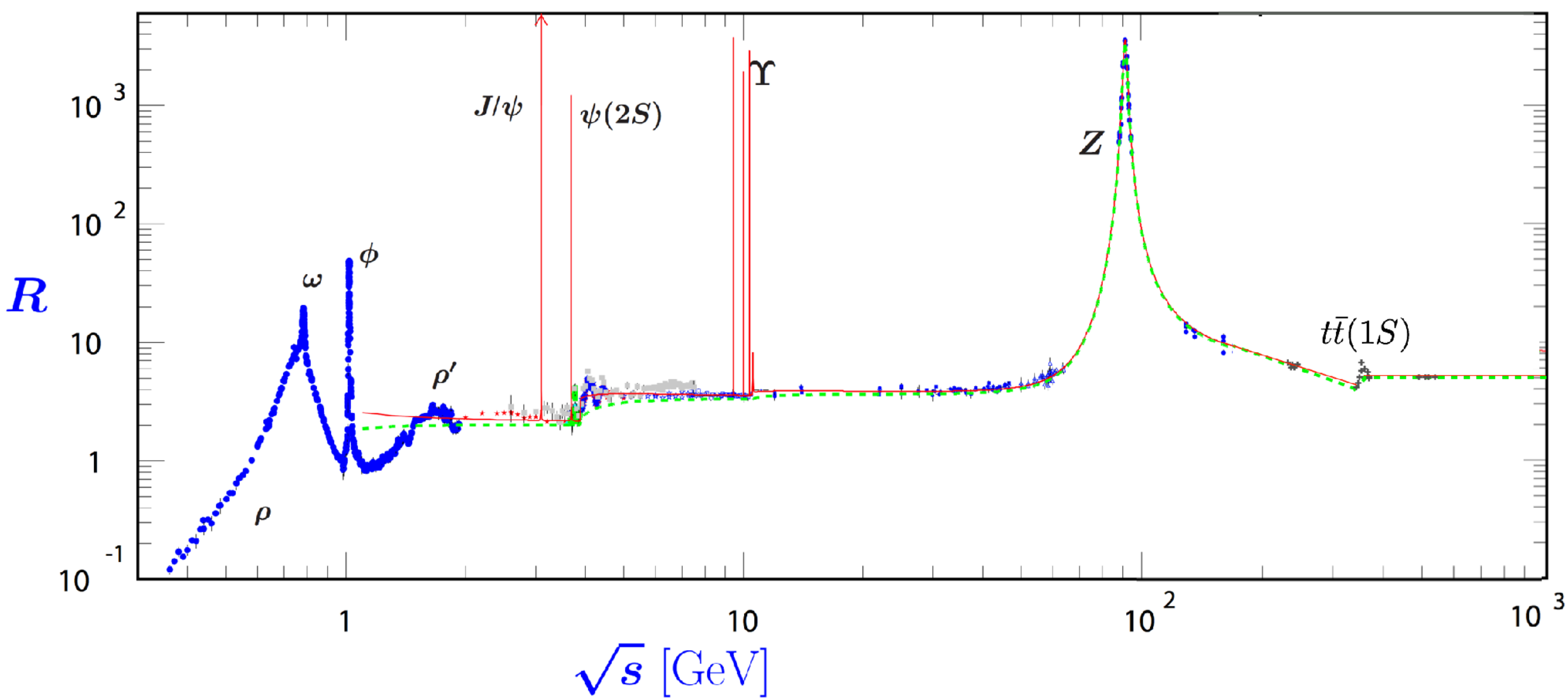


B A C K U P

tt continuum production (on- & off-shell)

- Paradigm processes at lepton colliders: precision determination of top properties
- Major background for EW measurements (*VVV* and VBS); any [most] BSM searches

