Top Physics in WHIZARD (+ NLO/QCD Status)

Jürgen R. Reuter, DESY

WHIZARD @ WHISTLER

My tribute to Canada …

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- *in memoriam* ✦

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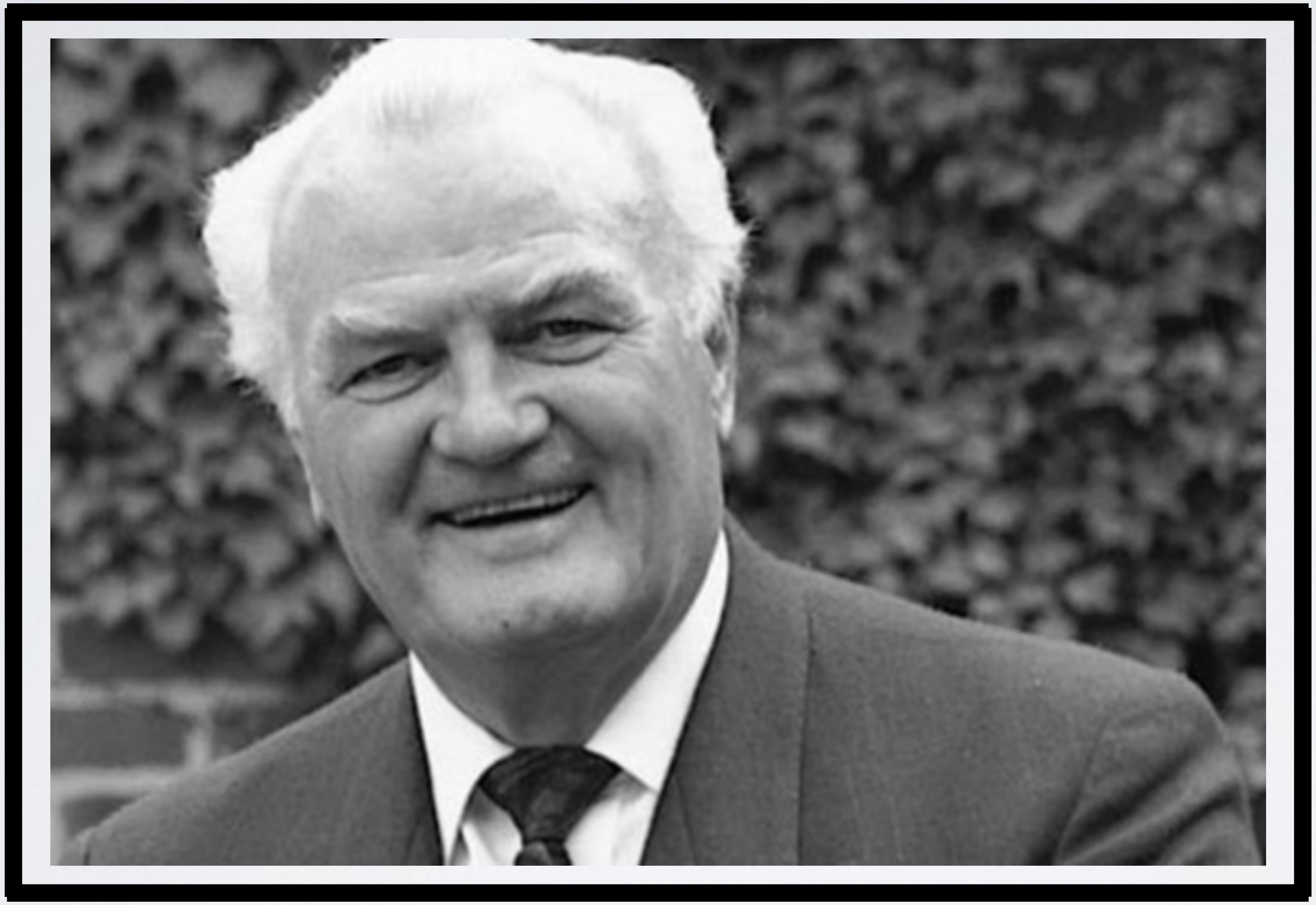

Jon Vickers, 29.10.1926 - 10.7.2015

"Vergeh' die Welt
meiner jauchzenden Eil'!
Die Leuchte verlischt, zu ihr!
Isolde!"

WHIZARD: Overview

WHIZARD v2.2.7 (11.08.2015) http://whizard.hepforge.org

<whizard@desy.de>

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

Simon Braß/Bijan Chokoufé/Marco Sekulla/Christian Weiss/Soyoung Shim/Florian Staub/Zhijie Zhao + *2 Master*

(some losses: C. Speckner [software engineering], F. Bach [European Commission], S. Schmidt [Philosophy])

Publication: EPJ C71 (2011) 1742 (and others for O'Mega, Interfaces, color flow formalism)

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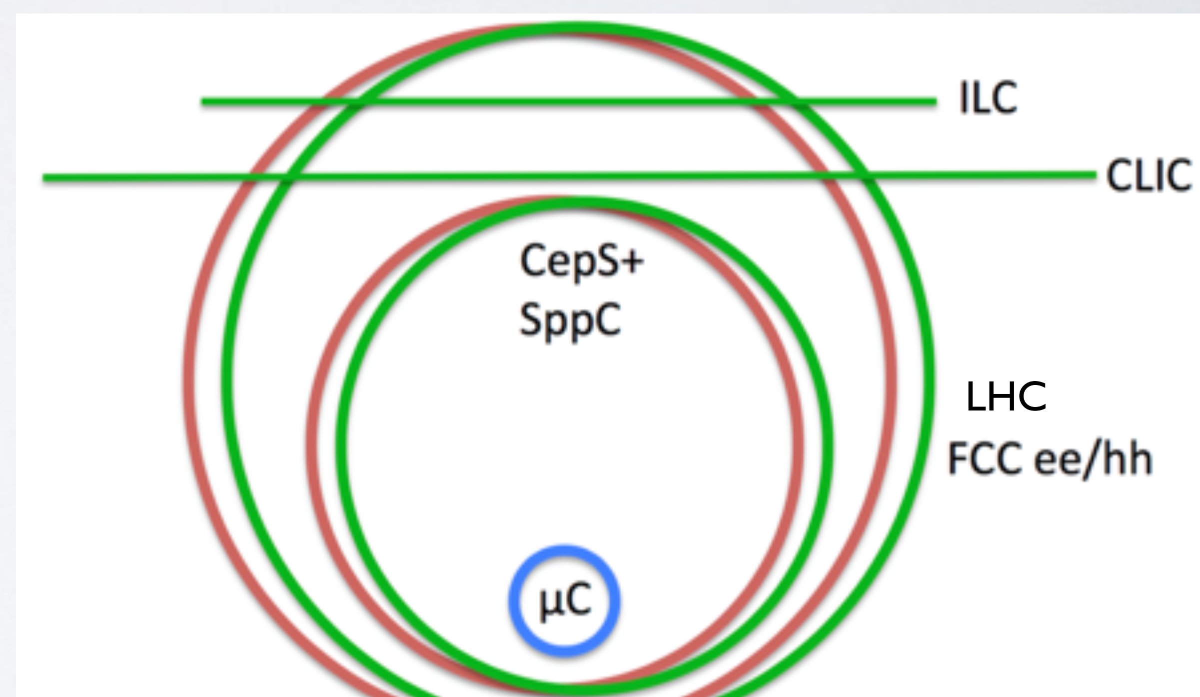
2nd WHIZARD Workshop Würzburg, 03/2015

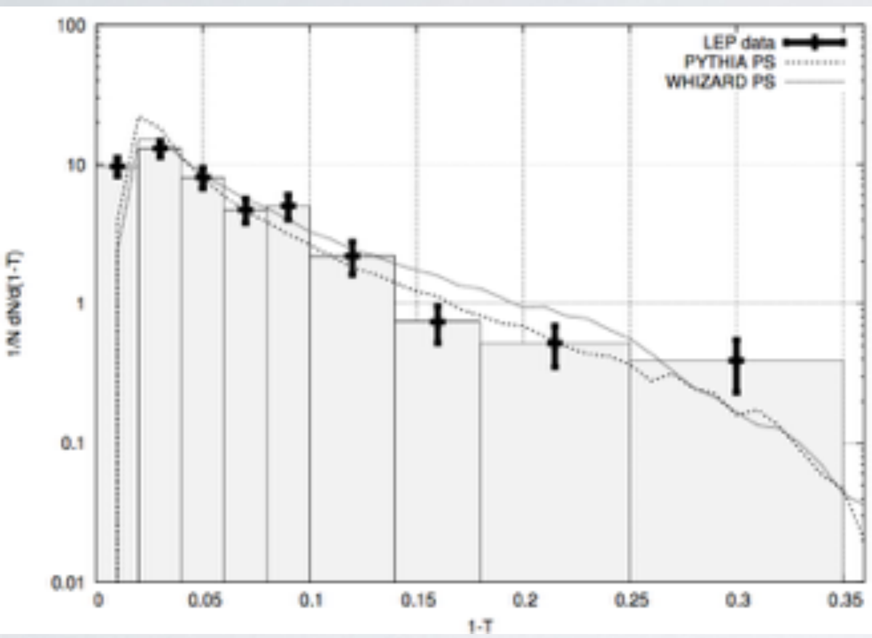


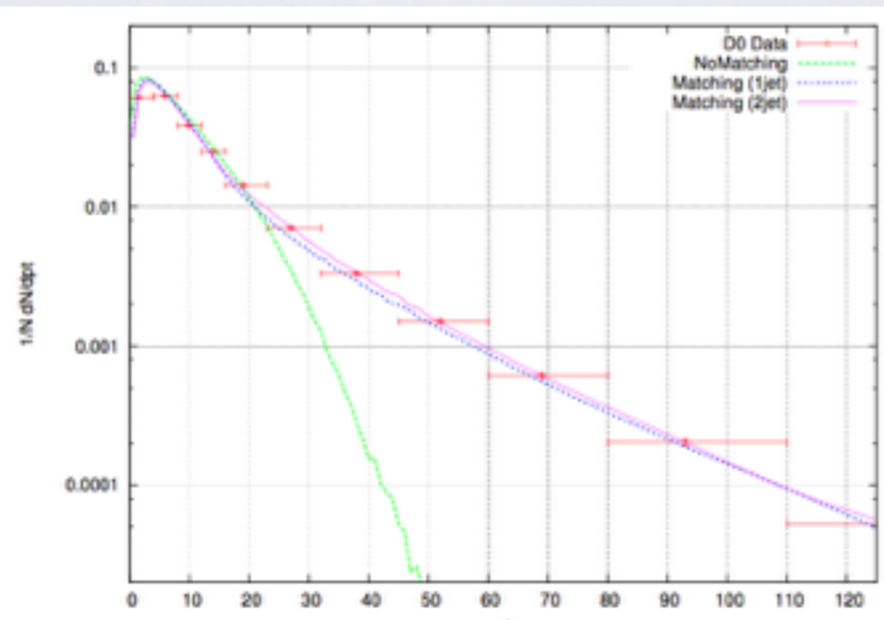
K. Desch, DESY Th-WS '15

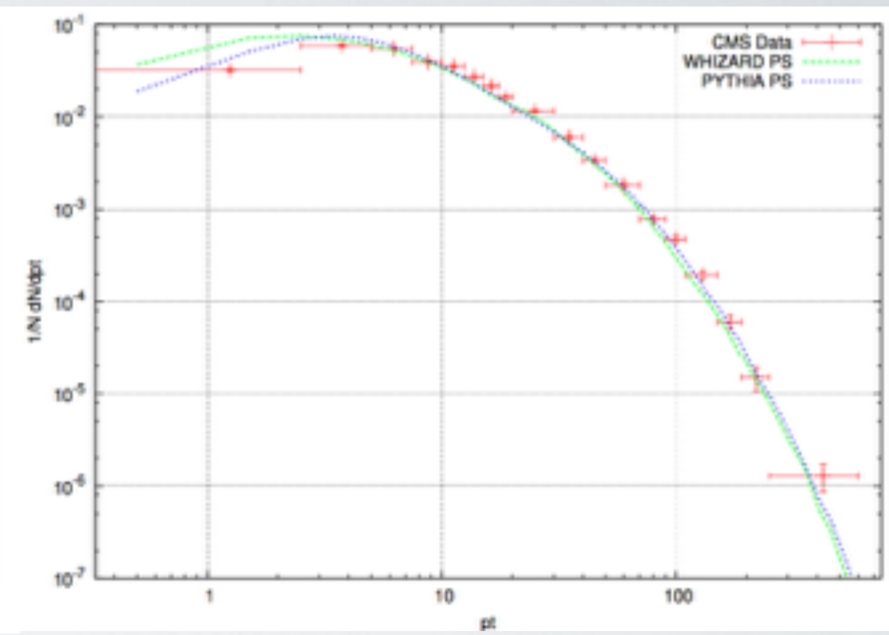
WHIZARD Parton Shower

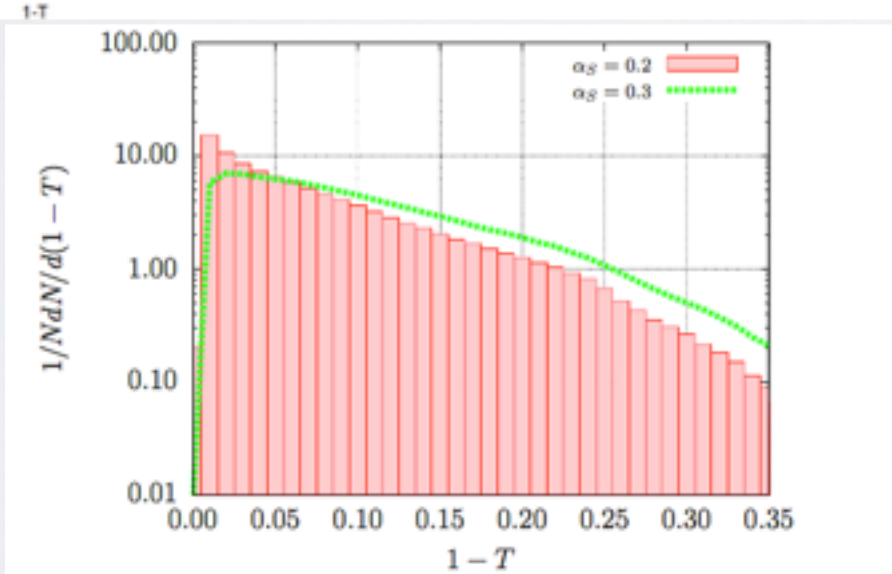
- Two independent implementations: kT-ordered QCD and Analytic QCD shower
- Analytic shower: no shower veto ⇒ exact shower history known, allows reweighting

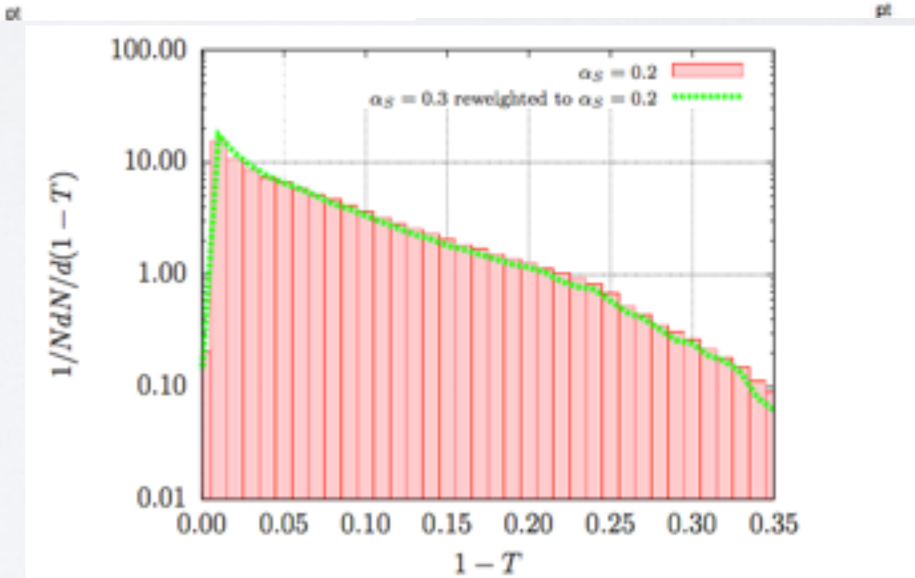
Kilian/JRR/Schmidt/Wiesler, JHEP **1204** 013 (2012)







