Top Physics at ILC

Jürgen R. Reuter, DESY

Paradigmatic Standard Candle Telescopes

Top quark: special while heaviest SM particle?
or: the only standard particle of the SM?

SM / top candles can be used as
Telescopes for [indirect] BSM searches

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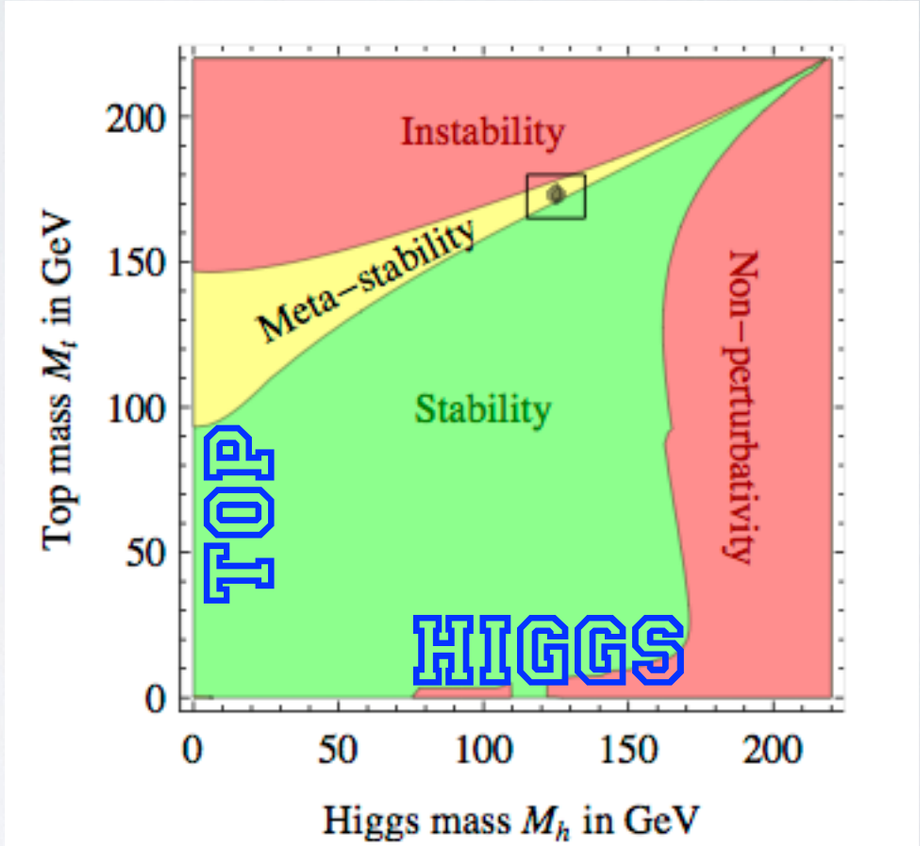
Electroweak vacuum & excitations:



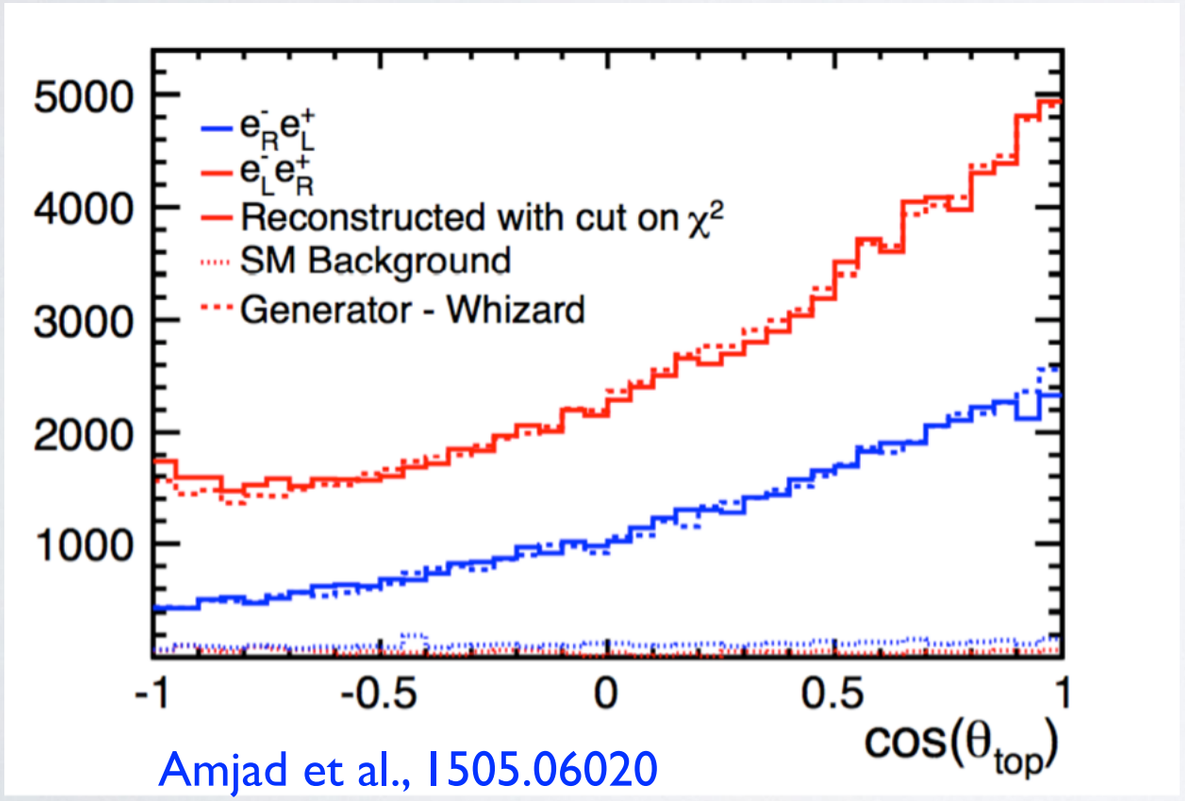
(note: plot under assumptions of NO additional BSM)

Telescope of Anomalous top couplings

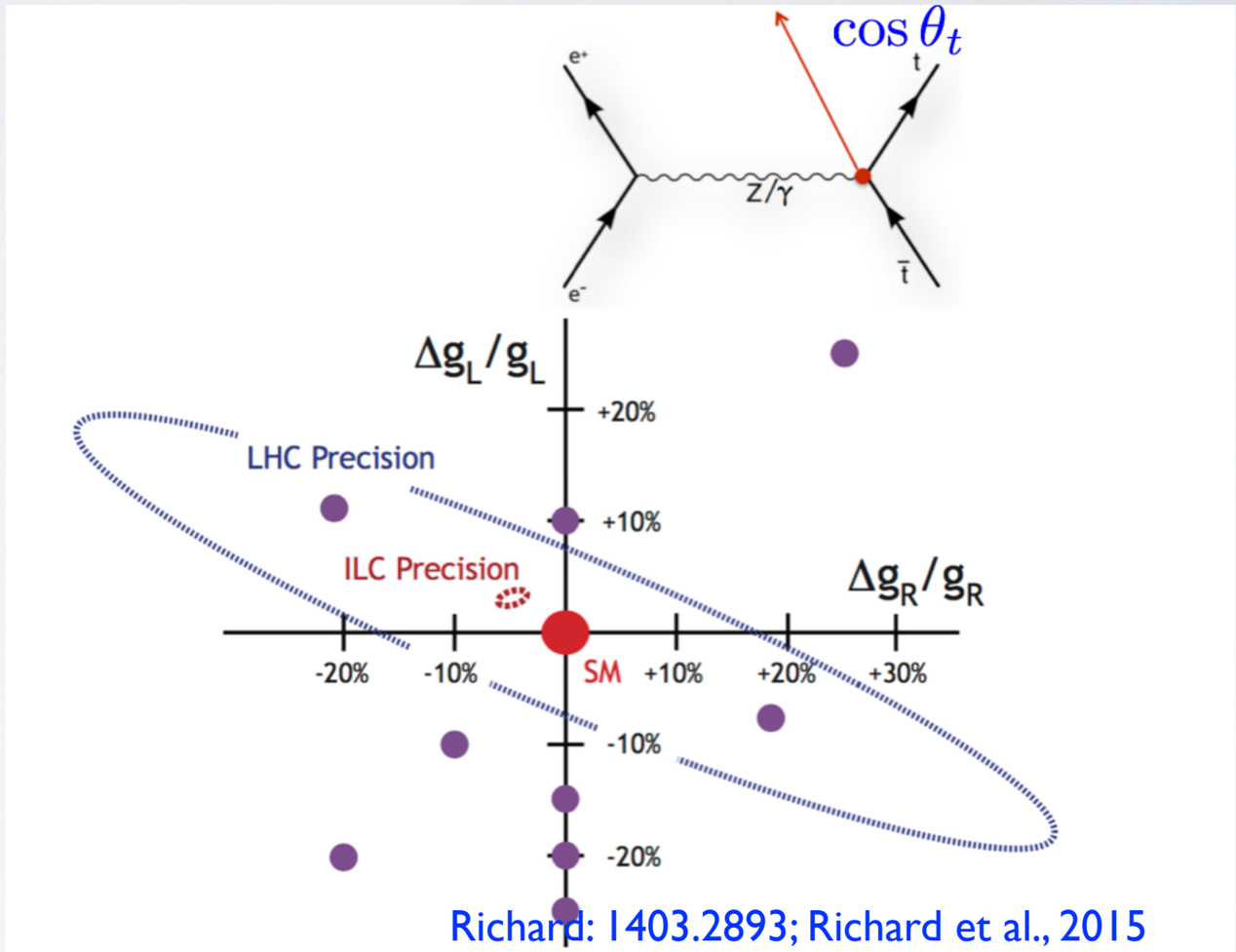
Anomalous Top couplings as BSM probes

$$\Gamma_\mu^{ttX}(k^2, q, \bar{q}) = ie\left\{\gamma_\mu\left(\widetilde{F}_{1V}^X(k^2) + \gamma_5\widetilde{F}_{1A}^X(k^2)\right) + \frac{(q-\bar{q})_\mu}{2m_t}\left(\widetilde{F}_{2V}^X(k^2) + \gamma_5\widetilde{F}_{2A}^X(k^2)\right)\right\}$$

- Strong handle on BSM (e.g. compositeness)
- Excellent top reconstruction in e+e-
- Study of CP properties possible (!)



Amjad et al., 1505.06020



Richard: 1403.2893; Richard et al., 2015

ILC: *tt* continuum production (on- & off-shell)

- Paradigm processes at lepton colliders: precision determination of m_t and Y_t
- Major background for EW measurements (*VVV* and VBS); any [most] BSM searches
- Investigate processes of increasing complexity: $2 \to 2$ to $2 \to 4$ to $2 \to 6$

$e^+e^- \to$	$n_{\text{loop diags}}$	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

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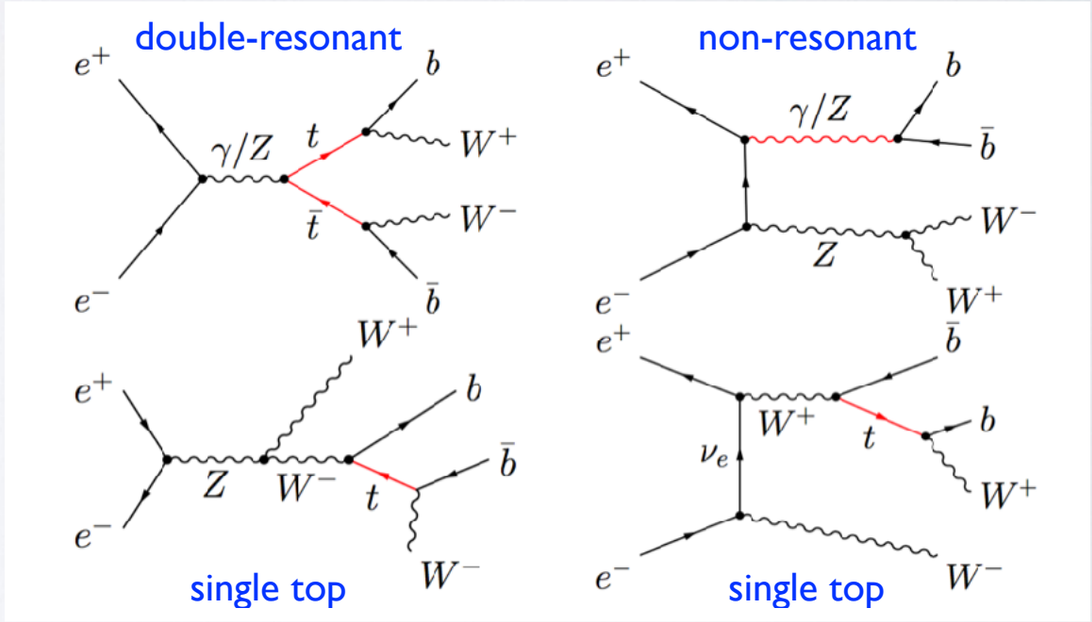

