Top Physics at Threshold

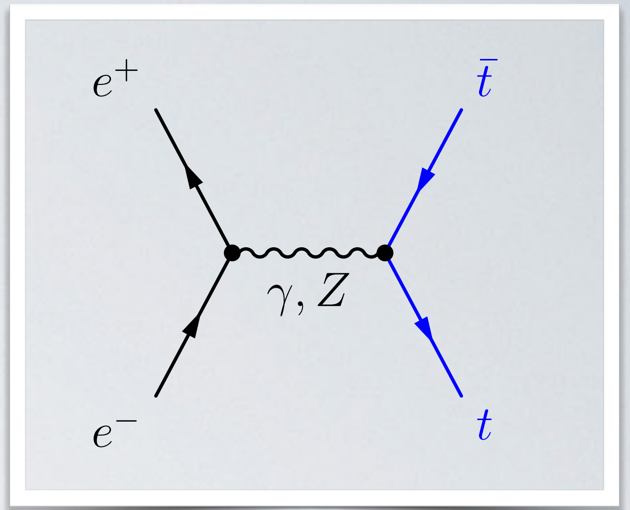
Jürgen R. Reuter, DESY

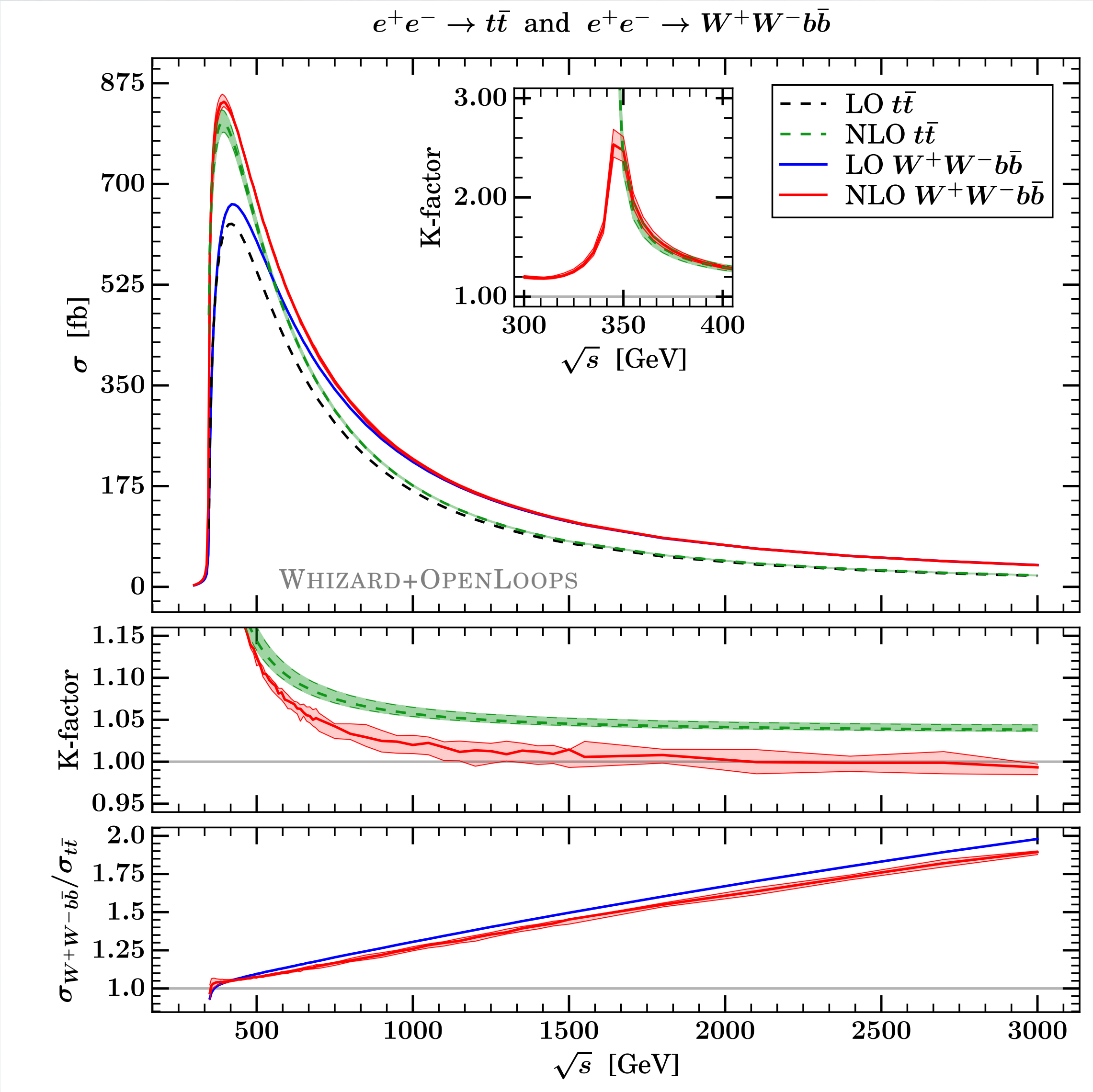
The Top as Window to New Physics

- Top Quark as only fermion has Yukawa coupling $\mathcal{O}(1)$
- Top decay happens before hadronization
- Either all other fermions are weird, or: Top quark is something special
- Top Quark could be **composite object** (e.g. if the Higgs were)
- Effect on Higgs potential: Top plays special role in EWSB
- Higgs used for Top Physics — and vice versa
- Top Quark portal to new physics
- Precision studies of the top quark needed

Top Quark Production

- s-channel production cross section: 0.1 - 1 pb (sub-TeV)
- 500 fb^{-1} : 500,000 top pairs @ threshold
- 4 ab^{-1} : 2,800,000 top pairs @ 500 GeV





- Access to vector- and
- axial-vector *ttZ* couplings
- Top helicities available from
- lepton / jet distributions

[For higher lepton energies]

- Major bkgd for EW measurements (*VVV* and VBS); any [most] BSM searches

Top Production & Decay: Theory Status

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

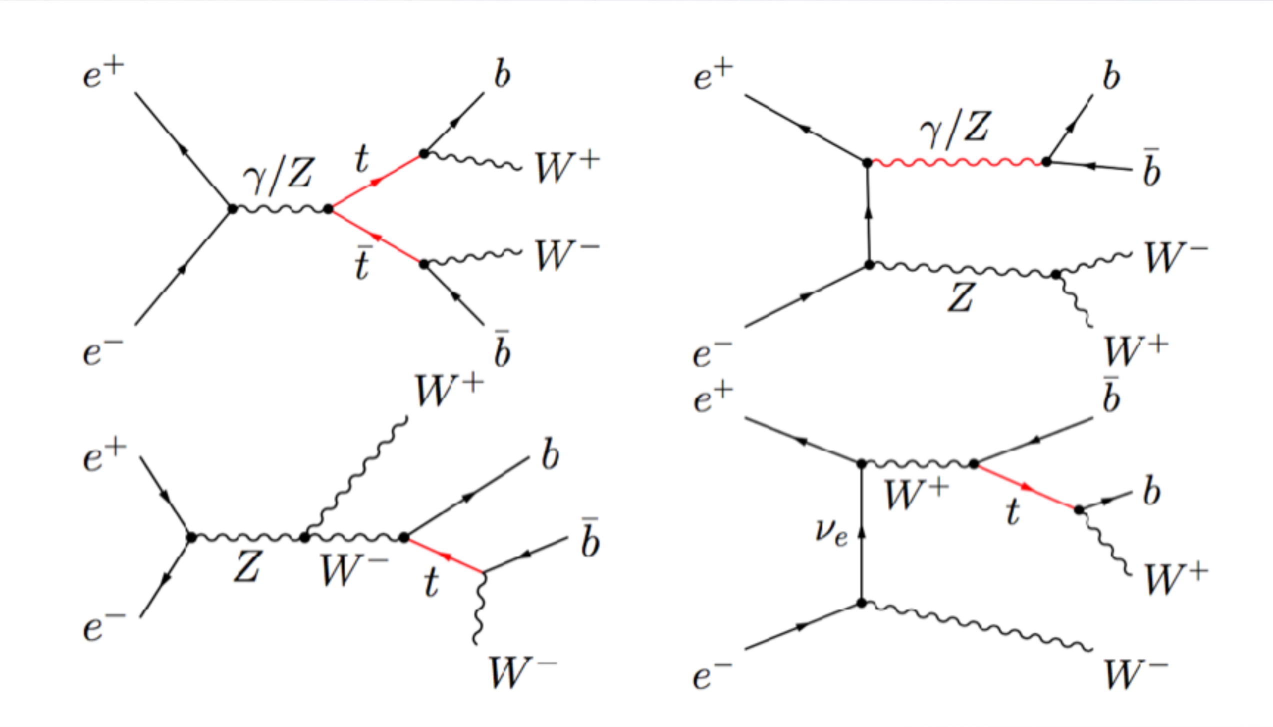
- NLO QCD [Jersak/Laermann/Zerwas, 1982]
- NNLO QCD [Chetyrkin/Kühn/Steinhauser, 1996; Harlander/Steinhauser, 1998; Chen/Dekkers/Heisler/Bernreuther/Si, 2016]
- NLO EW [Beenakker/von der Marck/Hollik, 1991; Beenakker/Denner/Kraft, 1993; Akhundov/Bardin/Leike, 1991]
- Threshold enhancement [Fadin/Khoze, 1987; Strassler/Peskin, 1991; Jezabek/Kühn/Teubner, 1992; Sumino et al., 1992]

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

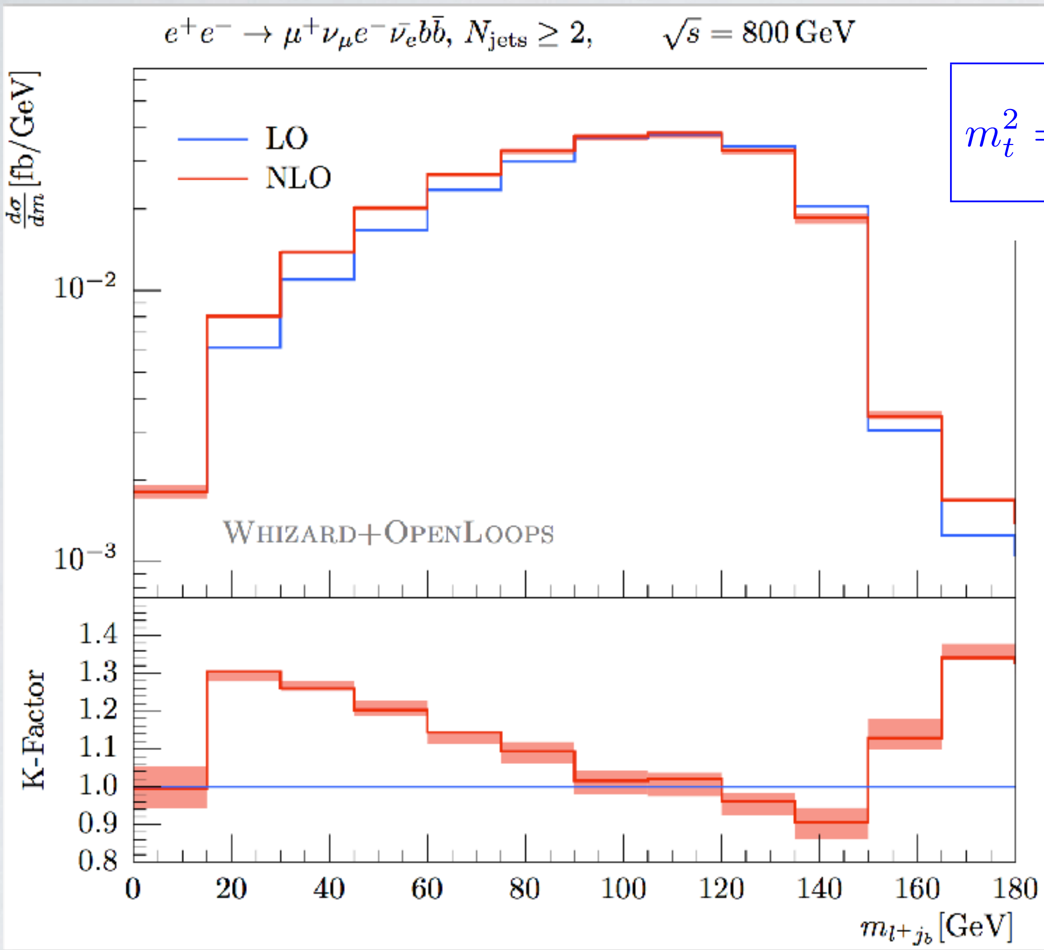
- NLO QCD [Guo/Ma/Wang/Zhang, 2008] ✘
- NLO QCD diff. [Chokoufe/JRR/Weiss, 2015; Liebler/Moortgat-Pick/Papanasthasiou, 2015; Chokoufe/Kilian/Lindert/JRR/Pozzorini/Weiss, 2016]

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

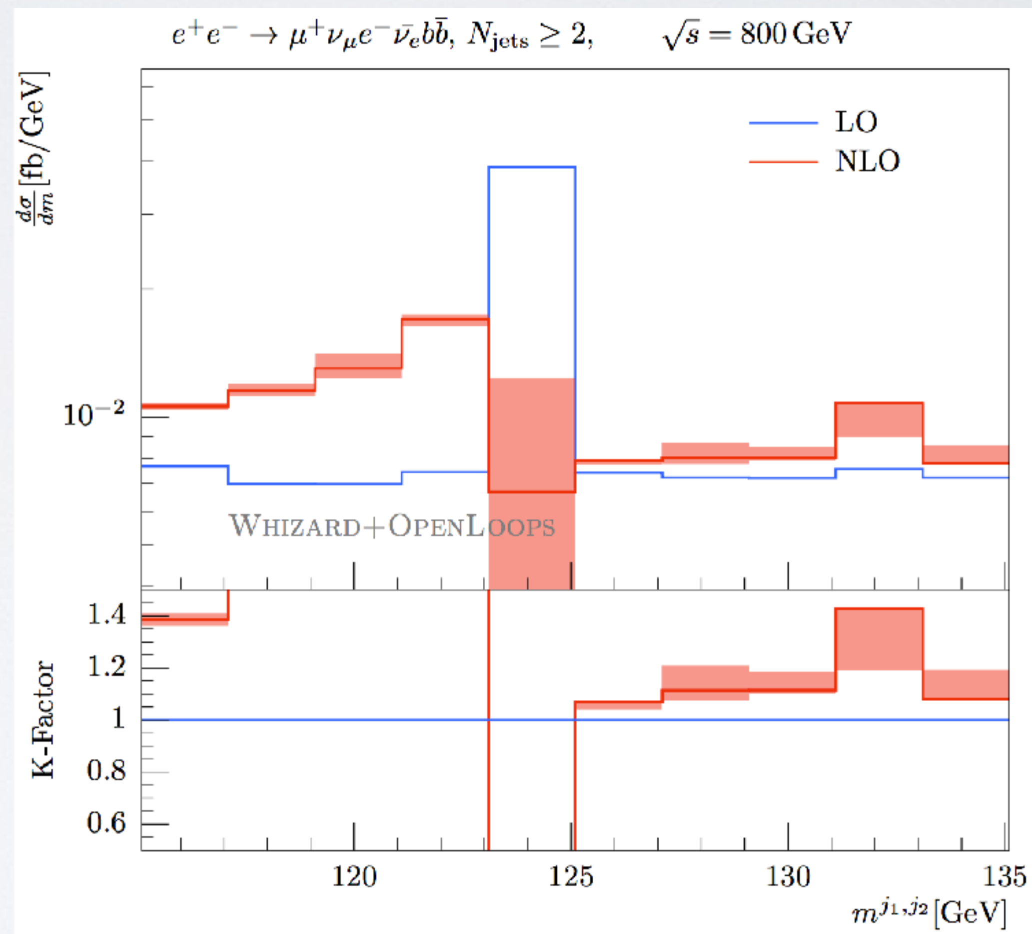
- NLO QCD [Jezabek/Kühn, 1989]
- NNLO QCD [Guo/Li/Zhu, 2012]



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



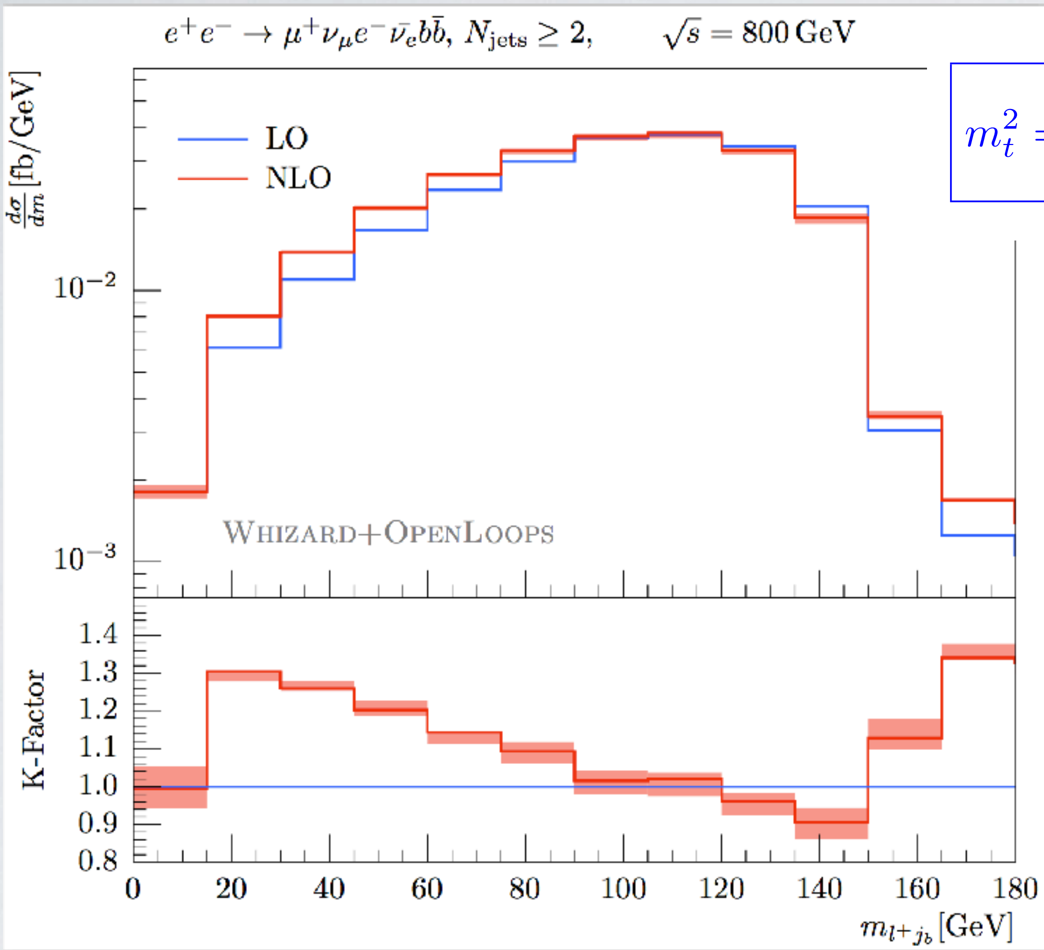
$$m_t^2 = m_W^2 + \frac{2\langle m_{\ell j_b}^2\rangle}{1 - \langle\cos\theta_{\ell j_b}\rangle}$$



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

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

- Full process $e^+e^- \to \mu^+ \nu_\mu e^- \nu_e bb$ contains also $e^+e^- \to W^+W^- H$ (!)