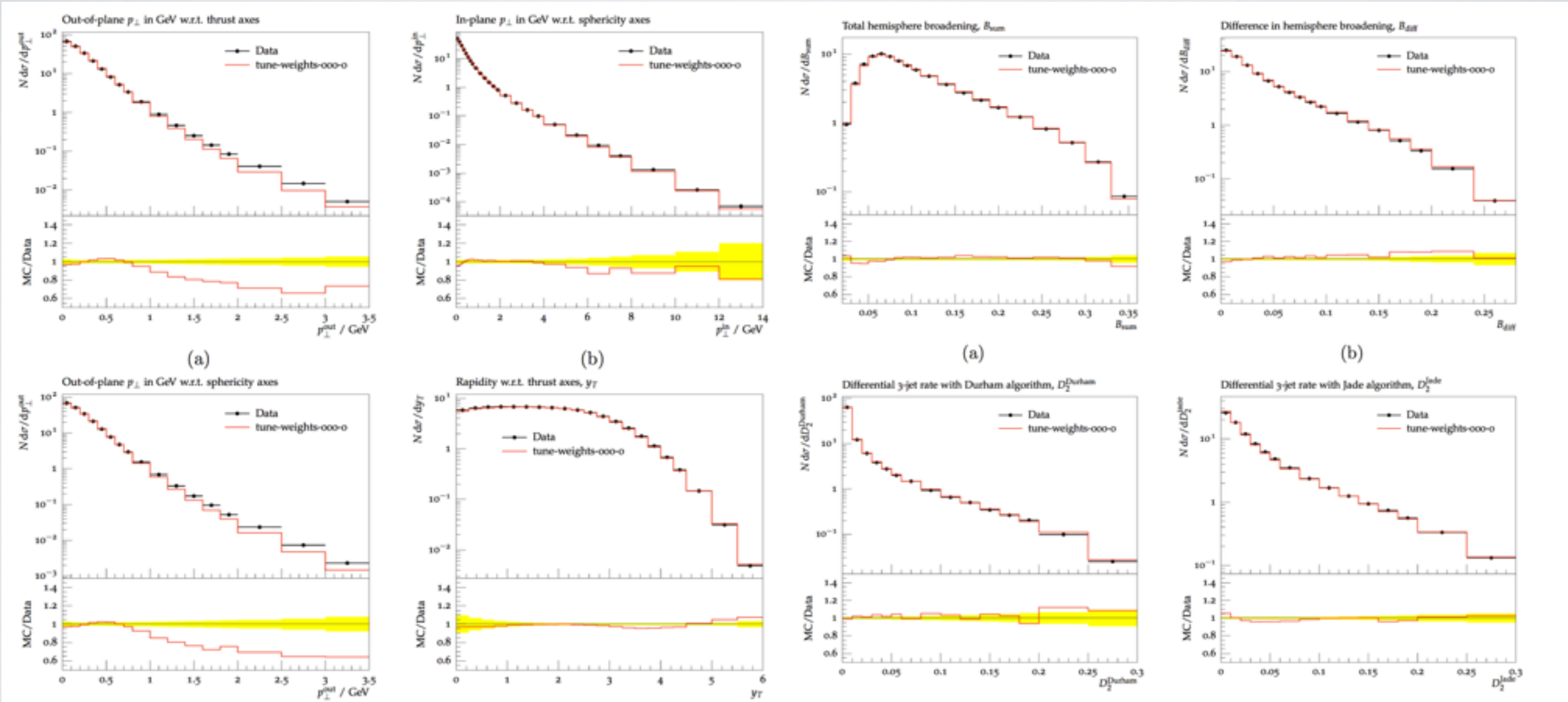




- Technical overhaul of the shower / merging part
- Plans: implement GKS matching, QED shower (also interleaved, infrastructure ready)

Tuning of the WHIZARD Parton Shower

- First tunes of both kT-ordered QCD and Analytic QCD shower   Chokoufe/Englert/JRR, 2015
- Di- and Multijet data from LEP as given in `RIVET` analysis
- Usage of the `PROFESSOR` tool for determining the best fit   Buckley et al., 2009



NLO Development in WHIZARD

- Need for precision predictions that match (sub-) percent experimental accuracy
- mainly NLO corrections, but also QED and electroweak (ee)

Binoth Les Houches Interface (BLHA): Workflow

1. Process definition in SINDARIN (contract to One-Loop Program [OLP])
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(first focus on QCD corrections)

- ⋆ `GoSam` [G. Cullen et al.]
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WHIZARD v2.2.6 contains alpha version

QCD corrections (massless and massive emitters)

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process eett = e1,E1 => t, tbar
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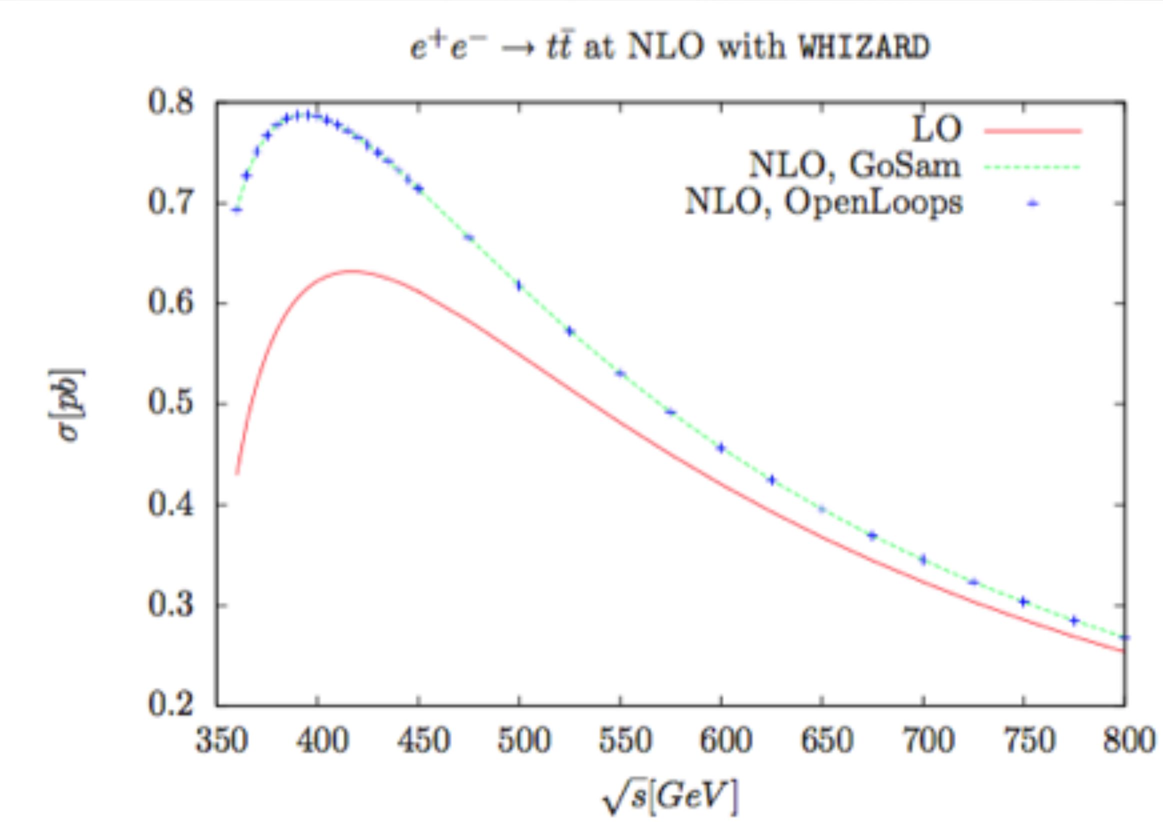

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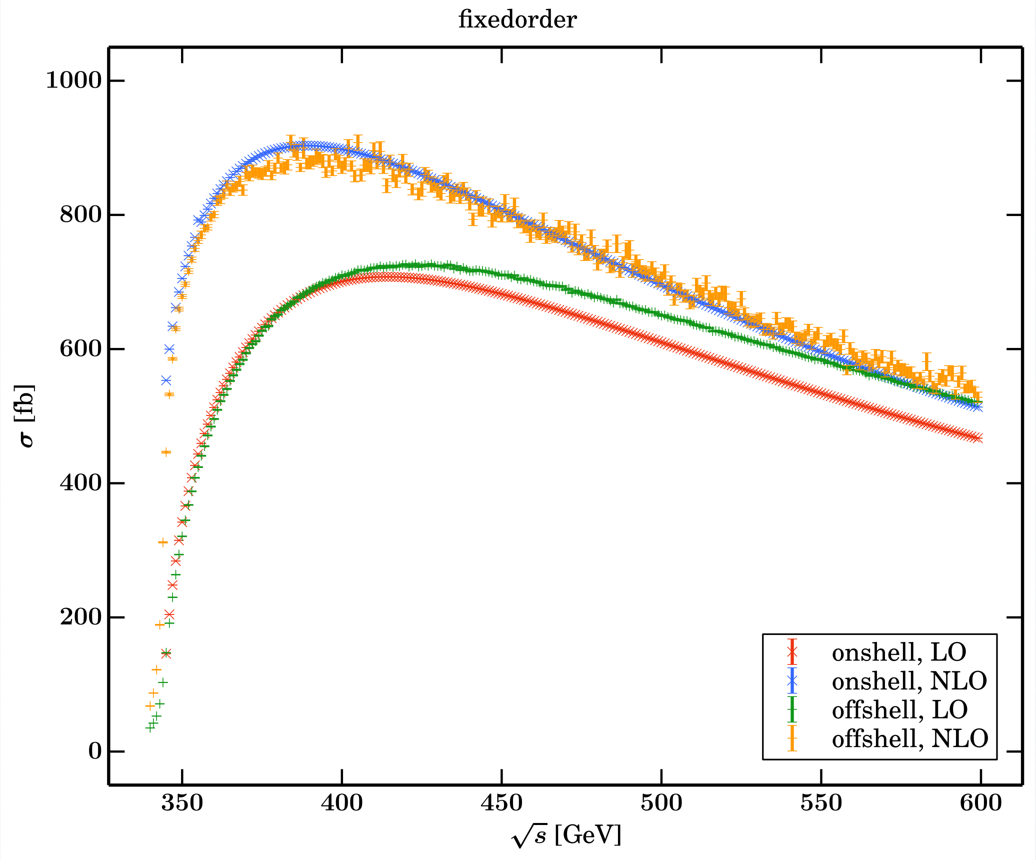

FKS Subtraction (Frixione/Kunszt/Signer)

Subtraction formalism to make real and virtual contributions separately finite

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

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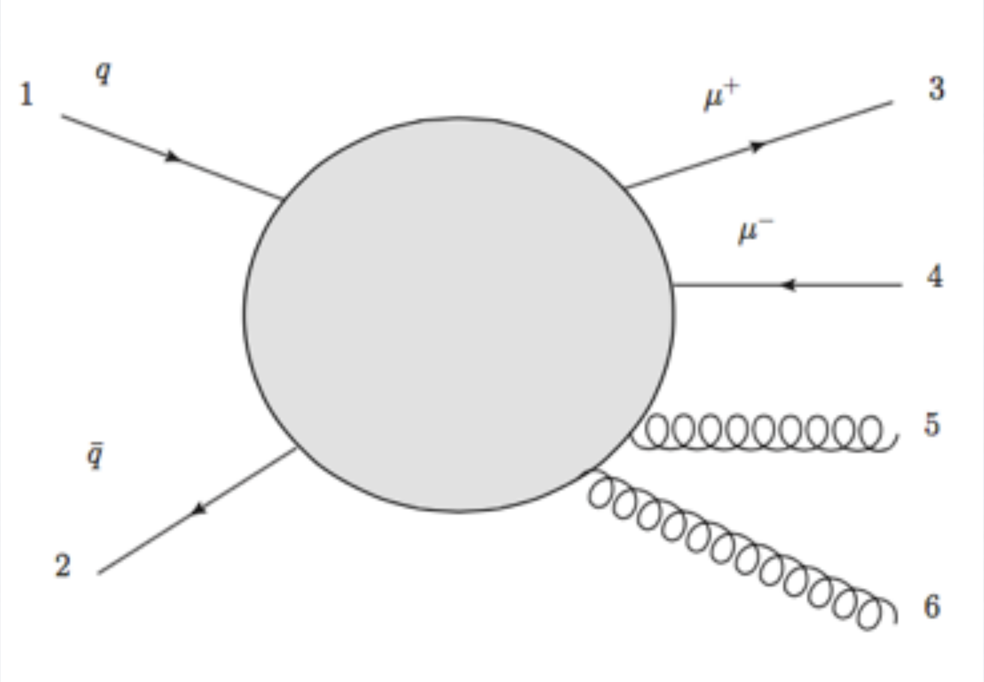

Automated subtraction terms in `WHIZARD`, algorithm:

- Find all singular pairs

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

- Partition phase space according to singular regions

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

- Generate subtraction terms for singular regions

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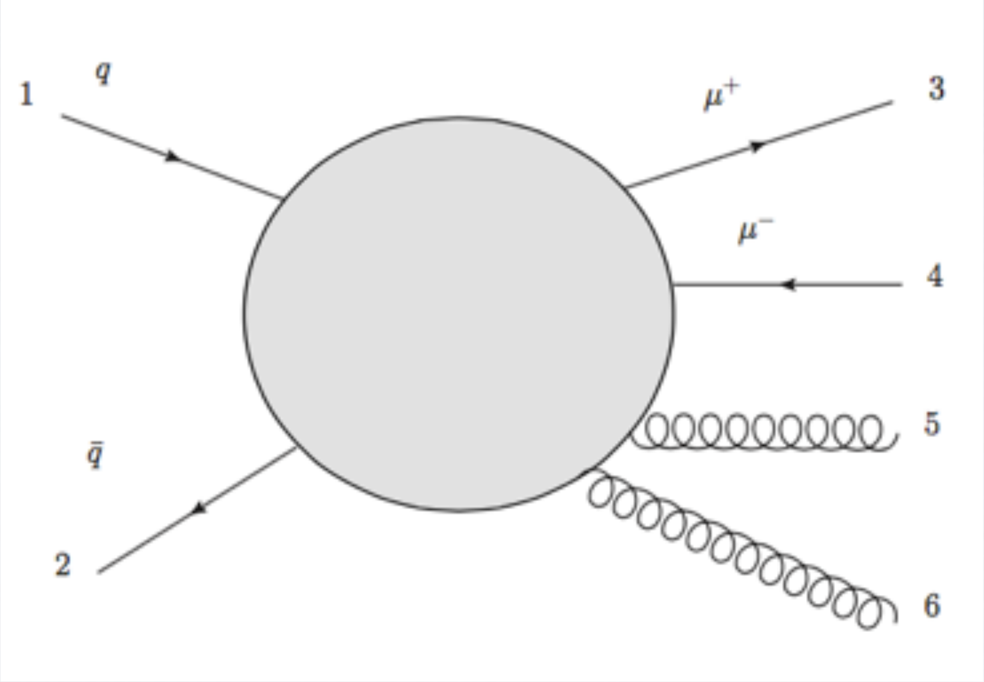

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- ✳ Generate subtraction terms for singular regions

Soft subtraction involves color-correlated matrix elements:

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

Collinear subtraction involves spin-correlated matrix elements:

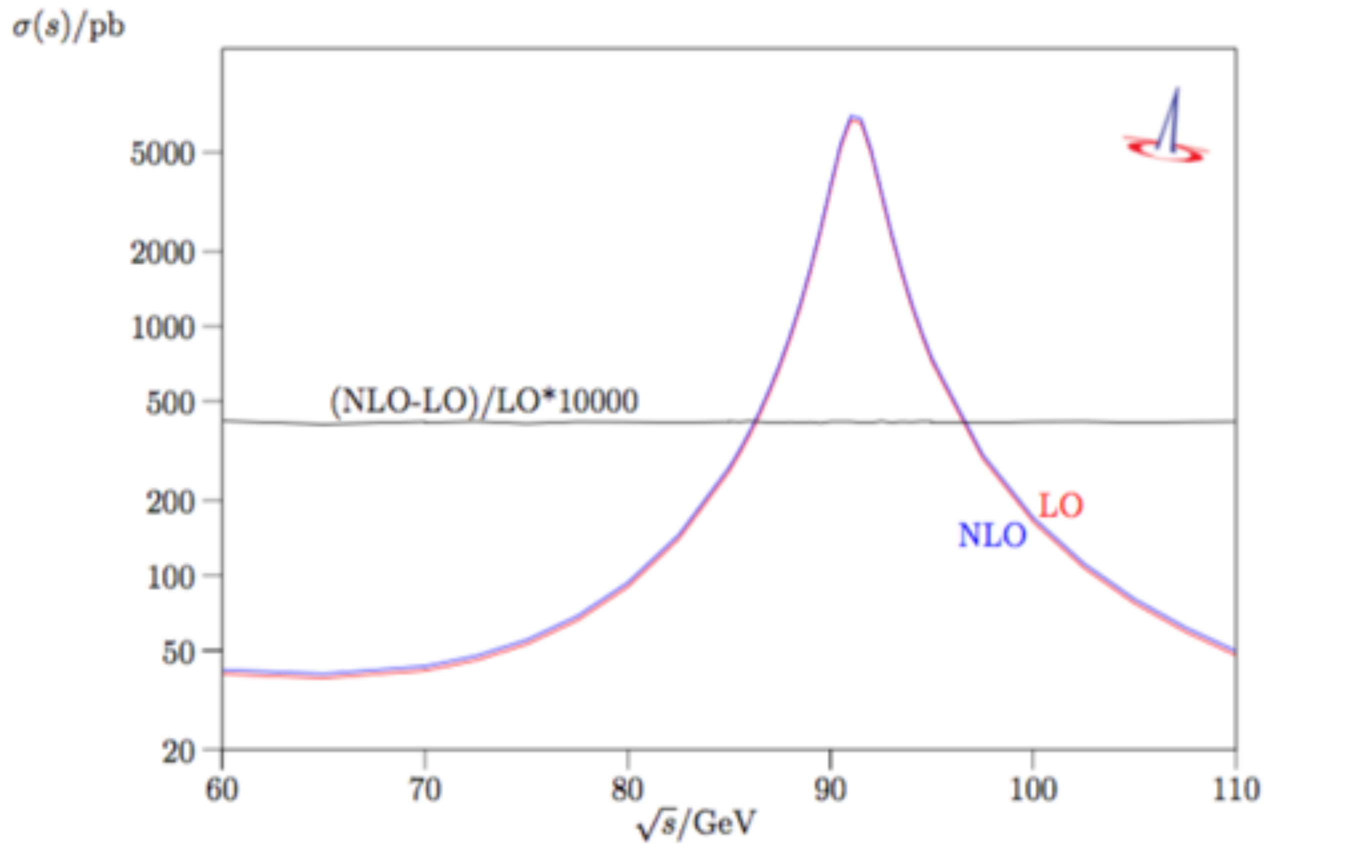
$$\mathcal{B}_{+-} \sim Re \left\{ \frac{\langle k_{\mathrm{em}} k_{\mathrm{rad}} \rangle}{[k_{\mathrm{em}} k_{\mathrm{rad}}]} \sum_{\substack{\text{color}\\ \text{spin}}} \mathcal{A}_+^{(n)} \mathcal{A}_-^{(n)*} \right\}$$