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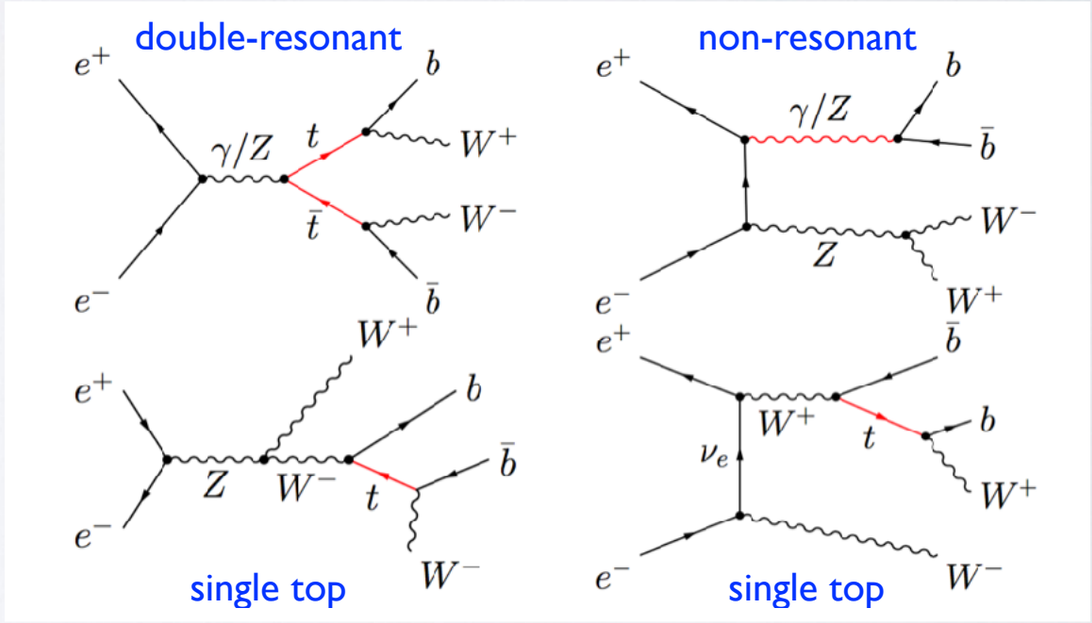
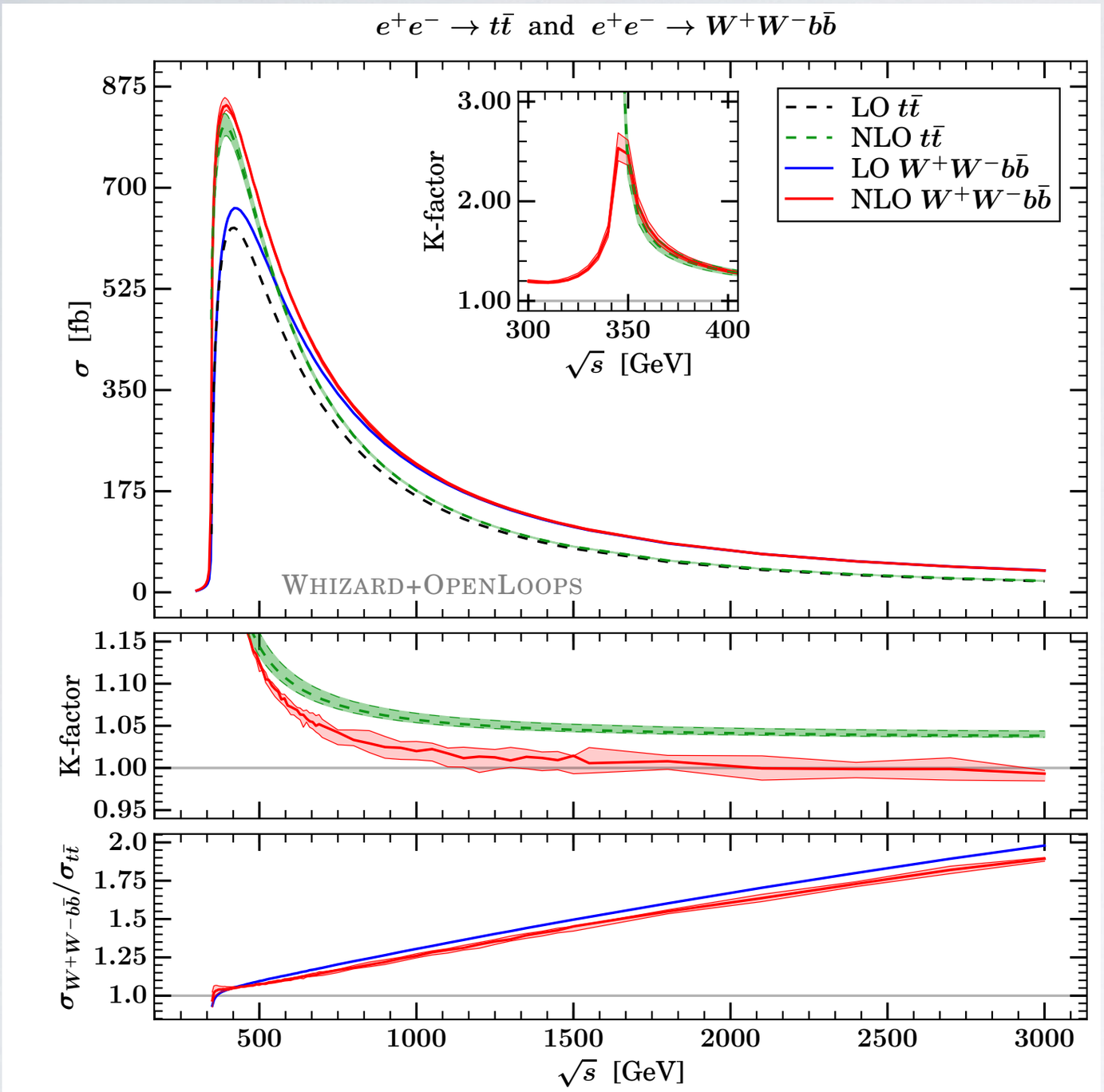
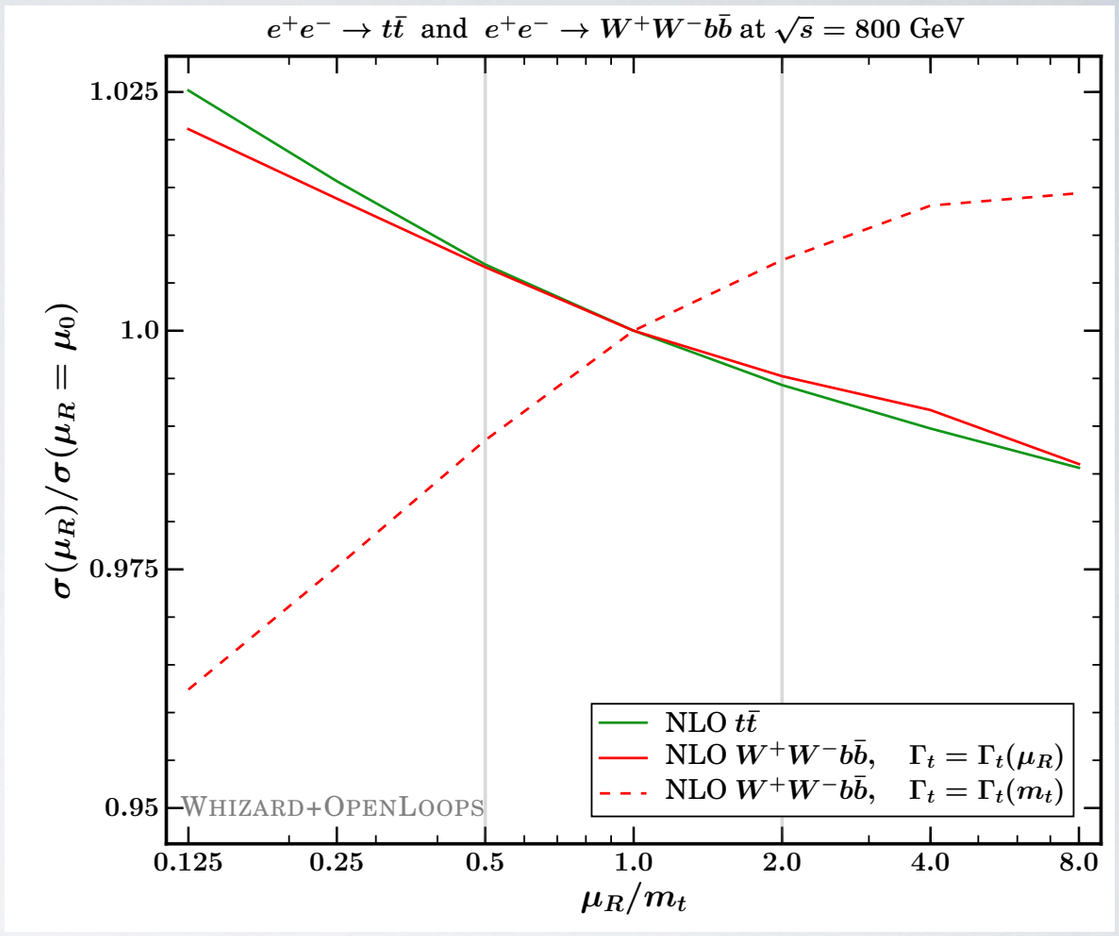


Top width: $t \to W^+b$

- NLO QCD [Jezabek/Kühn, 1989]

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

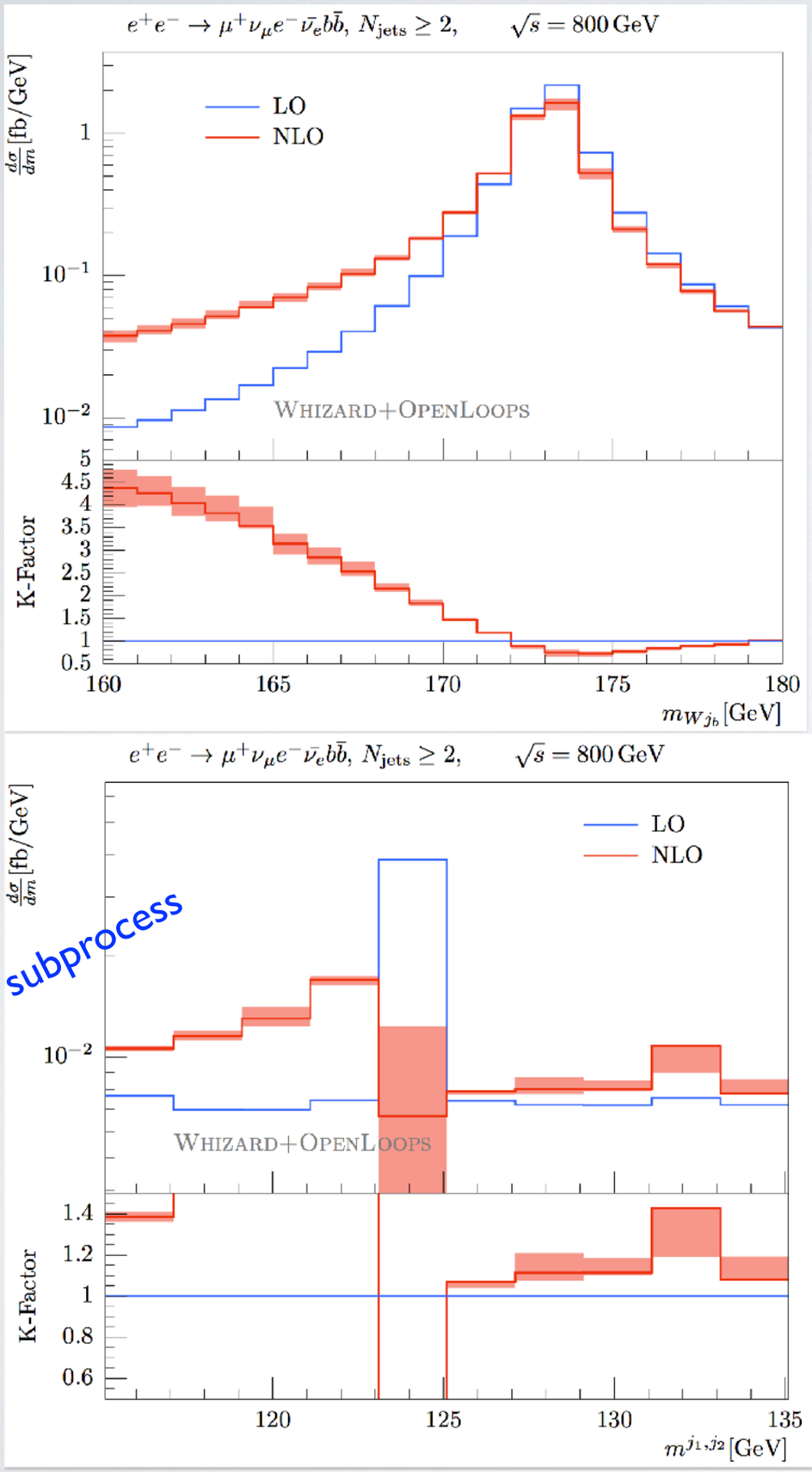


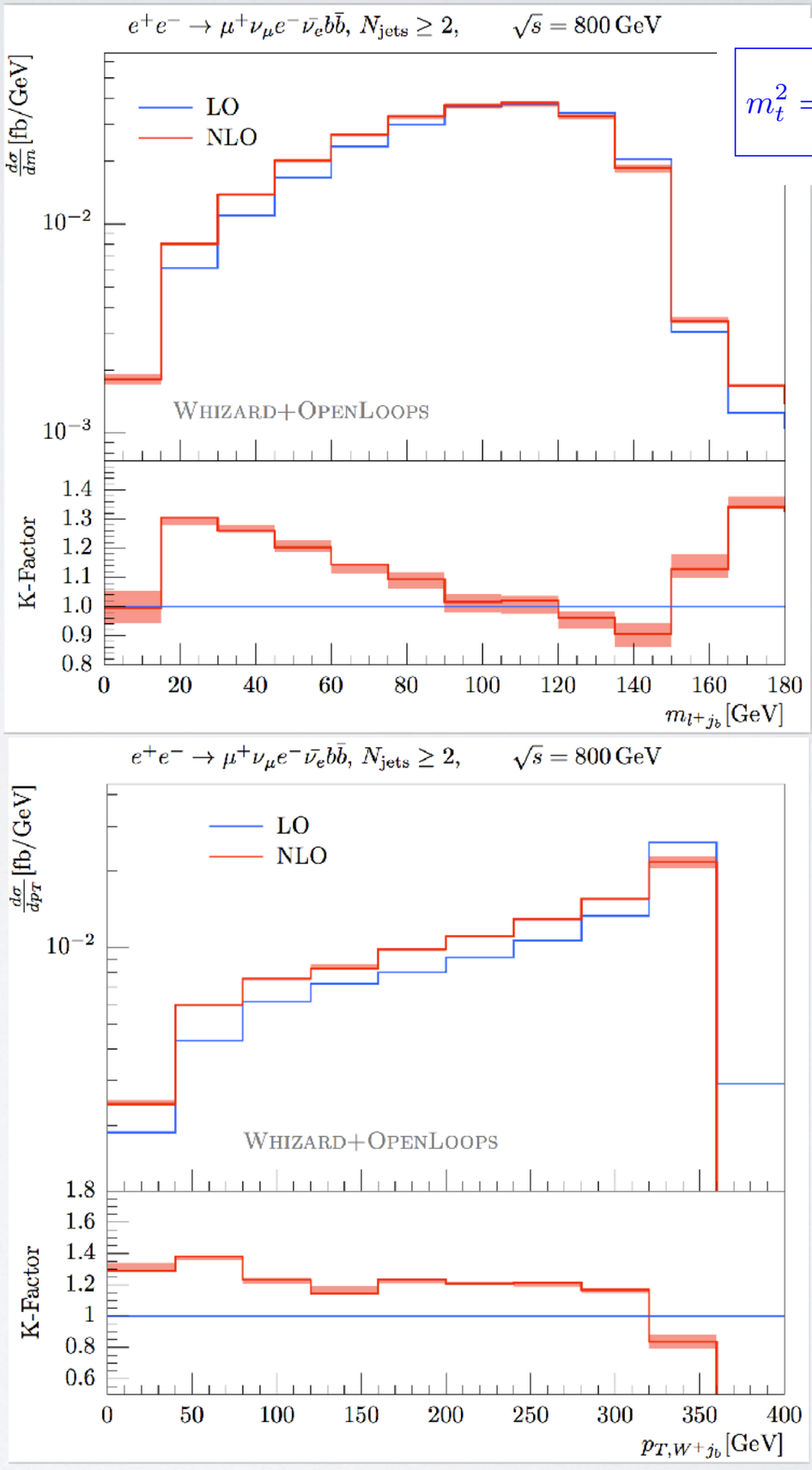


Chokoufé/Kilian/Lindert/Pozzorini/JRR/Weiss, 2016

	$e^+e^- \to t\bar{t}$			$e^+e^- \to W^+W^-b\bar{b}$		
$\sqrt{s}$ [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

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





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

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
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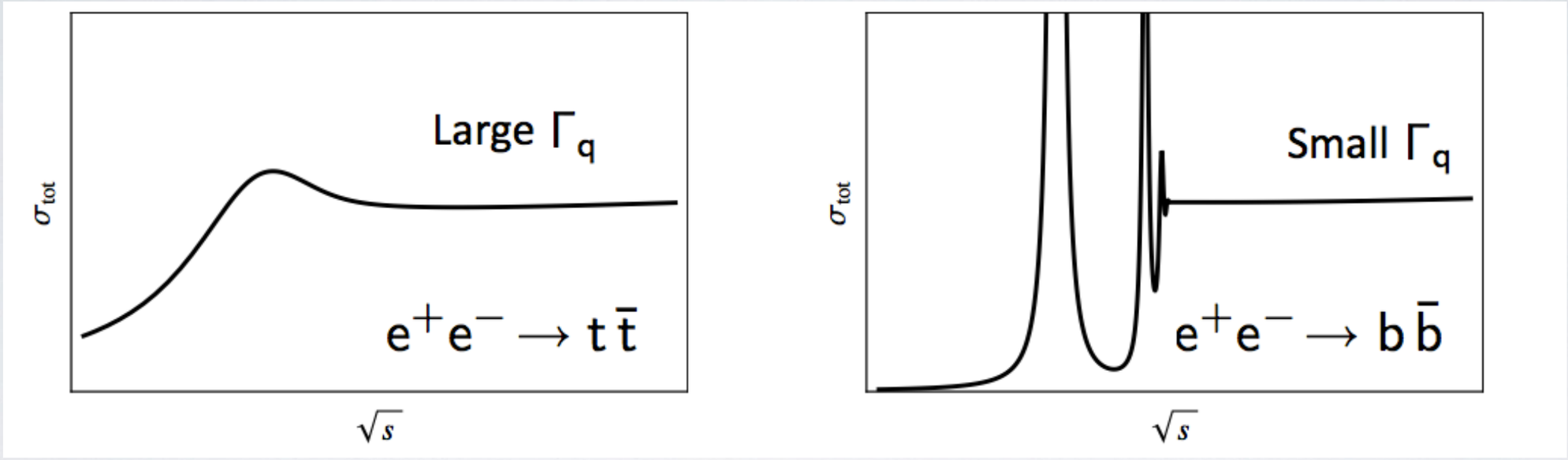
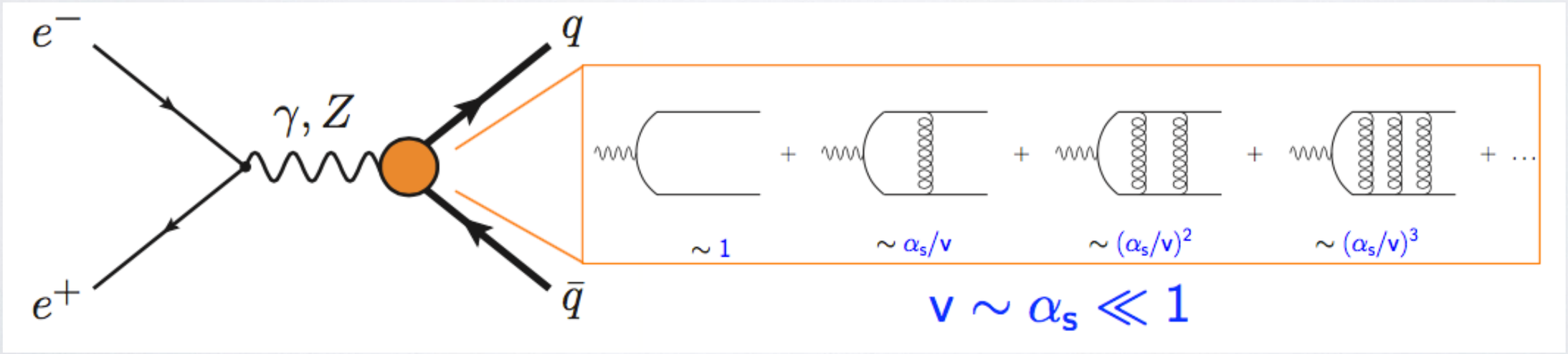
Top Threshold at ILC350