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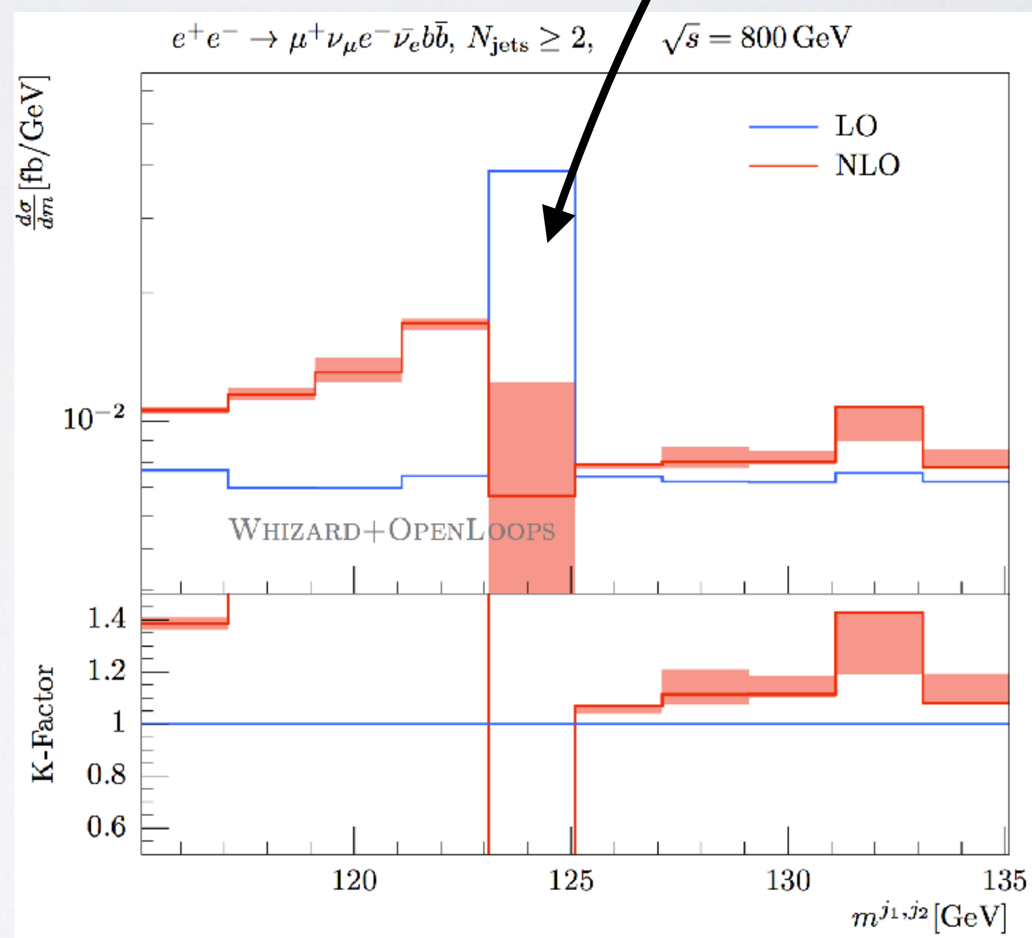

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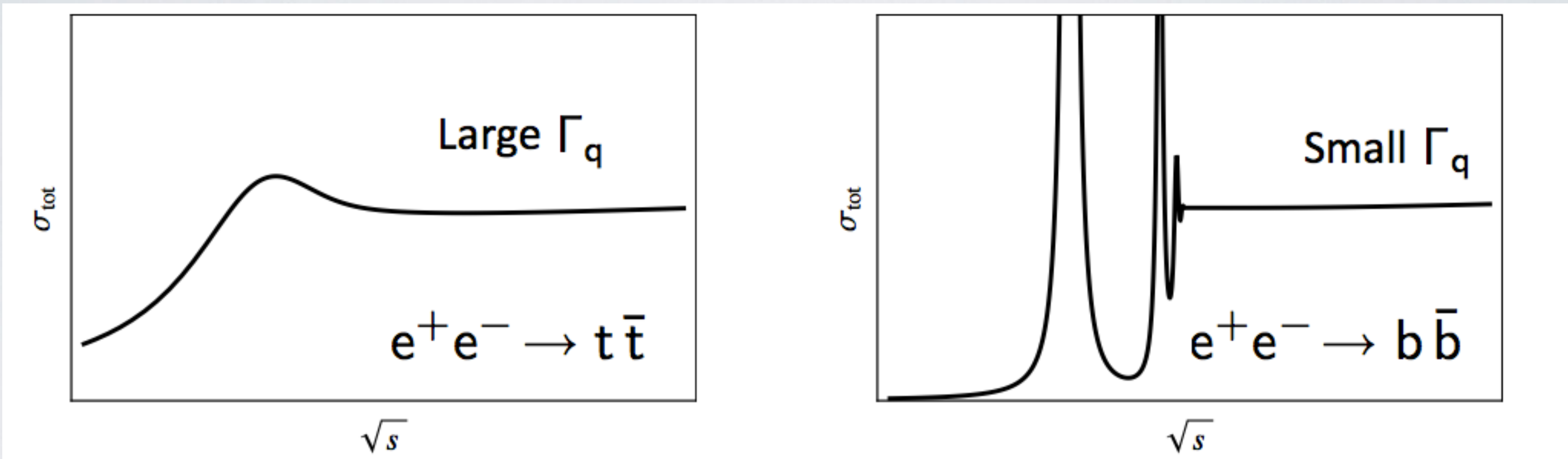
Top Mass Measurement: Threshold

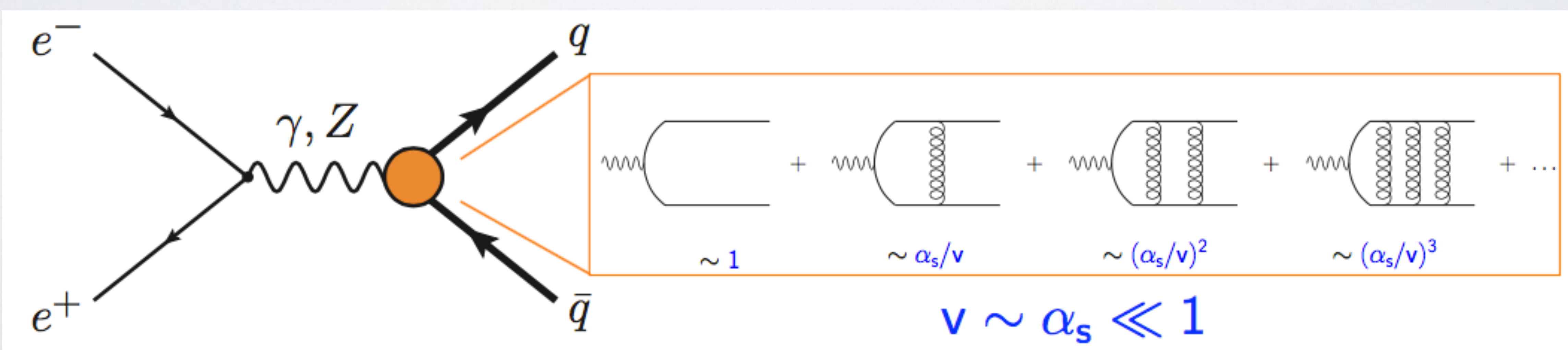
Top threshold scan best-known method to measure top quark mass, $\Delta M \sim 30\text{-}70$ MeV

Heavy quark production at lepton colliders, qualitatively:

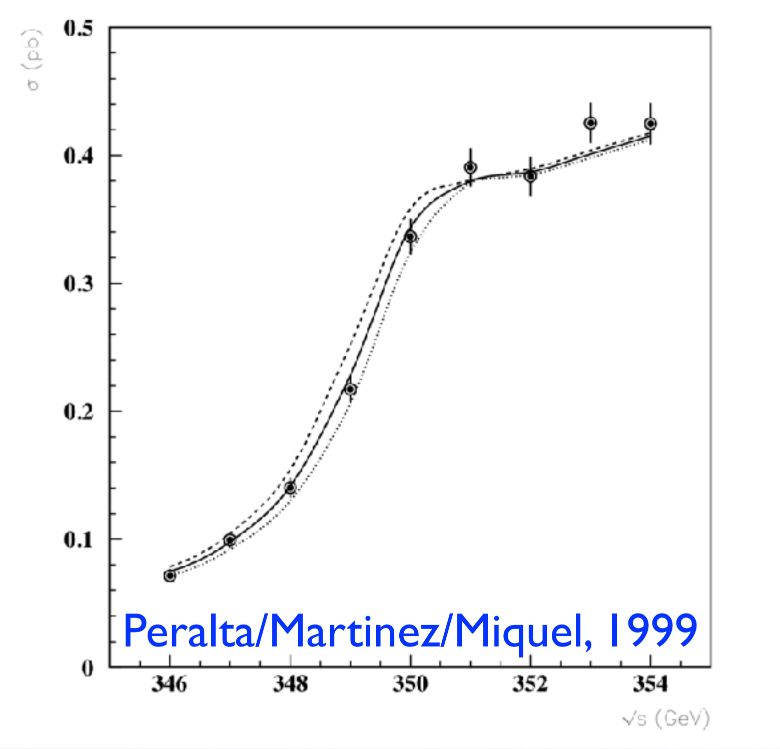


- Close to threshold: top quarks non-relativistic $v \sim \alpha_s \ll 1$
- Very strong QCD attraction due to "Coulomb" gluon exchange
- Leads to a remnant $1S$ toponium (quasi-) bound state

↪ Backup slide



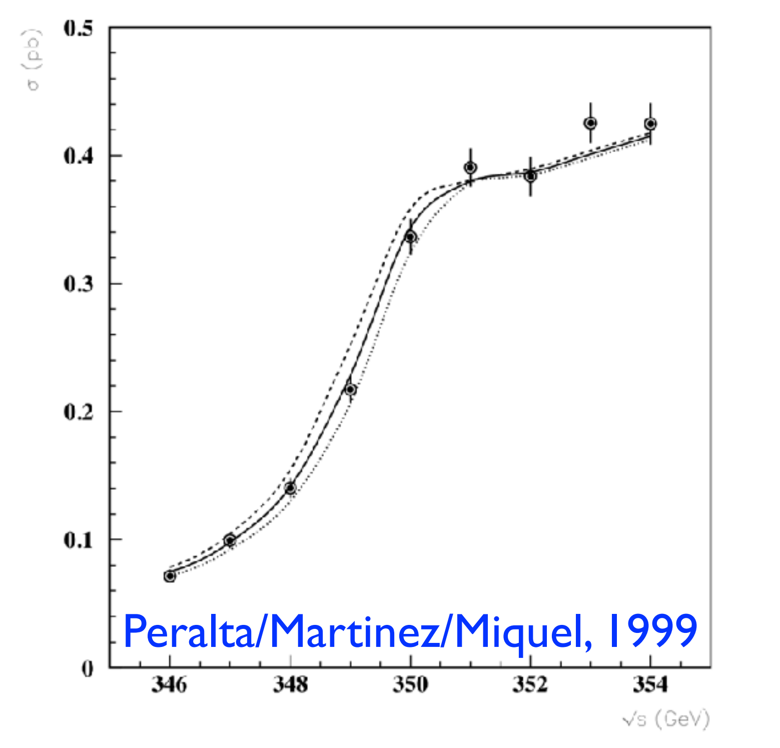
Top Threshold: overview of uncertainties



- ☑ Position and shape of threshold depends on M_{top}
- ☑ Hadron collider measurements: kinematic reco
- ☑ Top threshold uses well-defined (short-distance) mass definition ↪ Backup slide
- ☑ Joint theory/exp. effort to bring down uncertainties

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

Top Threshold: overview of uncertainties



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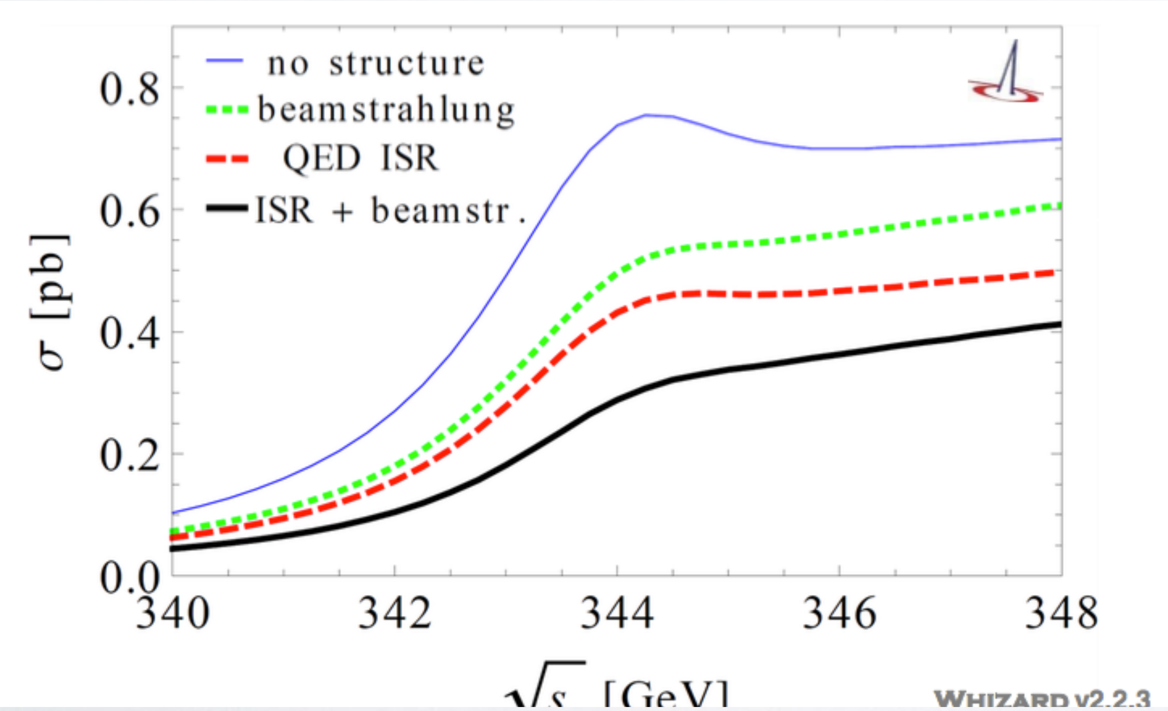