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

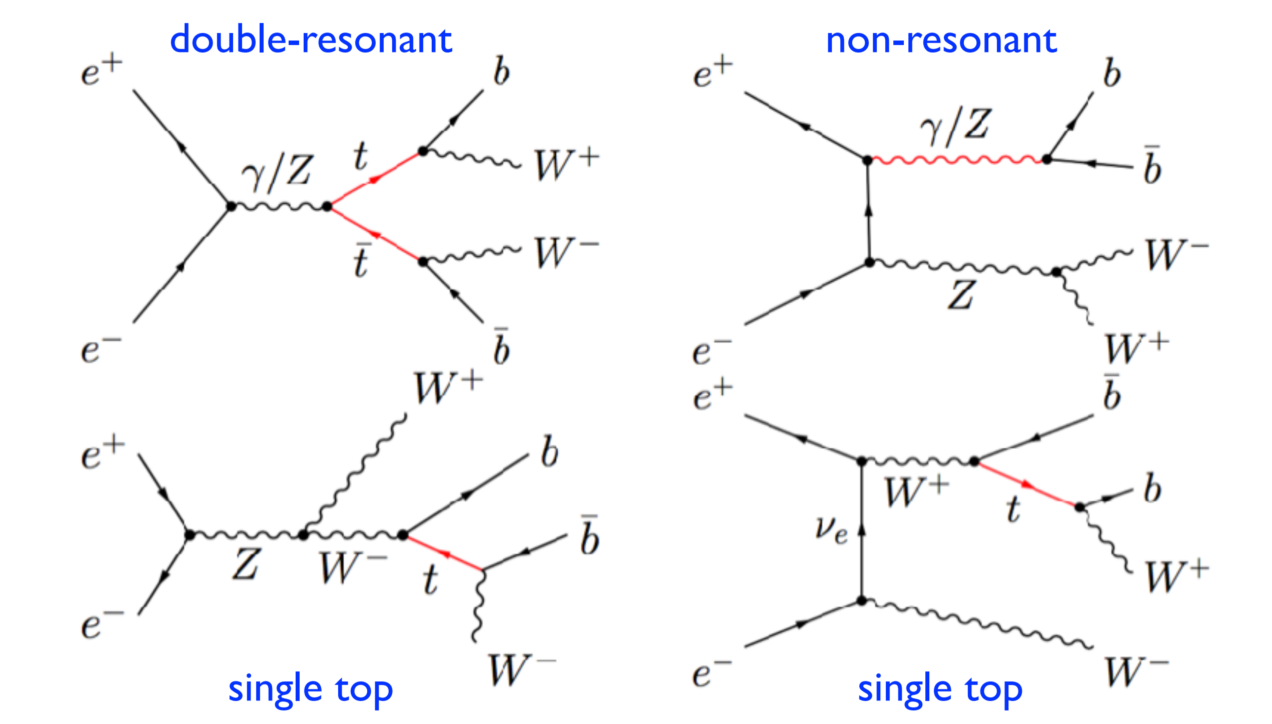
- NLO QCD [Jersak/Laermann/Zerwas, 1982]
- NNLO QCD [Chetyrkin/Kühn/Steinhauser, 1996; Harlander/Steinhauser, 1998]
- NLO EW [Beenakker/von der Marck/Hollik, 1991; Beenakker/Denner/Kraft, 1993]
- Threshold enhancement [Fadin/Khoze, 1987; Strassler/Peskin, 1991; Jezabek/Kühn/Teubner, 1992; Sumino et al.,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

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

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

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

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



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]

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alpha_power = 2
alphas_power = 0