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

Heavy quark production at lepton colliders, qualitatively:



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



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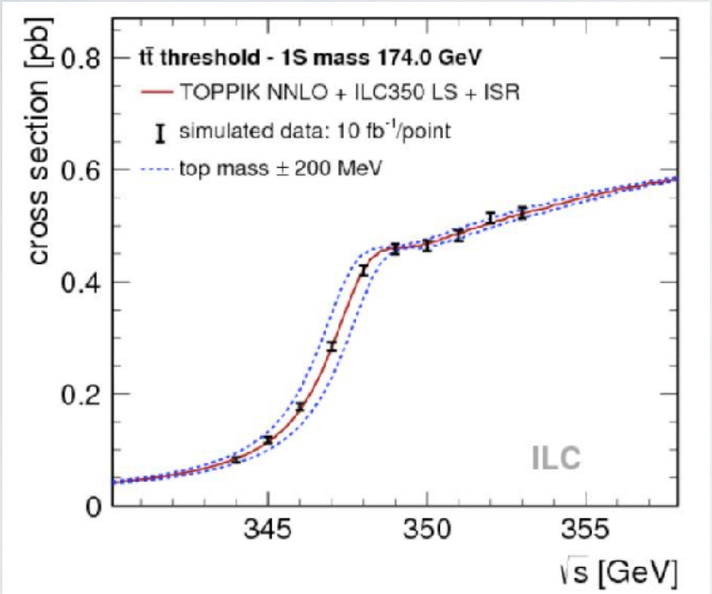

error source	$\Delta m_t^{\rm PS}$ [MeV]
stat. error (200 fb^{-1})	13
theory (NNNLO scale variations, PS scheme)	40
parametric (α_s, current WA)	35
non-resonant contributions (such as single top)	< 40
residual background / selection efficiency	$10 - 20$
luminosity spectrum uncertainty	< 10
beam energy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

- Default parameters:

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

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

Marquard et al.

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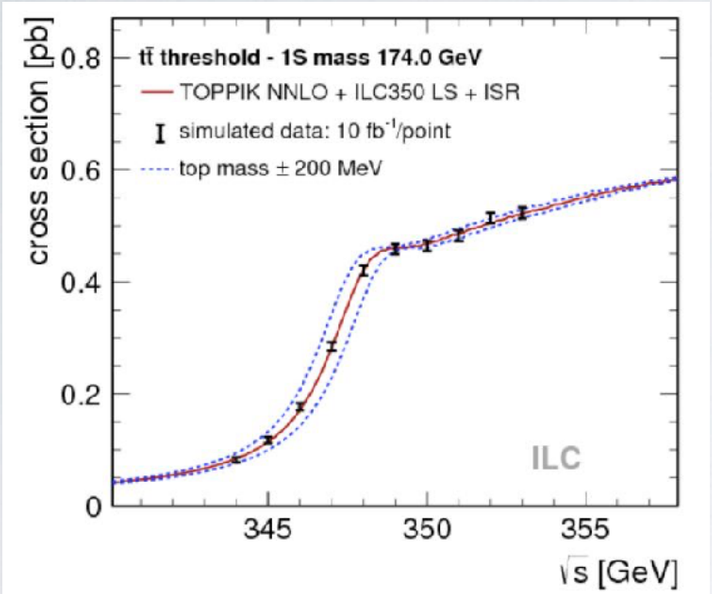

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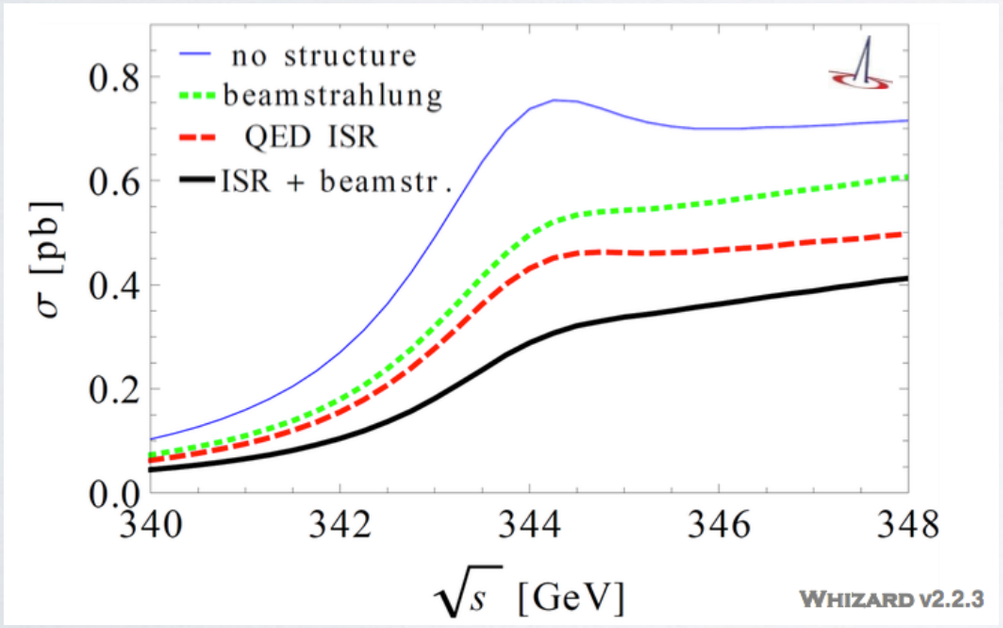

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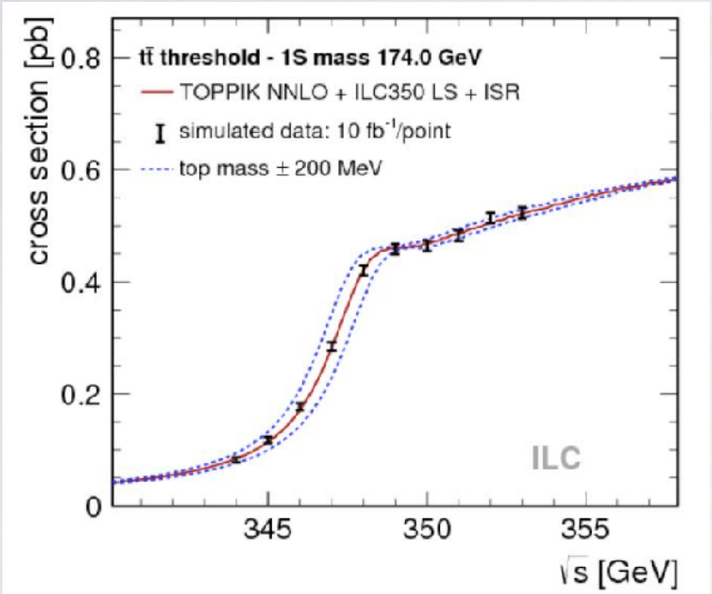

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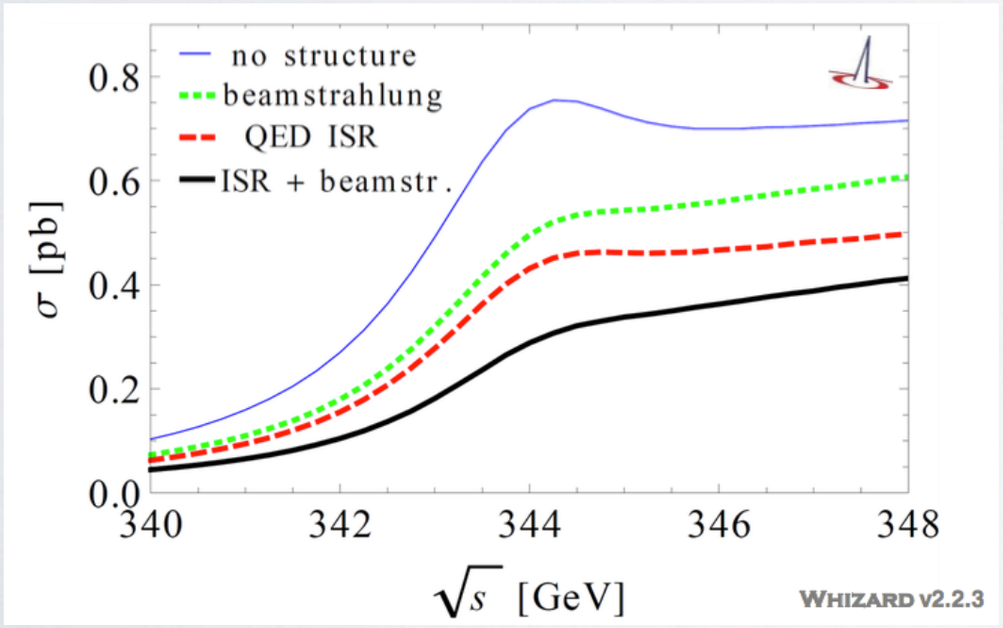
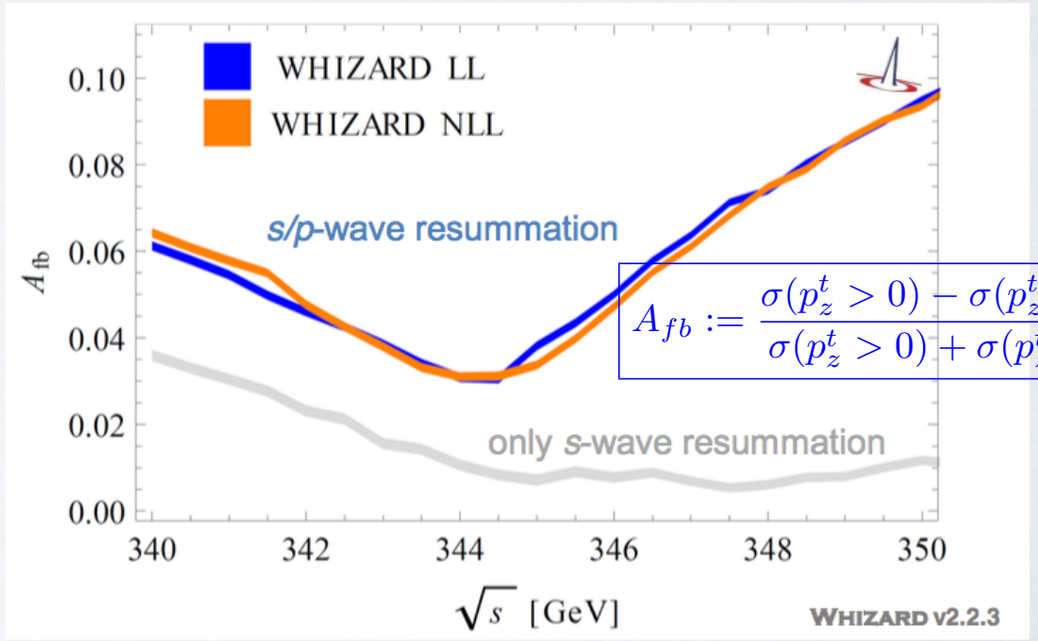




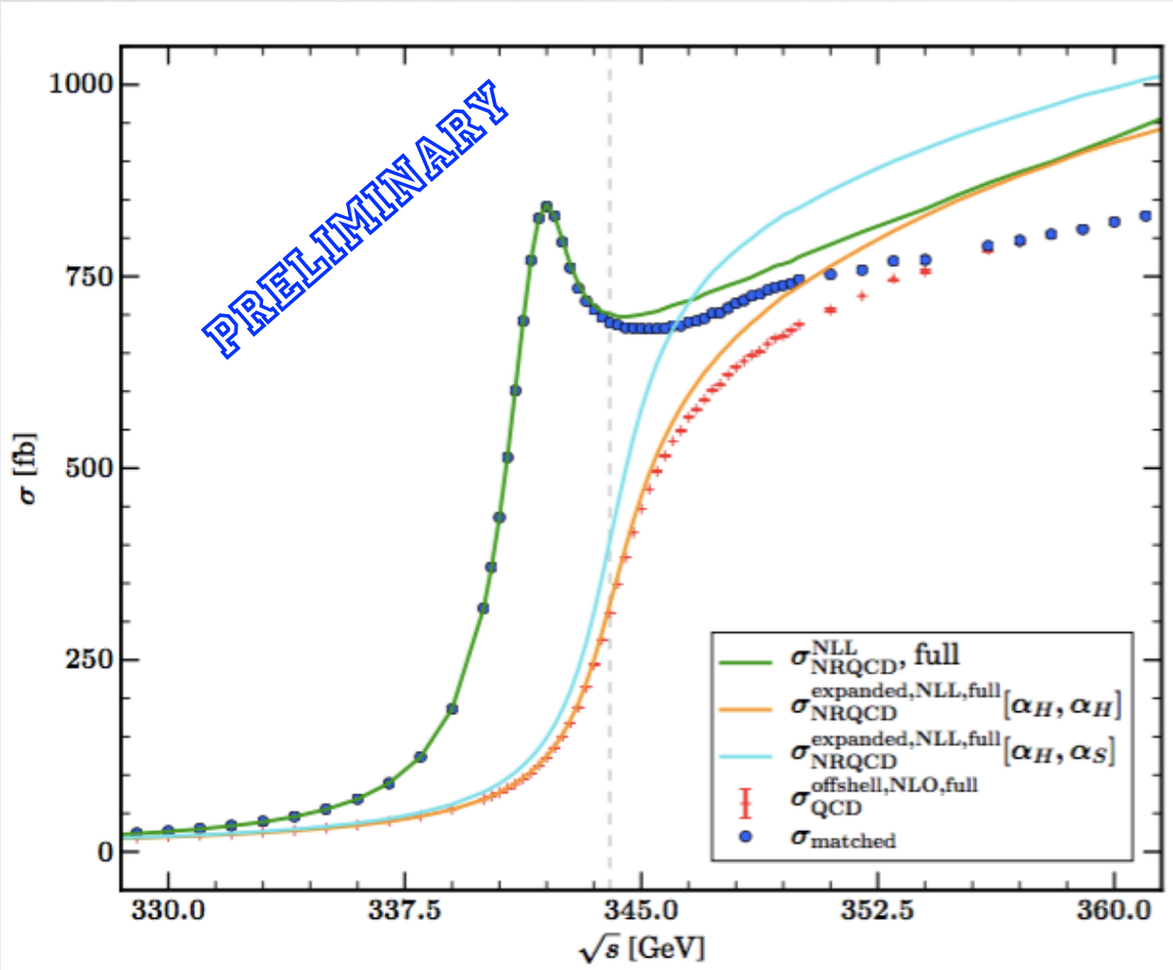
$$A_{fb} := \frac{\sigma(p_z^t > 0) - \sigma(p_z^t) < 0)}{\sigma(p_z^t > 0) + \sigma(p_z^t < 0)}$$