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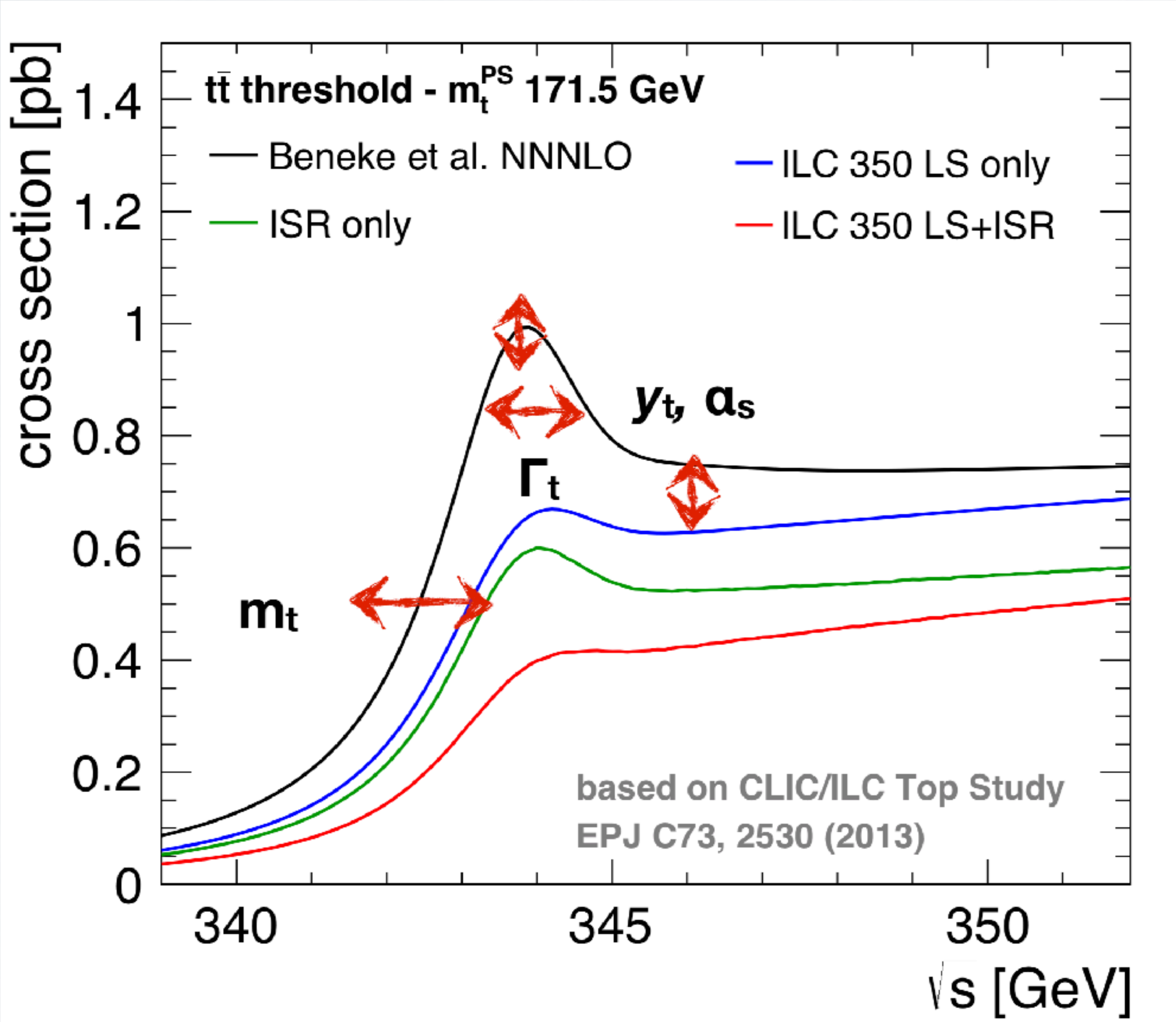
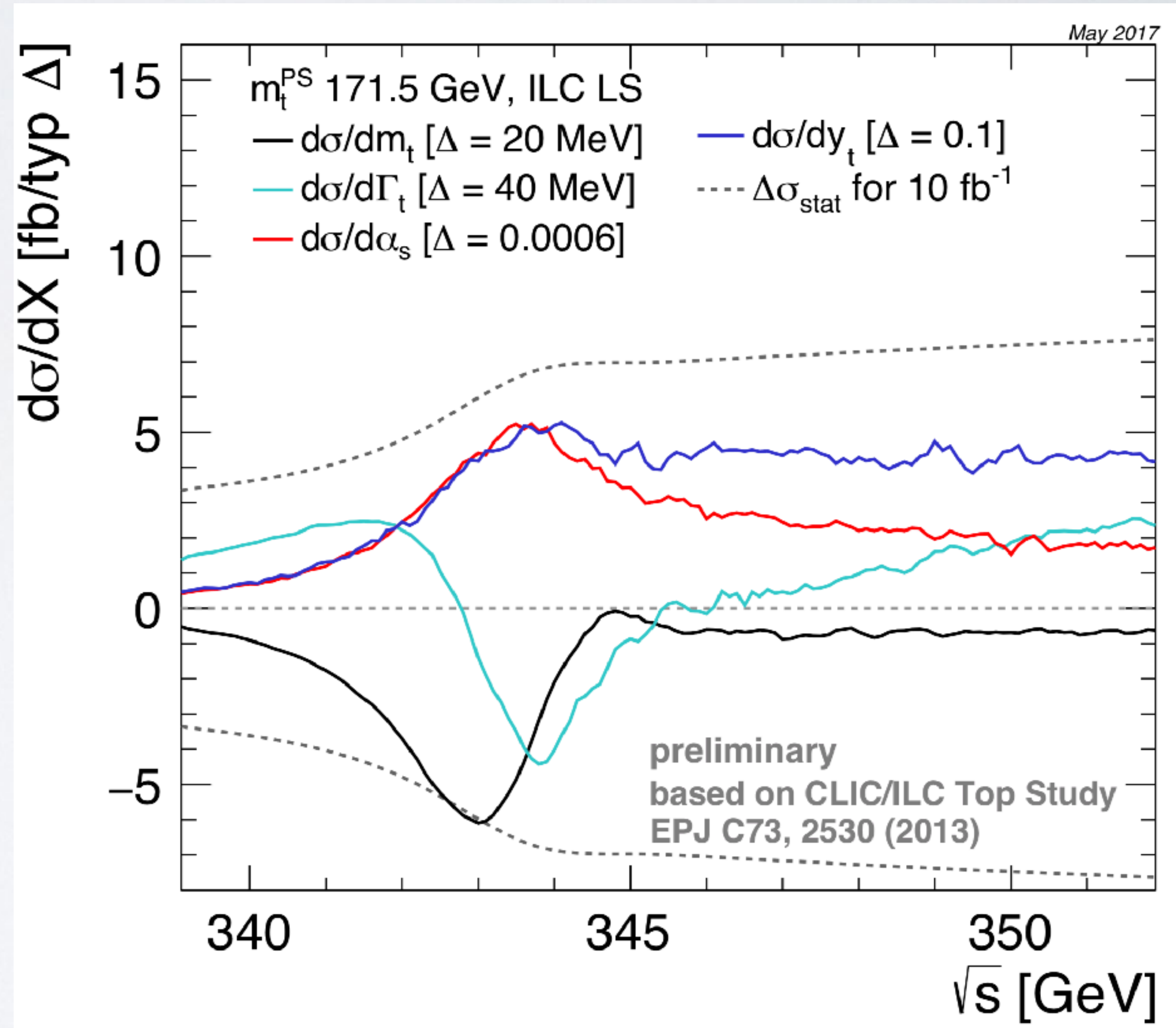
Top Threshold: parametric dependencies

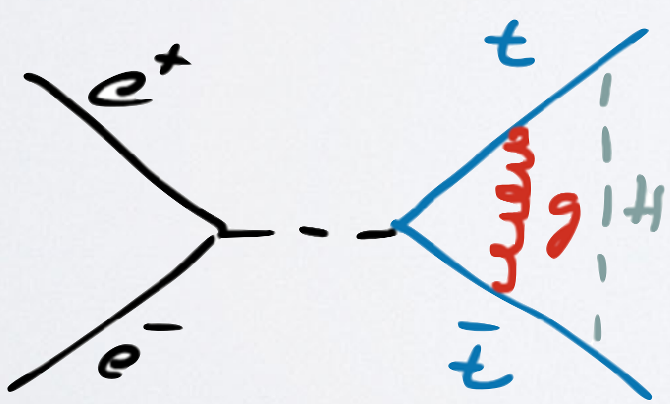


Dependence on M_t, Γ_t, α_s, y_t

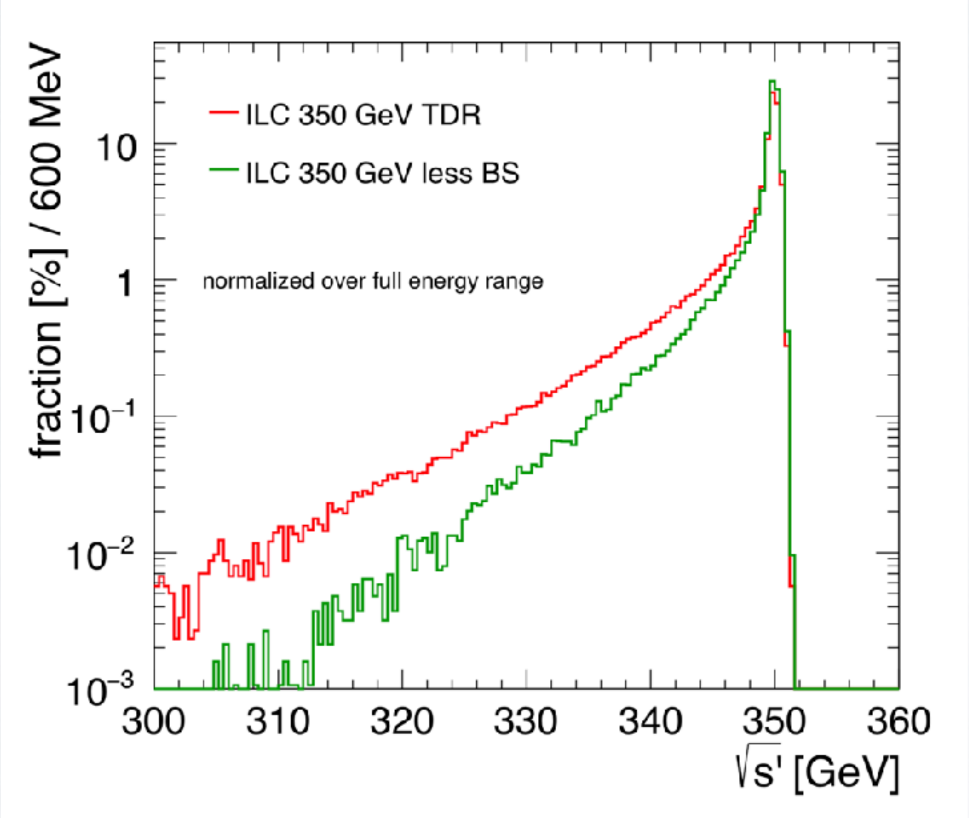
based on:

Beneke/Maier/Piclum/Rauh, 2015





Top Threshold: influence of beam profiles

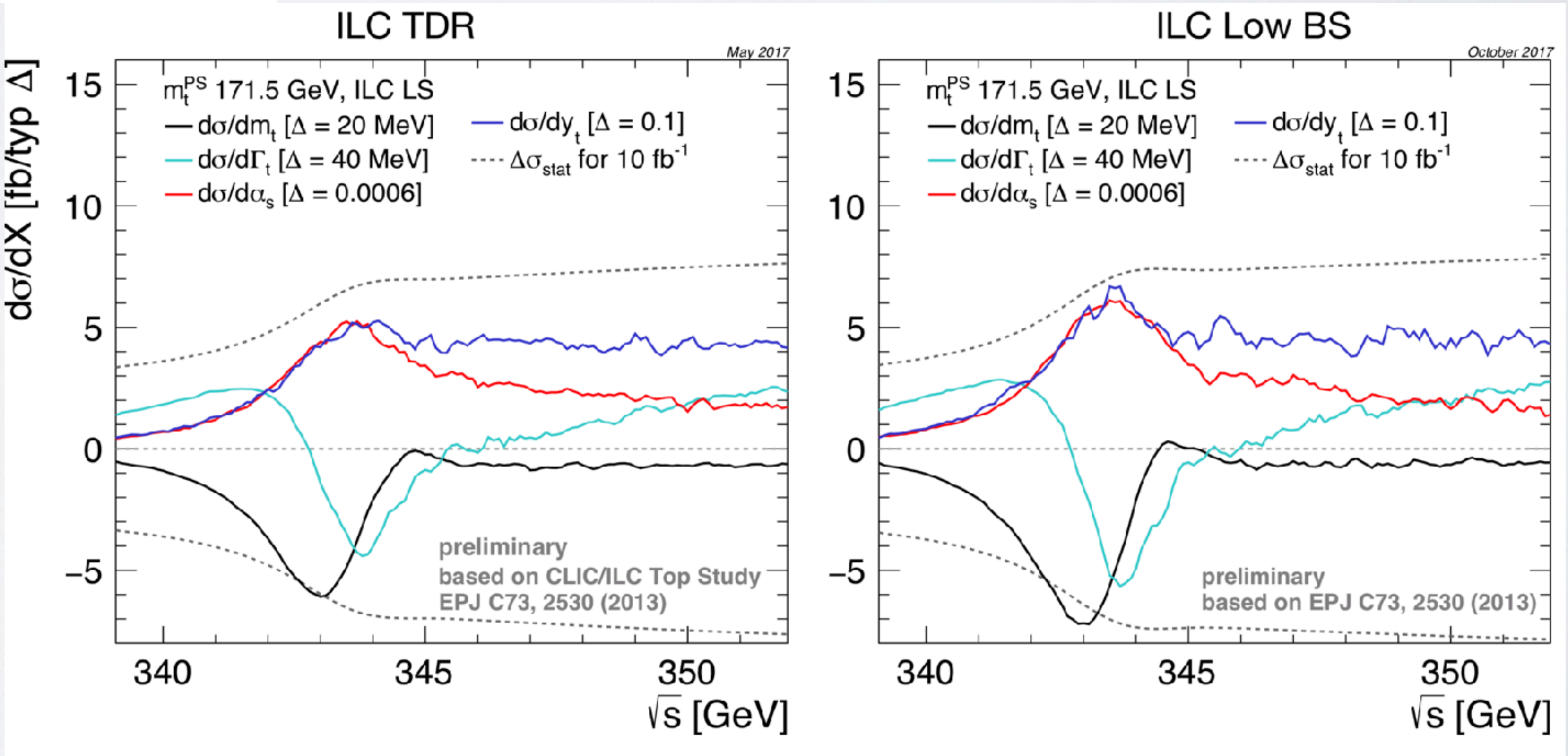


- Dependence on beamstrahlung?
- trade luminosity for beamstrahlung
- Mild reduction on statistic uncertainty