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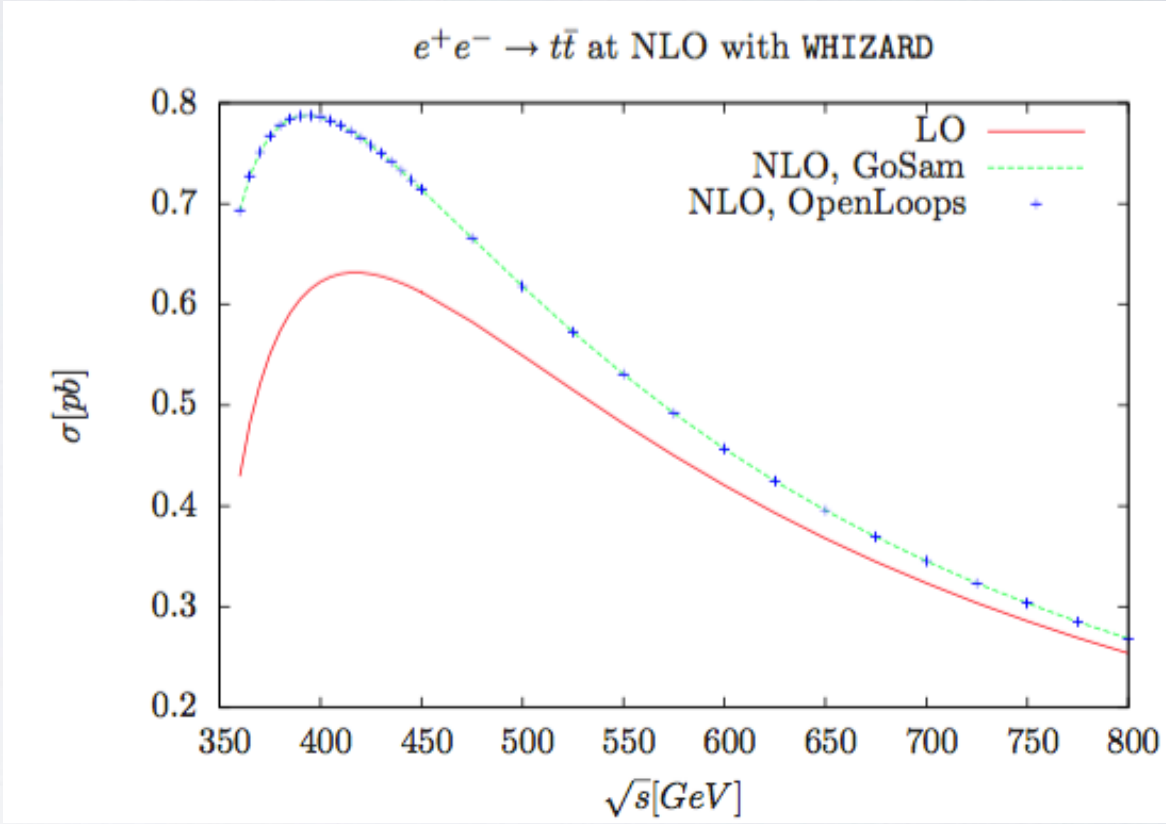
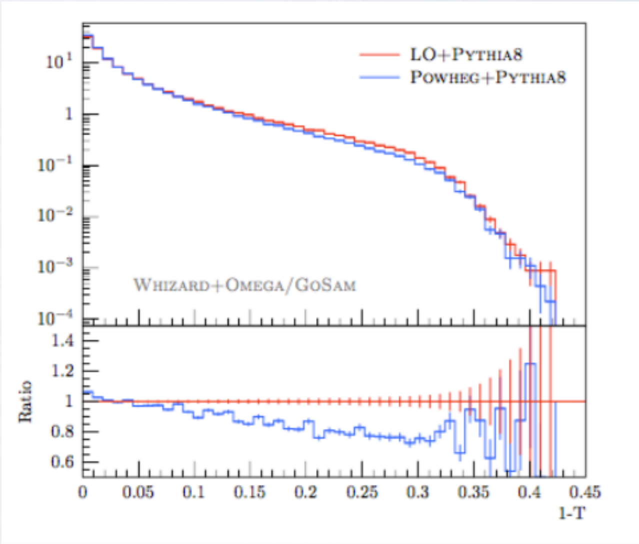


- FKS subtraction [Frixione/Kunszt/Signer, 1995]
- Resonance-aware treatment [Ježo/Nason, 1509.09071]
- Virtual MEs external
- Real and virtual subtraction terms internal
- NLO decays available for the NLO processes
- Fixed order events for plotting (weighted, either LHEF or HepMC)
- Automated POWHEG damping and matching
- NLO QCD (massless & massive emitters) fully supported
- Status of EW corrections: all parts

  technically completed, validation phase started [Rothe et al.]