Examples and Validation

Simplest benchmark process:

$$e^+e^- \to q\bar{q} \quad \text{with} \quad \left(\sigma^{\rm NLO} - \sigma^{\rm LO}\right)/\sigma^{\rm LO} = \alpha_s/\pi$$

Plot for total cross section for fixed strong coupling constant



List of validated QCD NLO processes

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

- Cross-checks with `MG5_aMC@NLO`
- Phase space integration for virtuals performs great

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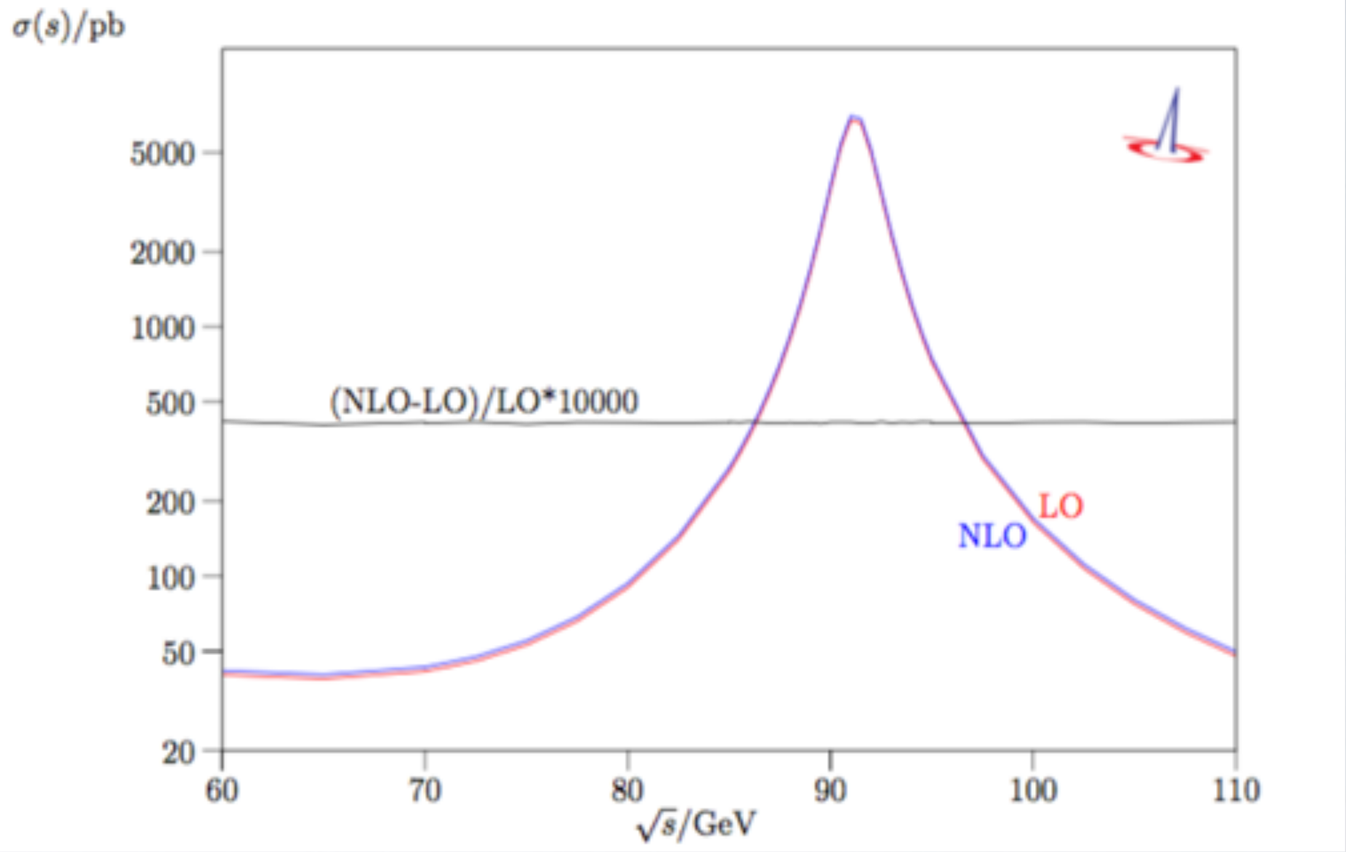

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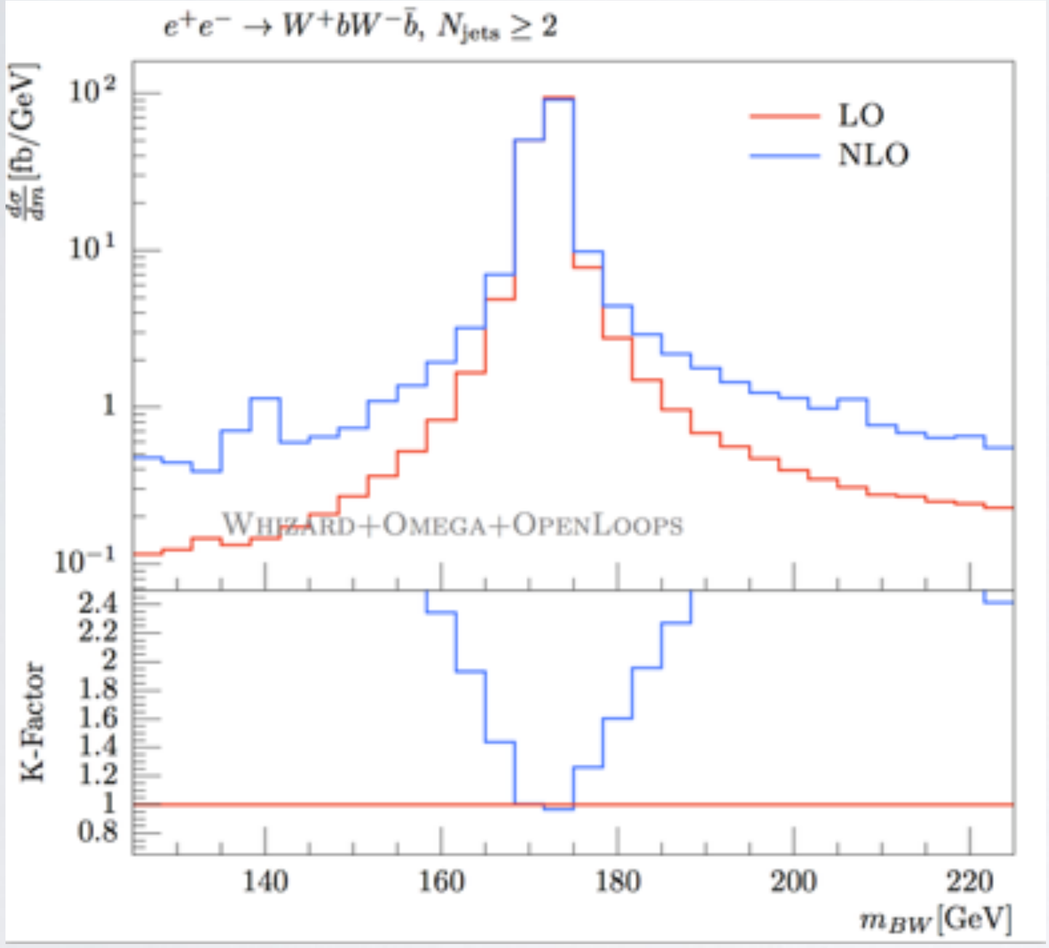
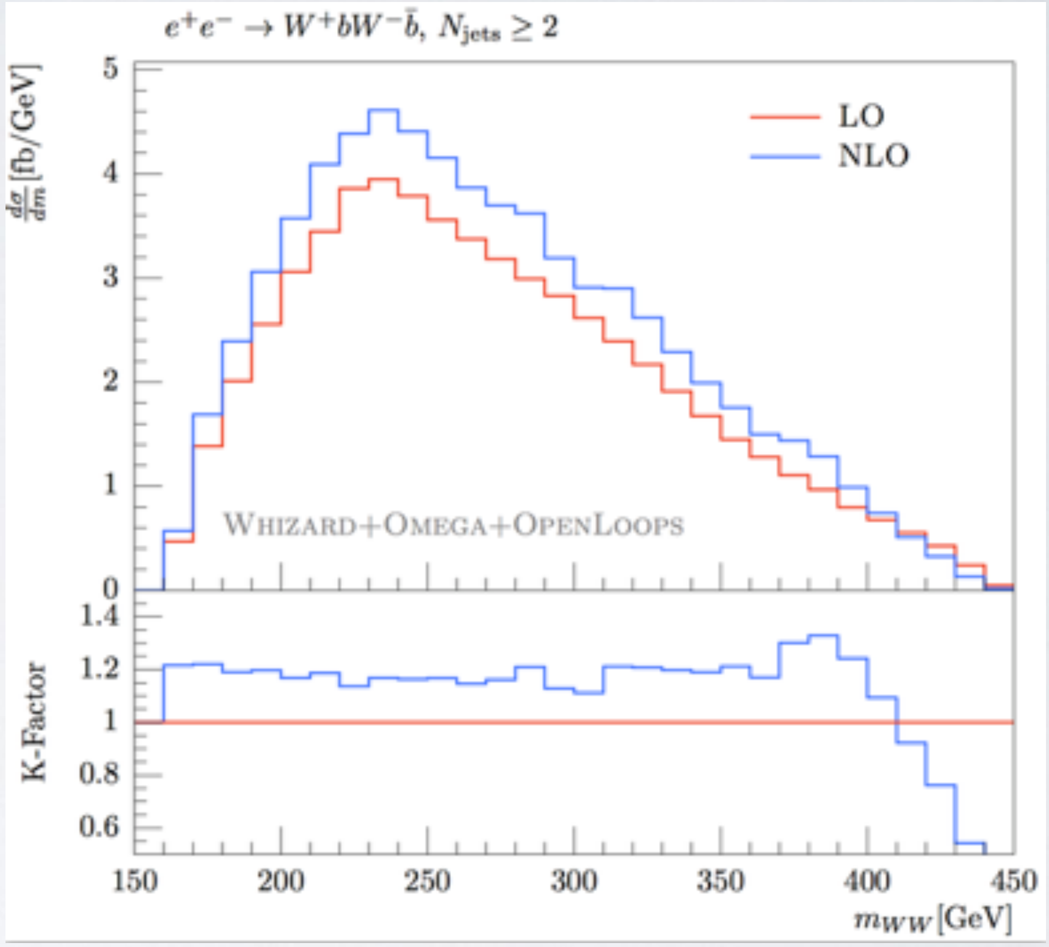
✦ QCD NLO infrastructure in pp complete

✦ First attempts on electroweak corrections, interfacing the `RECOLA` code [Denner et al.]

NLO Fixed-Order Events

- Add weights of real emission events to weight of Born kinematics using the FKS mapping
- Output weighted events in `WHIZARD` (e.g. using `HepMC`), then analysis with `Rivet`
- Example process: $e^+e^- \to W^+W^-b\bar{b}$





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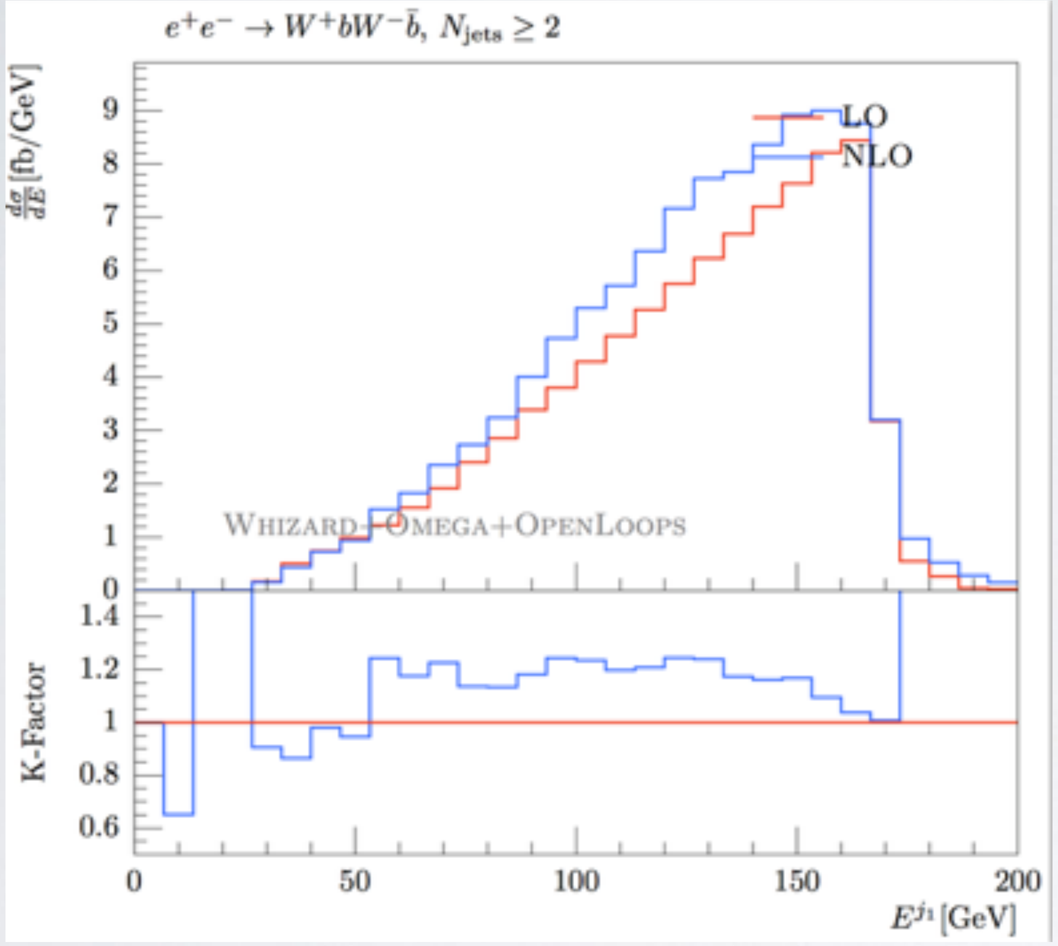