$$100 \text{ fb}^{-1}: \quad 17.6 \to 15.8 \text{ MeV (stat.)}$$

↪ Backup slide

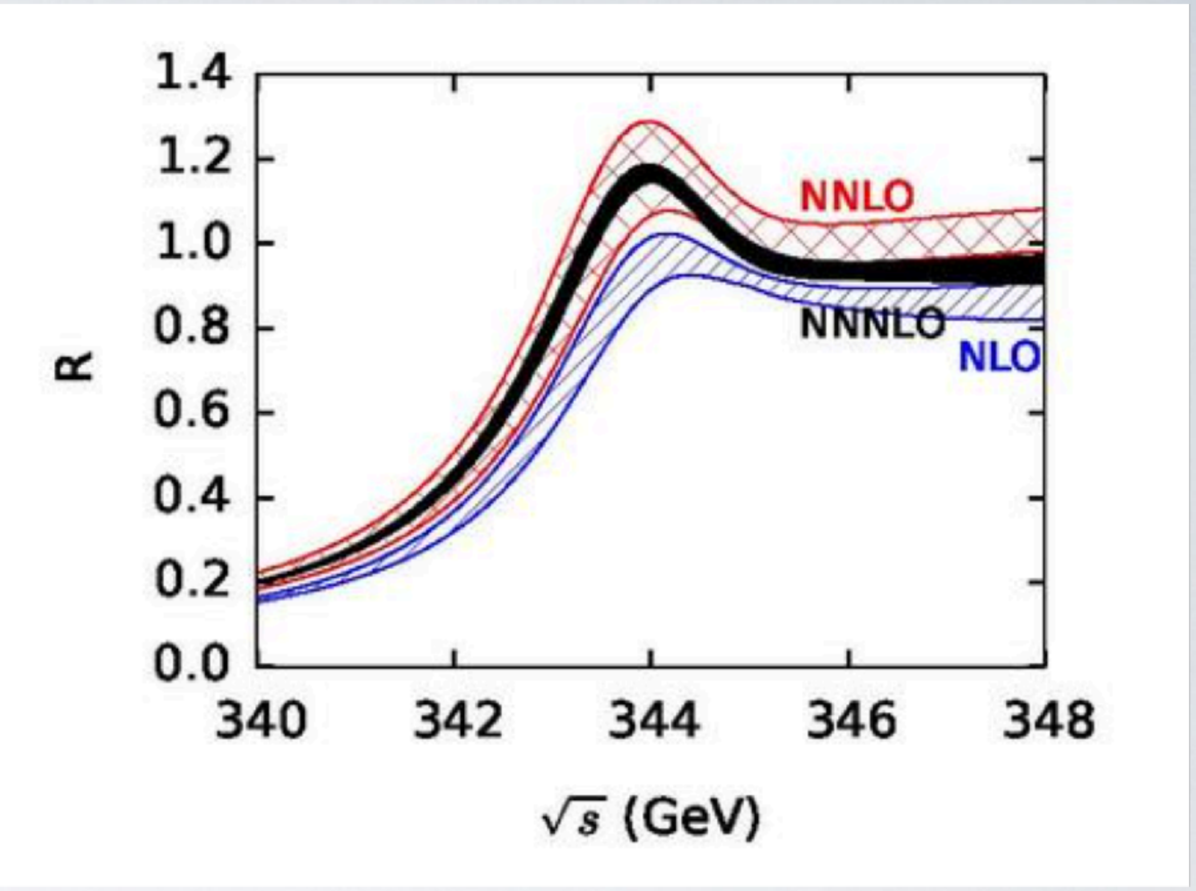
Simon, 10/2017



Fixed-order vs. resummation uncertainties

NRQCD NNNLO fixed order
+ α_s logarithms

Kiyo et al., 2005; Beneke et al., 2008-2015



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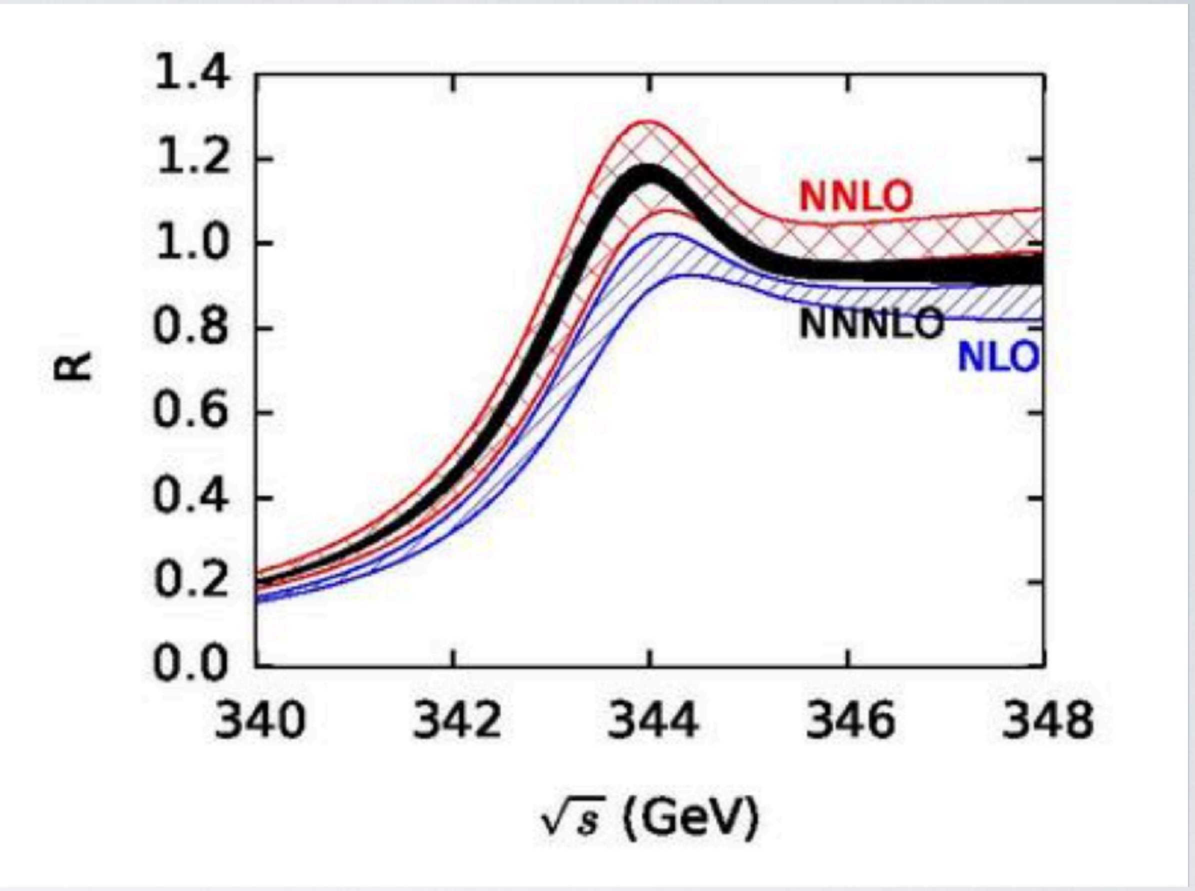
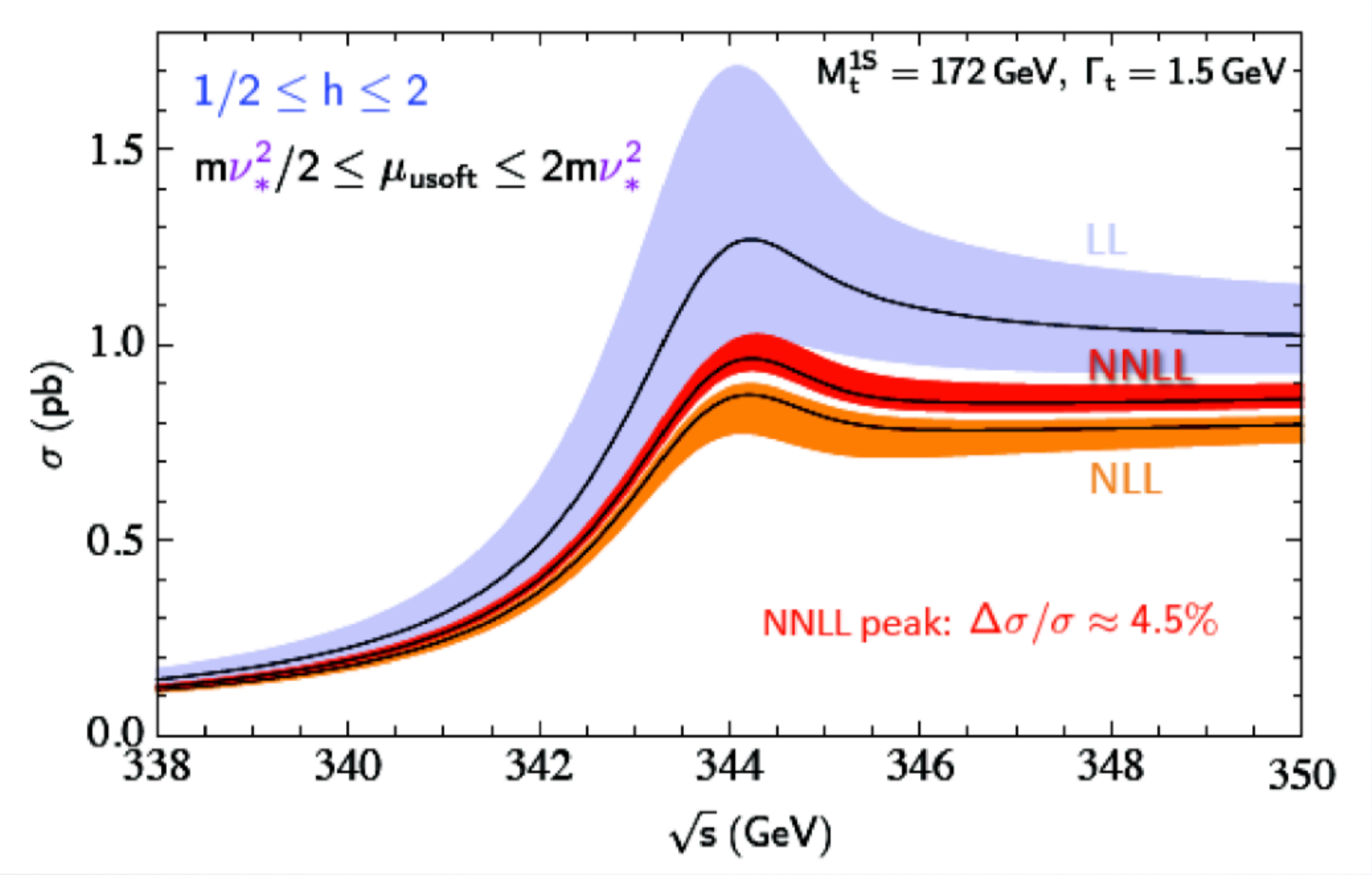