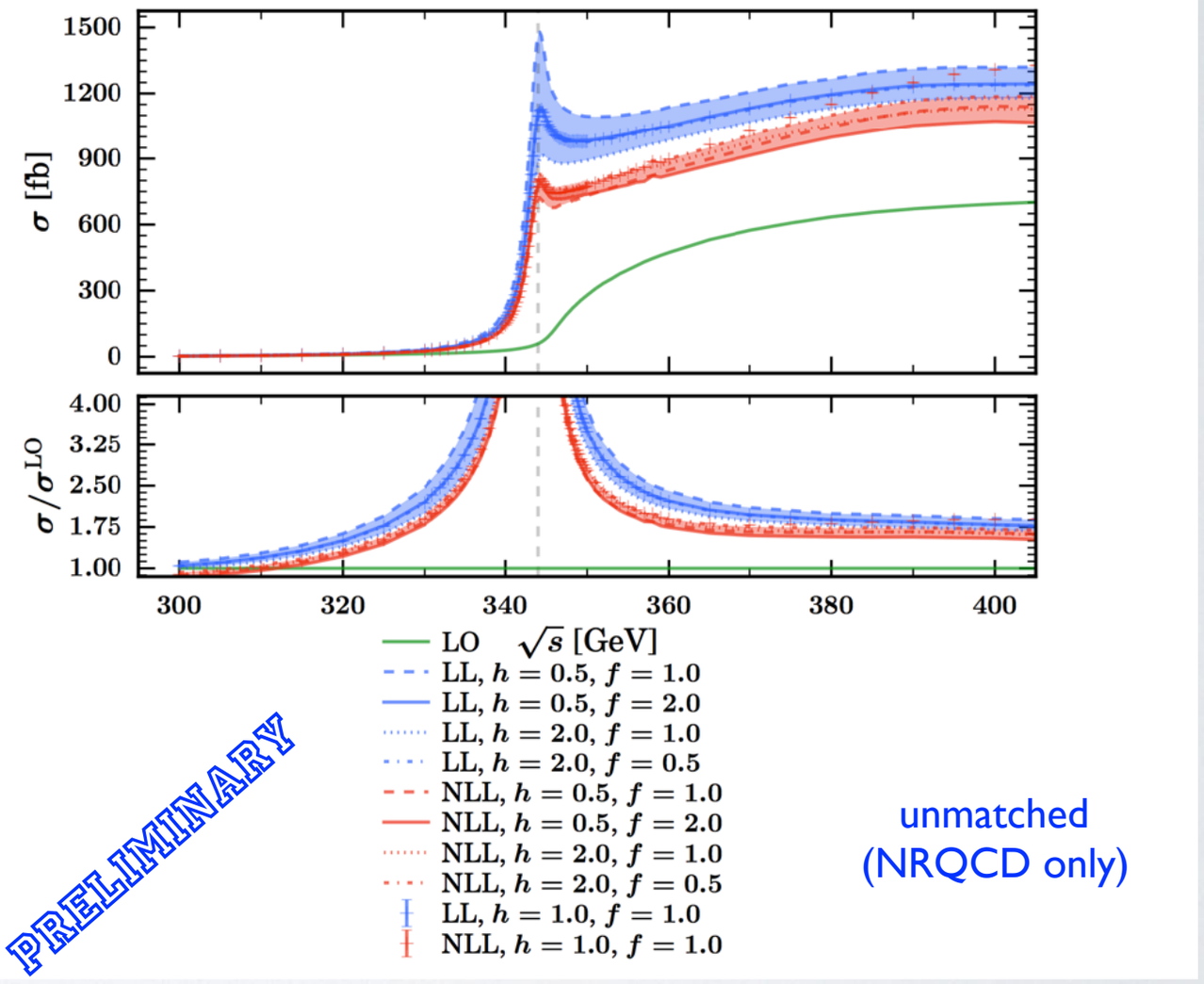
Matching to continuum at LO and NLO

- Transition region between relativistic and resummation effects
- CLIC benchmark energies:

  0.38 TeV, 1.4 TeV, 3.0 TeV

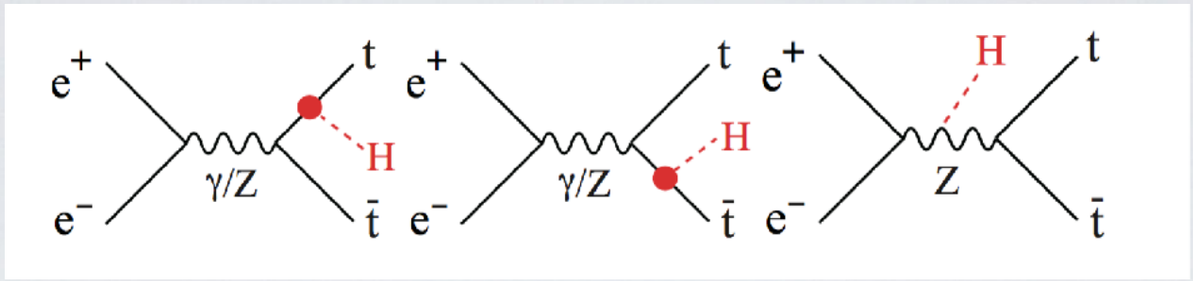
- Measurement not fully inclusive
- Important for determination of experimental efficiencies





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

Top pair + Higgs production



- $e^+e^- \to t\bar{t}h$ for top Yukawa meas. [Hagiwara/Murayama/Watanabe, 1991; Djouadi/Kalinowski/Zerwas, 1992]
- NLO QCD corrections [Dawson/Reina, 1998; Dittmaier/Krämer/Liao/Spira/Zerwas, 1998]
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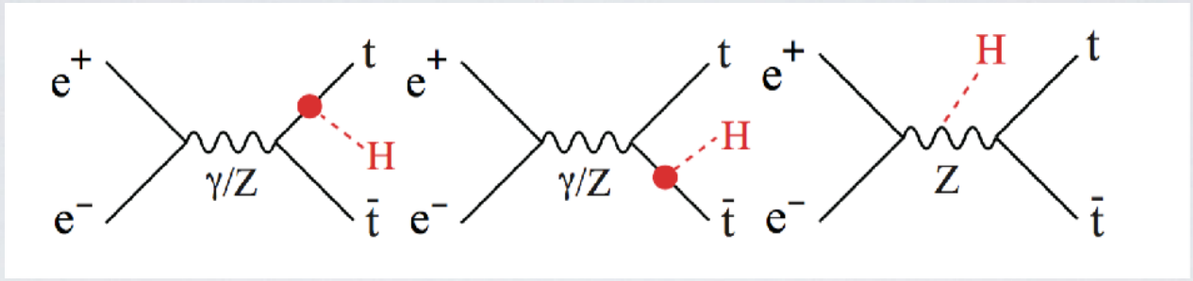

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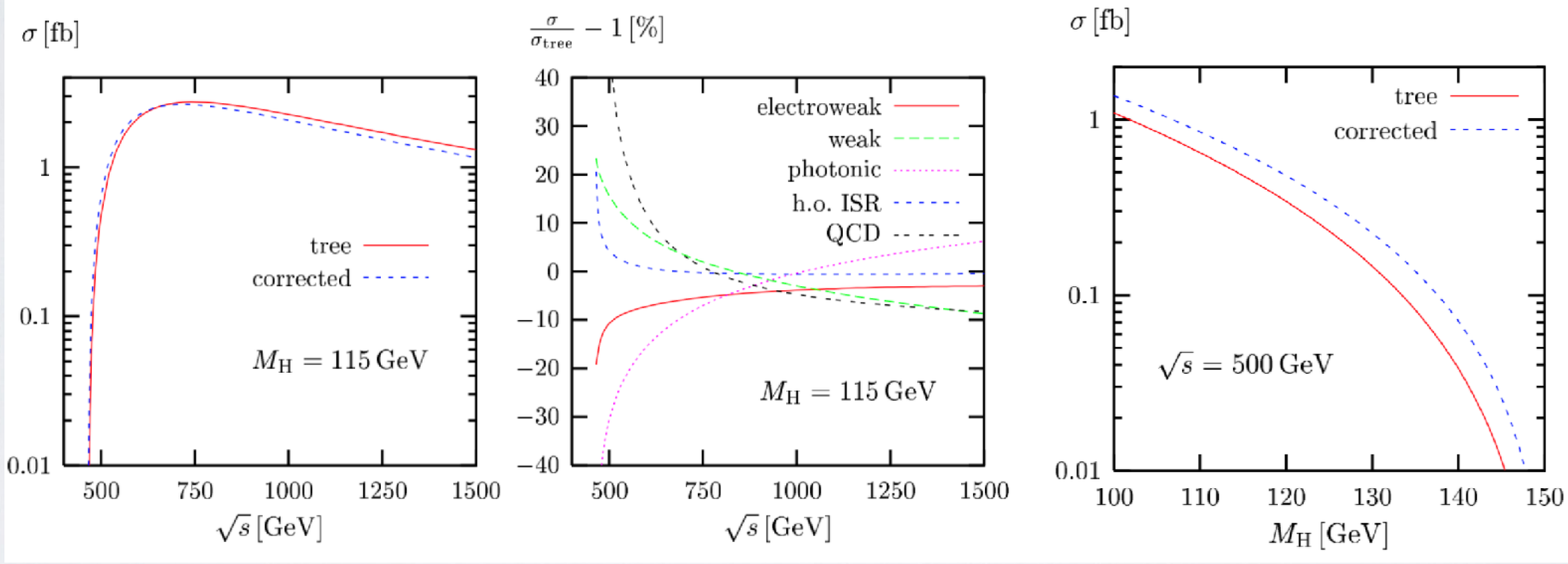
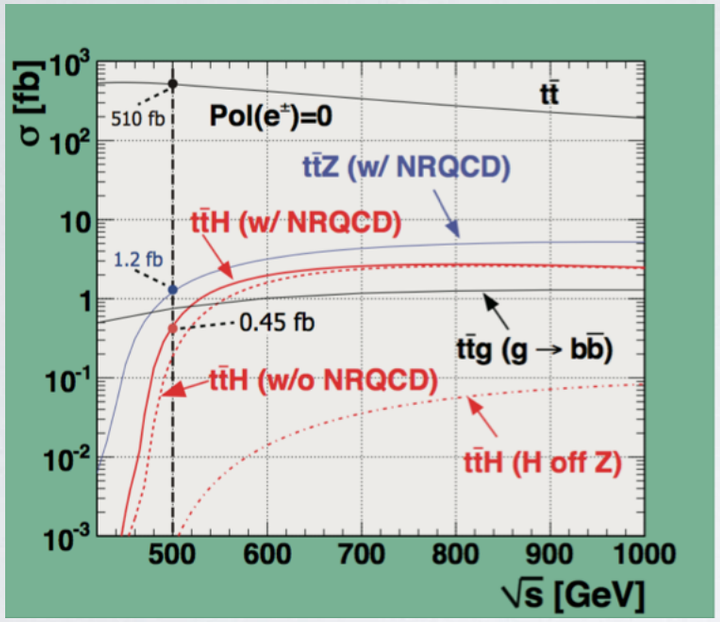
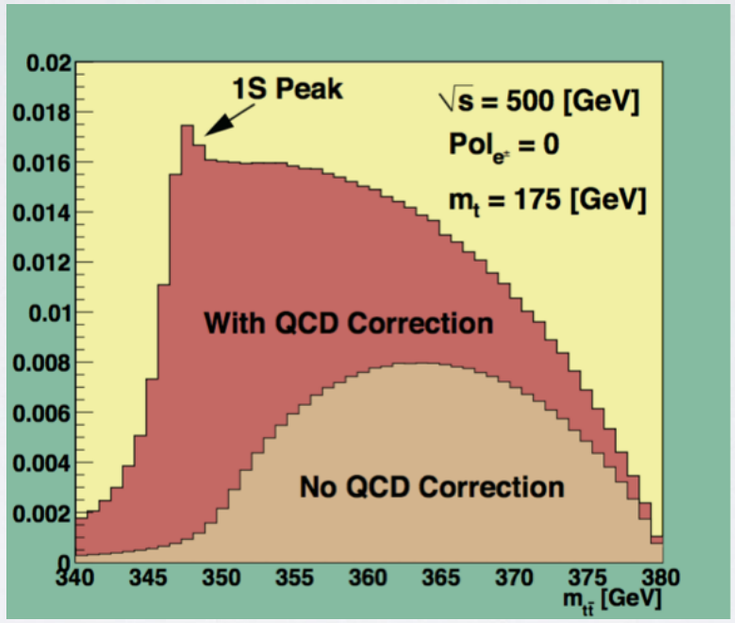


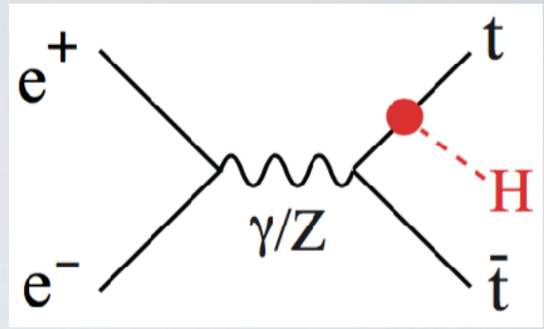
- Photonic and gluonic corrections largely cancel
- Large effects at threshold (ISR, but more so QCD → more soon)
- Depends crucially on Higgs mass: sweet spot for *M(h)* = 125 GeV is for *E* ~ 800 GeV

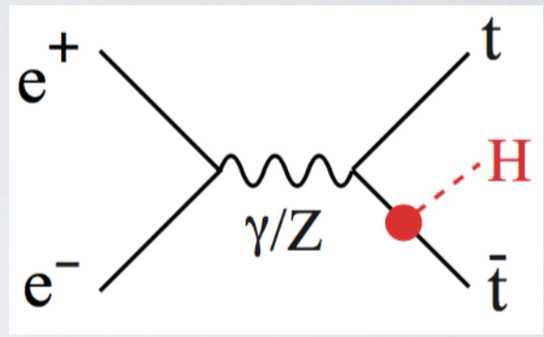
The top Yukawa coupling

- Measurement possible for $\sqrt{s} \gtrsim 500$ GeV [*tth* associated production]
- 8% Higgsstrahlung contamination, $Z^* \to tt$
- Cross section rises by factor of 4 between 500 and 550 GeV (!)
- Slight enhancement at threshold due to QCD Coulomb gluons









The top Yukawa coupling

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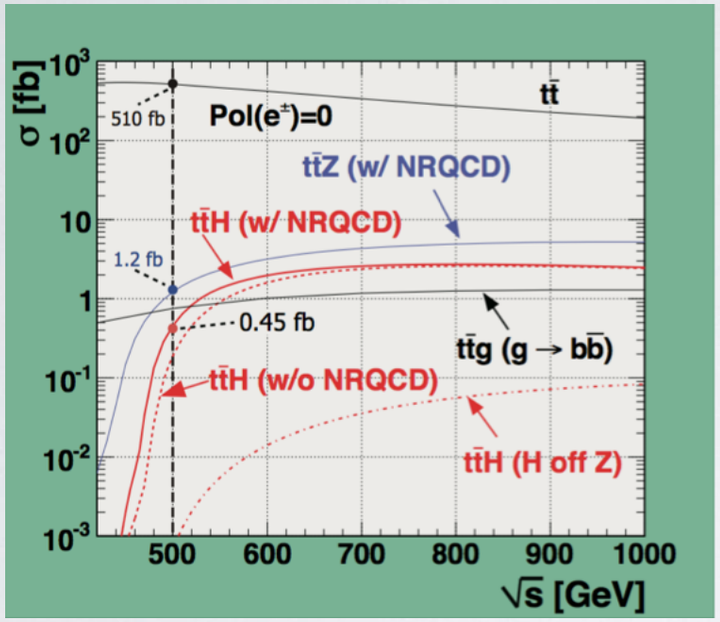