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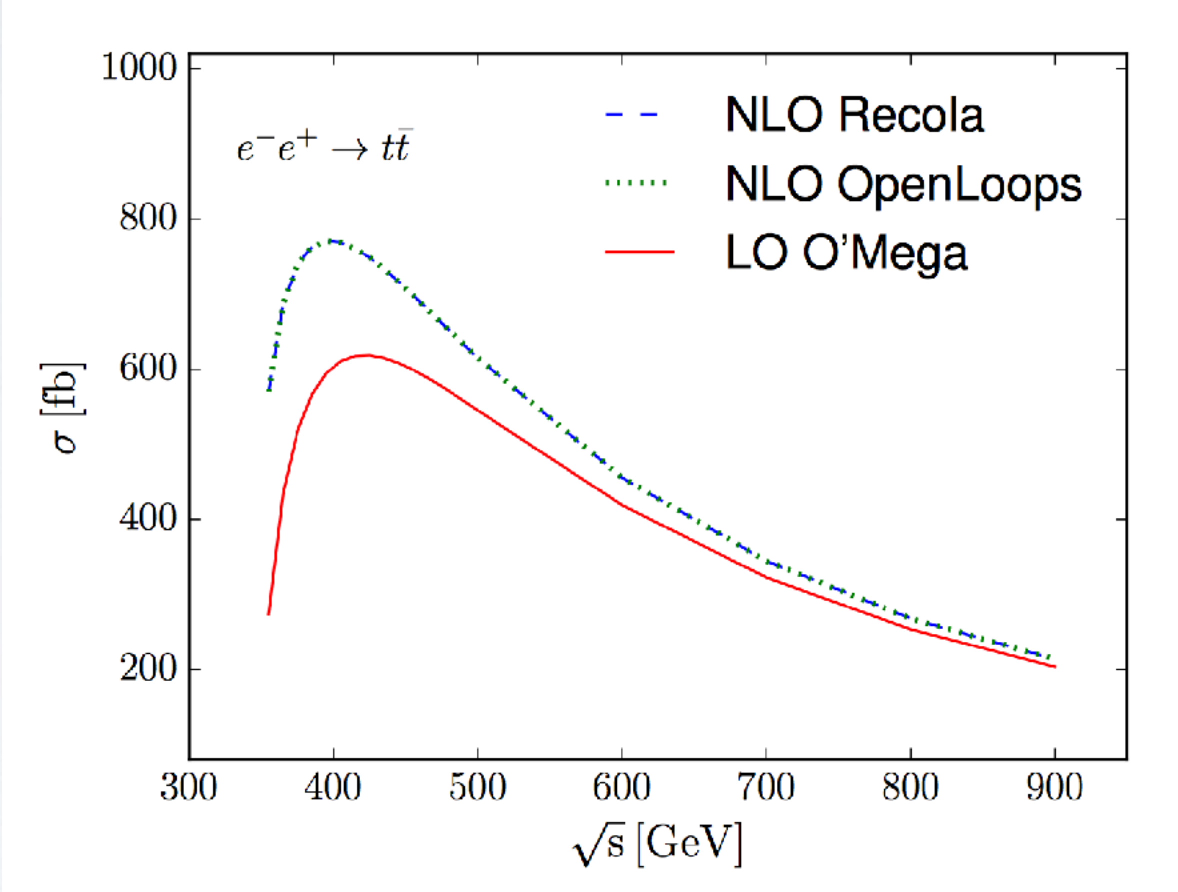