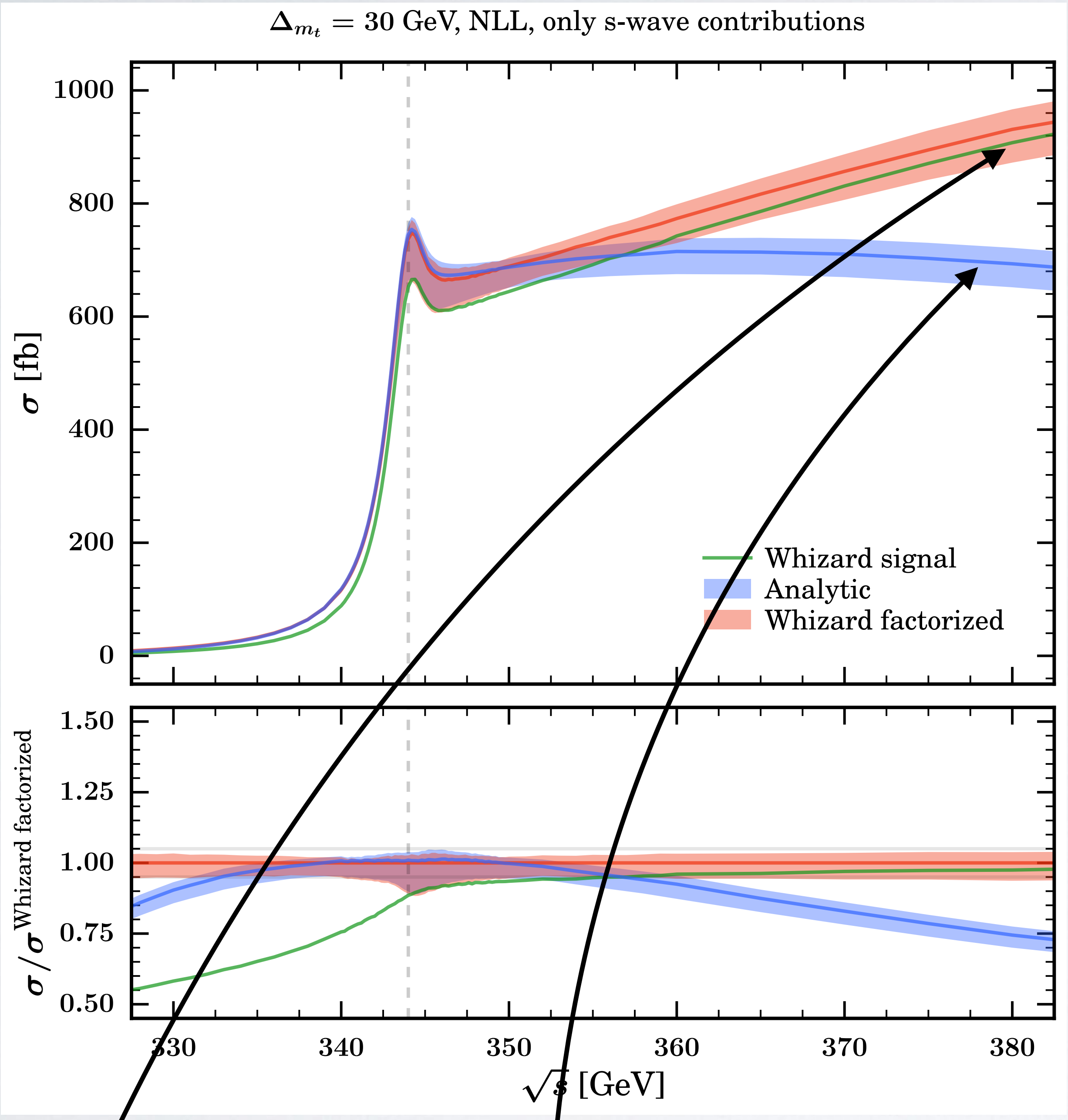


Resummation of
velocity logarithms

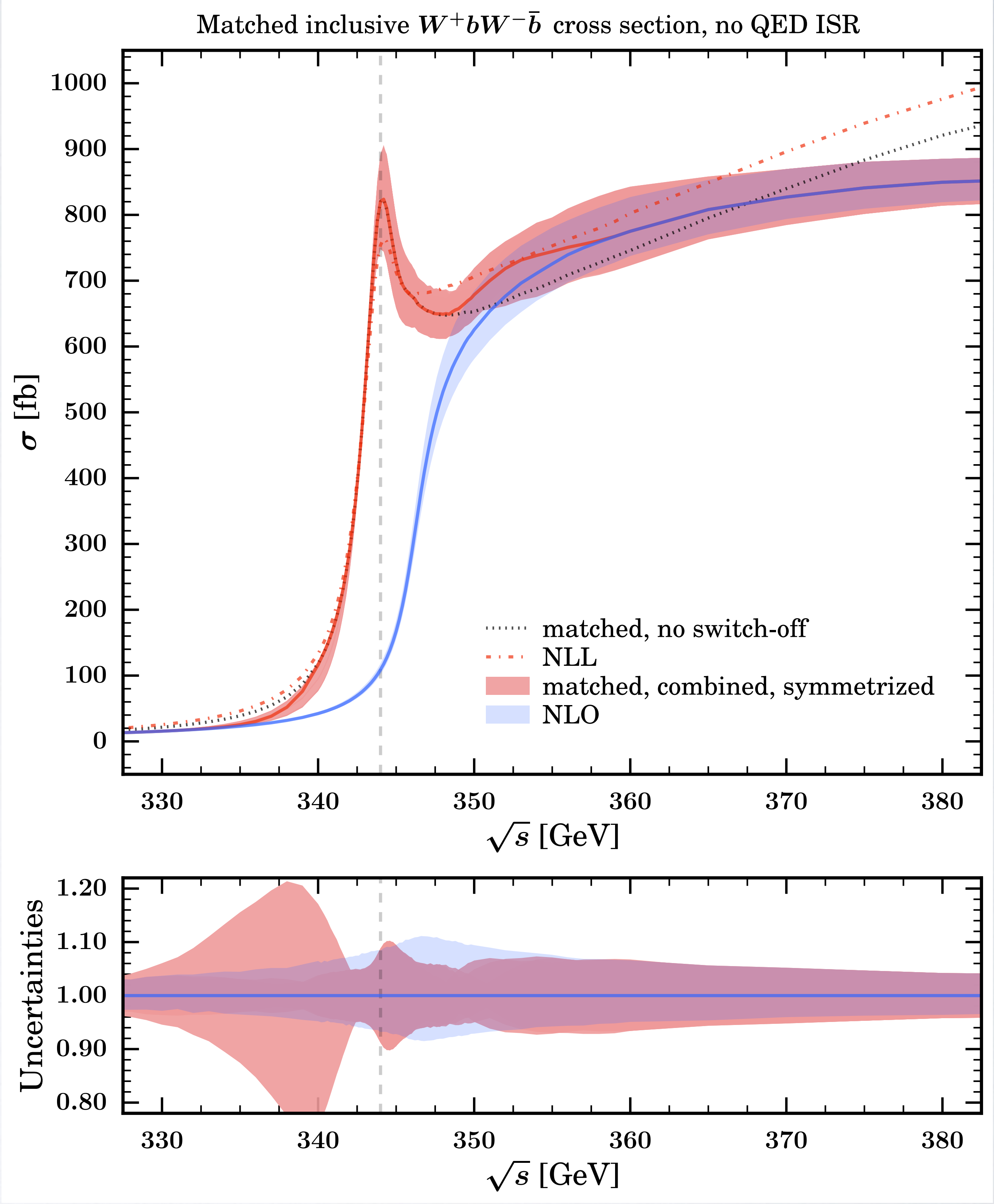
Hoang/Stahlhofen, 2012

Fully exclusive Threshold in $e^+e^- \to W^+W^-bb$

Fully Exclusive Events: assess selection uncertainties



NRQCD result invalid away from threshold



Bach/Chokoufé/Hoang/Kilian/JRR/Stahlhofen/Teubner/Weiss, 12/2017

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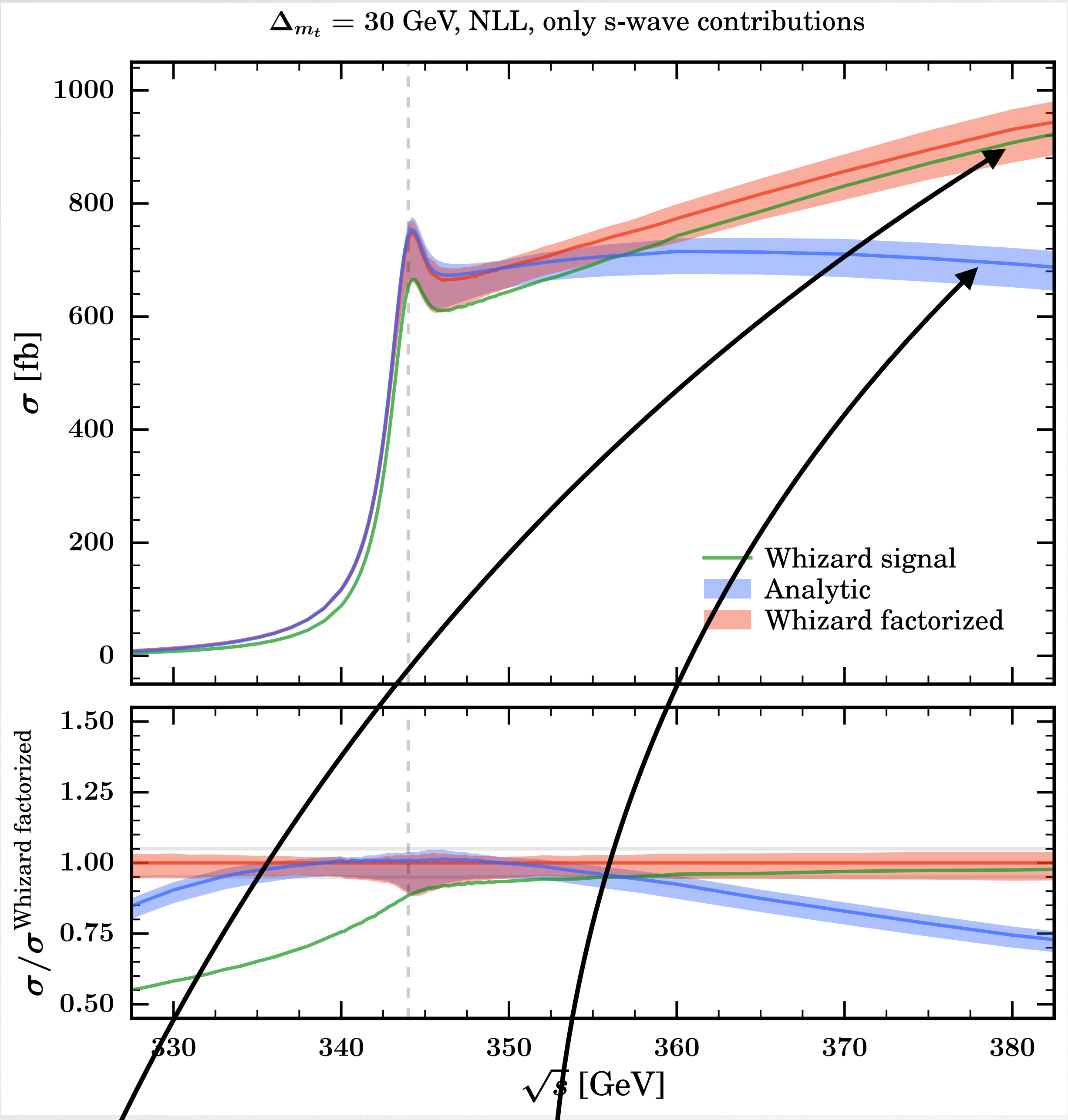

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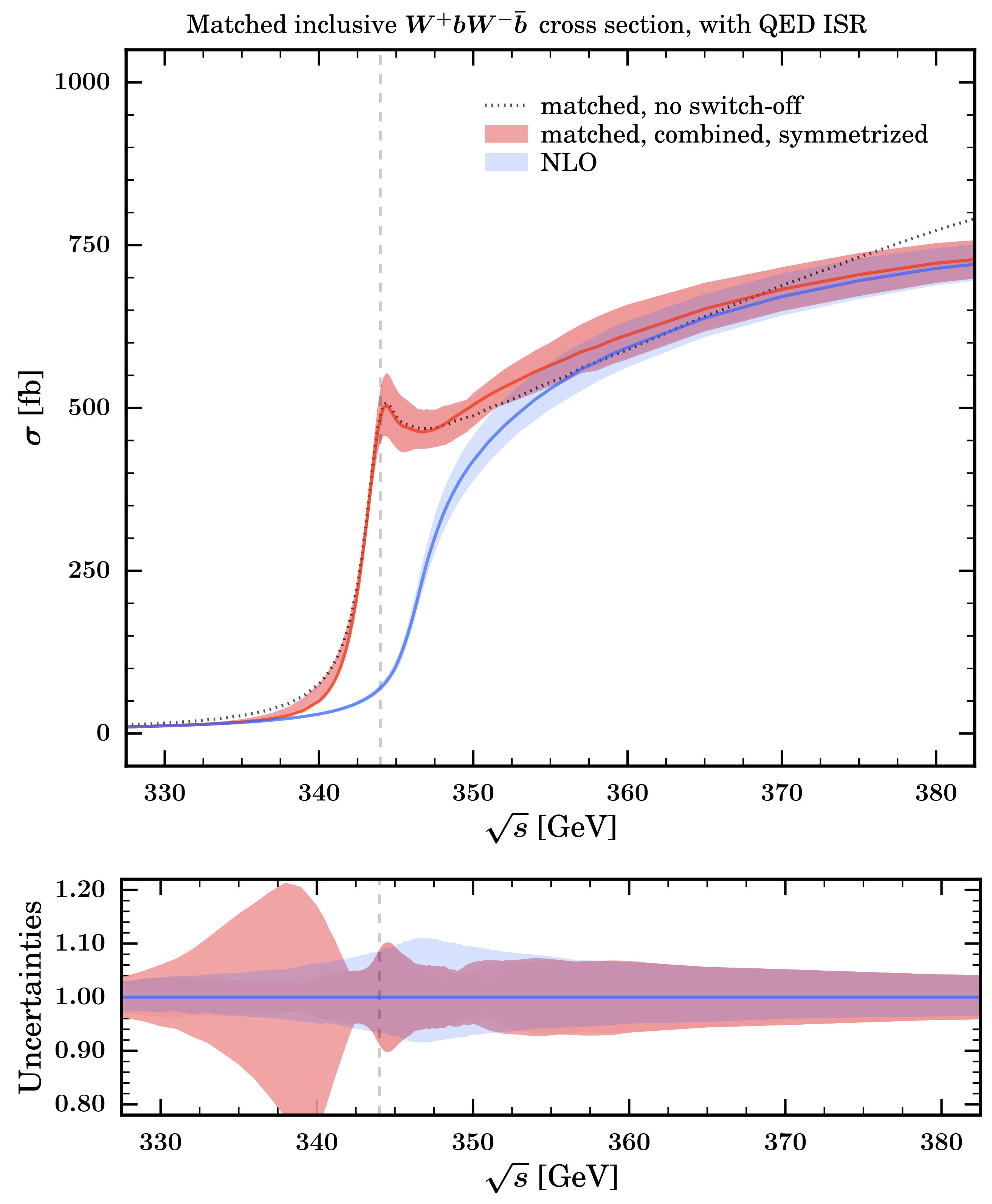
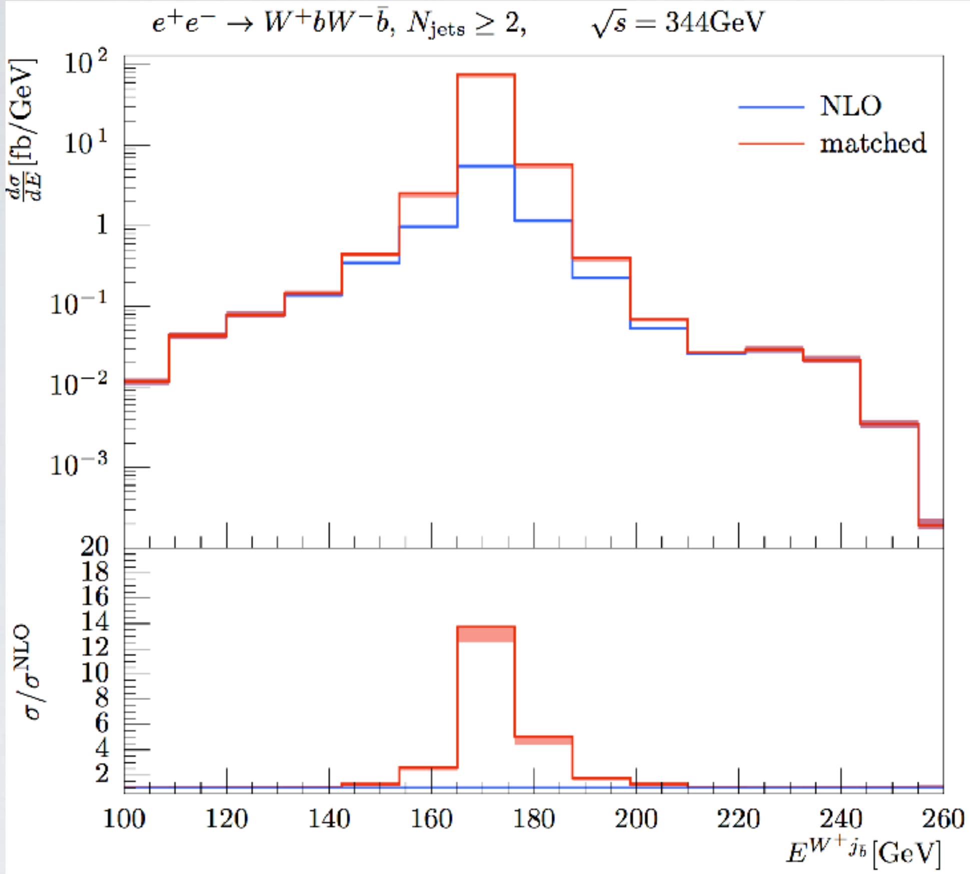
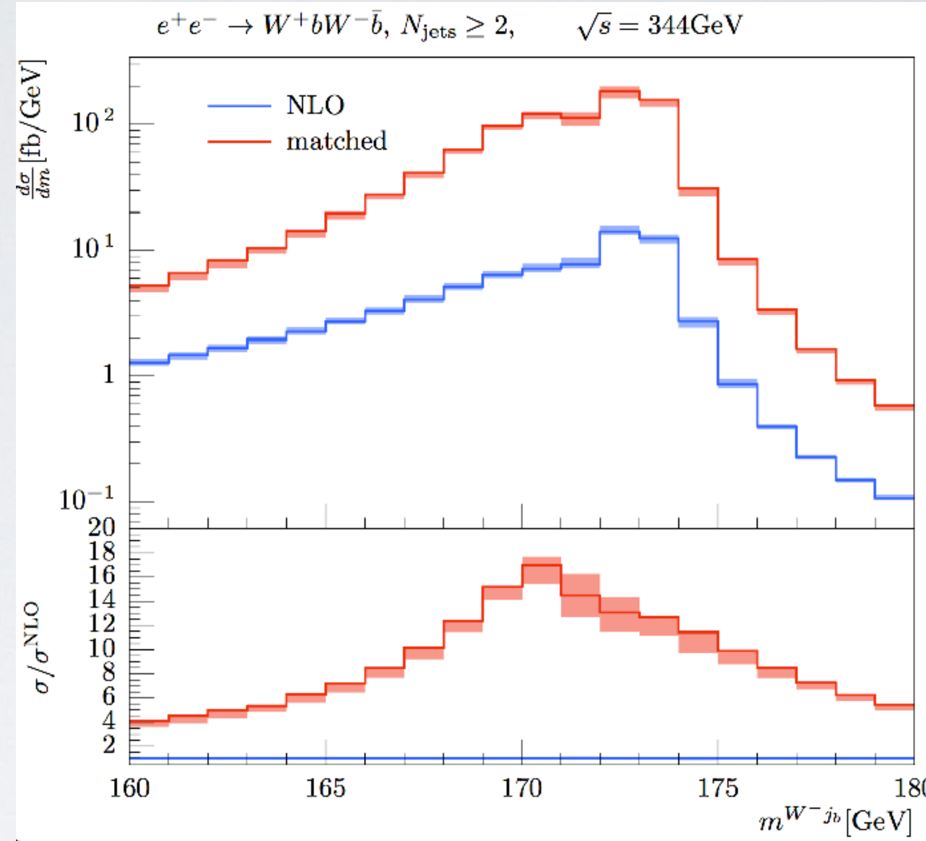
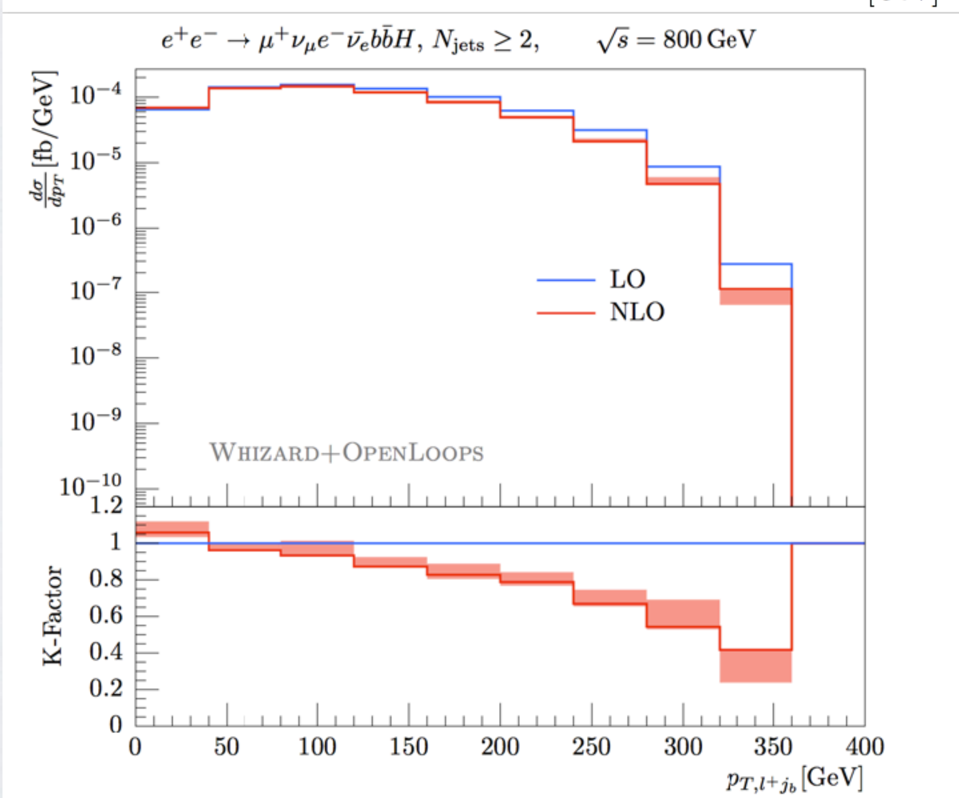


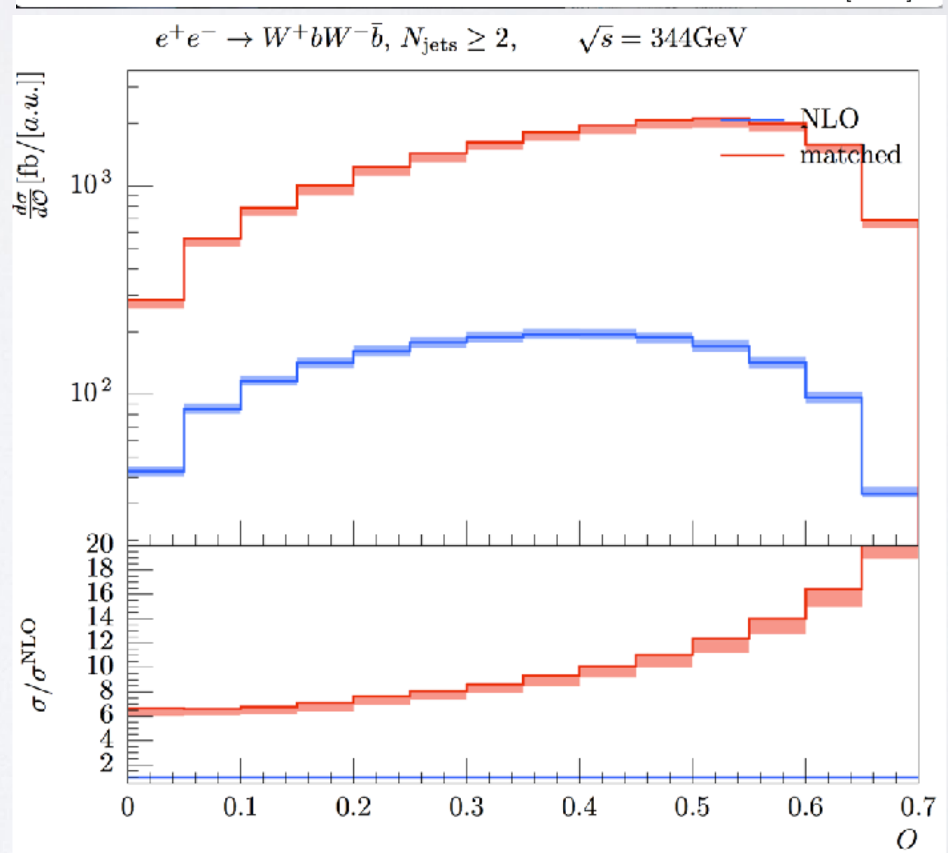
Bach/Chokoufé/Hoang/Kilian/JRR/Stahlhofen/Teubner/Weiss, 12/2017