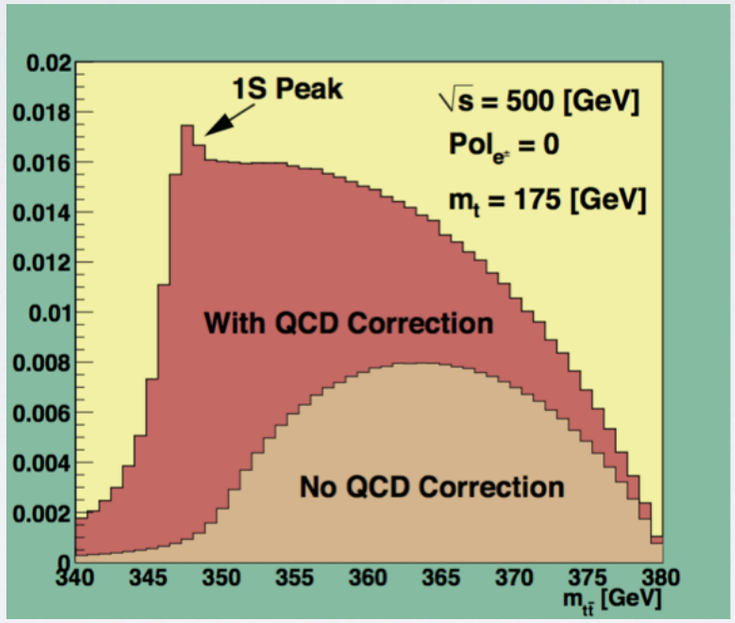

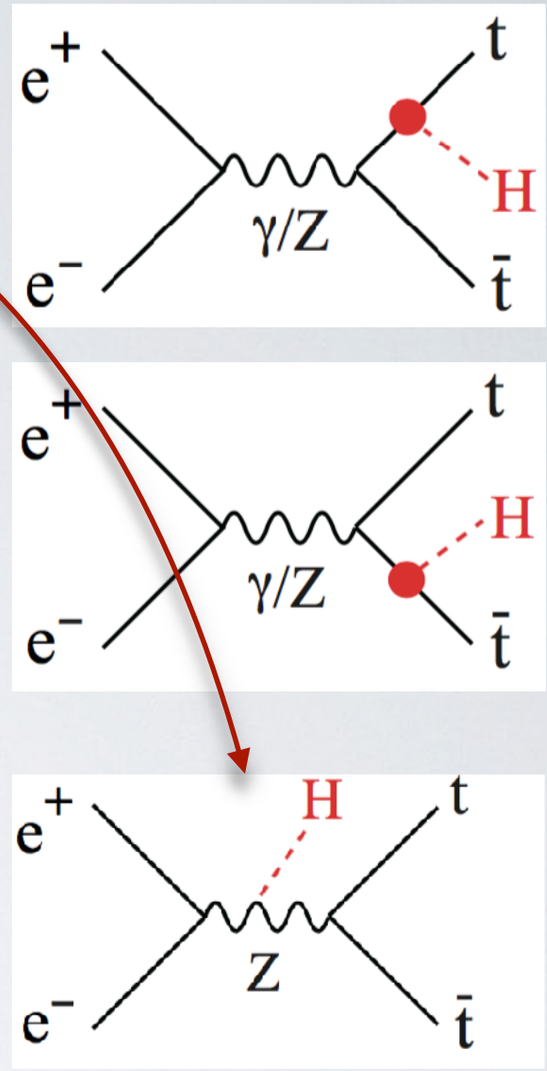

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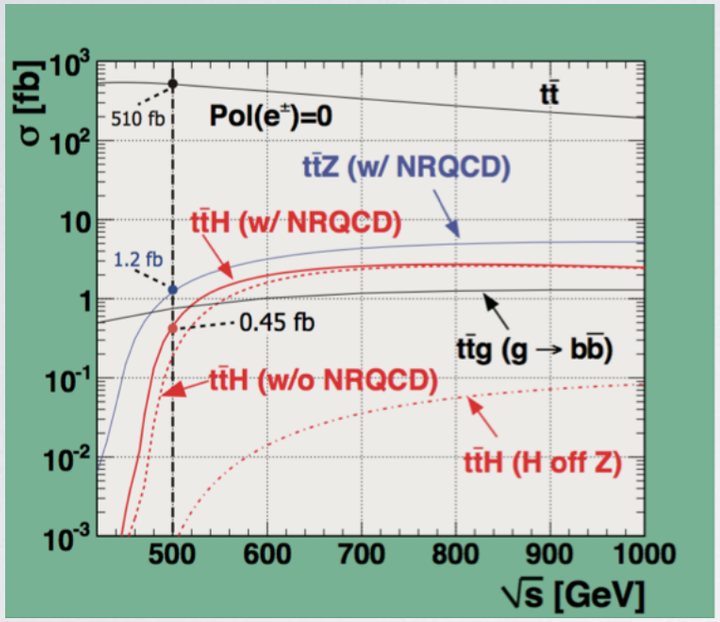

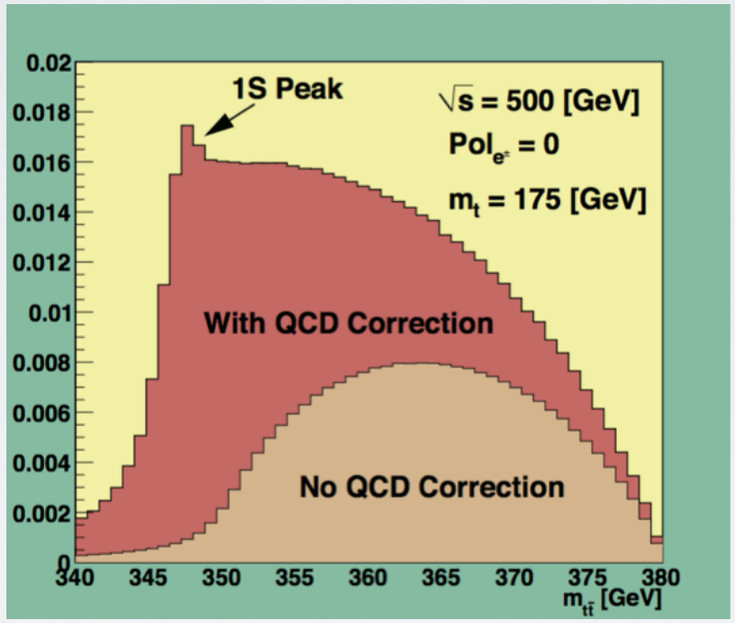

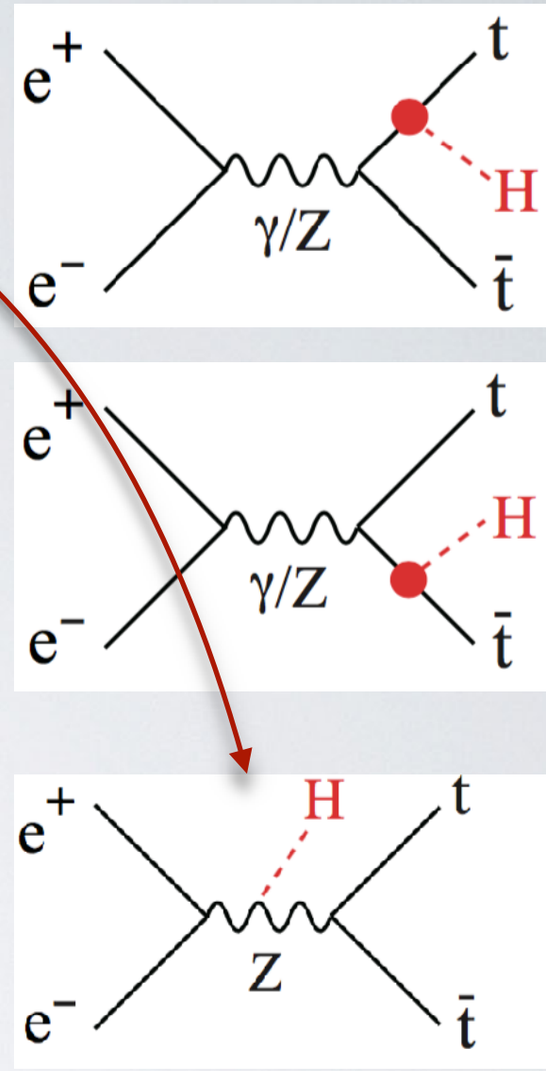

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- Larger xsec, (much) less *tt* bkgd.
- Simulation demanding !!!
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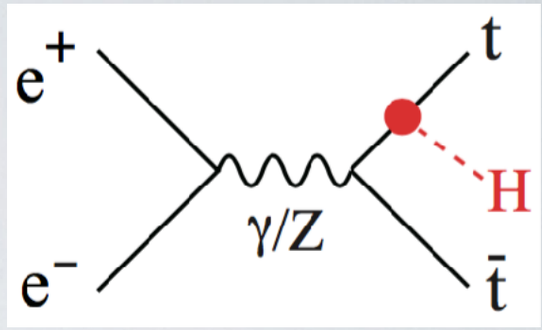