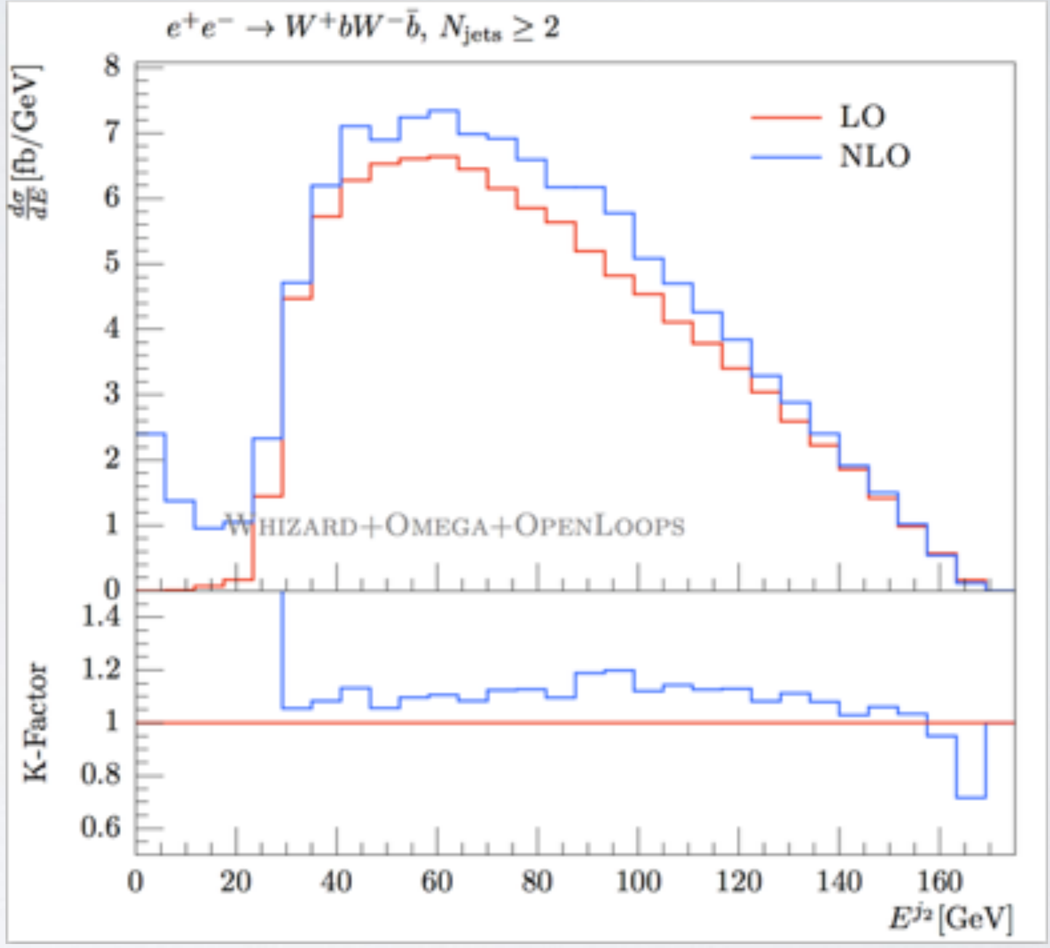

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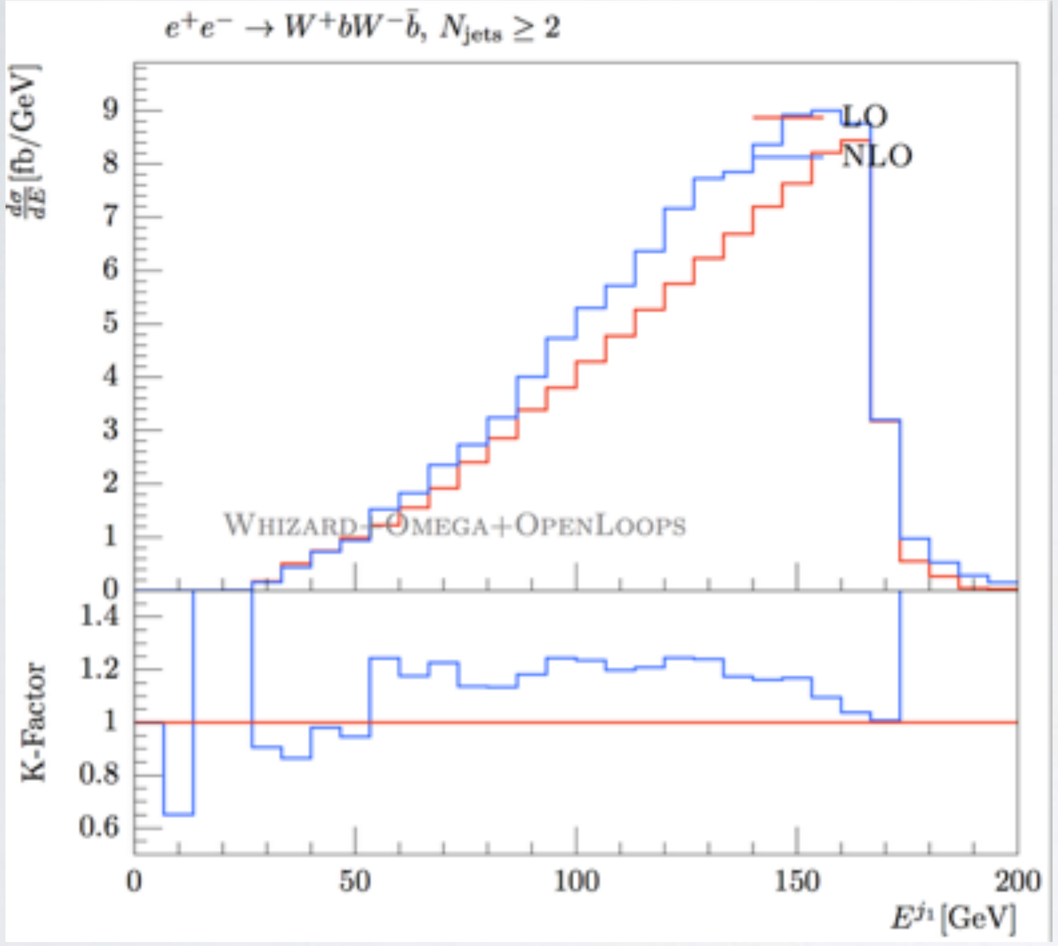
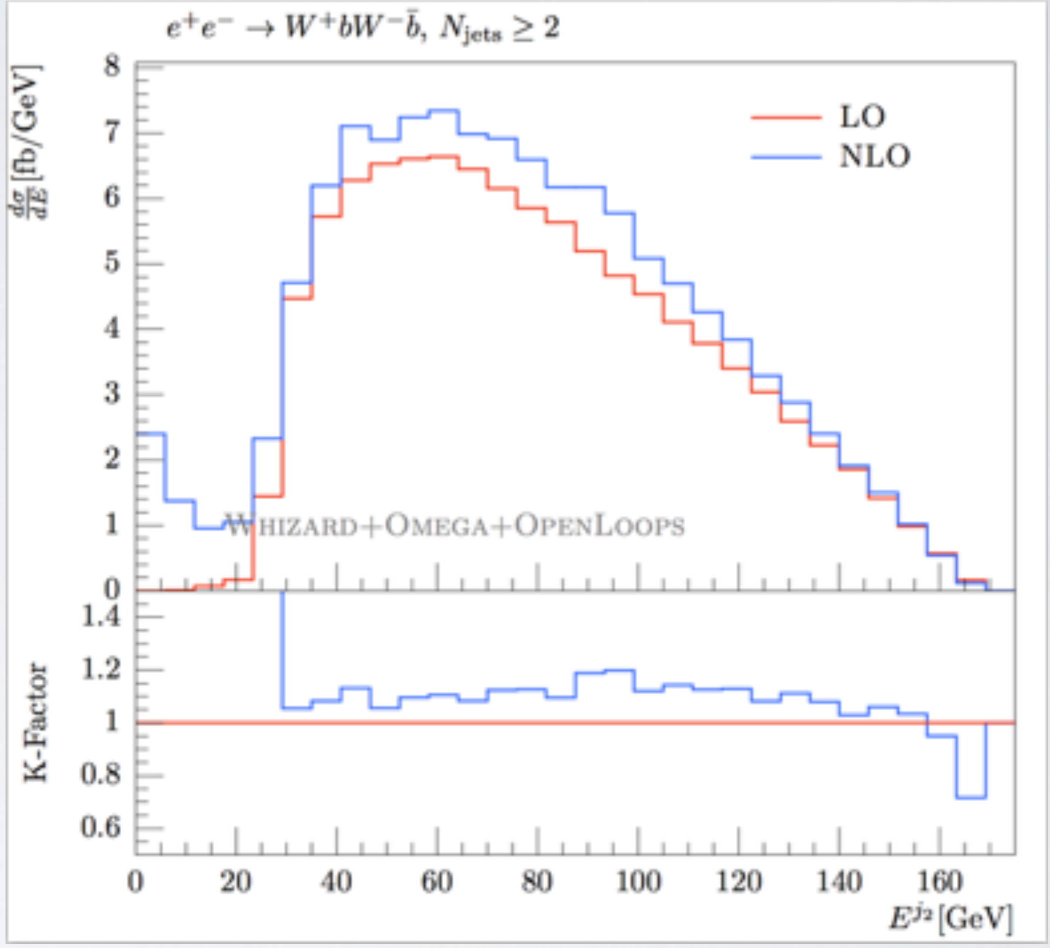
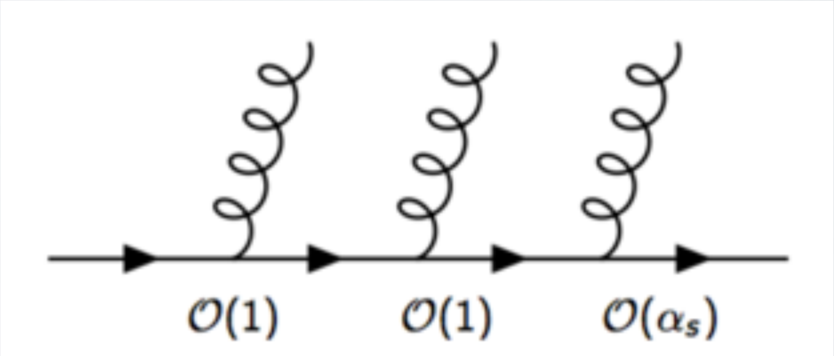




- Completed: polarized NLO results (remember: ILC will always run with polarization)
- Produce also plots including complete ISR photon radiation and beamstrahlung
- NLO decays also available (Initial state Jacobian, important for consistent widths)
- Investigate the full 2 → 6 process: e+e- → bbeμνν [Chokoufé/Kilian/Lindert/JRR/Pozzorini/Weiss]

Automated POWHEG Matching in WHIZARD

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



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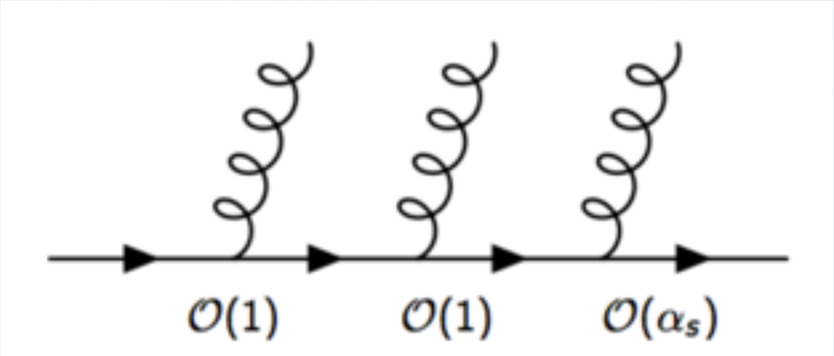

- Complete NLO events

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

- POWHEG generate events according to the formula:

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

- Uses the modified Sudakov form factor:

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

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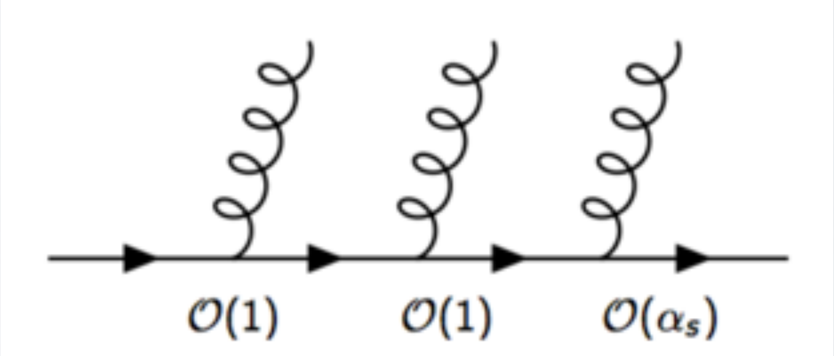

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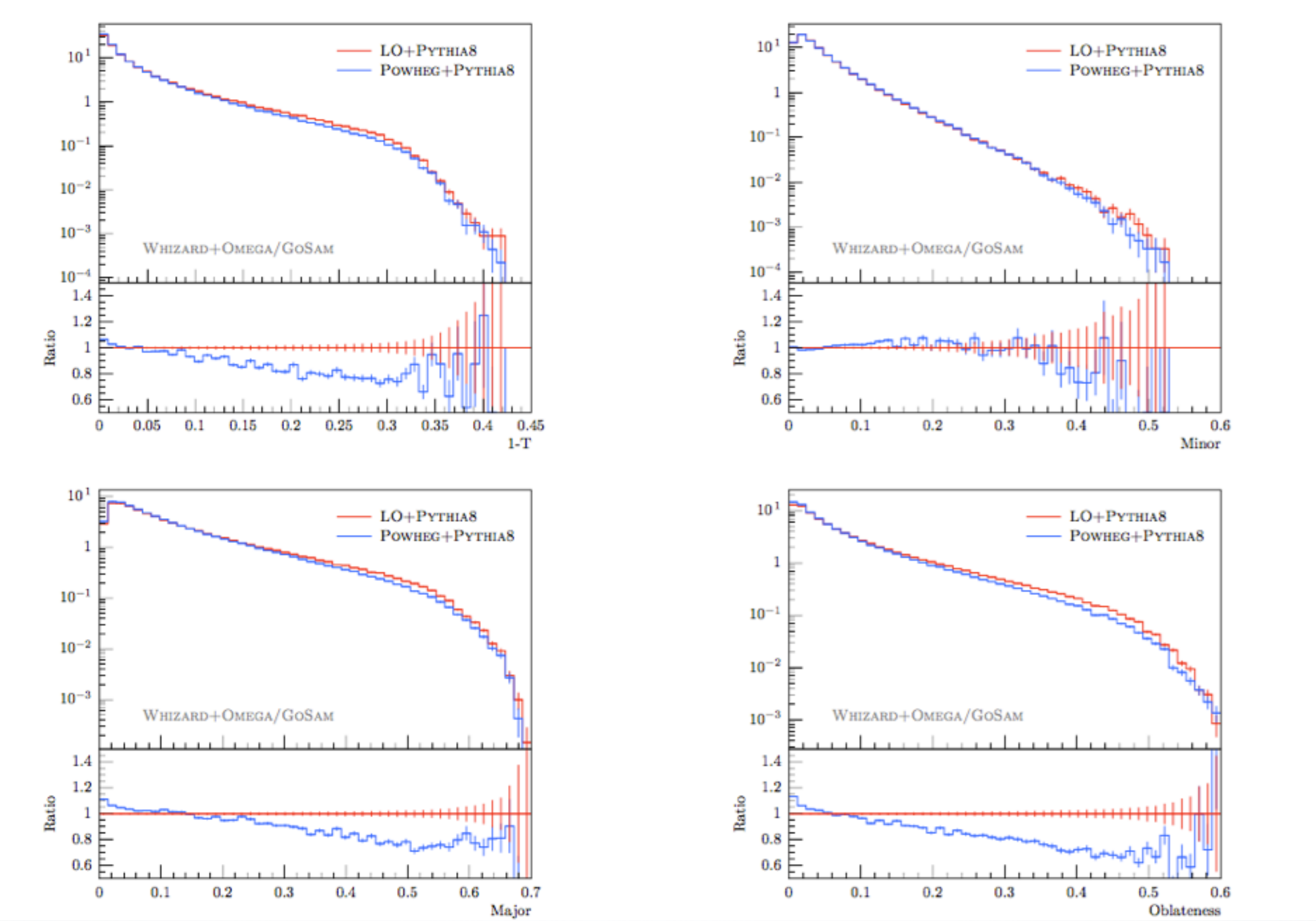
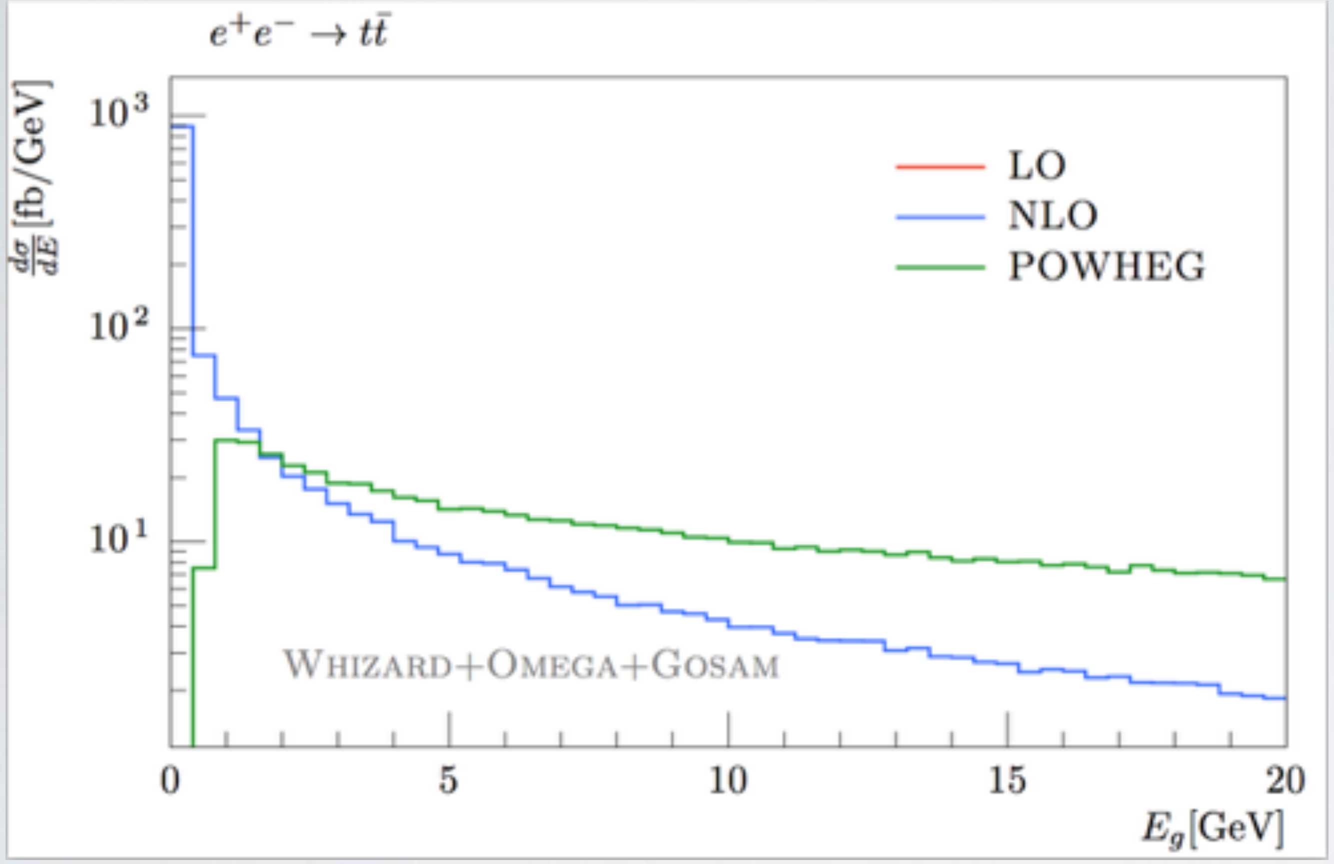
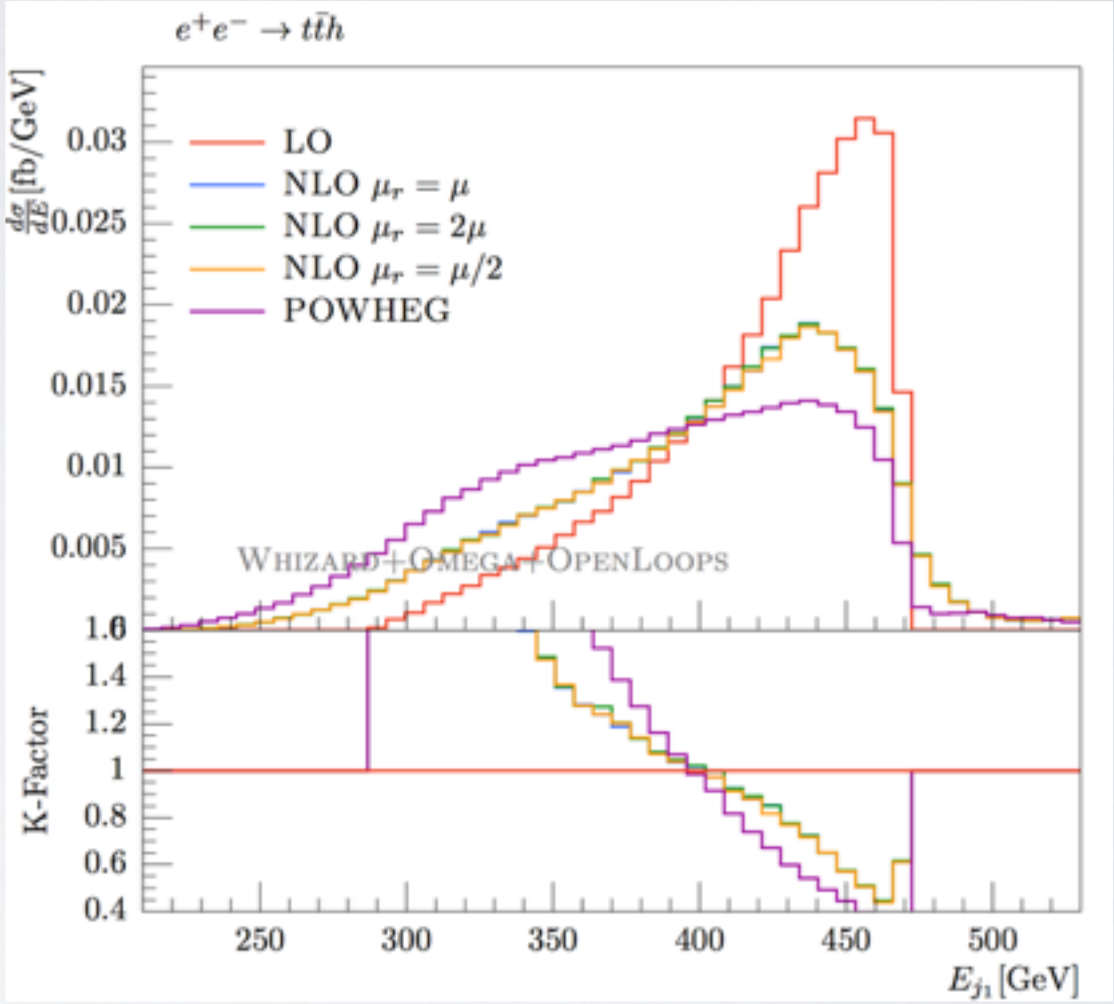
- Hardest emission: $k_T^{\rm max}$; shower with imposing a veto
- $\overline{B} < 0$ if virtual and real terms larger than Born: shouldn't happen in perturbative regions
- Reweighting such that $\overline{B} > 0$ for all events
- POWHEG: Positive Weight Hardest Emission Generator own implementation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