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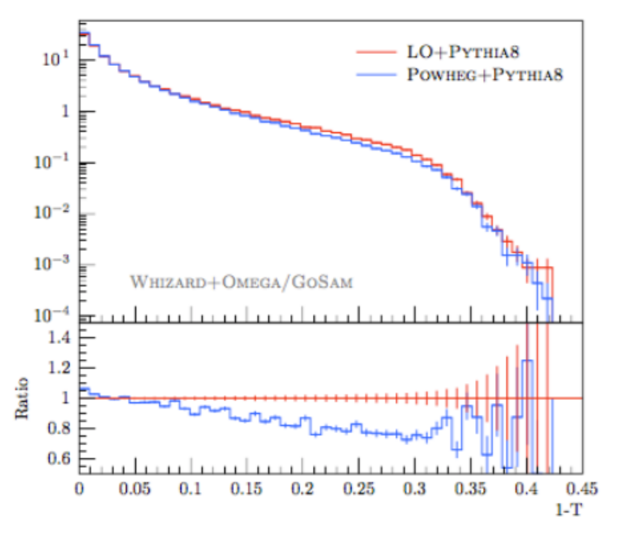
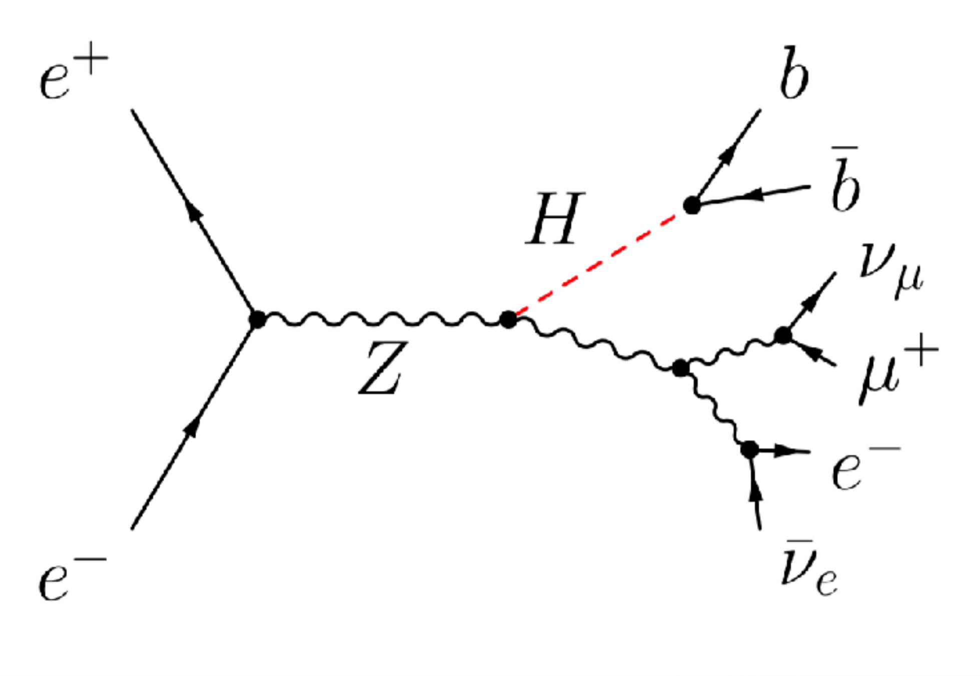


Resonance mappings for NLO processes

- Amplitudes (except for pure QCD/QED) contain resonances (Z, W, H, t)
- In general: resonance masses *not* respected by modified kinematics of subtraction terms
- Algorithm to include resonance histories

[Ježo/Nason, 1509.09071]

- Most important for narrow resonances ($H \to bb$)
- Additional soft mismatch integration component



- $D_H^{\text{Born}} = \left[\left(\bar{p}_{bb}^2 - m_H^2\right)^2 + m_H^2 \Gamma_H^2\right]^{-1}$,
- $D_H^{\text{Real}} = \left[\left(p_{bbg}^2 - m_H^2\right)^2 + m_H^2 \Gamma_H^2\right]^{-1}$

$$p_{bbg}^2 = \bar{p}_{bb}^2 + \Delta_{bbg}^2$$

$$\frac{D_H^{\text{Born}}}{D_H^{\text{Real}}} \overset{\bar{p}_{bb}^2 \to m_H^2}{=} 1 + \frac{\Delta_{bbg}^4}{m_H^2 \Gamma_H^2}$$

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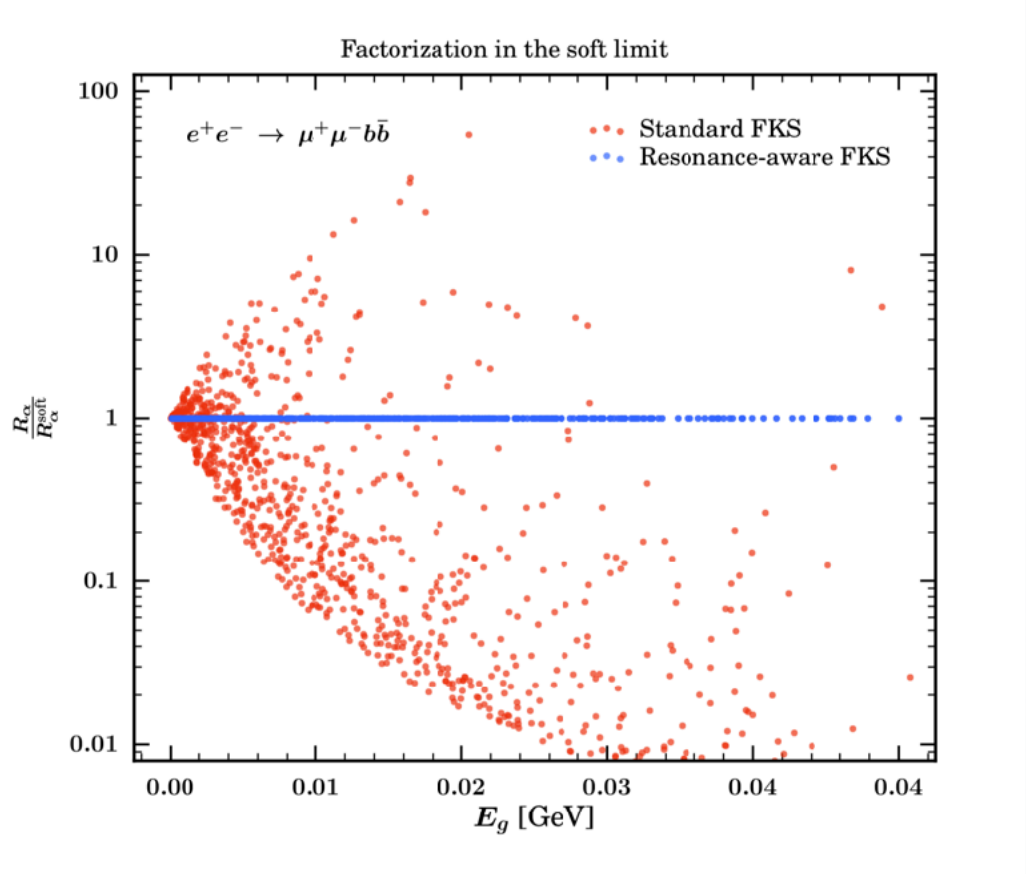

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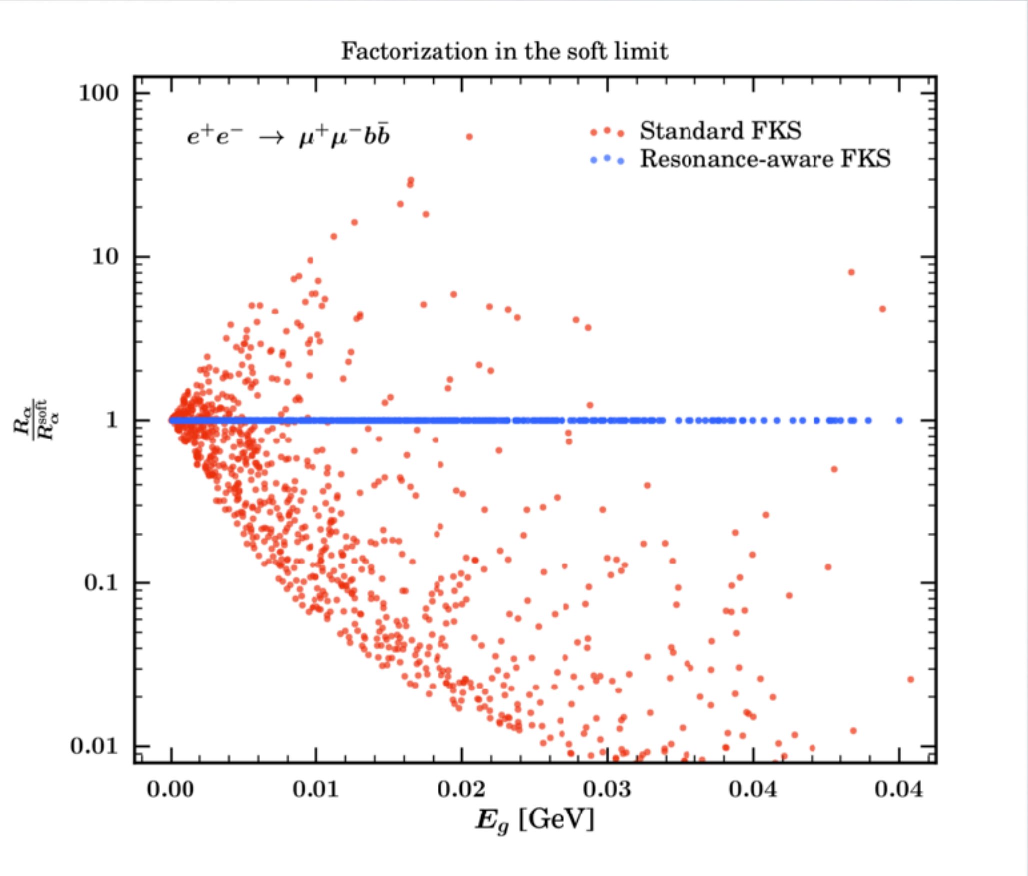

- WHIZARD complete automatic implementation: example $e^+e^- \to \mu\mu bb$ (ZZ, ZH histories)

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		
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standard FKS

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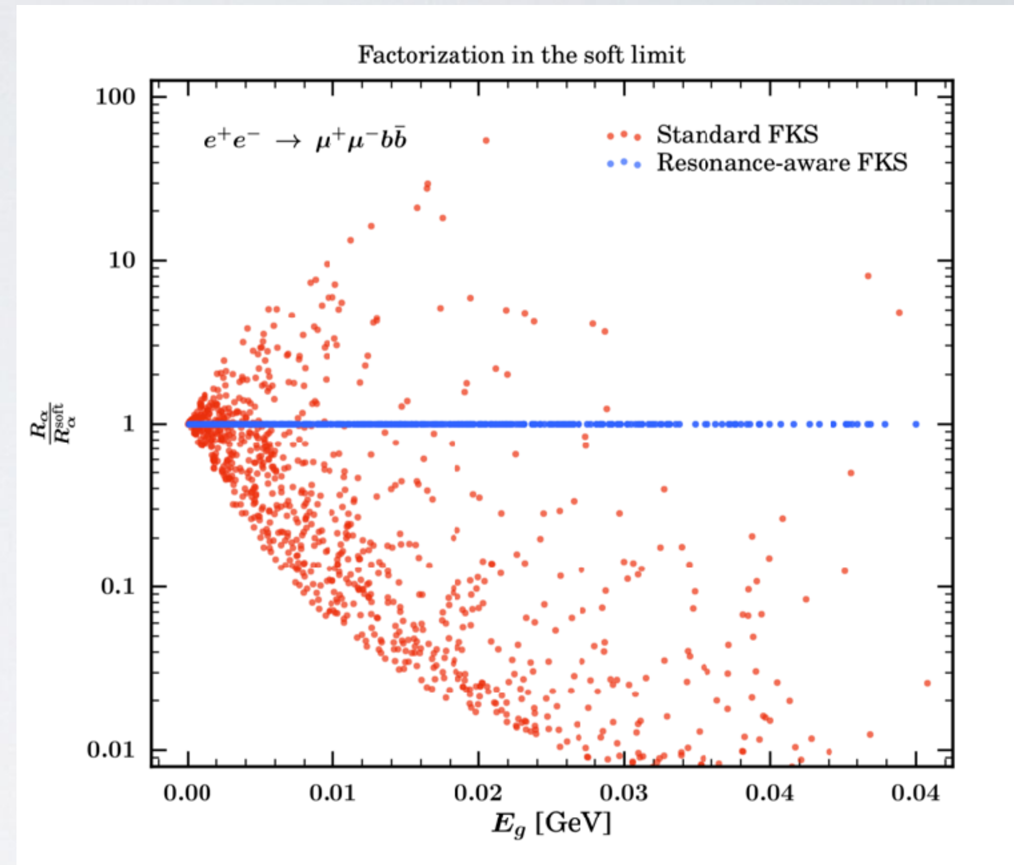

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2	11962	2.8591952E+00	5.20E-02	1.82	1.99*	10.91		
3	11936	2.9277880E+00	4.09E-02	1.40	1.52*	14.48		
4	11902	2.8512337E+00	3.98E-02	1.40	1.52*	13.70		
5	11874	2.8855399E+00	3.87E-02	1.34	1.46*	17.15		
5	59662	2.8842006E+00	2.04E-02	0.71	1.72	17.15	0.53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

FKS with resonance mappings

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

	$e^+e^- \to$	$A_{FB}^{\rm LO}$	$A_{FB}^{\rm NLO}$	$A_{FB}^{\rm NLO}/A_{FB}^{\rm LO}$
A_{FB}	$t\bar{t}$	-0.535	-0.539	1.013
	$W^+W^-b\bar{b}$	-0.428	-0.426	0.995
	$\mu^+e^-\nu_\mu\bar{\nu}_e b\bar{b}$	-0.415	-0.409	0.986
	$\mu^+e^-\nu_\mu\bar{\nu}_e b\bar{b}$, without neutrinos	-0.402	-0.387	0.964
$\bar{A}_{FB}$	$t\bar{t}$	0.535	0.539	1.013
	$W^+W^-b\bar{b}$	0.428	0.426	0.995
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Matched NLO QCD results

- Precise predictions of multi-parton final states require properly matched samples
- NLO QCD including POWHEG matching already available [WHIZARD+OpenLoops]
- All descriptions at NLO at the moment for the on-shell process
- Even LO simulations are demanding, e.g.: $e^+e^- \to b\bar{b}b\bar{b}jj\ell\nu_\ell, \quad b\bar{b}jjjjj\ell\nu_\ell$

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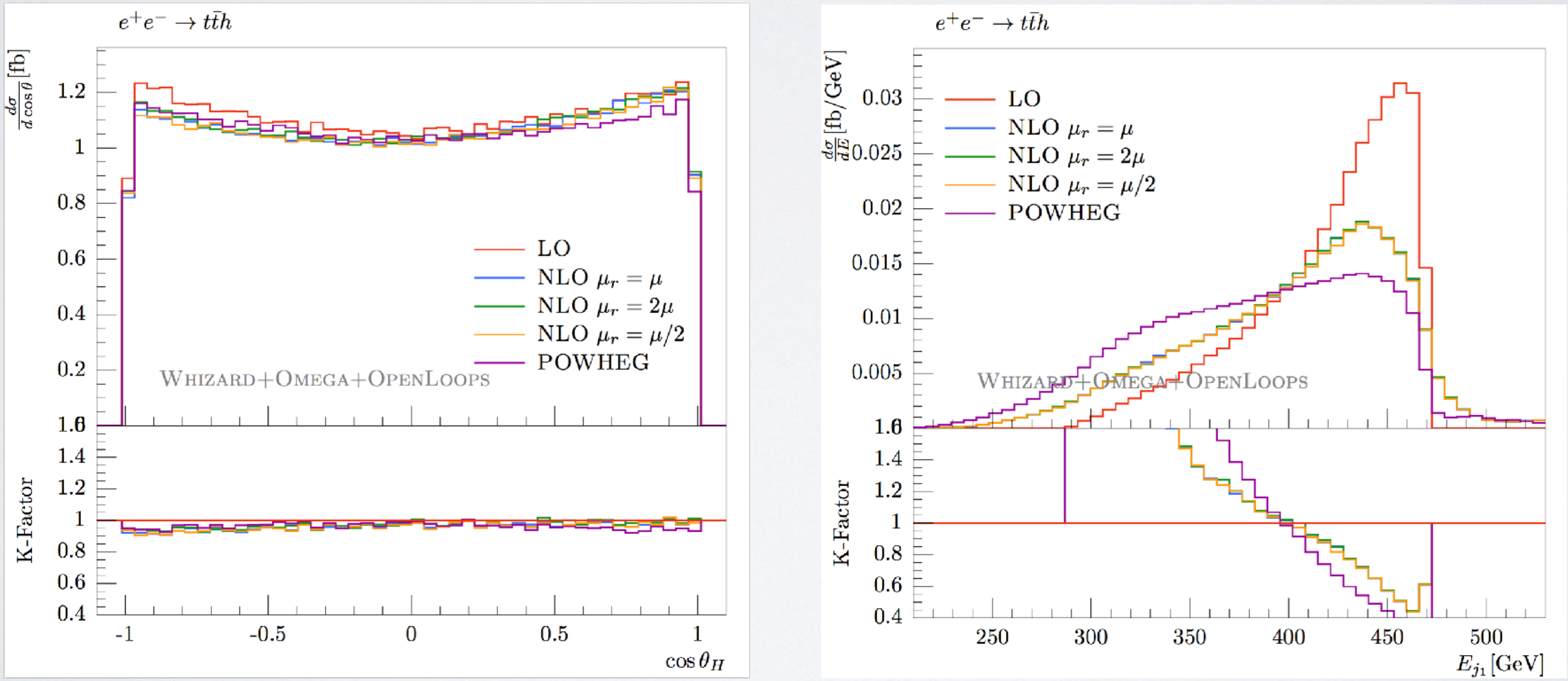

[Chokoufe/JRR/Weiss]