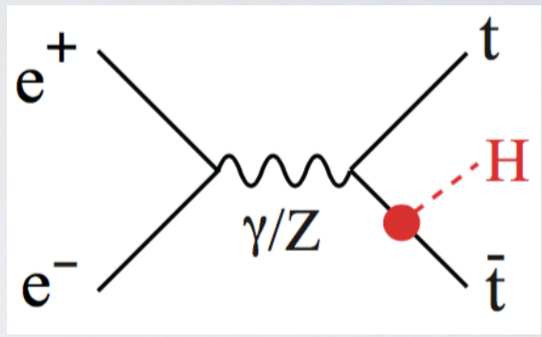

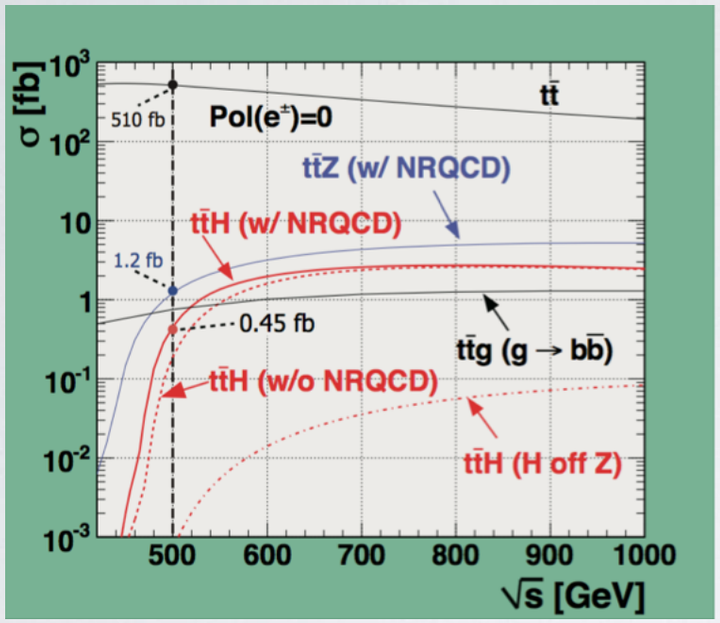

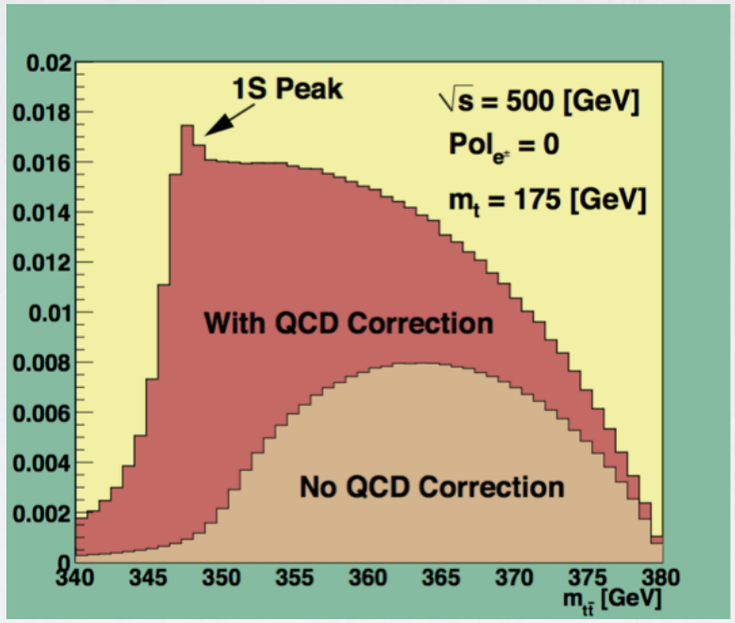

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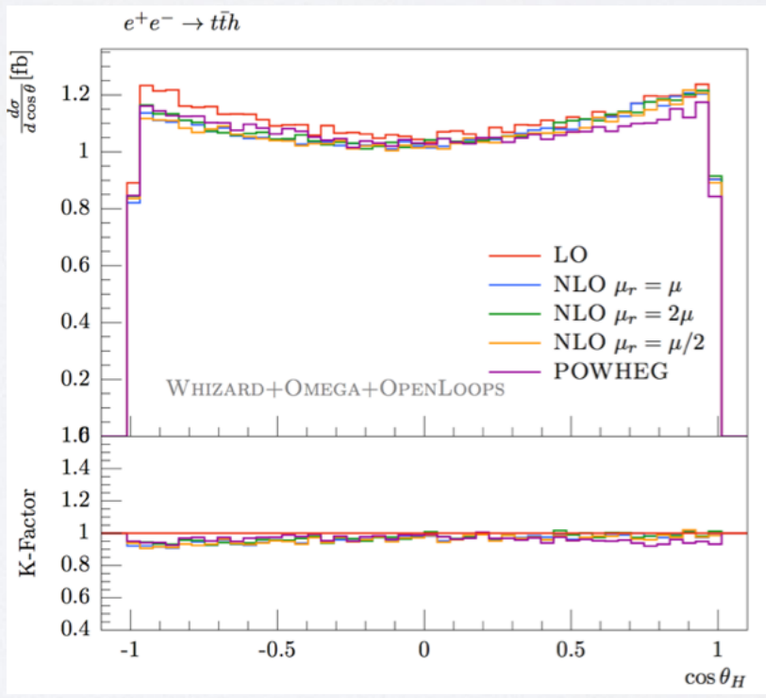
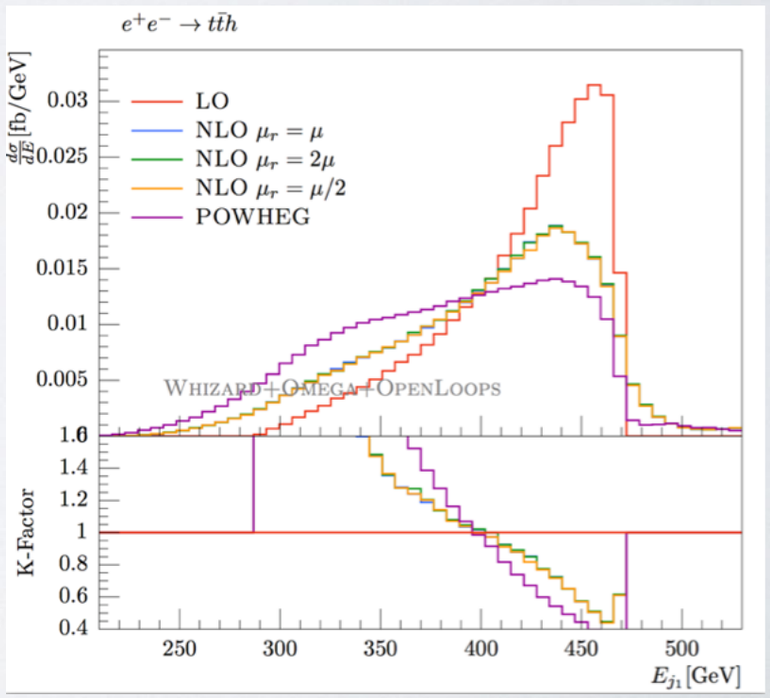
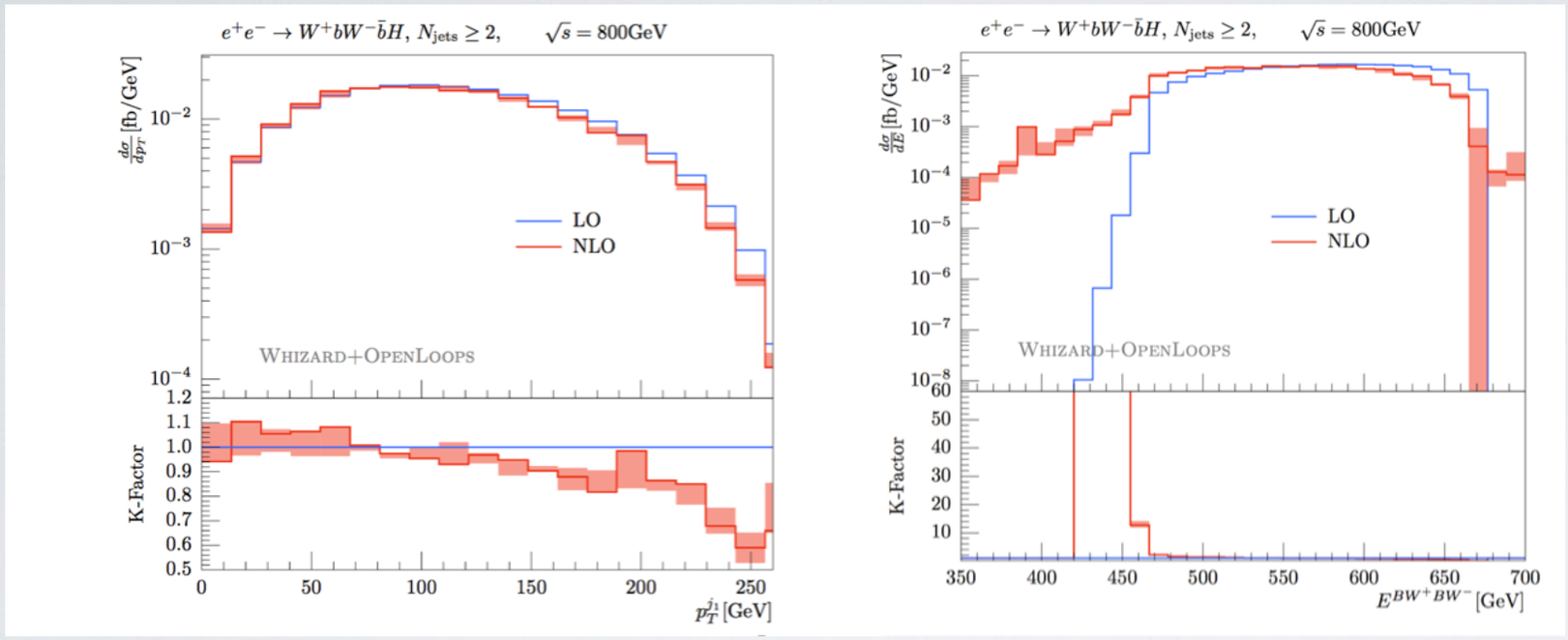
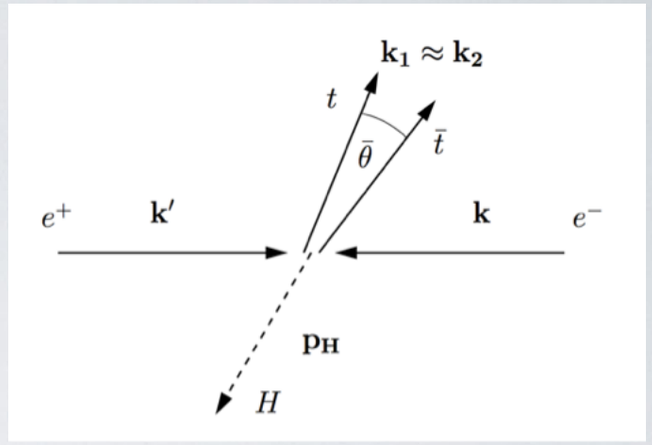




Differential Results for off-shell *ttH*





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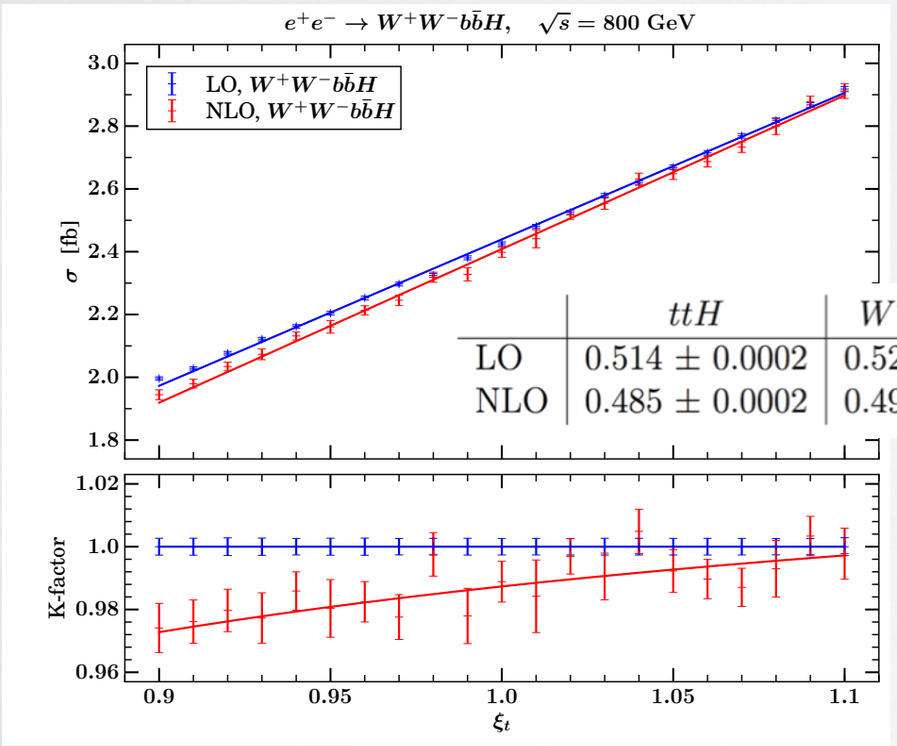
Determination of top Yukawa coupling (*ttH*)



	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, 2016

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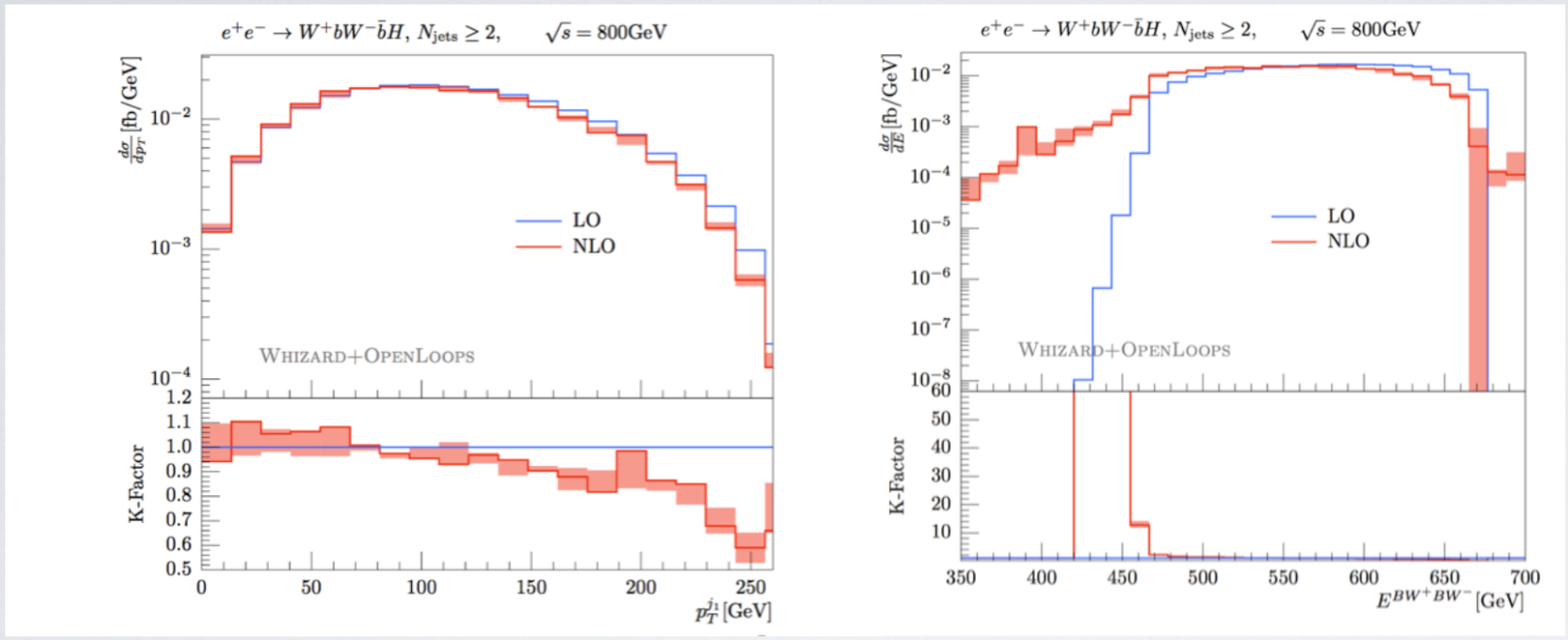

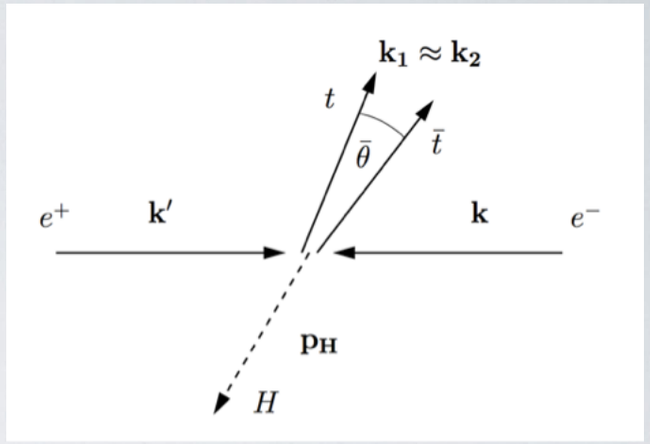

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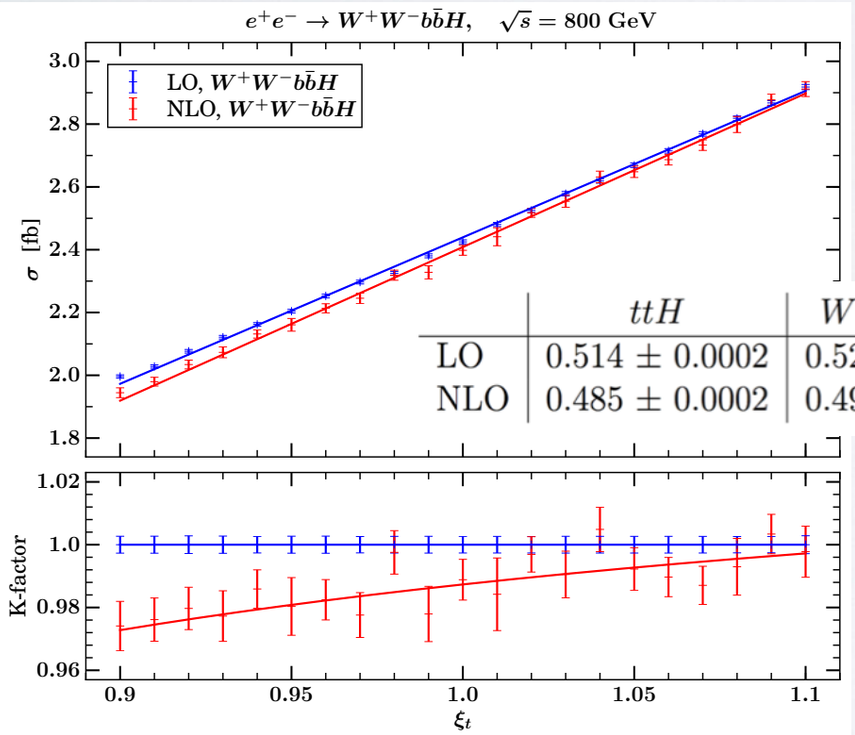

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Polarized Results (*tt*)

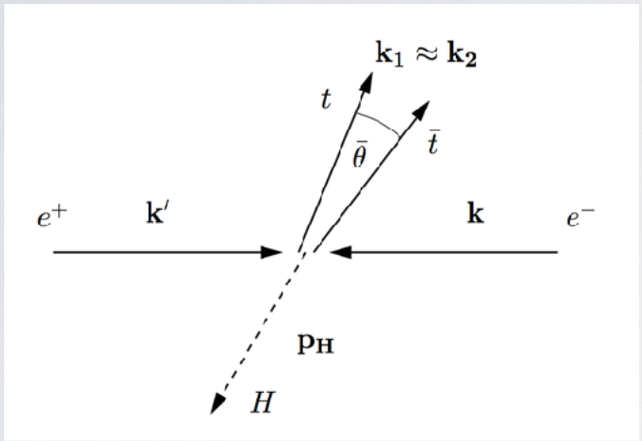
- ILC will always run polarized
- Polarized 1-loop amplitudes beyond BLHA

$P(e^-)$	$P(e^+)$	$\sqrt{s} = 800$ GeV σ^{LO}[fb]	σ^{NLO}[fb]	K-factor	$\sqrt{s} = 1500$ GeV 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, 2016

Threshold enhancement @ 500 GeV for tth

- Close to threshold: Coulomb enhancement of non-relativistic top pair
- Energy distribution of Higgs enhanced in top pair recoil [Farrell/Hoang, 2005-2006]



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Enhancement most pronounced in Higgs energy distribution

$$\lim_{E_h \to E_h^{\max}} \frac{d\sigma(e^+e^- \to t\bar{t}h)}{E_h} \quad \longrightarrow \quad \text{vNRQCD resummation}$$

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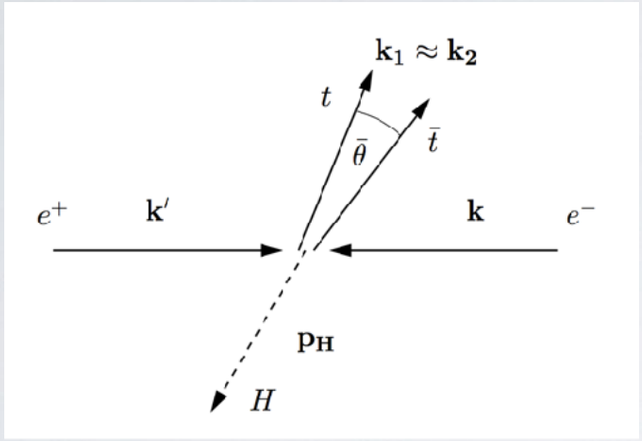