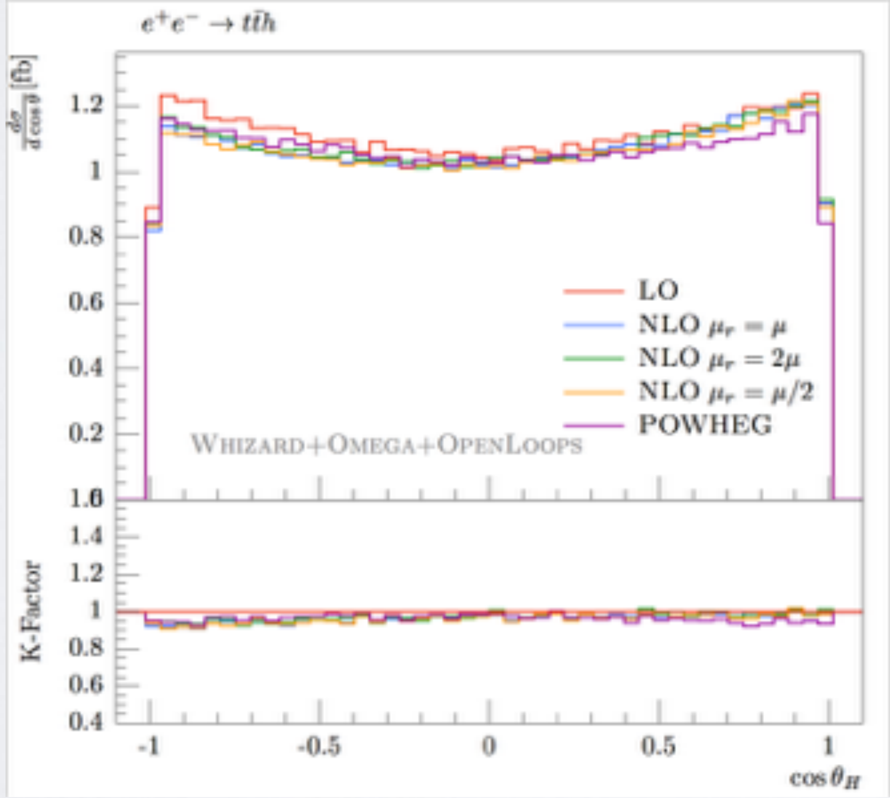
POWHEG Matching, example: e+e- to dijets



Examples: Top pairs and tth production



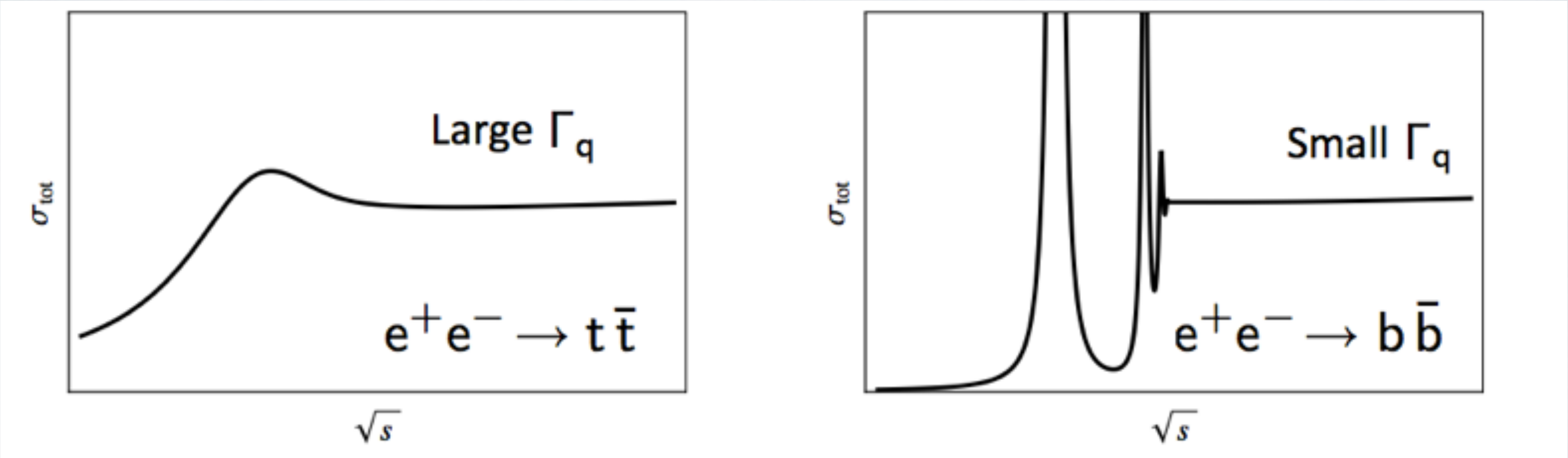




Top Threshold at lepton colliders

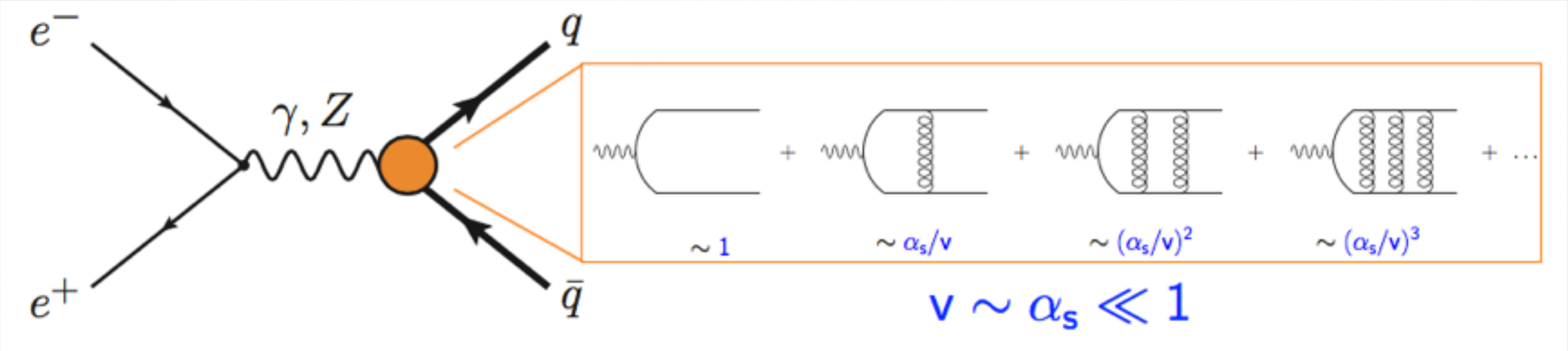
ILC top threshold scan best-known method to measure top quark mass, ΔM ~ 30-50 MeV

Heavy quark production at lepton colliders, qualitatively:



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

$$\nu = \sqrt{\frac{\sqrt{s} - 2m_t + \mathrm{i}\Gamma_t}{m}}$$



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
at NLL differentially!

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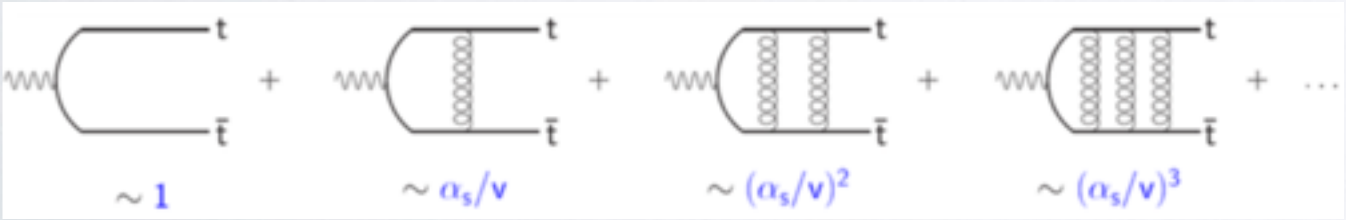
$$R^{\gamma,Z}(s) = \underbrace{F^v(s)R^v(s)}_{\text{s-wave: LL+NLL}} + \underbrace{F^a(s)R^a(s)}_{\text{p-wave}\sim v^2\text{:NNLL}}$$

but contributes at NLL differentially!

Coulomb potential gluon ladder resummation



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

$$R \equiv \frac{\sigma_{t\bar{t}}}{\sigma_{\mu\mu}} = v \sum_k \left(\frac{\alpha_s}{v}\right)^k \sum_i (\alpha_s \ln v)^i \times$$

$$\times \left\{1\,(\mathrm{LL});\ \alpha_s, v\,(\mathrm{NLL});\ \alpha_s^2, \alpha_s v, v^2\,(\mathrm{NNLL})\right\}$$

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but contributes
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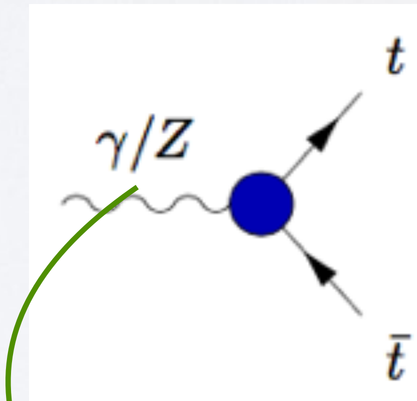
can be mapped onto effective *ttV* vertex



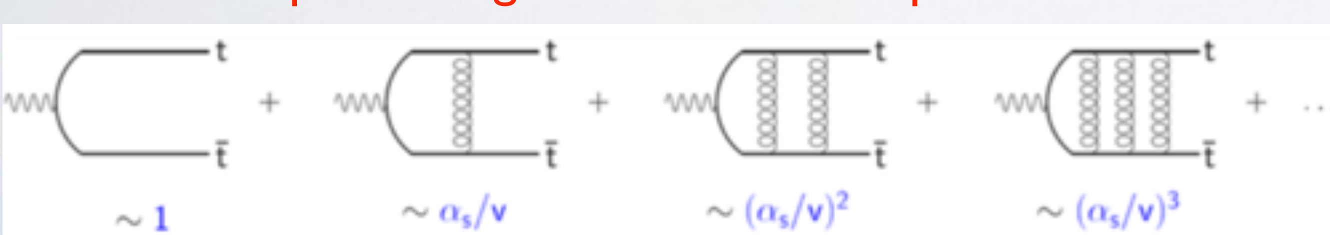
$$\sim \sqrt{R^{v/a}_{\mathrm{(N)LL}}} \sim \frac{\mathcal{G}^{v/a}_{\mathrm{(N)LL}}}{\mathcal{G}^{v/a}\big|_{\alpha_s=0}} \longrightarrow 1$$

far away from
threshold

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

differential in off-shell *tt* phase space

Coulomb potential gluon ladder resummation



Top Threshold in WHIZARD

with F. Bach/B. Chokoufe/A. Hoang/M. Stahlhofen/C. Weiss

- Implement resummed threshold effects as effective vertex [form factor] in `WHIZARD`
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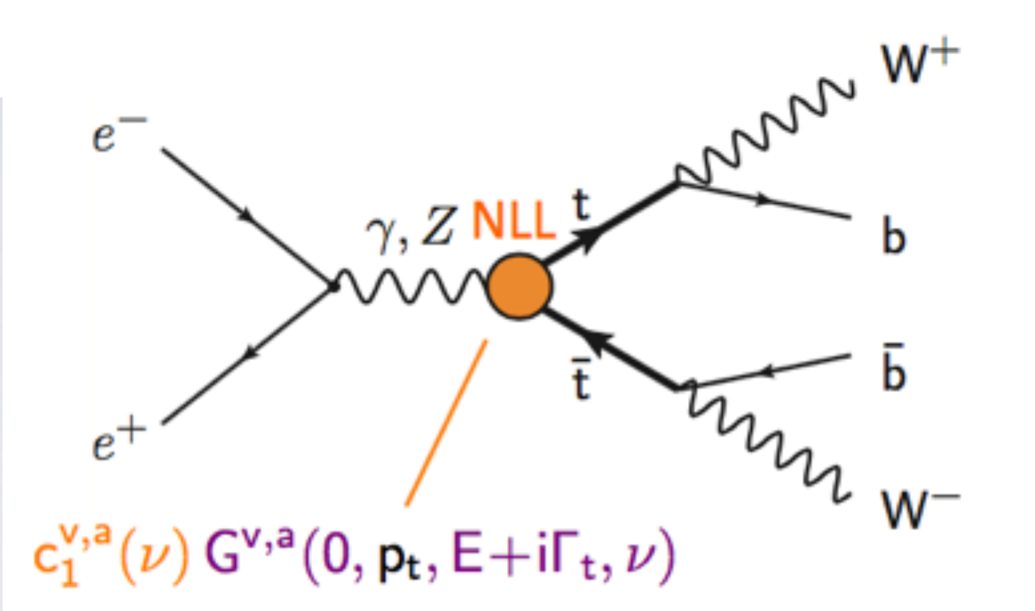