Matched threshold differential distributions









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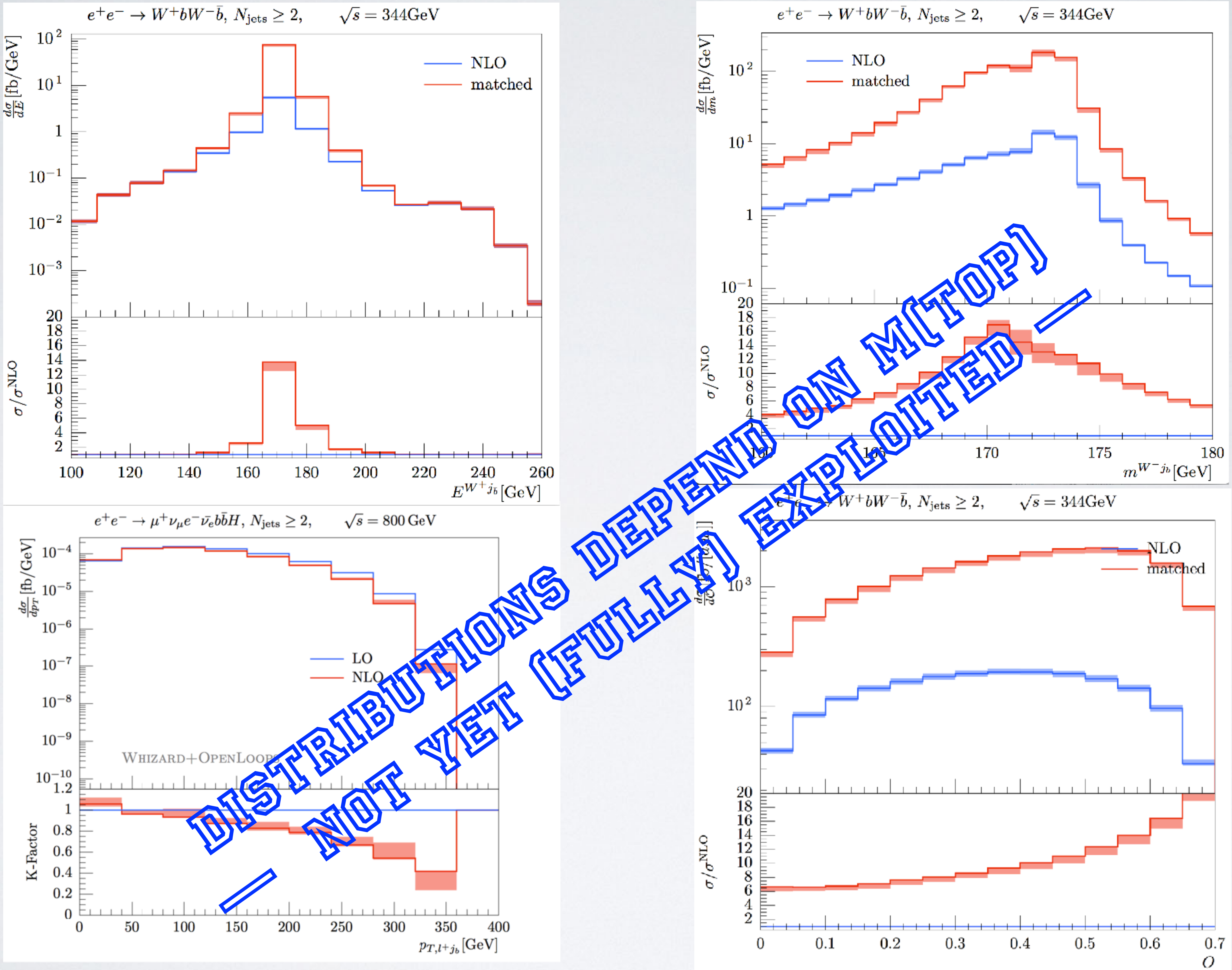
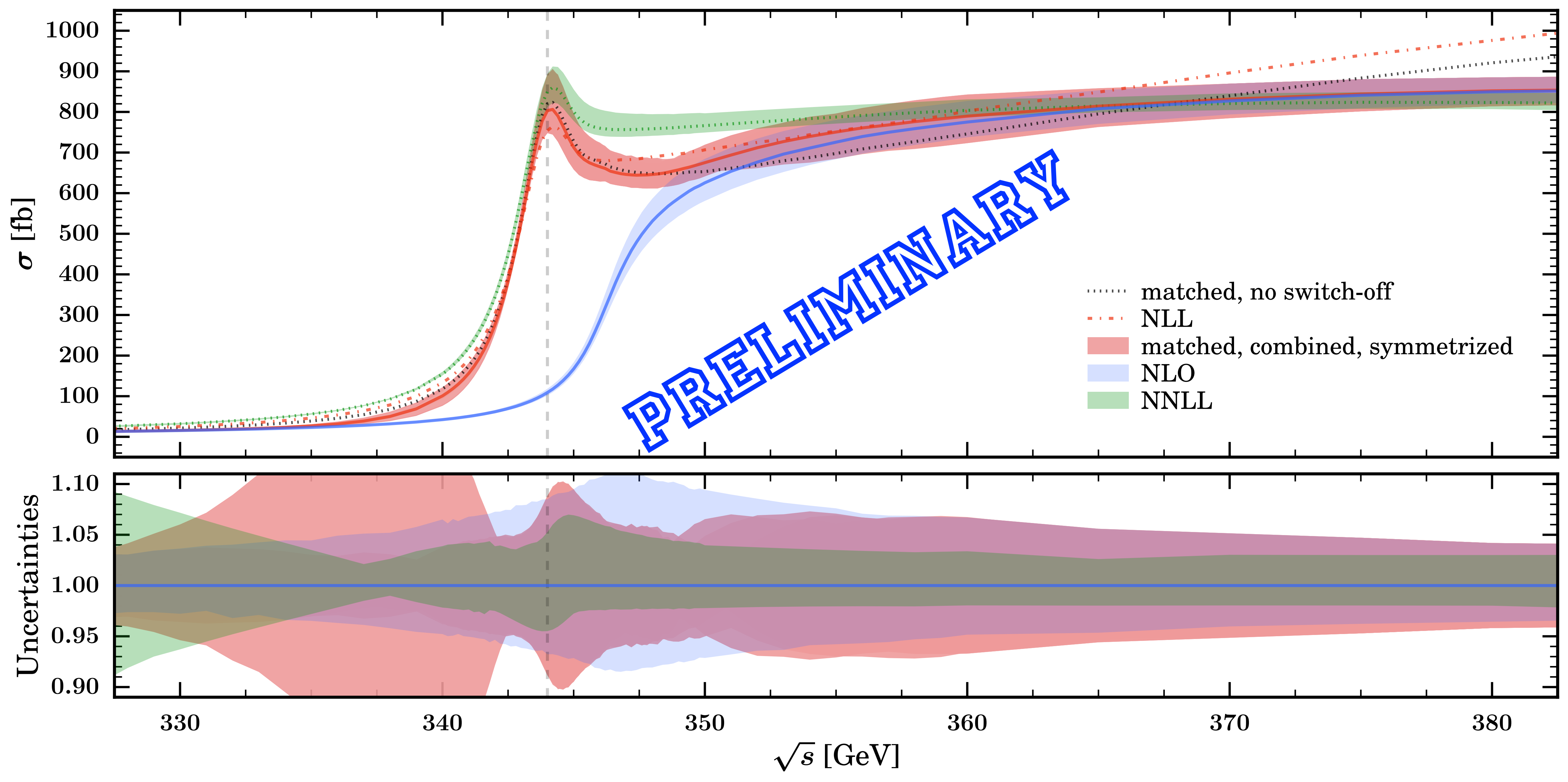


Challenges for the top threshold …

Theory improvements: higher QCD order, EW corrections (ISR matching!!), soft gluons … … …

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



Top-Forward Backward Asymmetry

	$e^+e^- \to$	A_{FB}^{LO}	A_{FB}^{NLO}	A_{FB}^{NLO}/A_{FB}^{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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NLO QCD Corrections

Gluon emission symmetric in θ ⇒

NLO QCD corrections small

Djouadi/Lampe/Zerwas, hep-ph/9411386

Bardin/Christova/Jack/Kalinovskaya/Olchevski/S. Riemann/T. Riemann, hep-ph/9908433

Altarelli/Lampe, NPB391 (1993) 3

Ravindran/van Neerven, hep-ph/9809411

Catani/Seymour, hep-ph/9905424

A_{FB} of the top quark

Forward-backward asymmetry

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

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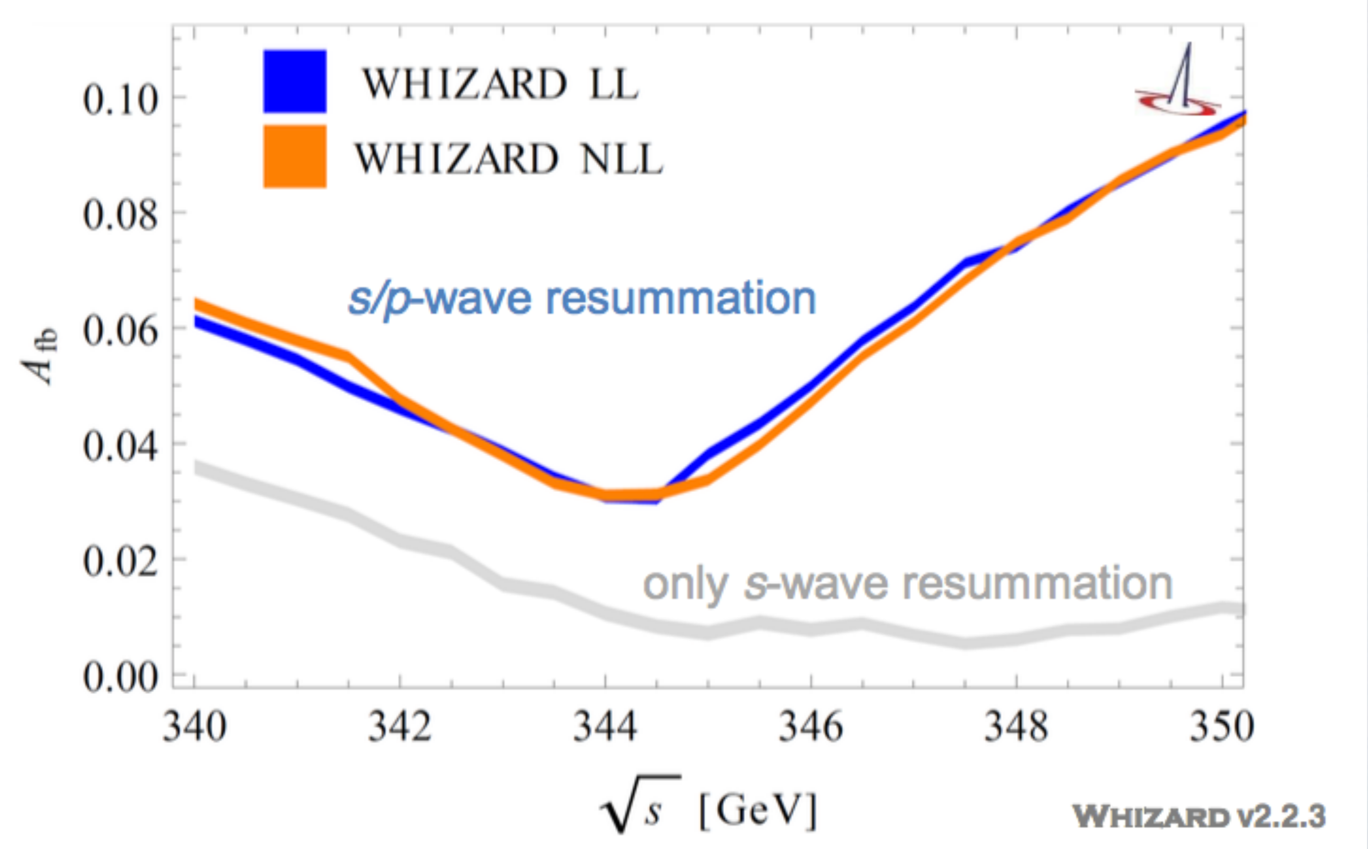
Threshold region: *P*-wave (axial vector) resummation important



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Chen/Dekkers/Heisler/Bernreuther/Si, 1610.07897

A_{FB} of the top quark

$$A_{\rm FB}^{\rm NNLO} = A_{\rm FB}^{\rm LO}(1 + A_1 + A_2)$$

$\sqrt{s}$ [GeV]	$A_{\rm FB}^{\rm LO}$ [%]	$A_{\rm FB}^{\rm NLO}$ [%]	$A_{\rm FB}^{\rm NNLO}$ [%]	A_1 [%]	A_2 [%]	$\delta A_{\rm FB}^{\rm NNLO}$ [%]
360	14.94	$15.54^{+0.05}_{-0.04}$	$16.23^{+0.12}_{-0.10}$	$4.01^{+0.35}_{-0.29}$	$4.58^{+0.46}_{-0.38}$	± 0.59
400	28.02	$28.97^{+0.08}_{-0.07}$	$29.63^{+0.11}_{-0.10}$	$3.41^{+0.29}_{-0.25}$	$2.36^{+0.11}_{-0.11}$	± 0.27
500	41.48	$42.42^{+0.08}_{-0.07}$	$42.91^{+0.08}_{-0.07}$	$2.28^{+0.19}_{-0.16}$	$1.18^{+0.01}_{-0.01}$	± 0.13
700	51.34	$51.81^{+0.04}_{-0.03}$	$52.05^{+0.04}_{-0.04}$	$0.91^{+0.07}_{-0.06}$	$0.47^{+0.01}_{-0.01}$	± 0.06

Conclusions and Outlook

- **Top physics precision program: top mass, top width, top Yukawa, α_s**
- **Top threshold scan: high precision mass measurement ($\Delta M_t \approx$ 30-70 MeV)**
- **Severe theory challenges (!)**

- High precision top Yukawa measurement (needs ~550 GeV)
- Top: telescope to BSM physics ↪ Backup slide
- Top electroweak couplings: deviations guideline to distinguish BSM models

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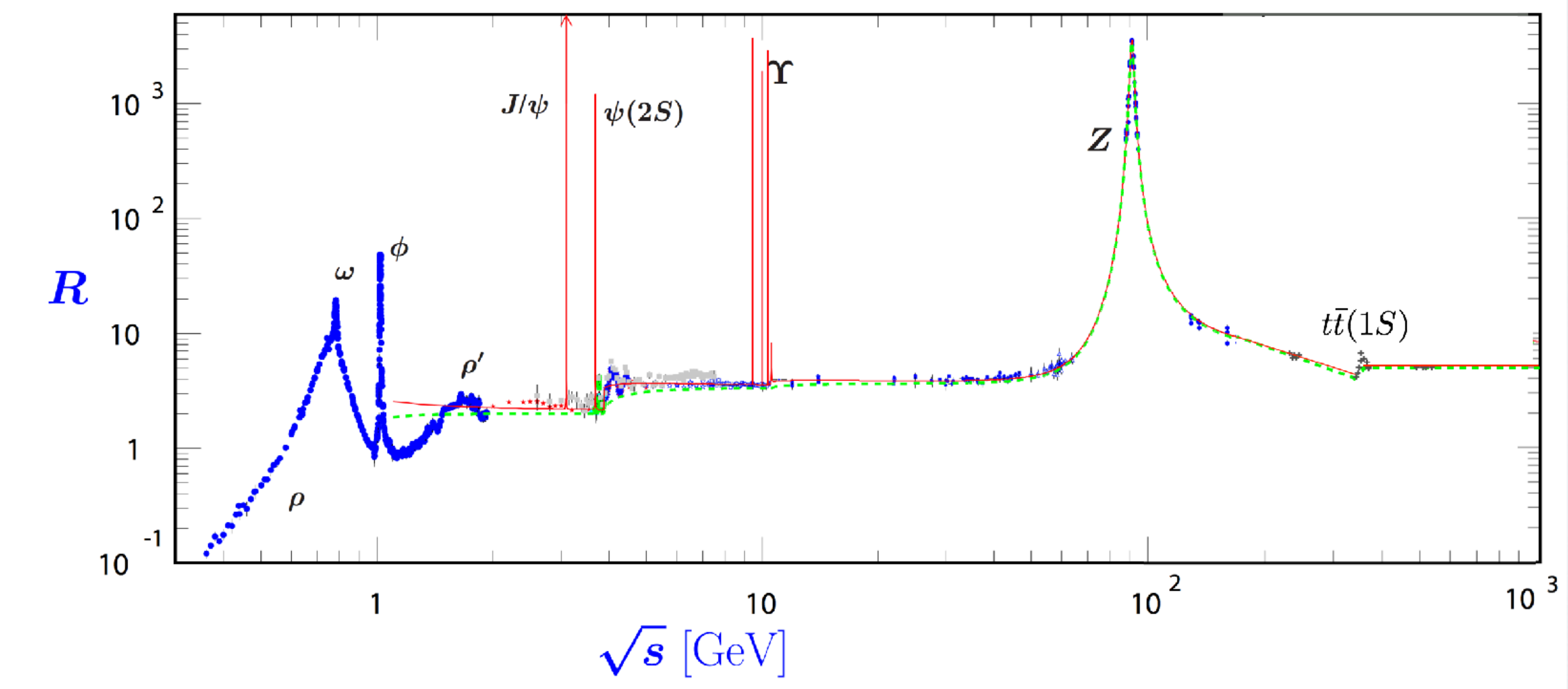


B A C K U P

Top-Forward Backward Asymmetry

$$\frac{d\sigma(e^+e^- \to t\bar{t})}{d\Omega_{\mathrm{CM}}} = \frac{\alpha^2}{4s}\sqrt{1-\frac{4M_t^2}{s}}\left\{\left(1+\cos\theta^2+\frac{4M_t^2}{s}\sin^2\theta\right)G_1(s) - \frac{8M_t^2}{s}G_2(s) + \sqrt{1-\frac{4M_t^2}{s}}\,2\cos\theta G_3(s)\right\}$$

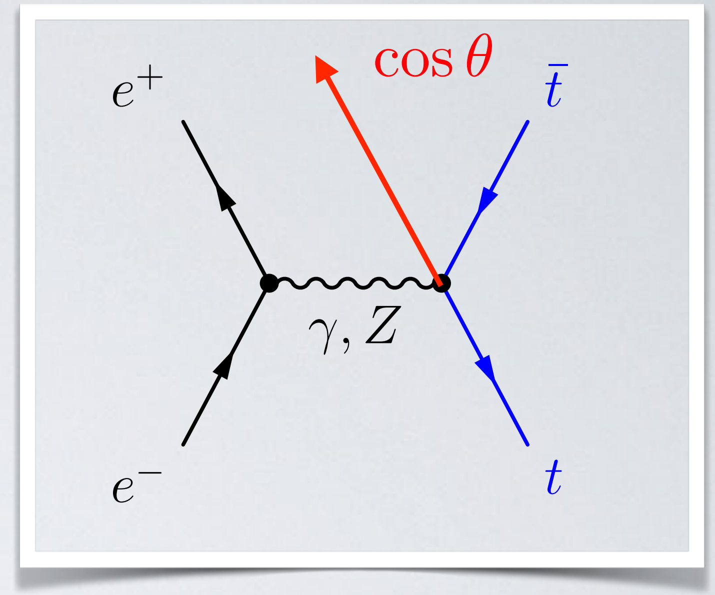
$$G_1(s) = Q_e^2 Q_t^2 + 2Q_eQ_tV_eV_t\,\mathrm{Re}\left[X_Z(s)\right] + \left(V_e^2+A_e^2\right)\left(V_t^2+A_t^2\right)\left|X_Z(s)\right|^2$$

$$G_2(s) = \left(V_e^2+A_e^2\right)A_t^2\left|X_Z(s)\right|^2$$

$$G_3(s) = 2\,Q_eQ_tA_eA_t\mathrm{Re}\left[X_Z(s)\right] + 4\,V_eV_tA_eA_t\left|X_Z(s)\right|^2$$

$$X_Z(s) = \frac{s}{s-M_Z^2+\mathrm{i}M_Z\Gamma_Z}$$

$$-\frac{g}{2c_W}\,\overline{f}\left[V_f\gamma^\mu - A_f\gamma^\mu\gamma^5\right]f\,Z_\mu$$



- Axial vector photon-Z and vector—axial-vector interference
- Linearly dependent term generates Forward-Backward Asymmetry

Top-Forward Backward Asymmetry

$$\frac{d\sigma(e^+e^- \to t\bar{t})}{d\Omega_{\rm CM}} = \frac{\alpha^2}{4s}\sqrt{1-\frac{4M_t^2}{s}}\left\{\left(1+\cos\theta^2+\frac{4M_t^2}{s}\sin^2\theta\right)G_1(s) - \frac{8M_t^2}{s}G_2(s) + \sqrt{1-\frac{4M_t^2}{s}}\,2\cos\theta G_3(s)\right\}$$

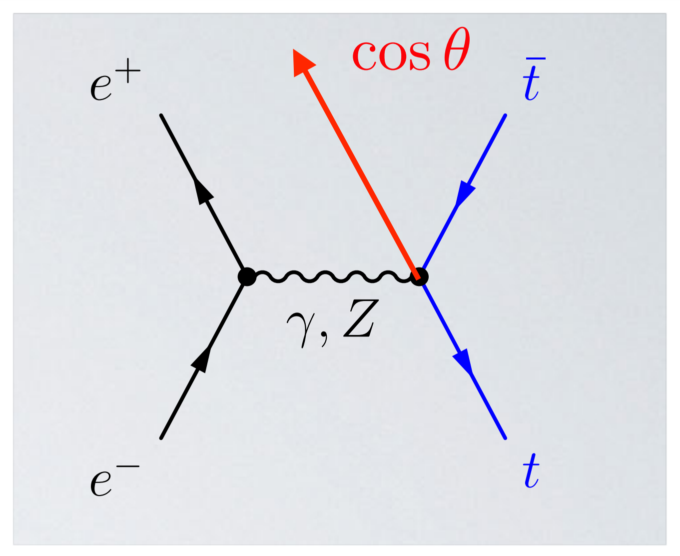
$$G_1(s) = Q_e^2Q_t^2 + 2Q_eQ_tV_eV_t\,{\rm Re}\left[X_Z(s)\right] + \left(V_e^2+A_e^2\right)\left(V_t^2+A_t^2\right)|X_Z(s)|^2$$

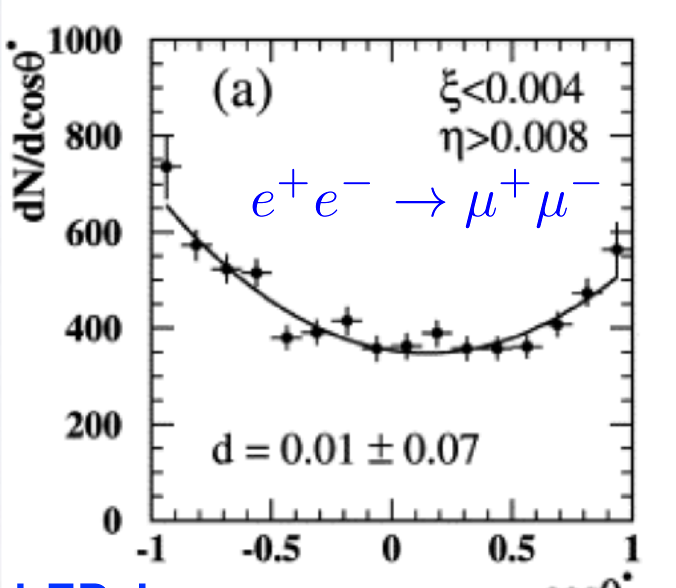
$$G_2(s) = \left(V_e^2+A_e^2\right)A_t^2\,|X_Z(s)|^2$$

$$G_3(s) = 2\,Q_eQ_tA_eA_t{\rm Re}\left[X_Z(s)\right] + 4\,V_eV_tA_eA_t\,|X_Z(s)|^2$$

$$X_Z(s) = \frac{s}{s-M_Z^2+{\rm i}M_Z\Gamma_Z}$$

$$-\frac{g}{2c_W}\bar{f}\left[V_f\gamma^\mu - A_f\gamma^\mu\gamma^5\right]f\,Z_\mu$$





LEP I

- Axial vector photon-Z and vector—axial-vector interference
- Linearly dependent term generates Forward-Backward Asymmetry

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

Asymmetry is function of collider energy

Top Threshold: a demanding theory calculation

- 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. Hoang et al. '99-'01; Beneke et al., '13-'14
- Resummation of singular terms close to threshold (v = 0), NNNLO/NNLL available (!)

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
at NLL differentially!

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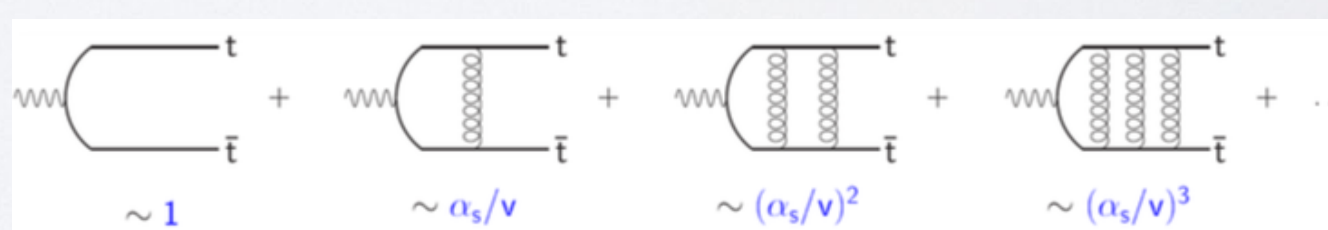
Coulomb potential gluon ladder resummation



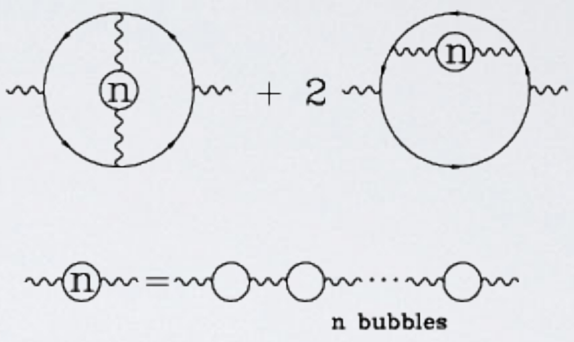
Top Mass Definitions

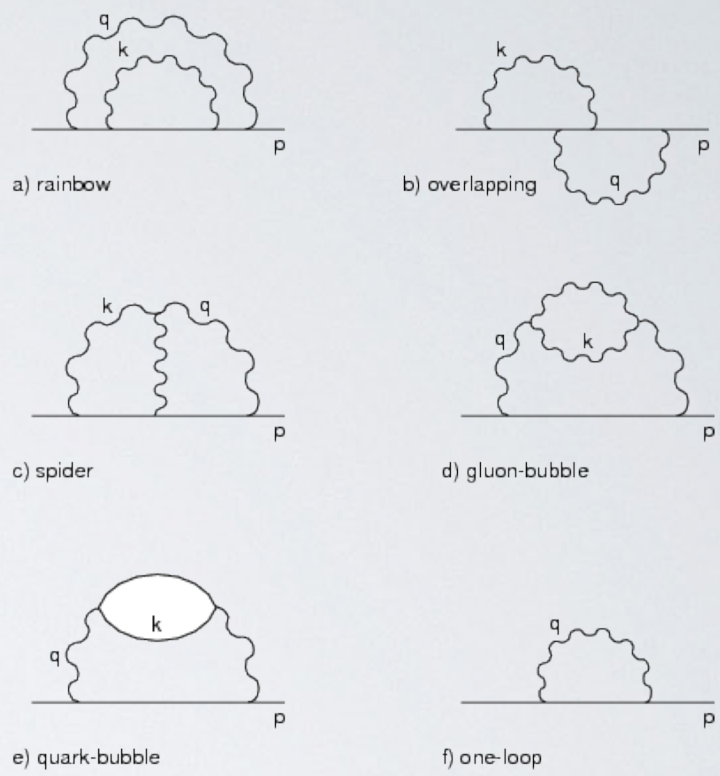
- On-shell mass M: inverse quark propagator has zero at on-shell mass
- $\overline{\mathrm{MS}}$ mass m: just divergent part is subtracted to achieve a finite quark propagator
- Short-distance masses: PS [potential subtr.], 1S, RS [renormalon subtr.] masses

$$m^0 = Z_m^{\overline{\mathrm{MS}}} m \qquad m^0 = Z_m^{\mathrm{OS}} M$$

$$Z_m^{\mathrm{OS}} = 1 + \Sigma_V(q^2 = M^2) + \Sigma_S(q^2 = M^2)$$

$$m^{\mathrm{PS}} = M - \frac{1}{2} \int_{|\vec{q}|<\mu_f} \frac{d^3 q}{(2\pi)^3} V(\vec{q})$$





- 1S mass is half the (pert.) mass of the $1\,{}^3S_1$ bound state

$$m^{1S} = M + \frac{1}{2} E_1^{pt} \Big|_{\alpha_s^n \to \alpha_s^n \epsilon^{n-1}}$$

- Relation between pole and $\overline{\mathrm{MS}}$ mass @ 4-loop

  Marquard/Smirnov/Smirnov/Steinhauser, 1502.01030

$$\begin{aligned} M_t = &\; m_t \left(1 + 0.4244\alpha_s + 0.8345\alpha_s^2 + 2.375\alpha^3 + (8.49 \pm 0.25)\alpha_s^4\right) \\ = &\; 163.643 + 7.557 + 1.617 + 0.501 + 0.195 \pm .005 \text{ GeV} \end{aligned}$$

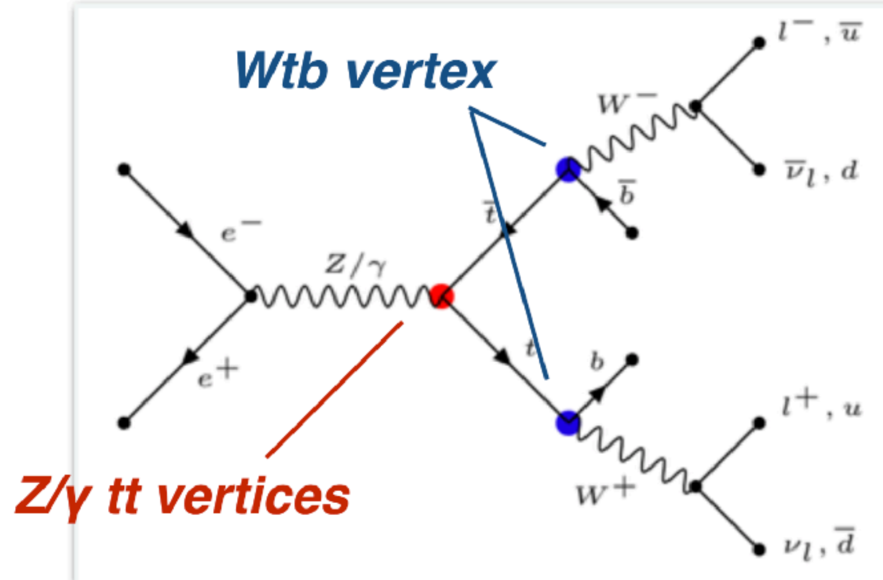
Final uncertainties from top mass conversions:

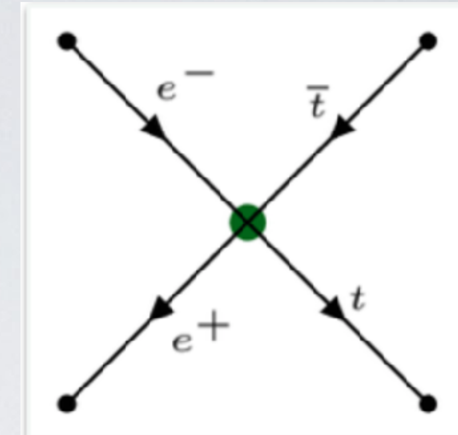
$$\Delta M_{PS} = 23\,\mathrm{MeV} \qquad \Delta M_{1S} = 7\,\mathrm{MeV} \qquad \Delta M_{RS} = 11\,\mathrm{MeV}$$

BSM Telescope: Anomalous top couplings

$$O^1_{\varphi q} \equiv \frac{y_t^2}{2} \quad \bar{q}\gamma^\mu q \quad \varphi^\dagger i\overleftrightarrow{D}_\mu \varphi$$
$$O^3_{\varphi q} \equiv \frac{y_t^2}{2} \quad \bar{q}\tau^I\gamma^\mu q \quad \varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi$$
$$O_{\varphi u} \equiv \frac{y_t^2}{2} \quad \bar{u}\gamma^\mu u \quad \varphi^\dagger i\overleftrightarrow{D}_\mu \varphi$$
$$O_{\varphi ud} \equiv \frac{y_t^2}{2} \quad \bar{u}\gamma^\mu d \quad \varphi^T \epsilon\, i D_\mu \varphi$$

$$O_{uG} \equiv y_t g_s \quad \bar{q}T^A\sigma^{\mu\nu}u \quad \epsilon\varphi^* G^A_{\mu\nu}$$
$$O_{uW} \equiv y_t g_W \quad \bar{q}\tau^I\sigma^{\mu\nu}u \quad \epsilon\varphi^* W^I_{\mu\nu}$$
$$O_{dW} \equiv y_t g_W \quad \bar{q}\tau^I\sigma^{\mu\nu}d \quad \epsilon\varphi^* W^I_{\mu\nu}$$
$$O_{uB} \equiv y_t g_Y \quad \bar{q}\sigma^{\mu\nu}u \quad \epsilon\varphi^* B_{\mu\nu}$$





Contact interactions

$$O^1_{lq} \equiv \bar{q}\gamma_\mu q \quad \bar{l}\gamma^\mu l$$
$$O^3_{lq} \equiv \bar{q}\tau^I\gamma_\mu q \quad \bar{l}\tau^I\gamma^\mu l$$
$$O_{lu} \equiv \bar{u}\gamma_\mu u \quad \bar{l}\gamma^\mu l$$
$$O_{eq} \equiv \bar{q}\gamma_\mu q \quad \bar{e}\gamma^\mu e$$
$$O_{eu} \equiv \bar{u}\gamma_\mu u \quad \bar{e}\gamma^\mu e$$

$$O^T_{lequ} \equiv \bar{q}\sigma^{\mu\nu}u \;\epsilon\; \bar{l}\sigma_{\mu\nu}e$$

$$O^S_{lequ} \equiv \bar{q}u \;\epsilon\; \bar{l}e$$
$$O_{ledq} \equiv \bar{d}q \quad \bar{l}e$$

BSM Telescope: Anomalous top couplings

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\begin{aligned}
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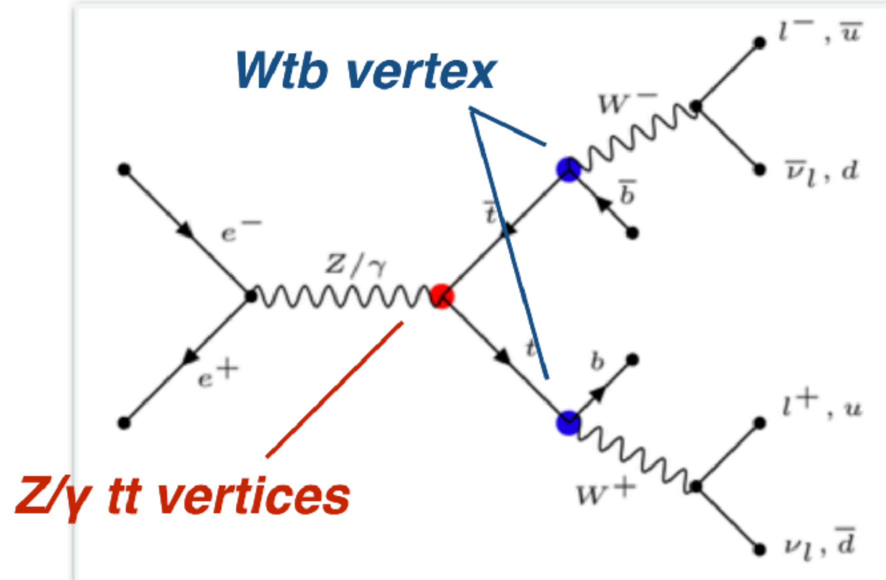

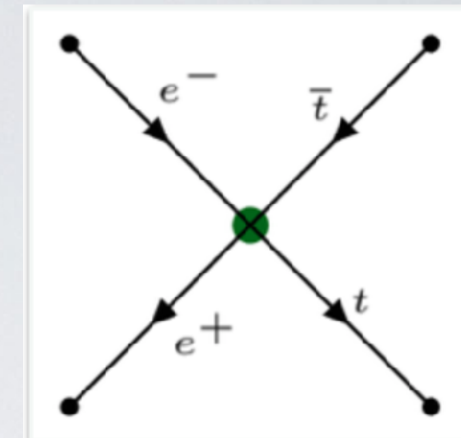

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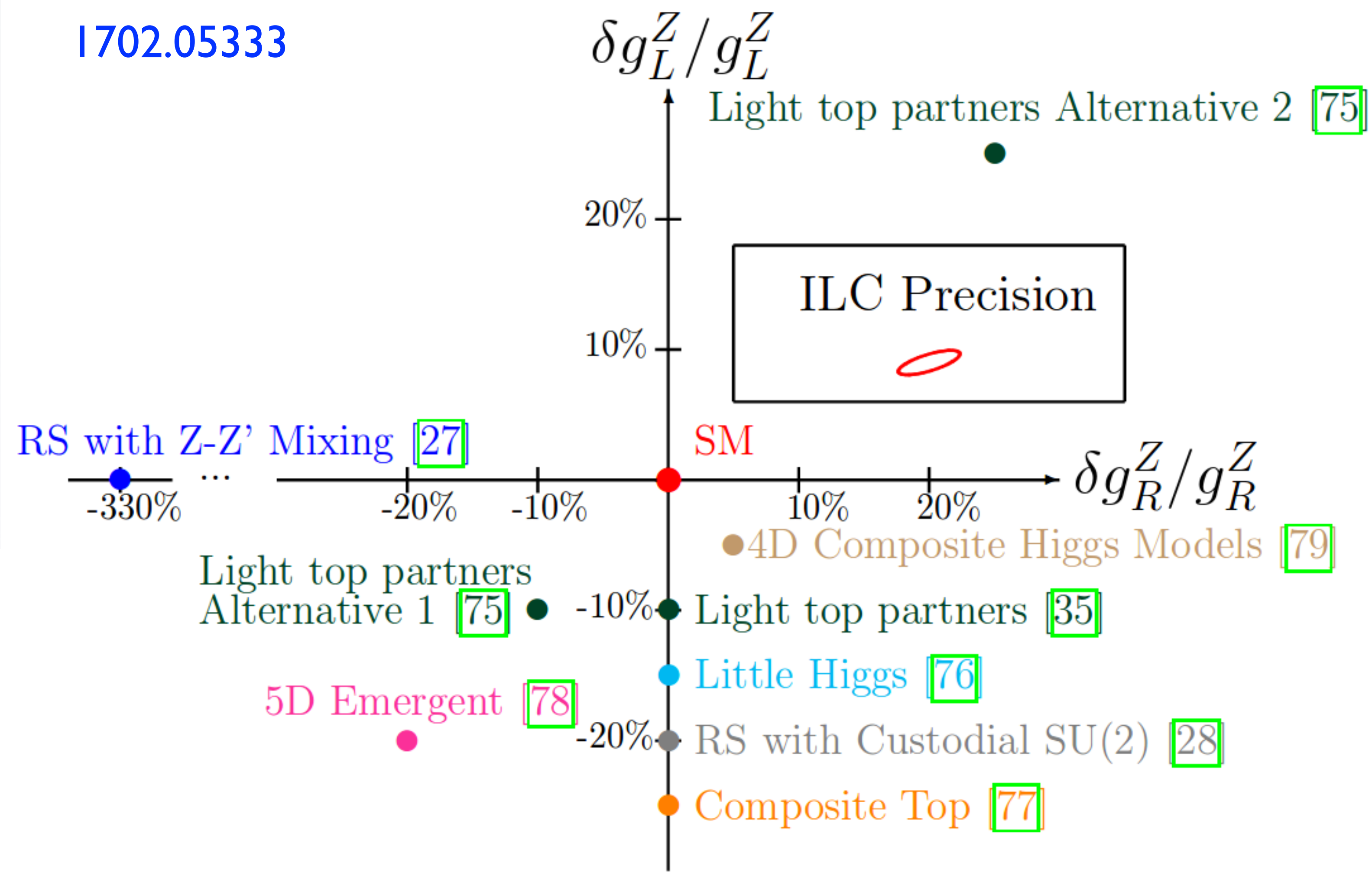
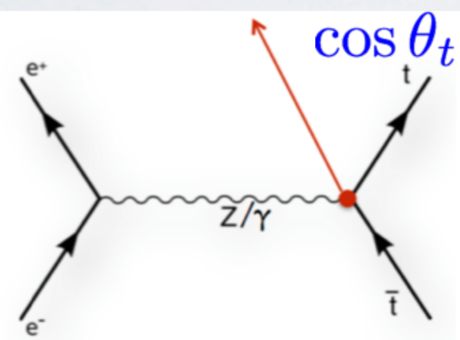
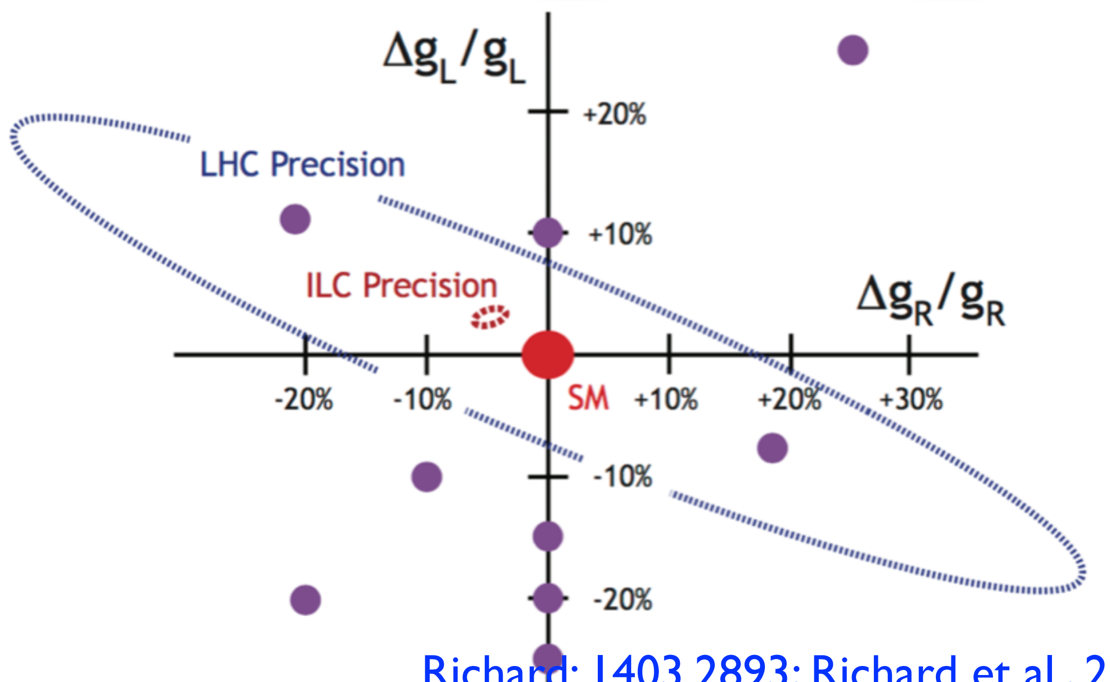
O_{ledq} &\equiv \bar{d}q \quad \bar{l}e
\end{aligned}
$$

- Strong handle on BSM (e.g. compositeness, partial compositeness, Little Higgs, SUSY etc.)
- Main Observables: cross section & Forward-Backward Asymmetry (A_{FB})
- Top quark polarization: spin correlations
- Optimally CP-odd observables: CP properties (!)
- Statistically optimal observables
- Excellent top reconstruction in e^+e^-

Precision means Discriminative Power







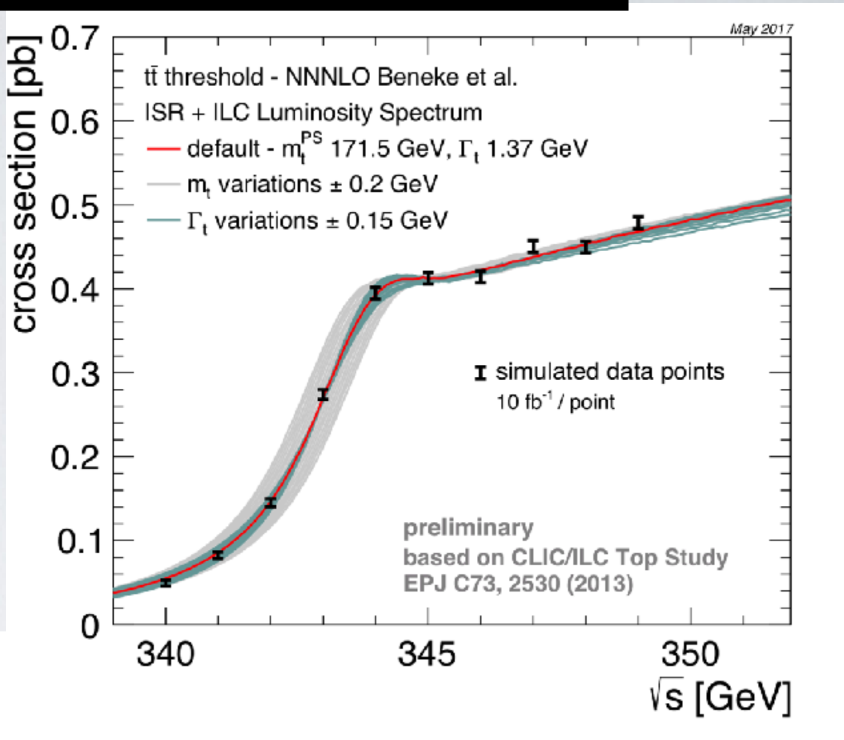
Richard: 1403.2893; Richard et al., 2015

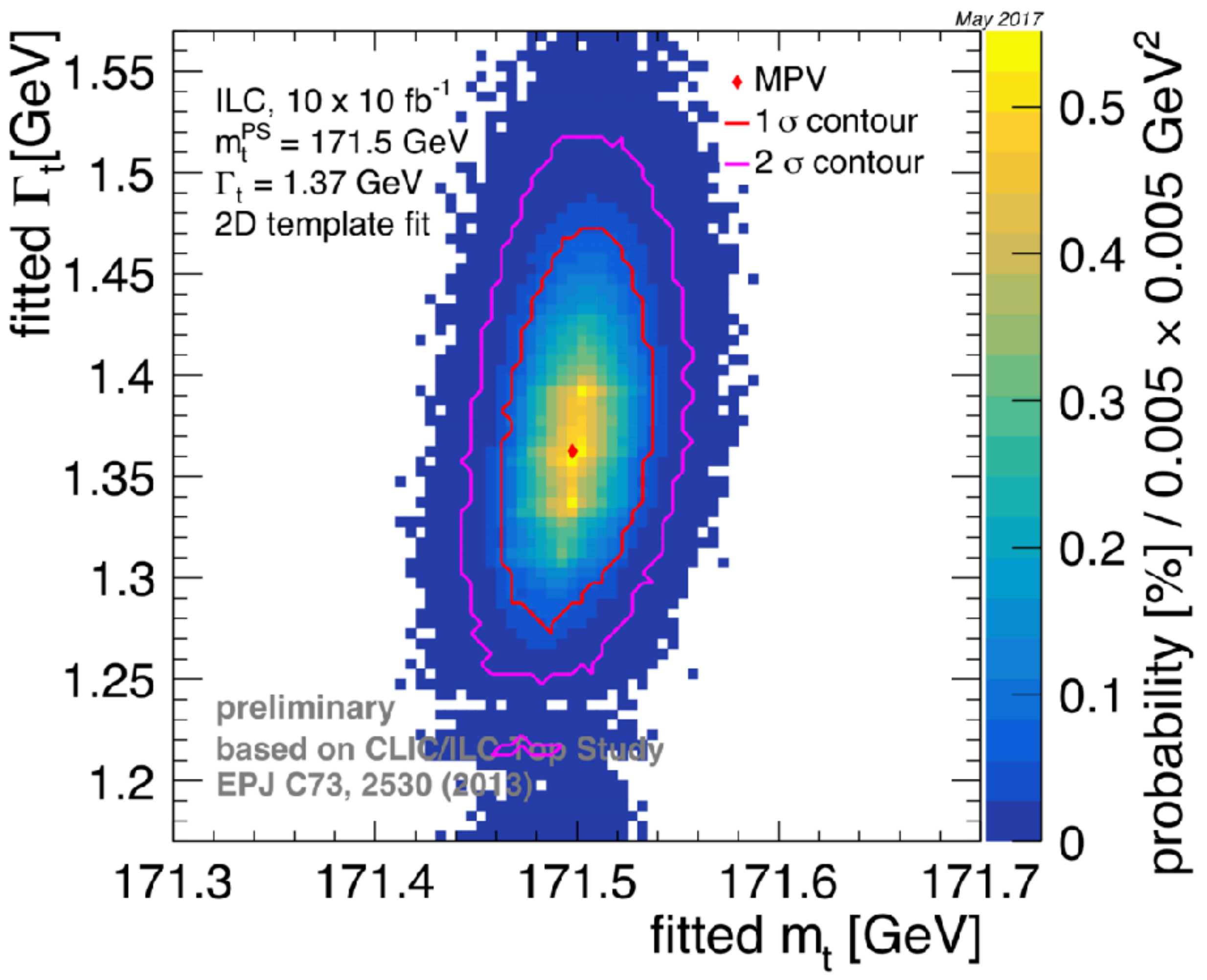
- ☑ Typical deviations in models ≲ 10-20%
- ☑ Below resolution power of HL-LHC
- ☑ Unique opportunity for lepton collider
- ☑ Sensitivity at 365 GeV?

↪ cf. Talk by Patrizia Azzi, Yuichi Okugawa

1D/2D Template Fits for the Top Threshold

- Method of Template Cross Sections
- Generate (pseudo-) signals with different parameters
- Fit the data to the (pseudo-)signal distributions
- Compare which values fit [pseudo-] data best





- 1D mass resolution (assuming def. Γ_t) **18 MeV**
- 1D width resolution (assuming def. m_t) **43 MeV**
- Extension of 2D 1 σ contour:
  m_t +39 -35 MeV
  Γ_t +109 - 90 MeV
  - correlation 0.26

Simon, 10/2017

Ongoing studies:
F. Żarnecki