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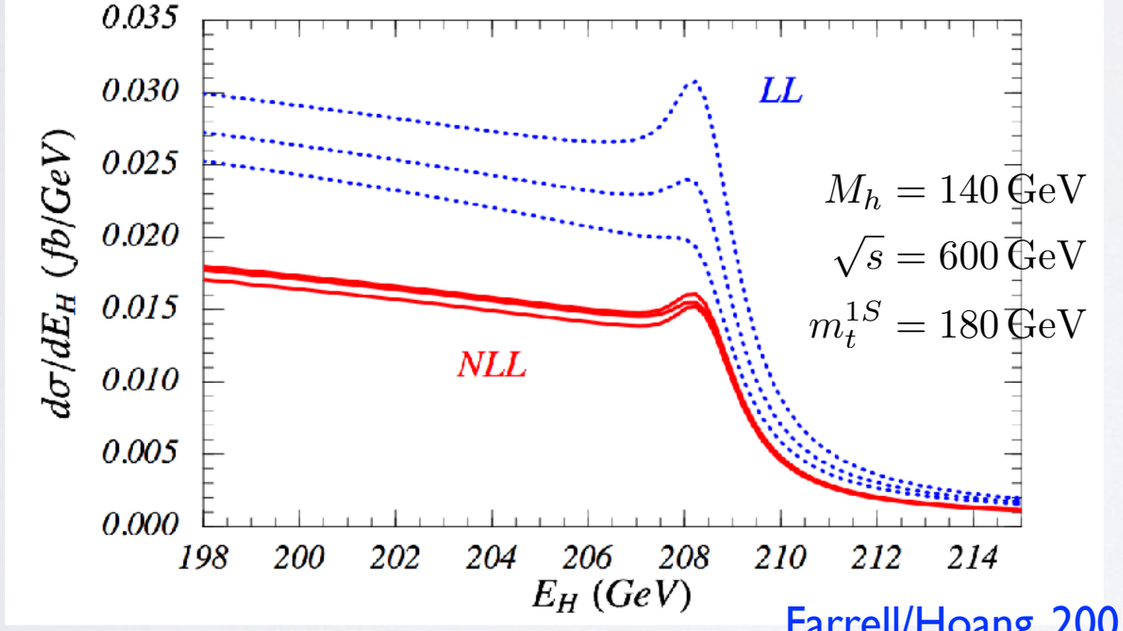

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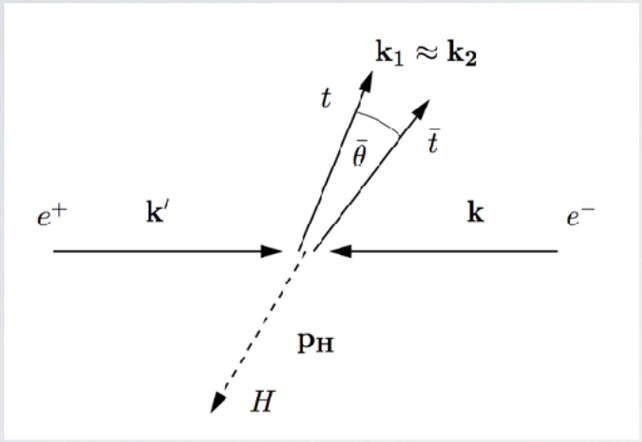

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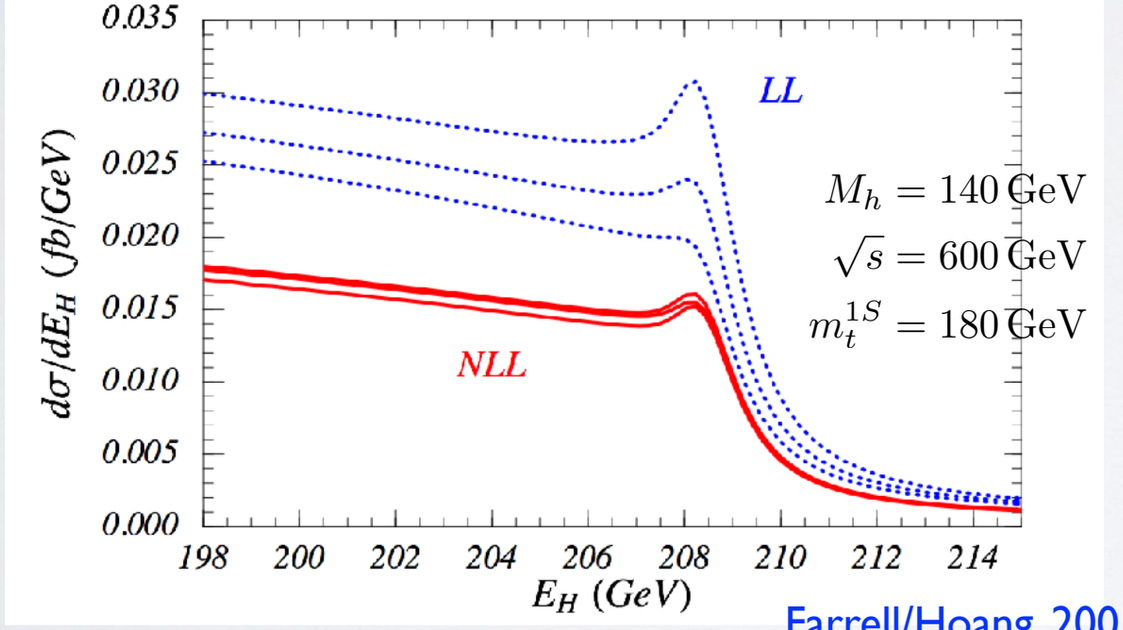

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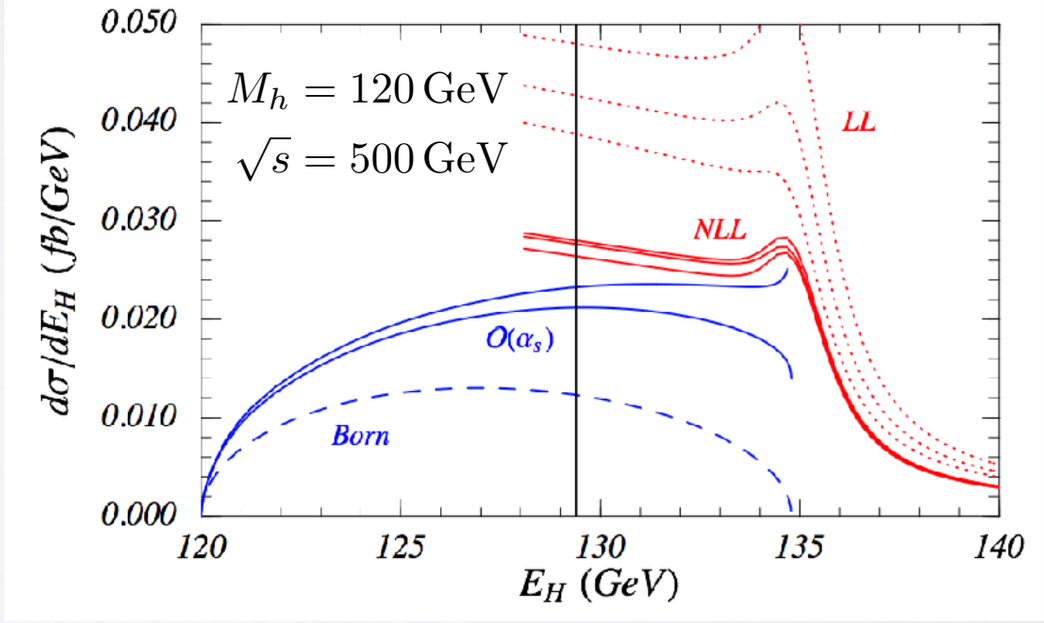

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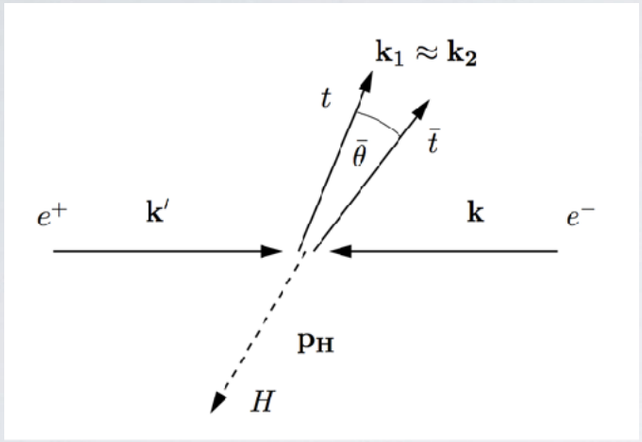

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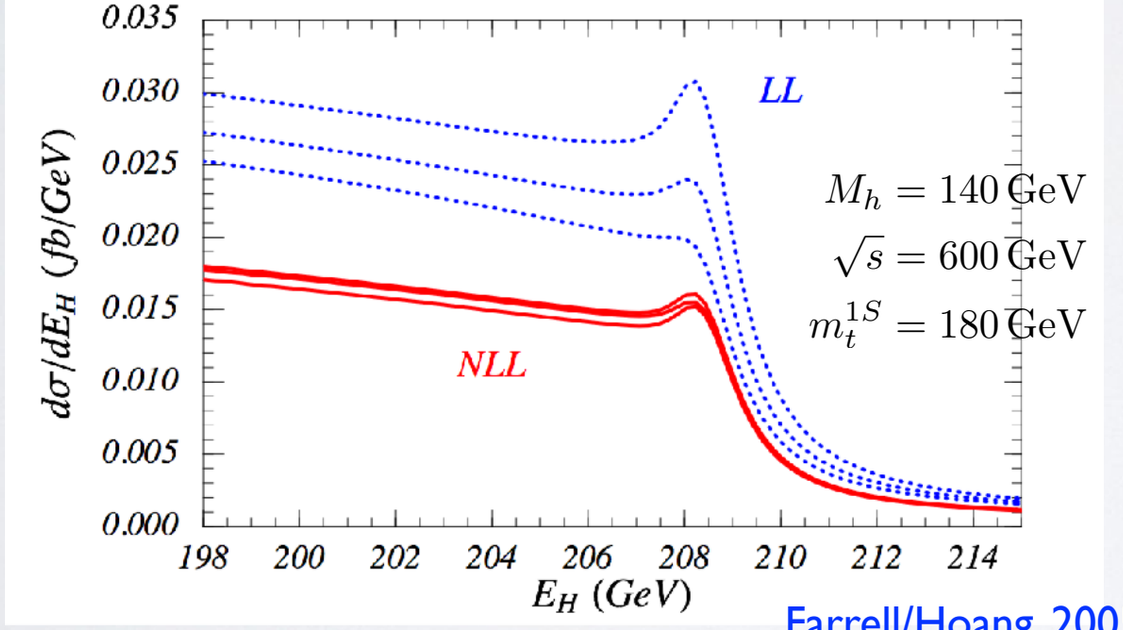

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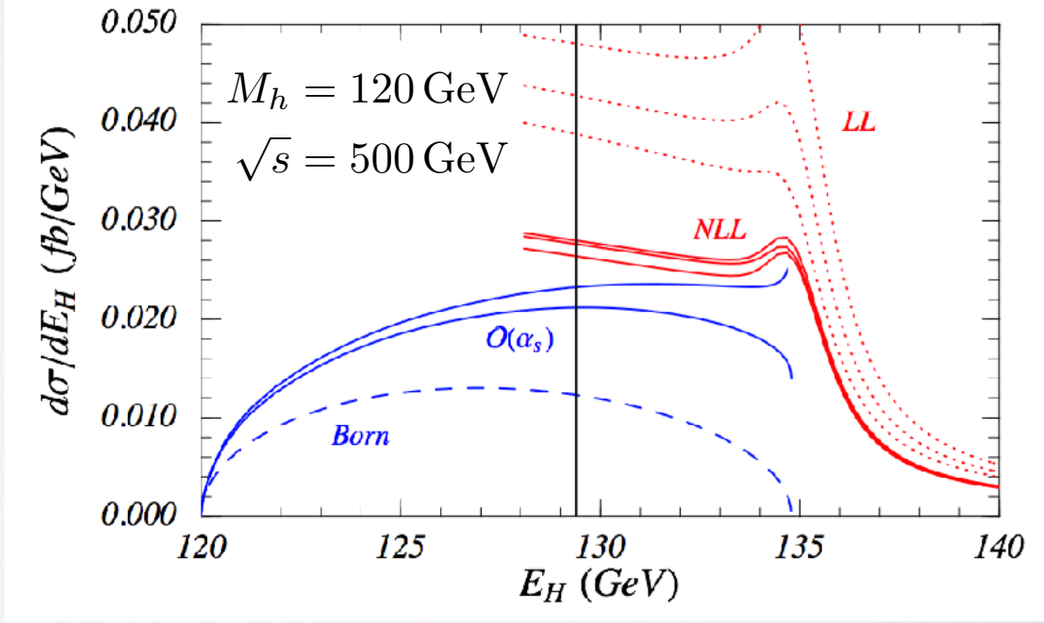
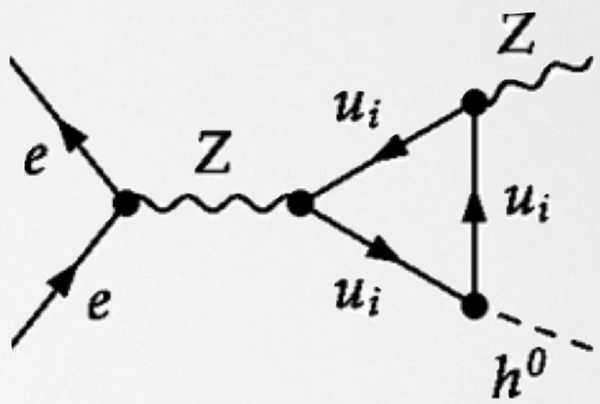


- Goal: properly matched NLL threshold/NLO cont. [Chokoufe/Hoang/JRR/Stahlhofen/Weiss, *in prep.*]

Top Physics for 5.99 Billion $?

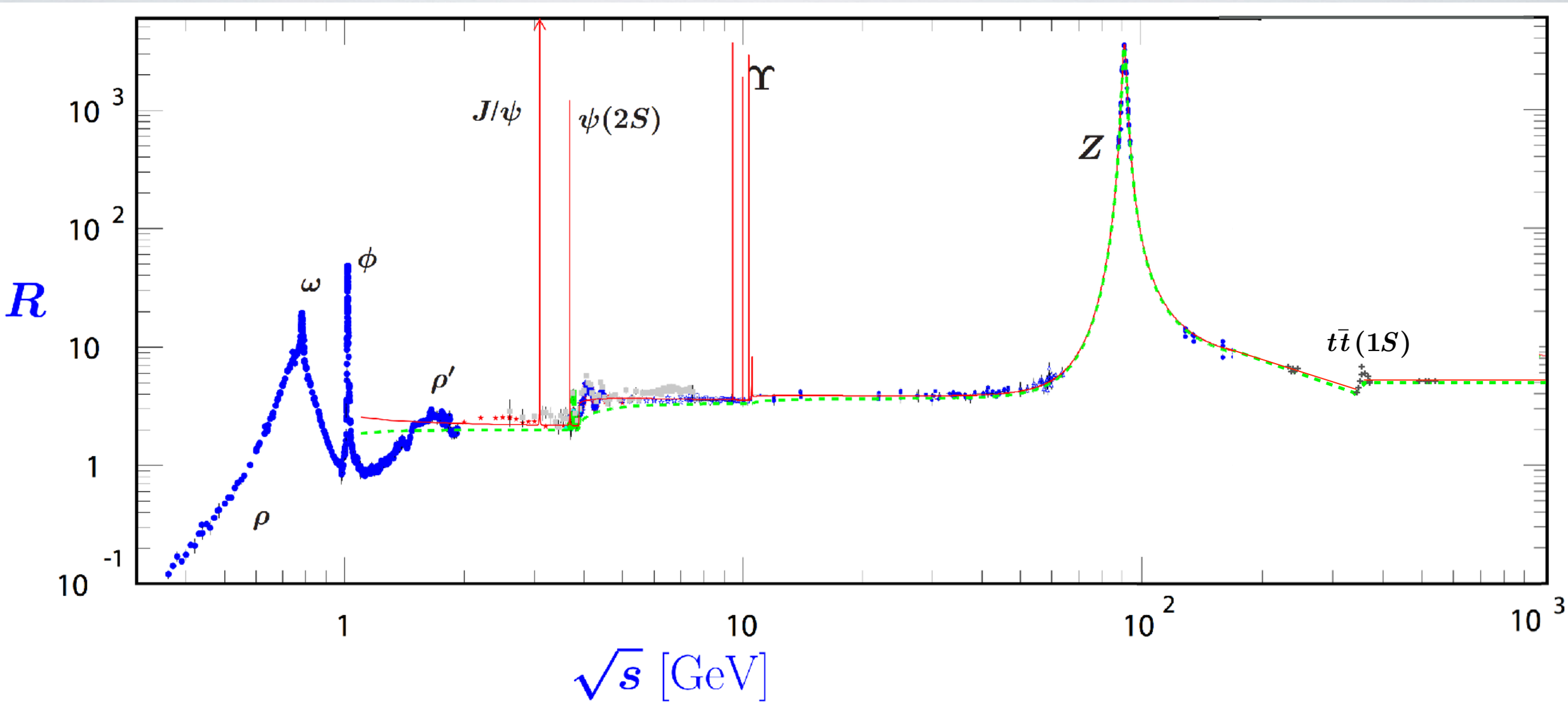
- Staged approach: start at 250 GeV without dedicated top programme
- Off-shell top measurements from *WbWb* continuum
- Equiv. to single top: $tWb \longrightarrow WbWb$
- No recent systematic study: interplay of QCD and EW corrections
- Top mass determination from Higgs recoil measurement (radiative corr.)