- Default parameters:

$$M^{1S} = 172 \text{ GeV}, \quad \Gamma_t^{\text{NLO}} = 1.409 \text{ GeV}$$
$$\alpha_s(M_Z) = 0.118$$

$$M^{1S} = M_t^{pole}(1 - \Delta_{(Coul.)}^{LL/NLL})$$ [P. Marquard's talk]

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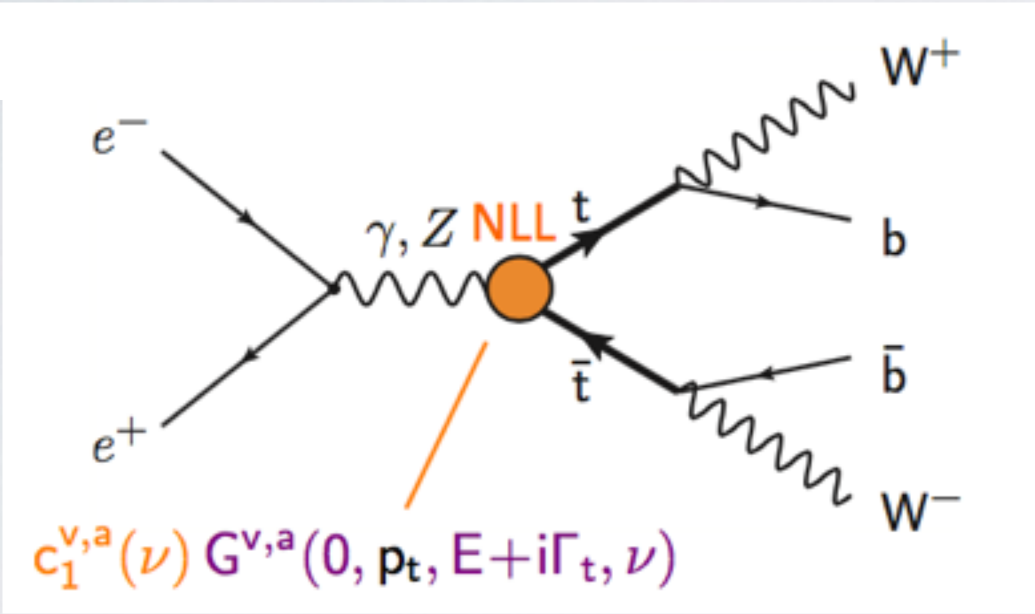

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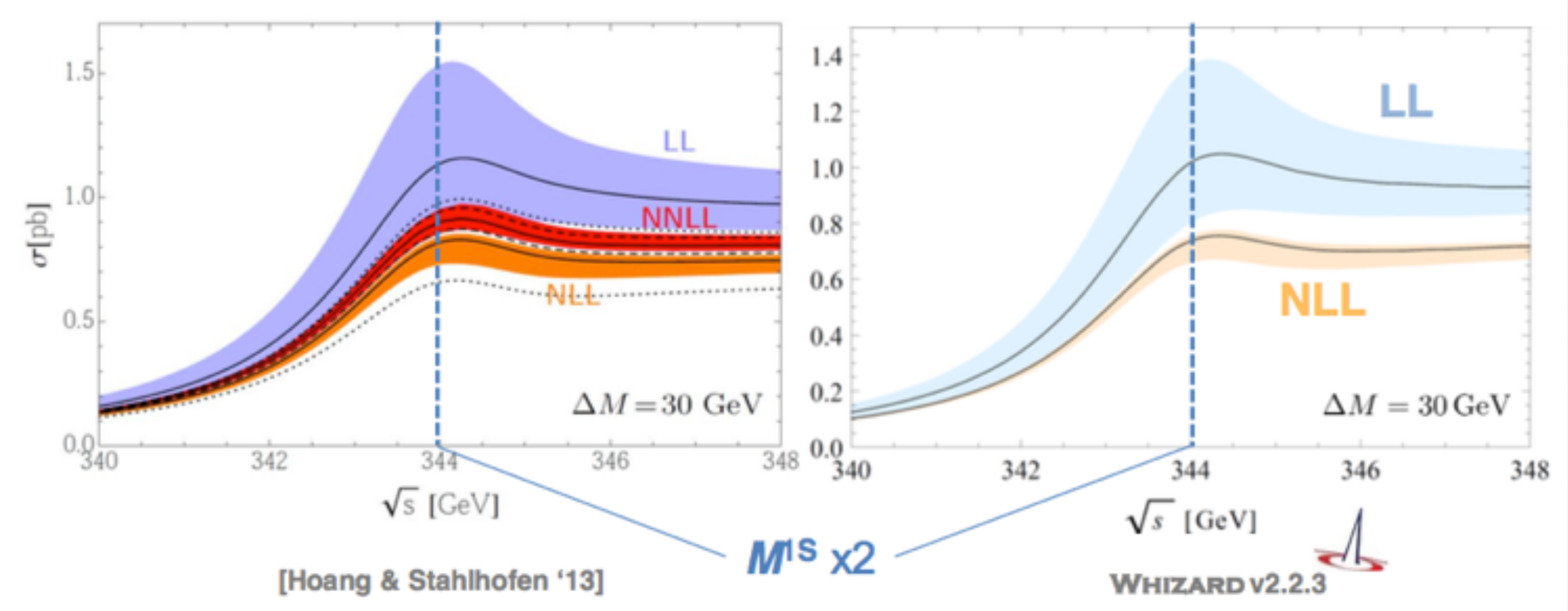

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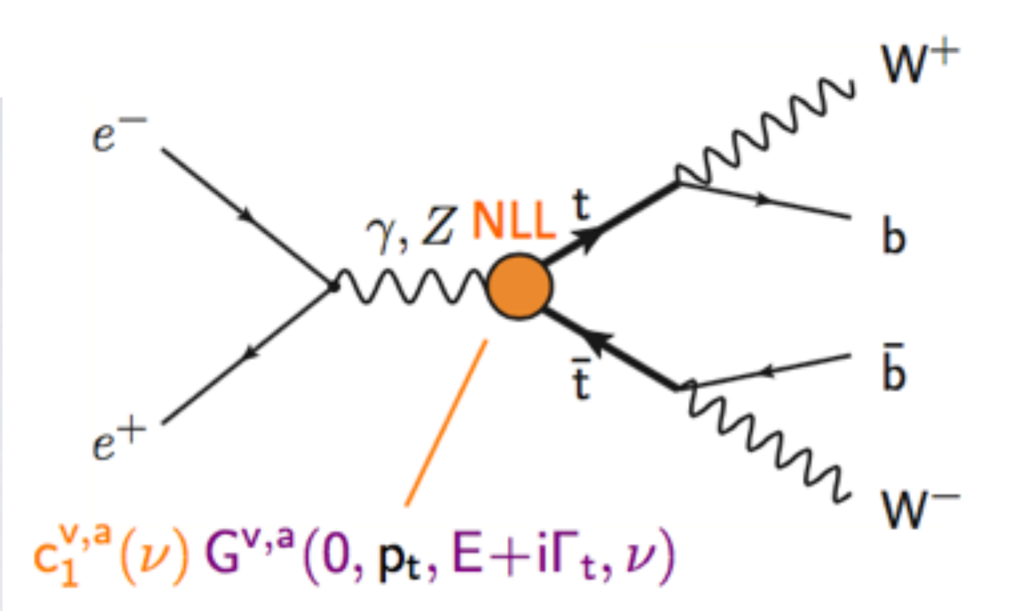

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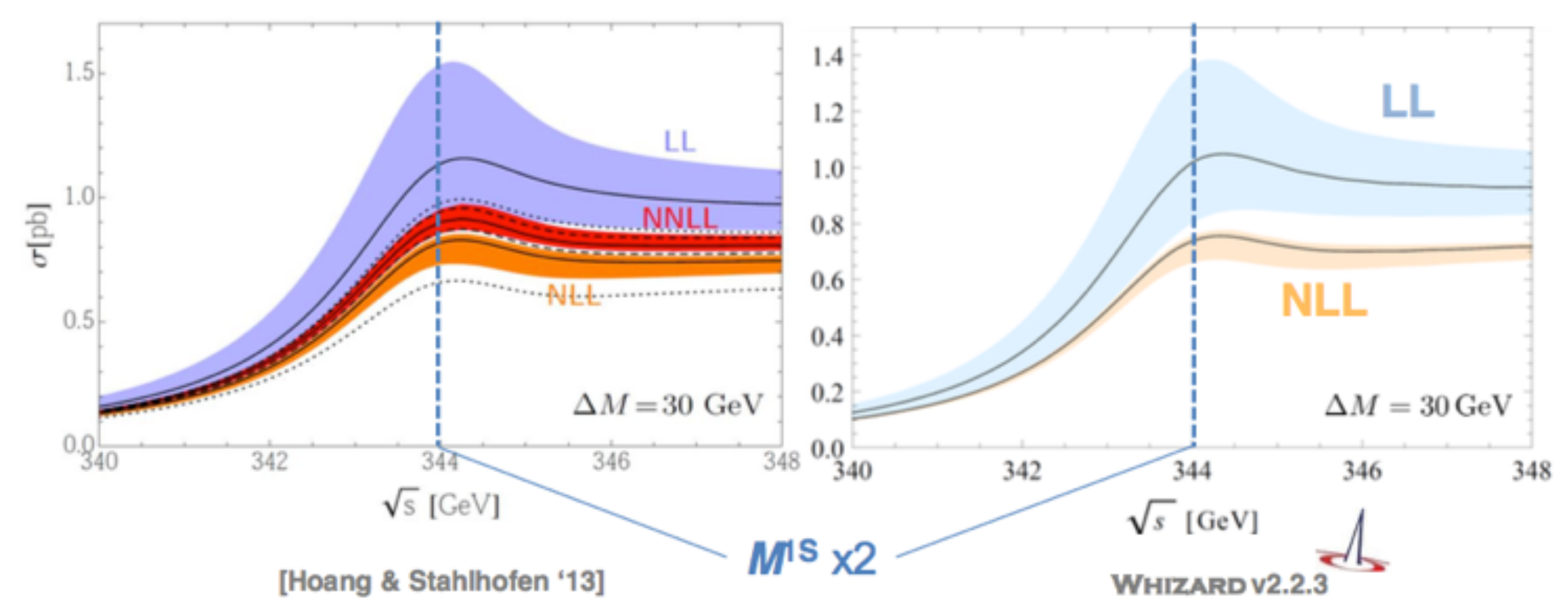
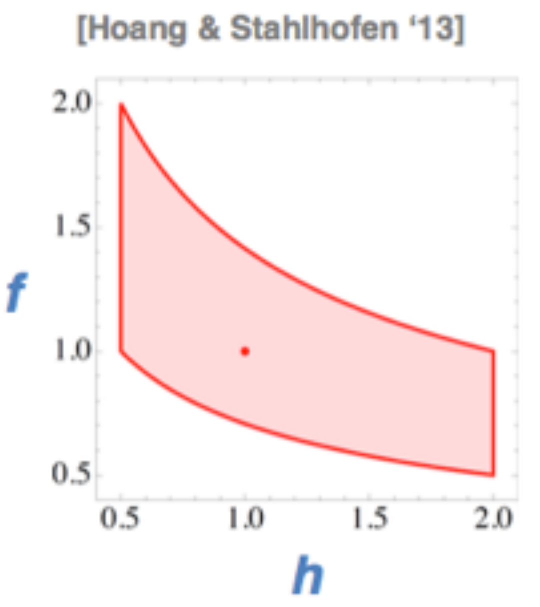
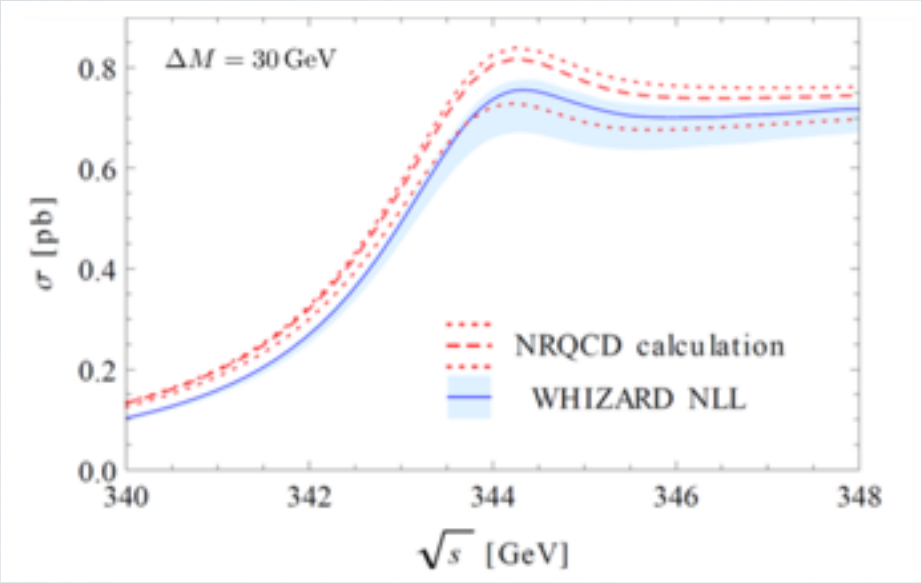
Theory uncertainties from scale variations: hard and soft scale

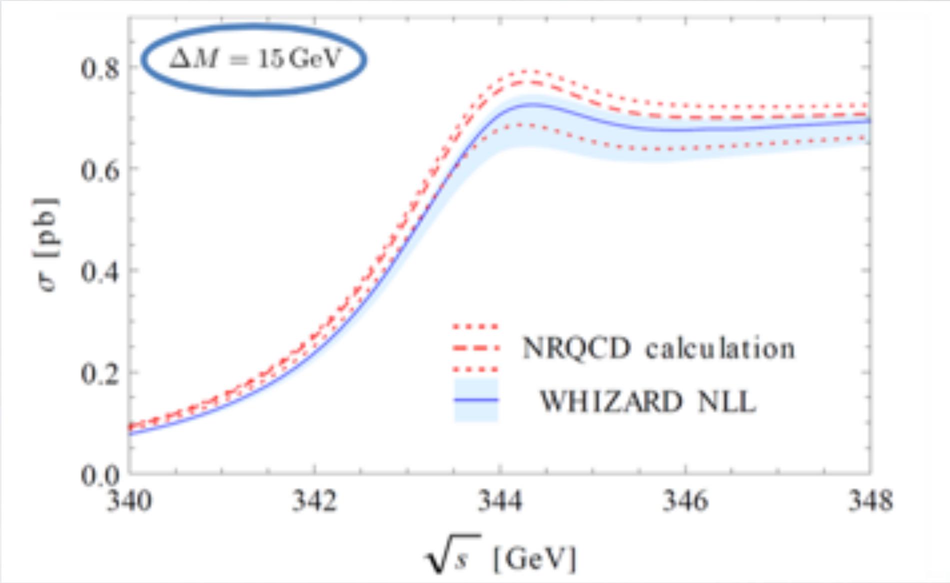
$$\mu_h = h \cdot m_t \qquad \mu_s = f \cdot m_t v$$





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





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

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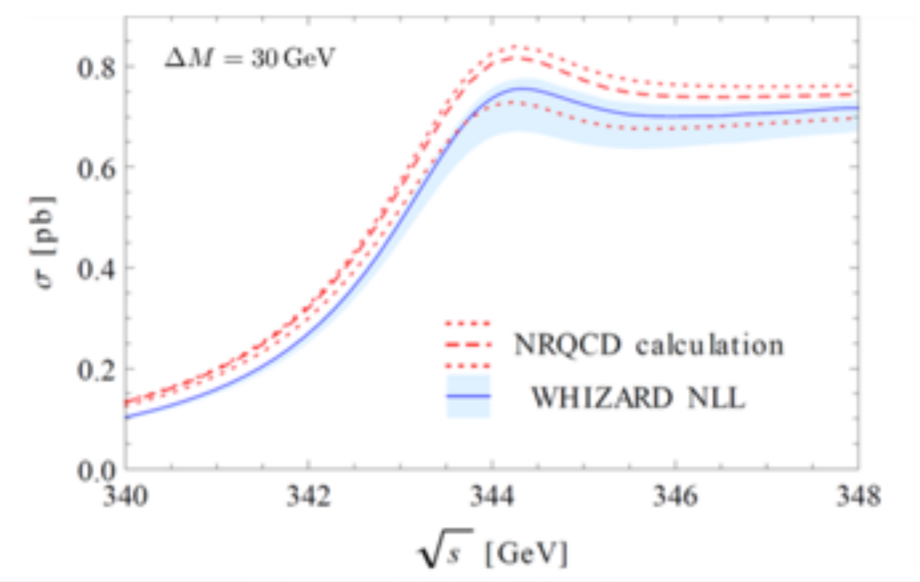

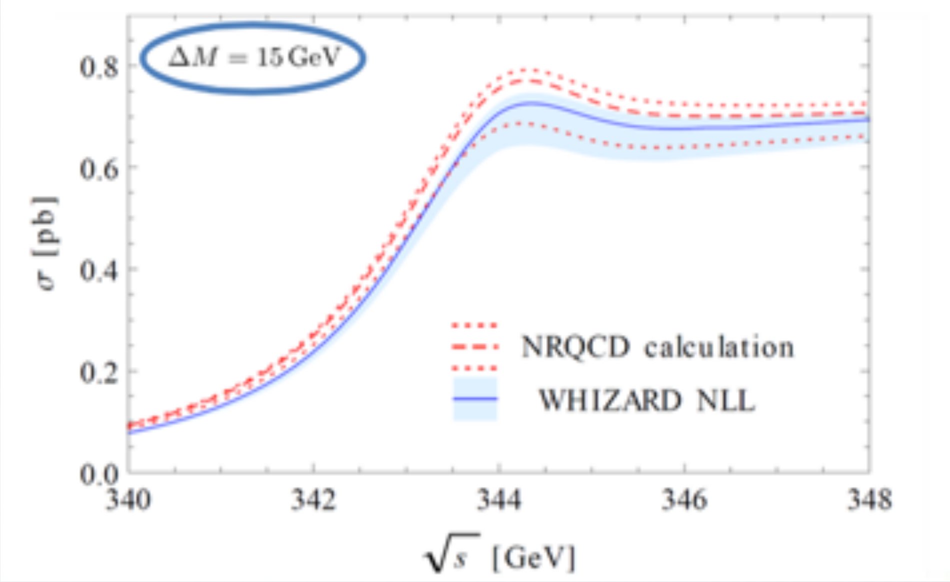

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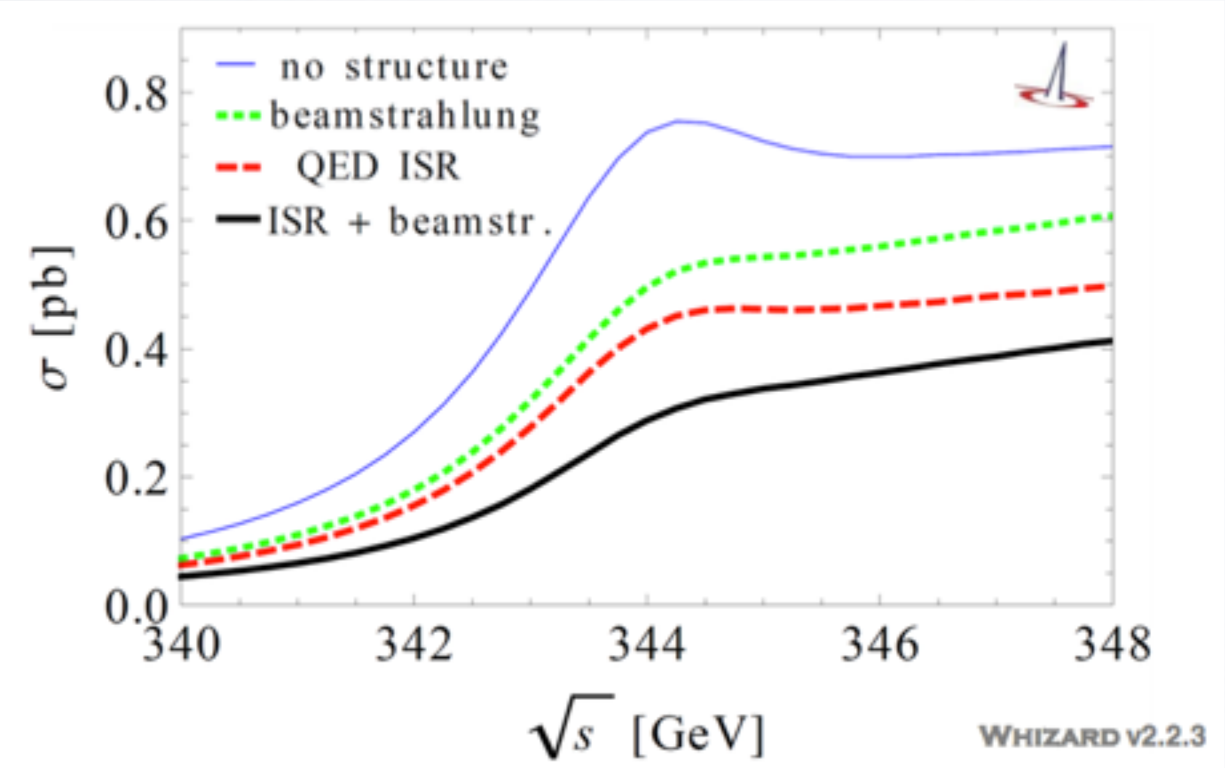

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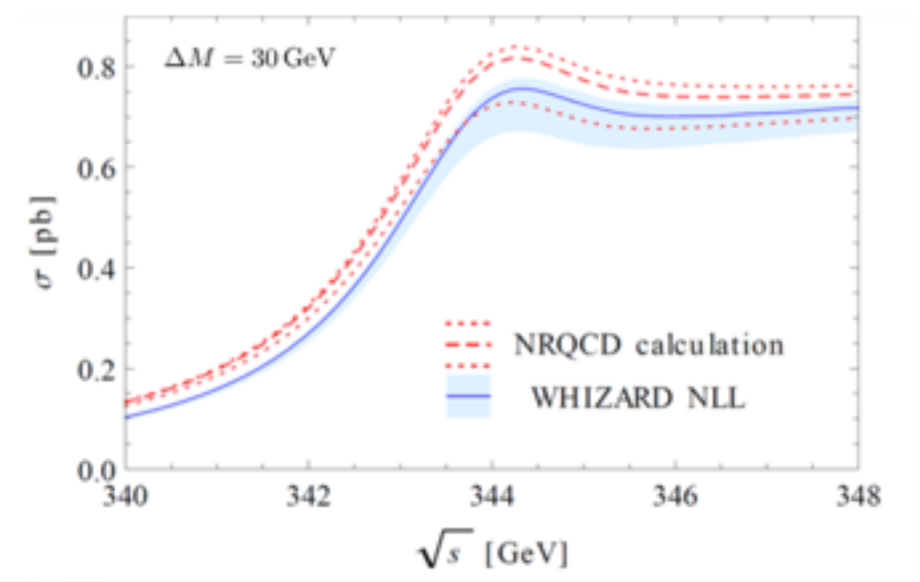

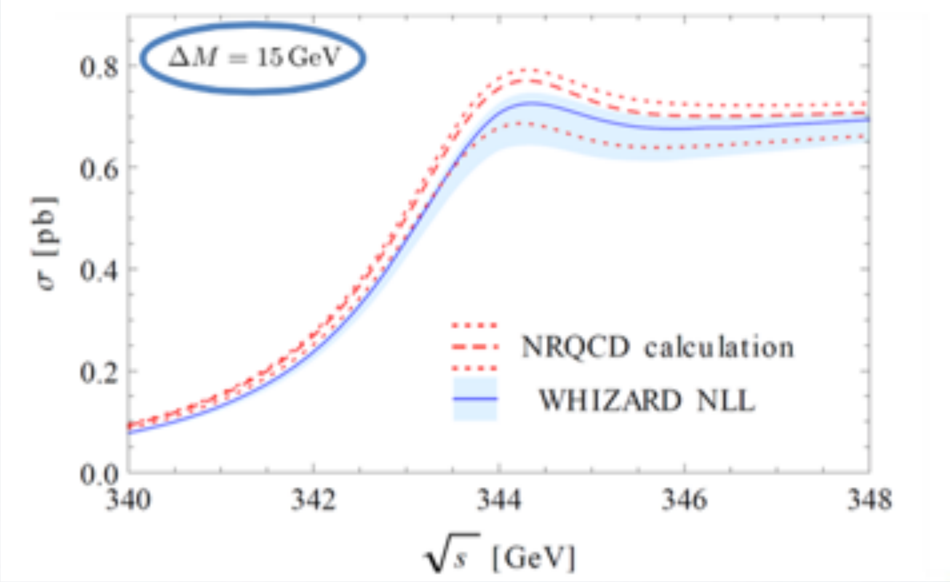

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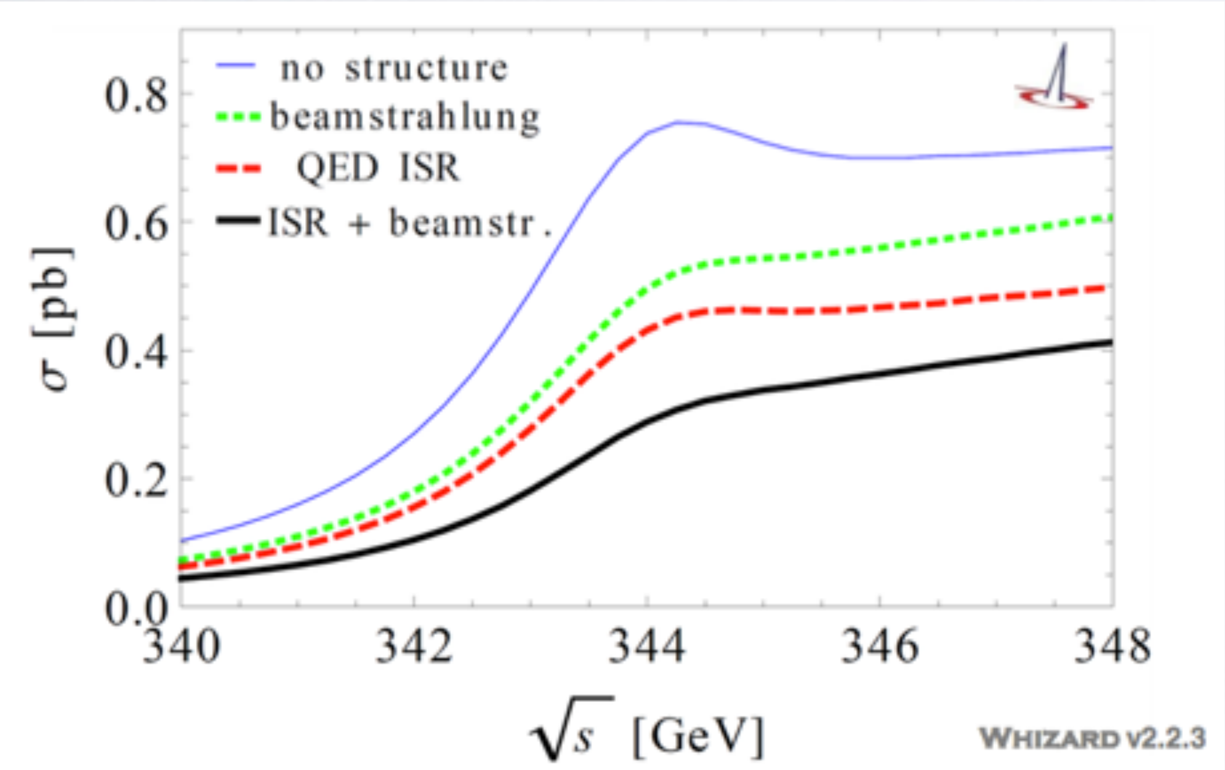
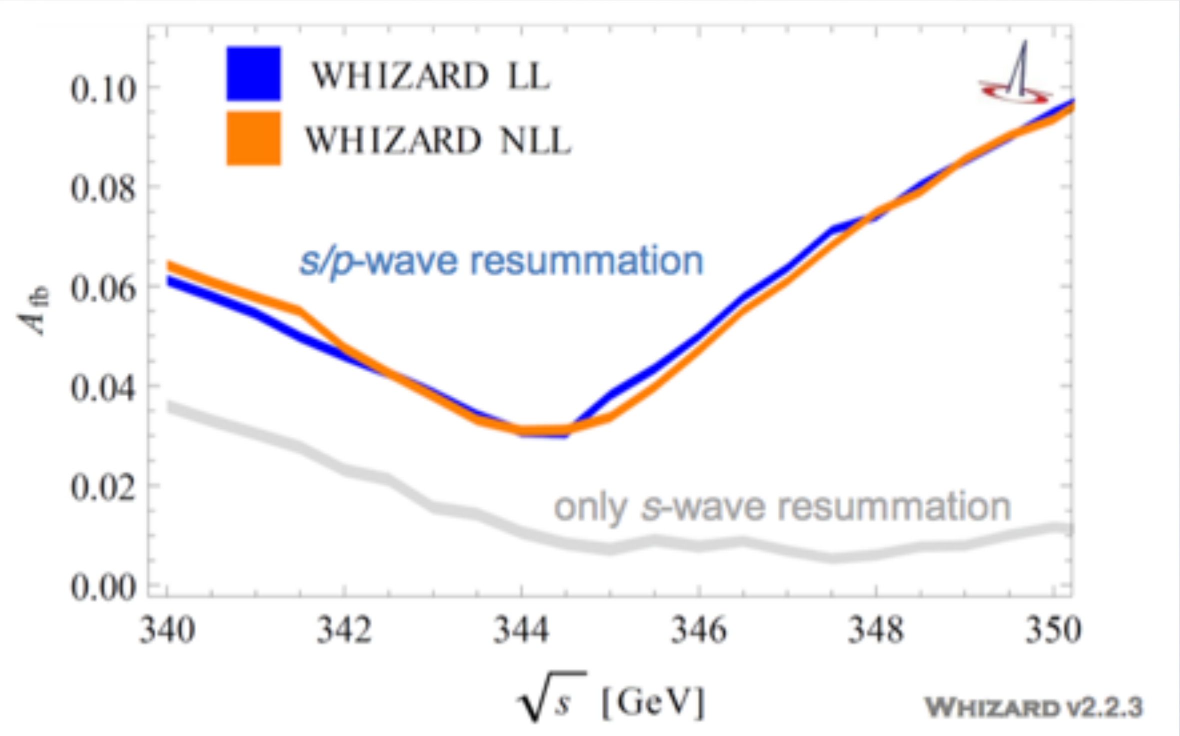
Forward-backward asymmetry (norm. ⇒ good shape stability)

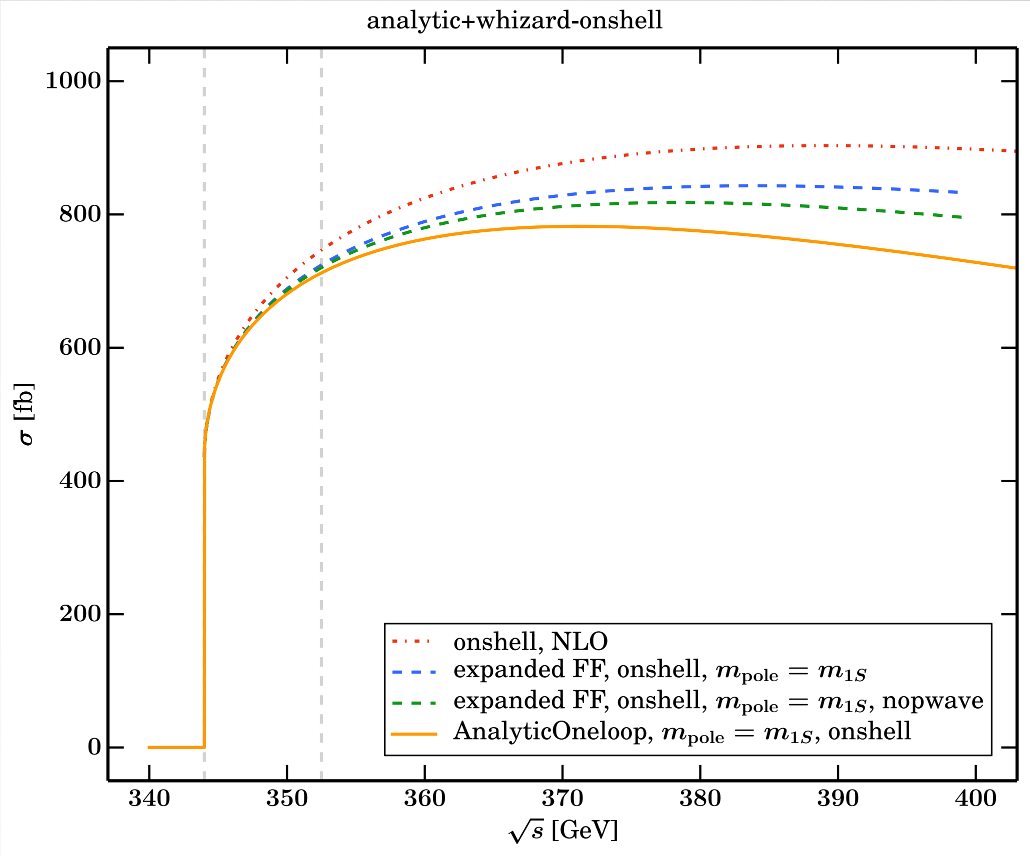
$$A_{fb} := \frac{\sigma(p_z^t > 0) - \sigma(p_z^t) < 0)}{\sigma(p_z^t > 0) + \sigma(p_z^t < 0)}$$





Matching to continuum at LO and NLO

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



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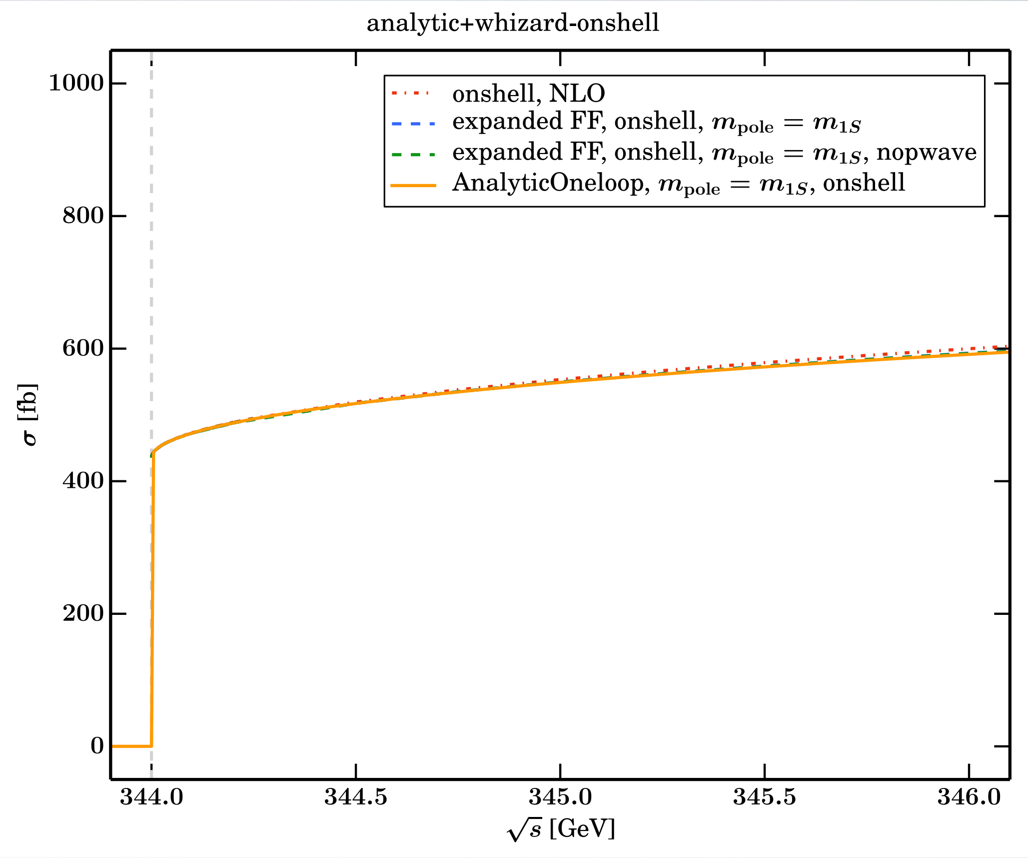

Resummed formfactor, expanded to $\mathcal{O}(\alpha_s)$

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

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

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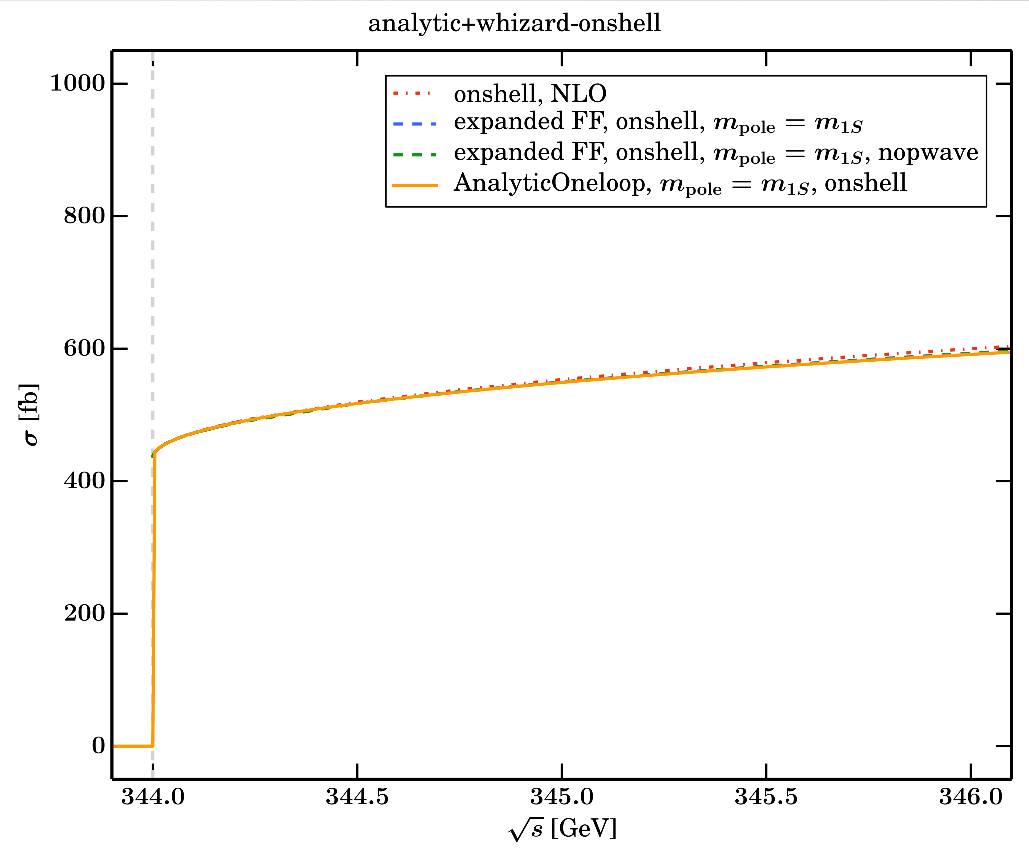

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Matching formula

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

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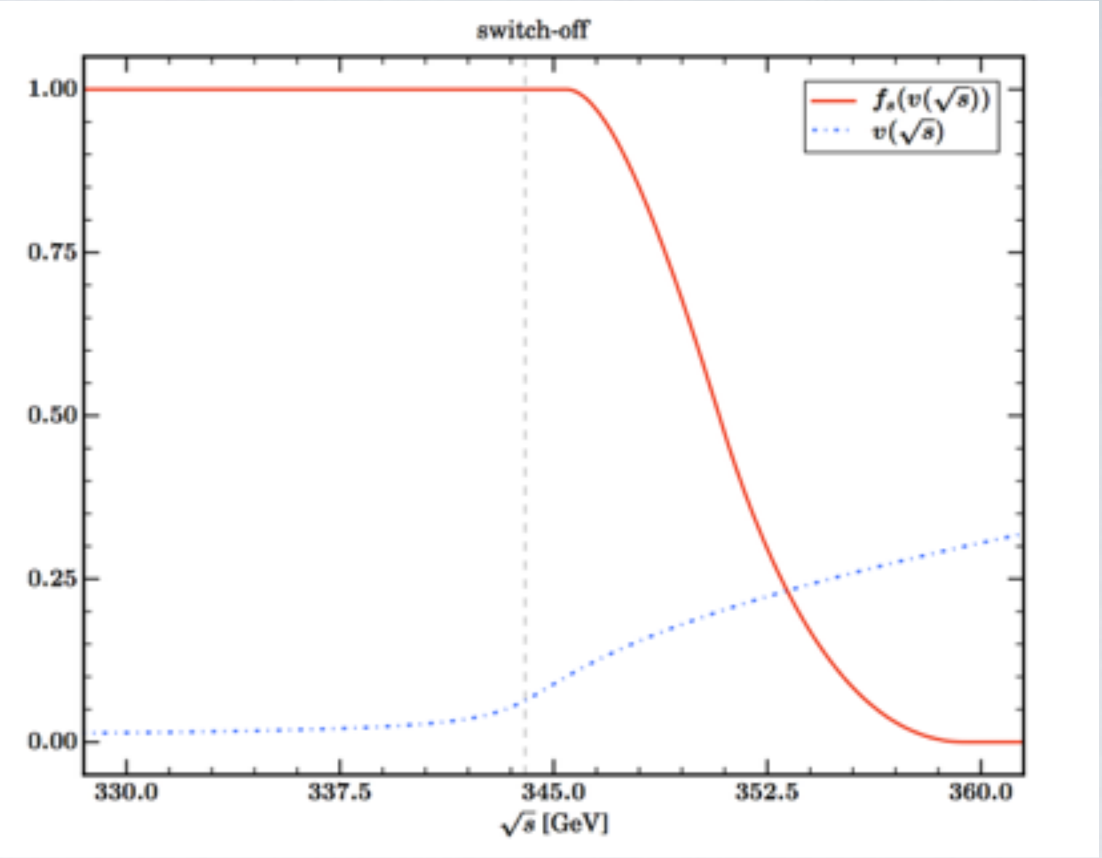

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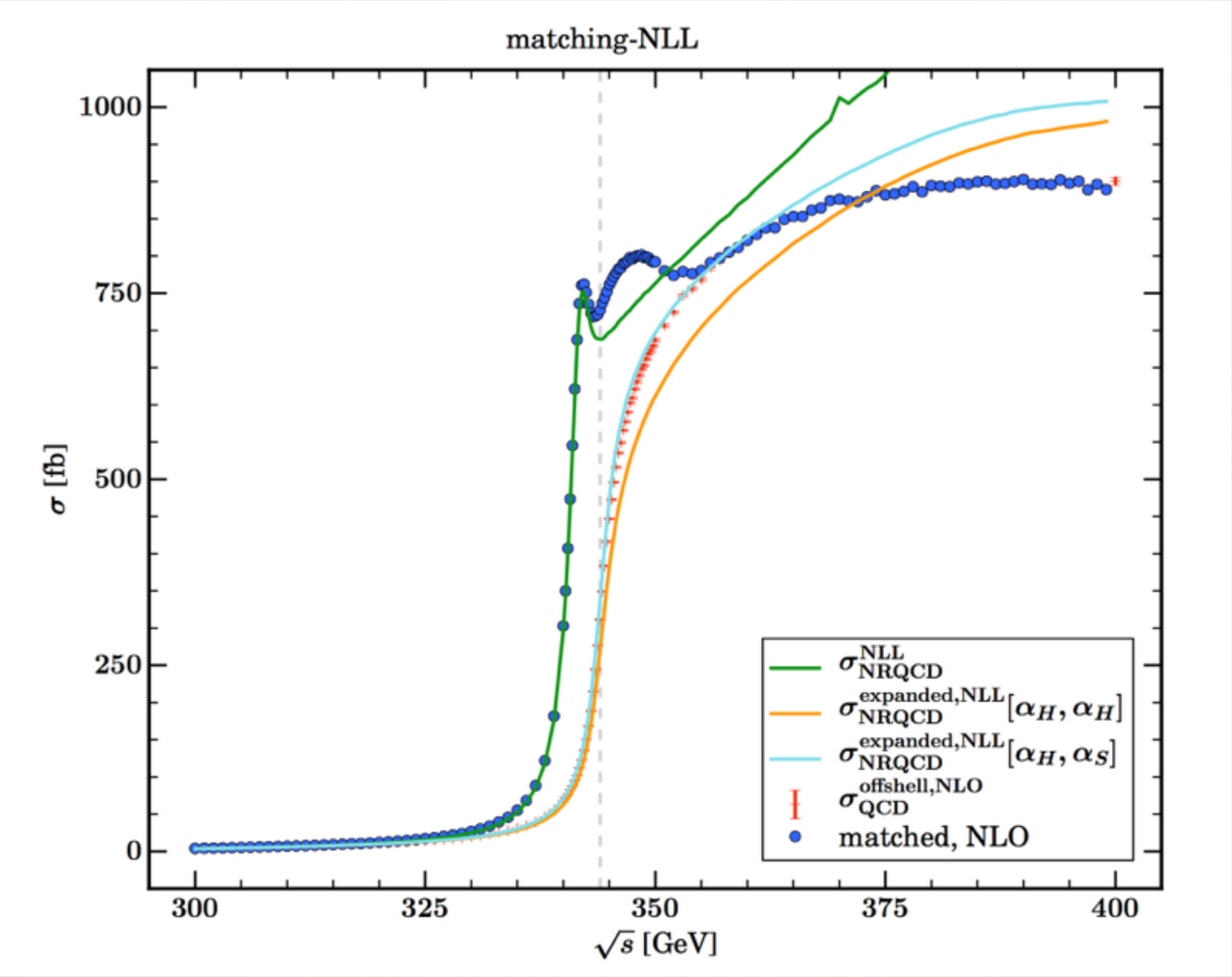
Switch-off function

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

Threshold-continuum matching



Conclusions & Outlook

- `WHIZARD 2.2` event generator for collider physics (ee, pp, ep)
- Focus here on top physics at ee colliders
- (QCD) NLO automation: reals and subtraction terms (FKS) [+ virtuals externally] → `WHIZARD 3.0`
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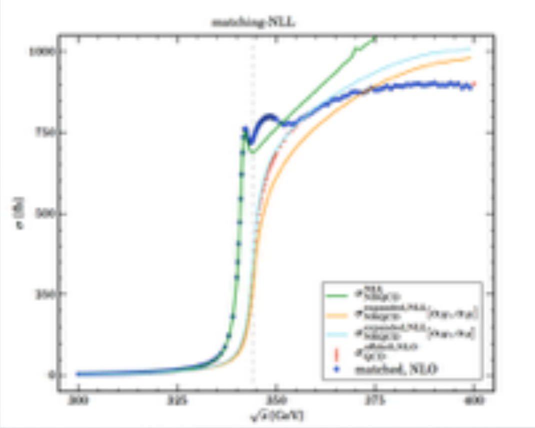

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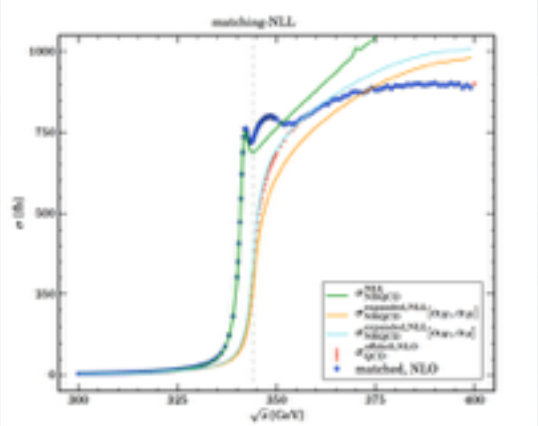

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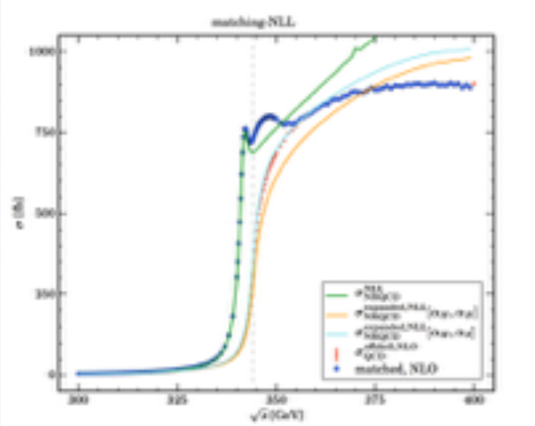

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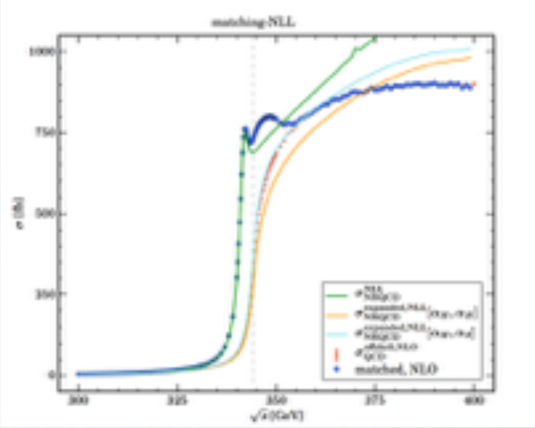

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**Time for the:
Experimentalists' ILC/CLIC NLO Wishlist**


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