Conclusions & Outlook

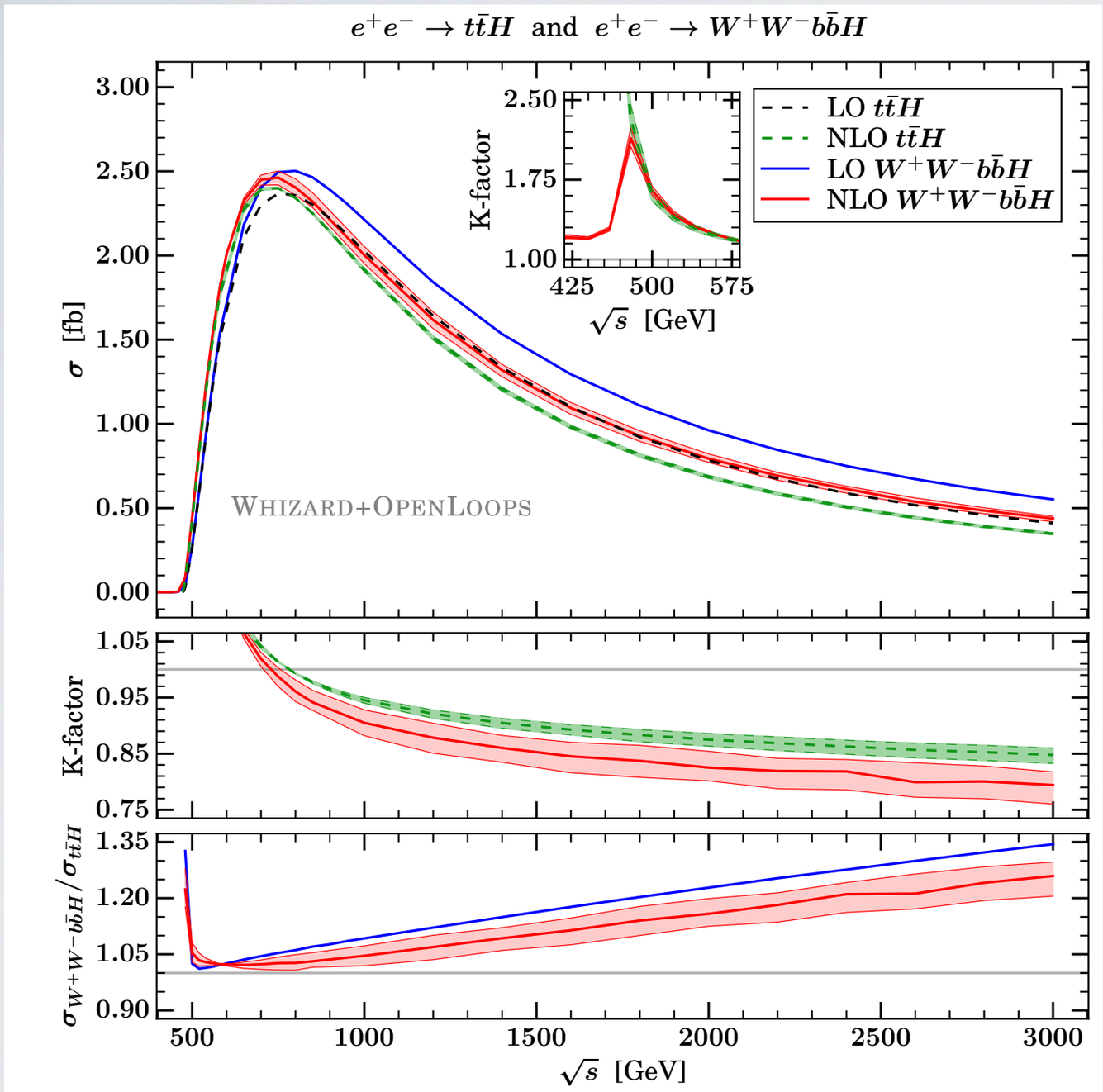
- Precision measurements at ILC elucidate top [-Higgs] sector
- Determination of fundamental parameters: m_t , Y_t , g_t^L , g_t^R
- BSM reach in top sector supersedes LHC searches in most models
- For almost all measurements: theory uncertainties dominate
- NLO QCD corrections well under control (10% at max, 1-2% at 3 TeV)
- Differential results as NLO fixed-order histograms (at the moment)
- Need for combined & matched NLO QCD+EW corrections in the future
- Work on this has started, also for the inclusion in event generators
- Top threshold in e+e-: measure top quark with ca. 50 MeV precision
- Assessment of theory uncertainties (NNLL + N(NN)LO matching)

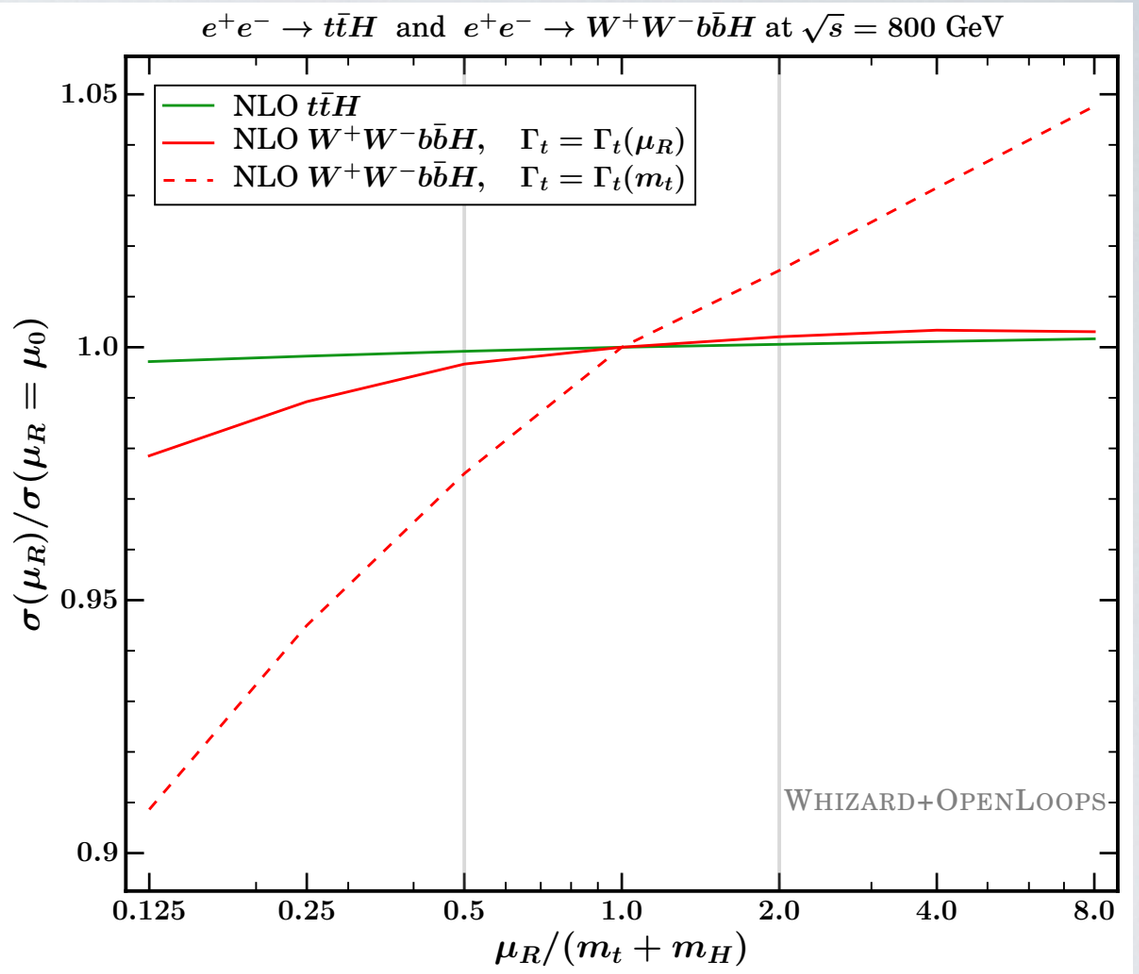
Looking forward to future data



BACKUP SLIDES

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

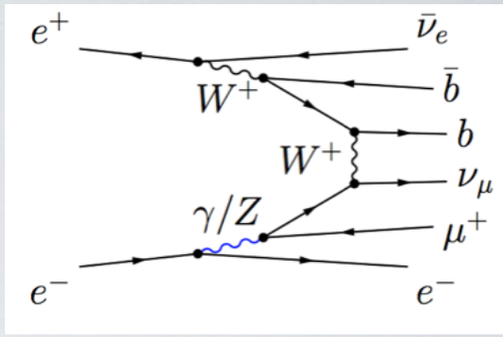




	$e^+e^- \to t\bar{t}H$			$e^+e^- \to W^+W^-b\bar{b}H$		
$\sqrt{s}$ [GeV]	σ^{LO}[fb]	σ^{NLO}[fb]	K-factor	σ^{LO}[fb]	σ^{NLO}[fb]	K-factor
500	0.26	$0.42^{+3.6\%}_{-3.1\%}$	1.60	0.27	$0.44^{+2.6\%}_{-2.4\%}$	1.63
800	2.36	$2.34^{+0.1\%}_{-0.1\%}$	0.99	2.50	$2.40^{+2.1\%}_{-1.9\%}$	0.96
1000	2.02	$1.91^{+0.5\%}_{-0.5\%}$	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

ILC: *tt* and *ttH* (on- & off-shell)

- 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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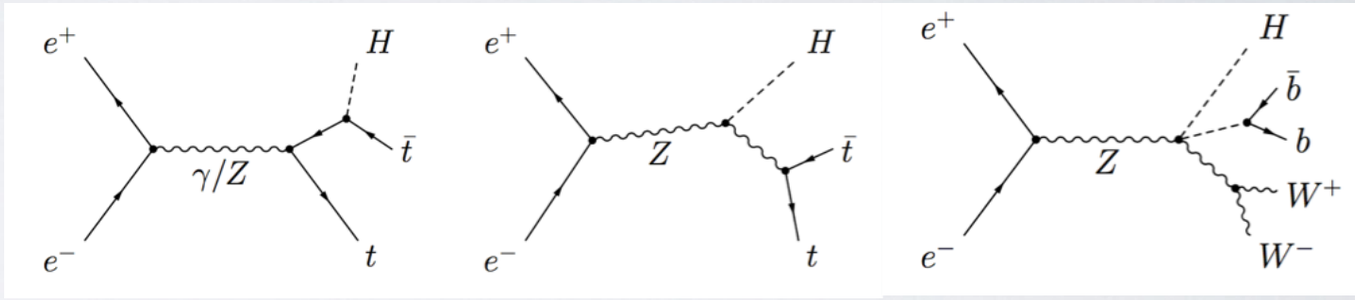
- Contribution from quartic SM vertices



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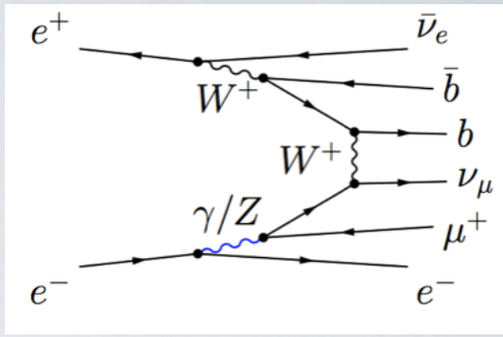

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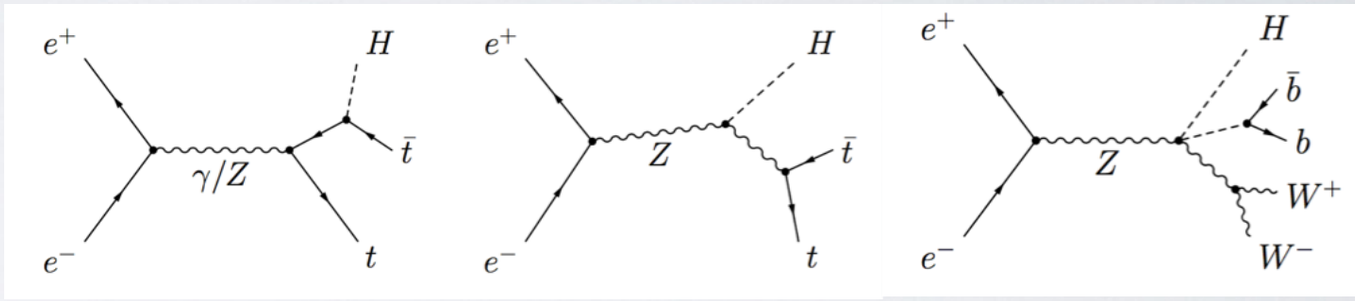


INPUT PARAMETERS:

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

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

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

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

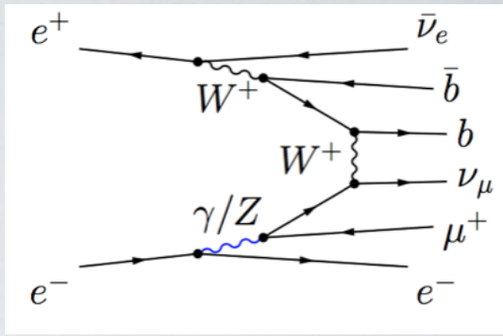
complex mass scheme:

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

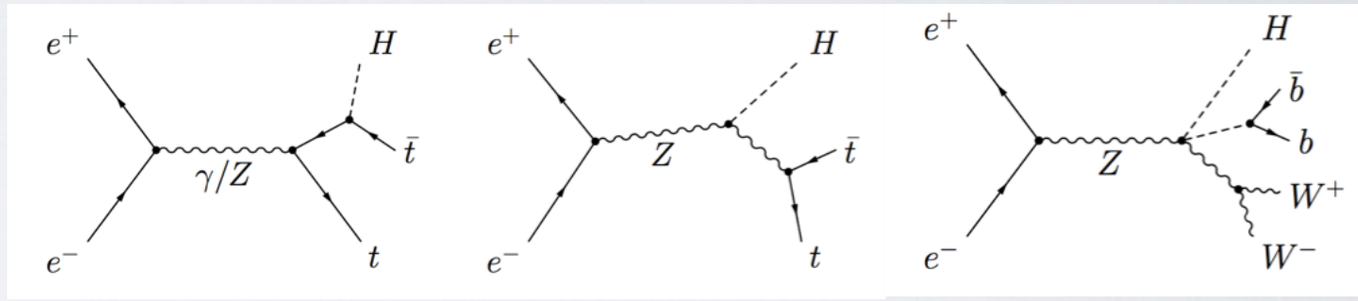
$$s_w^2 = 1 - c_w^2 = 1 - \frac{\mu_\mathrm{W}^2}{\mu_\mathrm{Z}^2}$$

ILC: *tt* and *ttH* (on- & off-shell)

- Using massive *b* quarks: no cuts necessary for $e^+e^- \to W^+W^-bb$
- Full process $e^+e^- \to \mu^+\nu_\mu e^-\bar{\nu}_e bb$ exhibits Coulomb singularity:



- *ttH* production: 8% contamination from Higgsstrahlung
- Contribution from quartic SM vertices



INPUT PARAMETERS:

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

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

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

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

complex mass scheme:

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

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

- Typical pentagons/hexagons: