# QCD NLO with Powheg Matching and Top Threshold Matching in WHIZARD

Jürgen R. Reuter, DESY

in collaboration with F. Bach, B. Chokoufé, A. Hoang, W. Kilian, M. Stahlhofen, C. Weiss

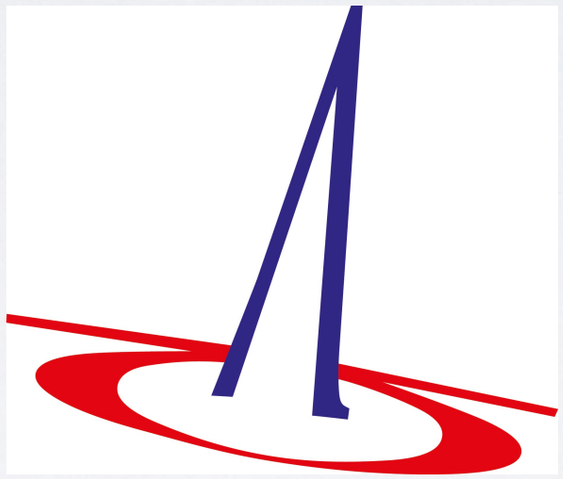
# Outline of the talk

1) Introduction into WHIZARD

2) Fixed-order NLO automation &
POWHEG matching in WHIZARD

3) Top threshold in (N)LL (p)NRQCD matched to fixed order (N)LO in WHIZARD

# 1) Introduction to WHIZARD



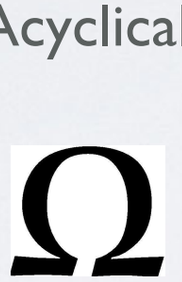
# WHIZARD: Introduction

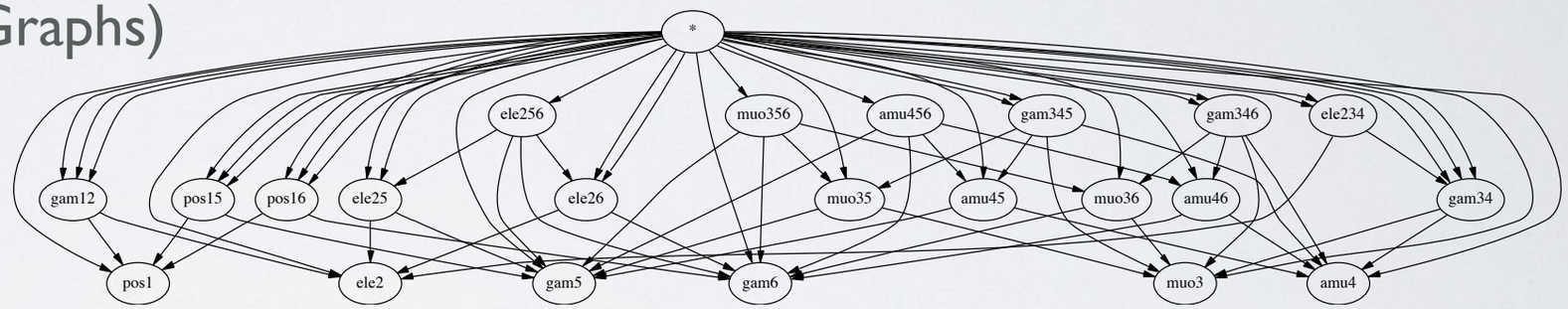
WHIZARD v2.2.6 (02.05.2015) *http://whizard.hepforge.org* <*whizard@desy.de*>

WHIZARD Team: *Wolfgang Kilian, Thorsten Ohl, JRR, Bijan Chokoufé/Marco Sekulla/Christian Weiss/Florian Staub* + *2 Master + 2 PhD (soon)*

EPJ C71 (2011) 1742

- Universal event generator for lepton and hadron colliders
- Modular package: - Phase space parameterization (resonances, collinear emission, Coulomb etc.)
  - O'Mega optimized matrix element generator (recursiveness via Directed Acyclical Graphs)





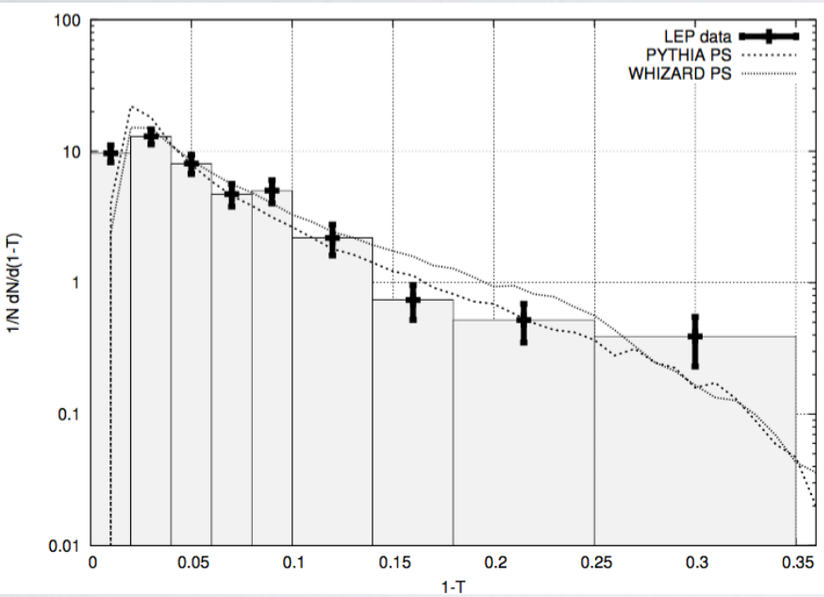

  - VAMP: adaptive multi-channel Monte Carlo integrator
  - CIRCE1/2: generator/simulation tool for lepton collider beam spectra
  - Lepton beam ISR Kuraev/Fadin, 2003; Skrzypek/Jadach, 1991
  - Color flow formalism Stelzer/Willenbrock, 2003; Kilian/Ohl/JRR/Speckner, 2011

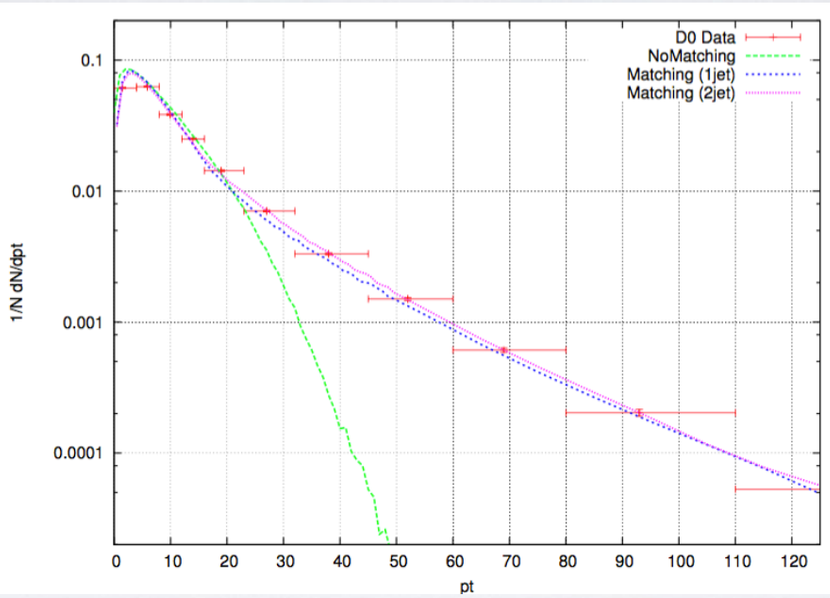
- Interfaces to external packages for Feynman rules, hadronization, tau decays, event formats, analysis, jet clustering etc. : `FastJet, GoSam, GuineaPig(++), HepMC, HOPPET, LCIO, LHAPDF(4/5/6), LoopTools, OpenLoops, PYTHIA6, [PYTHIA8], StdHep`

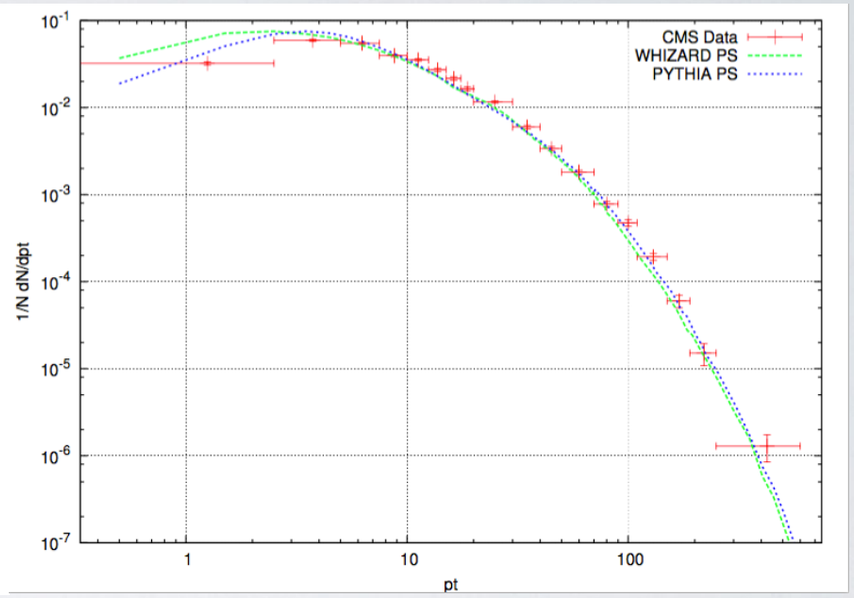
# WHIZARD Parton Shower

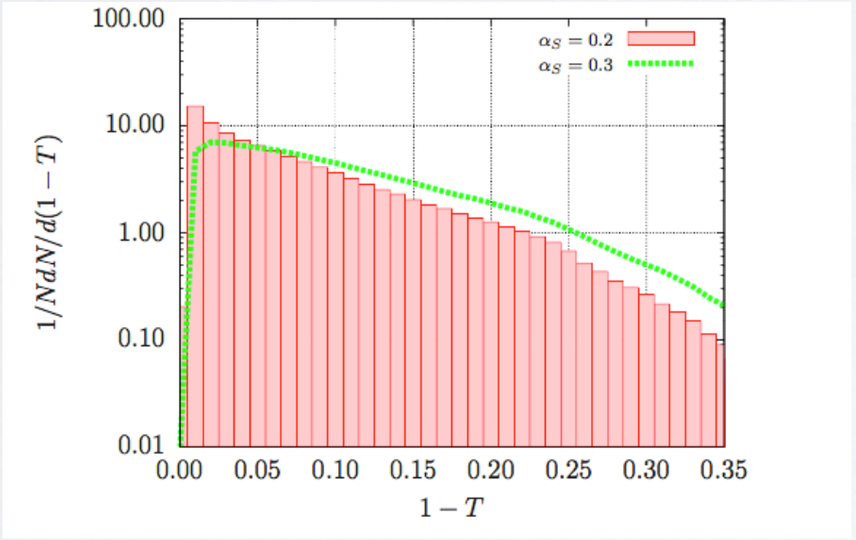
- Two independent implementations: kT-ordered QCD and Analytic QCD shower
- Analytic shower: no shower veto ⇒ exact shower history known, allows reweighting

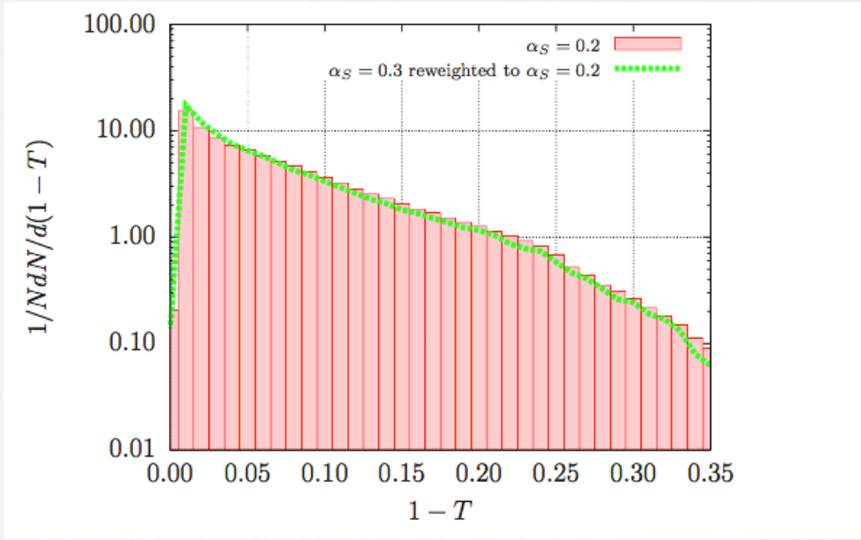
Kilian/JRR/Schmidt/Wiesler, JHEP **1204** 013 (2012)




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

# 2) Fixed-order NLO automation & POWHEG matching in WHIZARD

# 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.] (Talk by G. Ossola)
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WHIZARD v2.2.6 contains alpha version

QCD corrections (massless and massive emitters)

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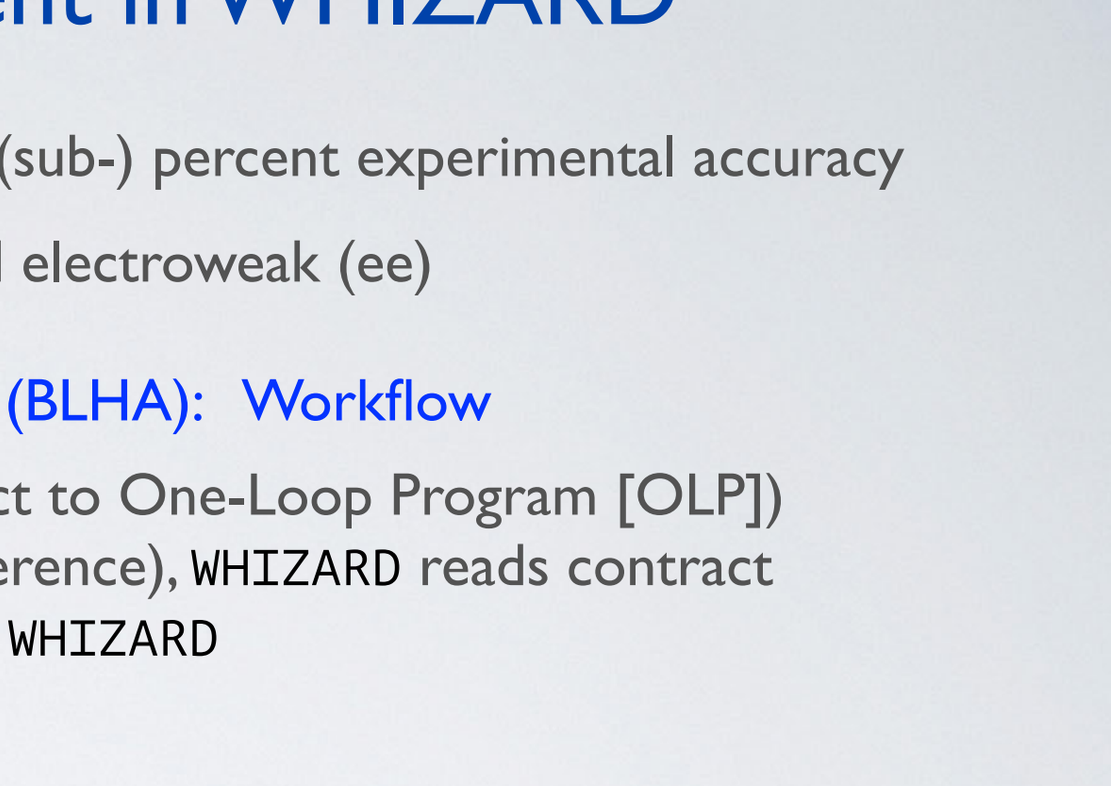

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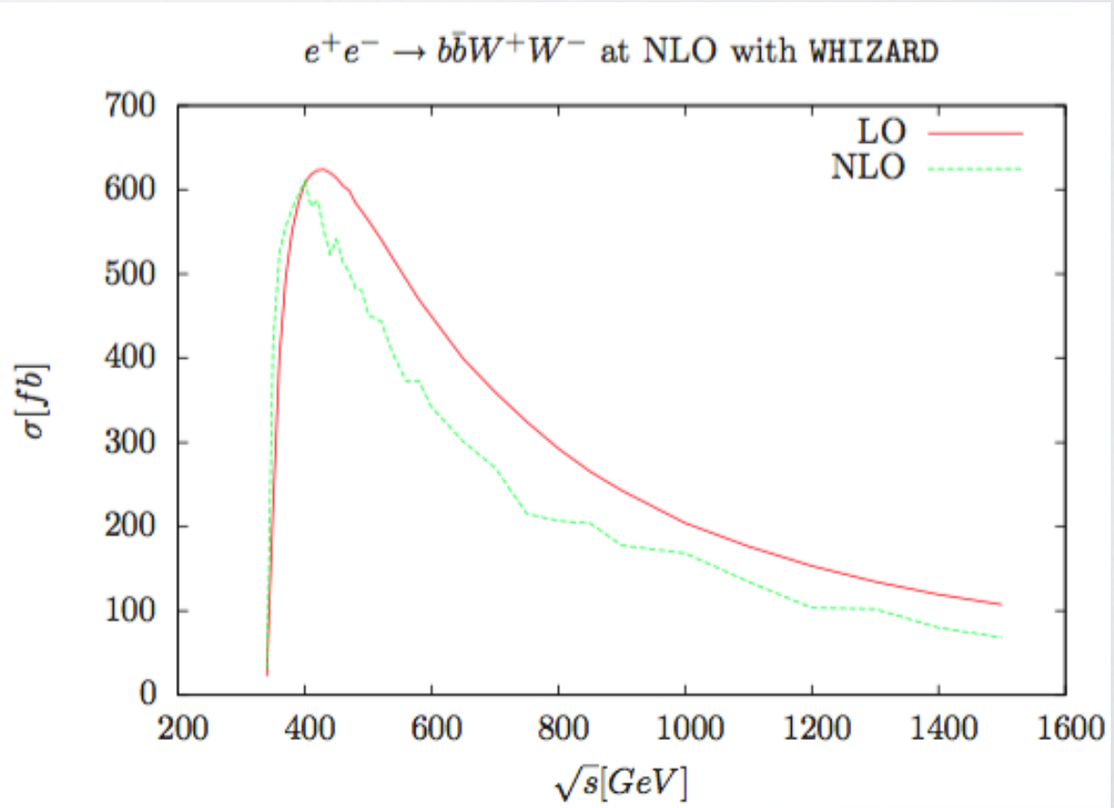

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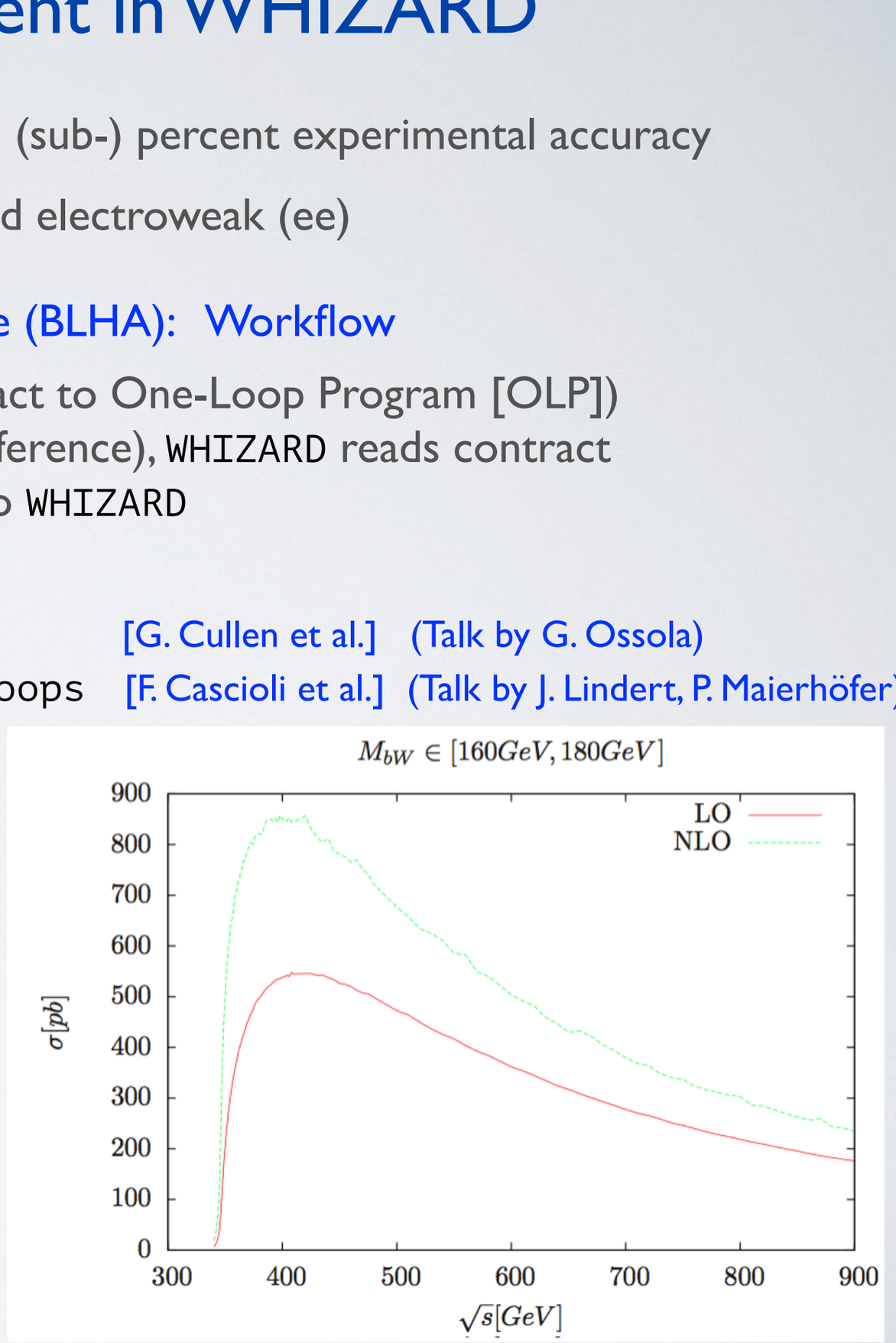

# FKS Subtraction (Frixione/Kunszt/Signer)

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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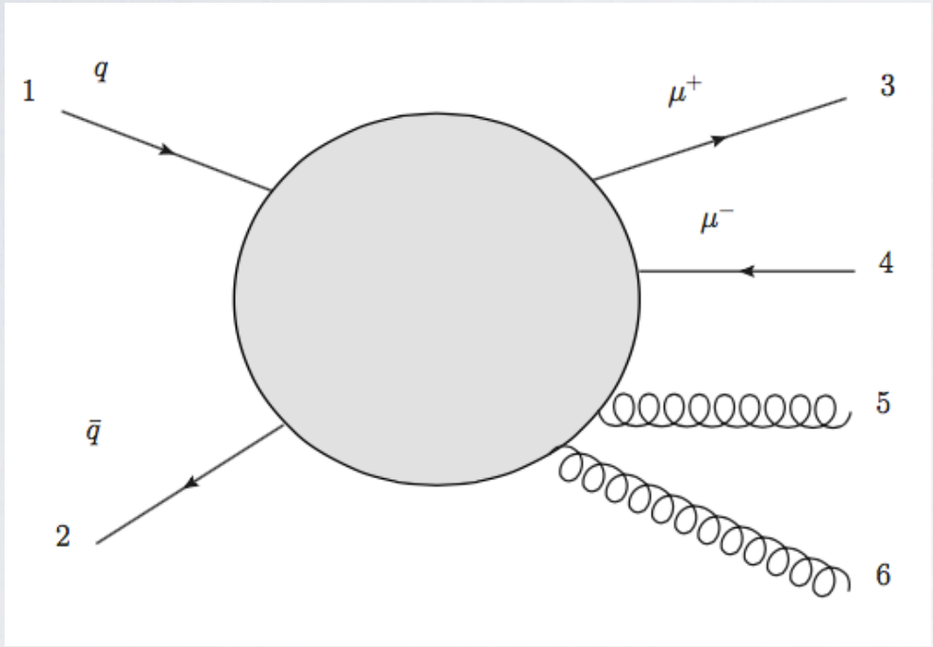


Automated subtraction terms in WHIZARD, algorithm:

- 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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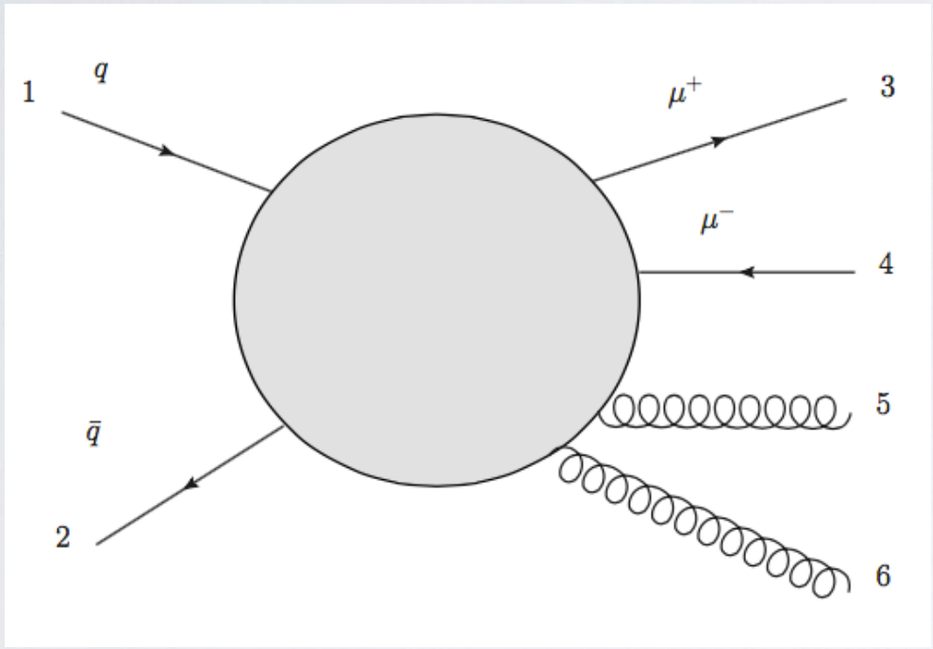


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Soft subtraction involves color-correlated matrix elements:

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

Collinear subtraction involves spin-correlated matrix elements:

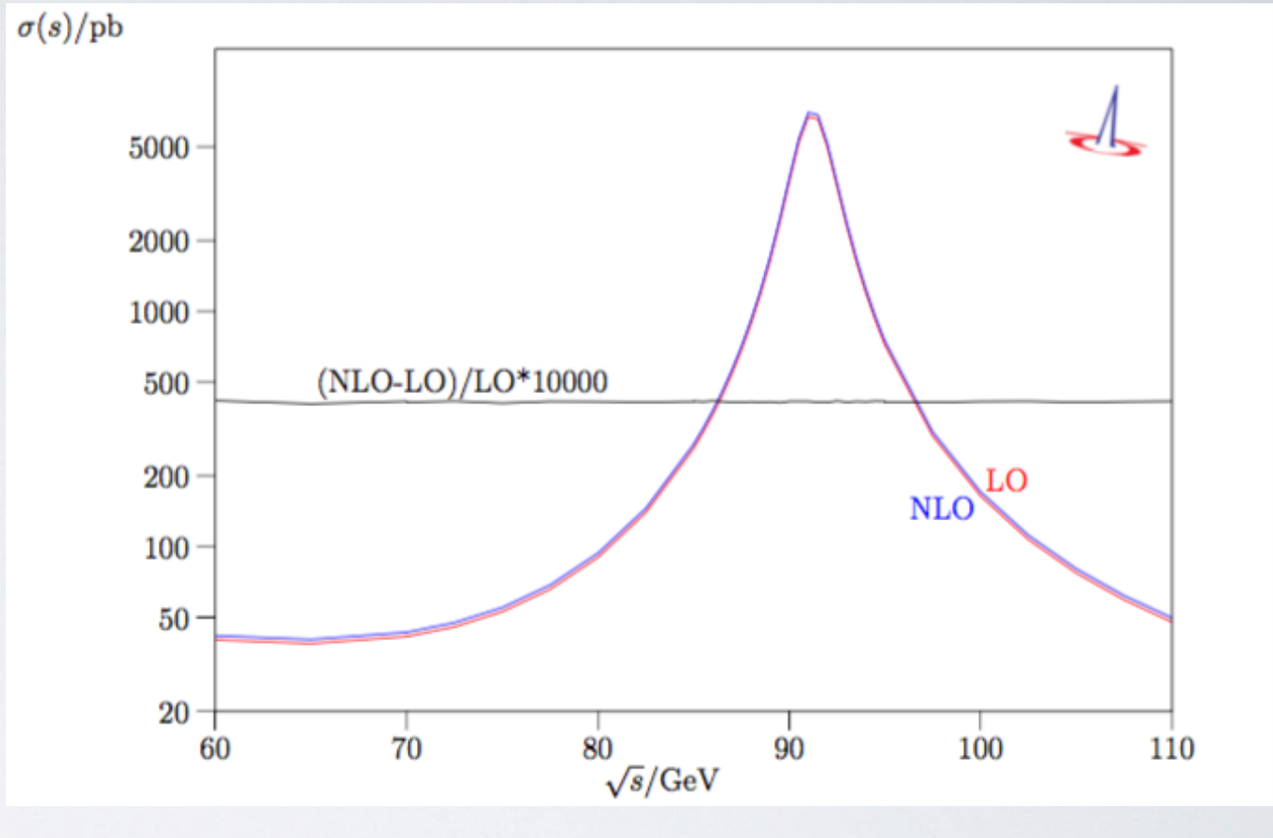
$$\mathcal{B}_{+-} \sim Re\left\{\frac{\langle k_{\mathrm{em}}k_{\mathrm{rad}}\rangle}{[k_{\mathrm{em}}k_{\mathrm{rad}}]}\sum_{\substack{\text{color}\\ \text{spin}}}\mathcal{A}_+^{(n)}\mathcal{A}_-^{(n)*}\right\}$$

# Examples and Validation

Simplest benchmark process:

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

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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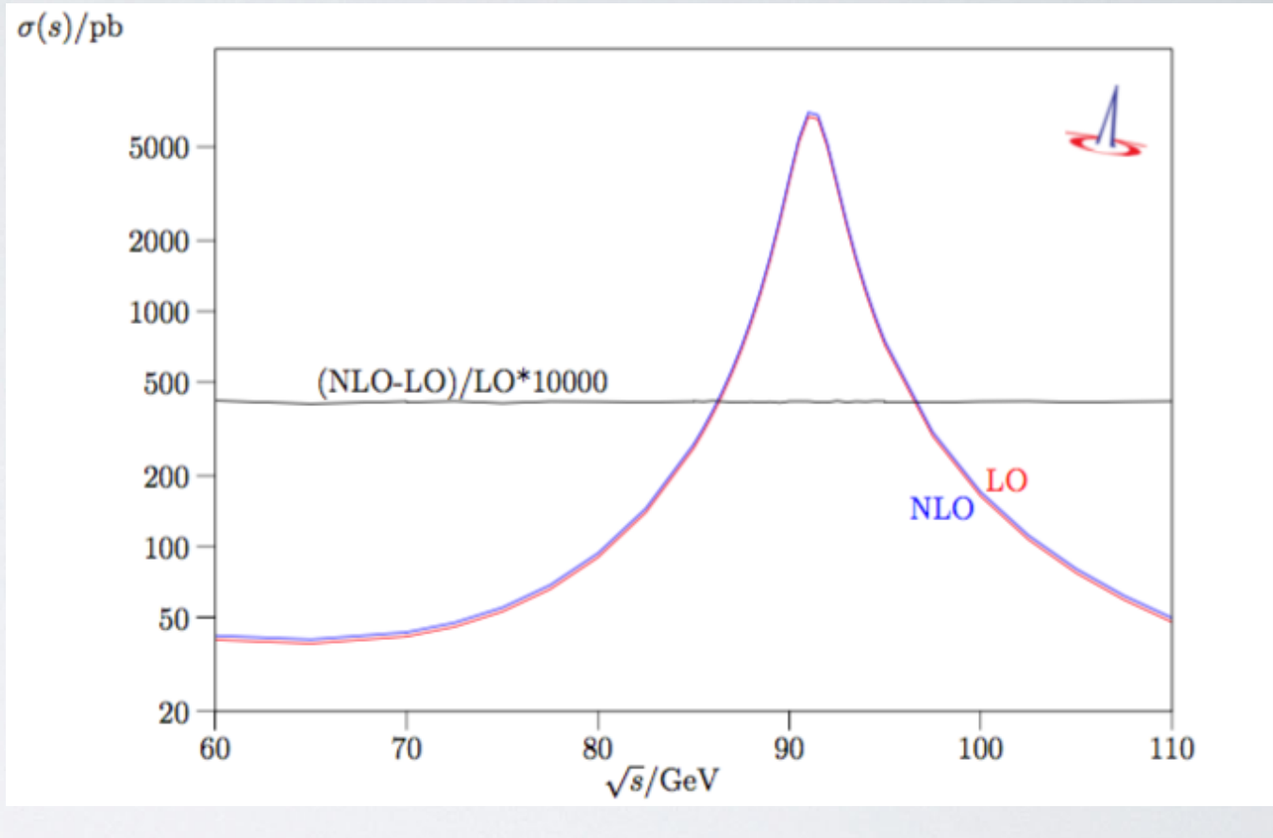


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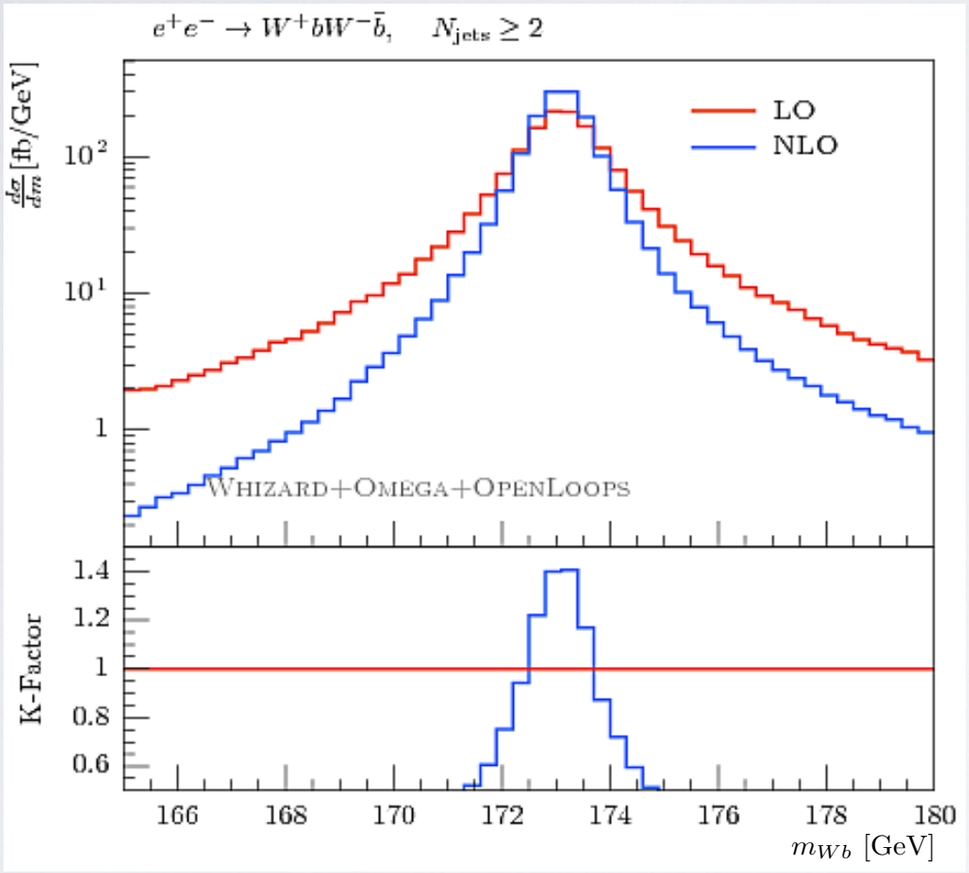
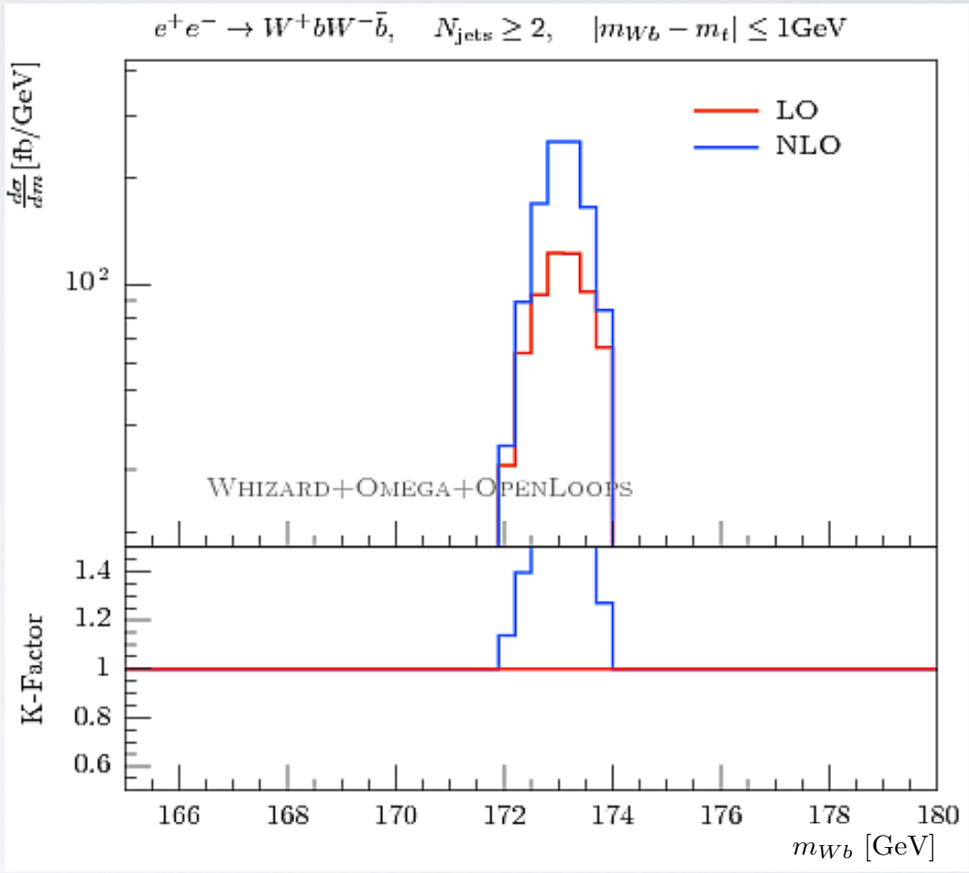
- ✦ QCD NLO infrastructure in pp almost complete
- ✦ First attempts on electroweak corrections, interfacing the RECOLA code [Denner et al.]

# 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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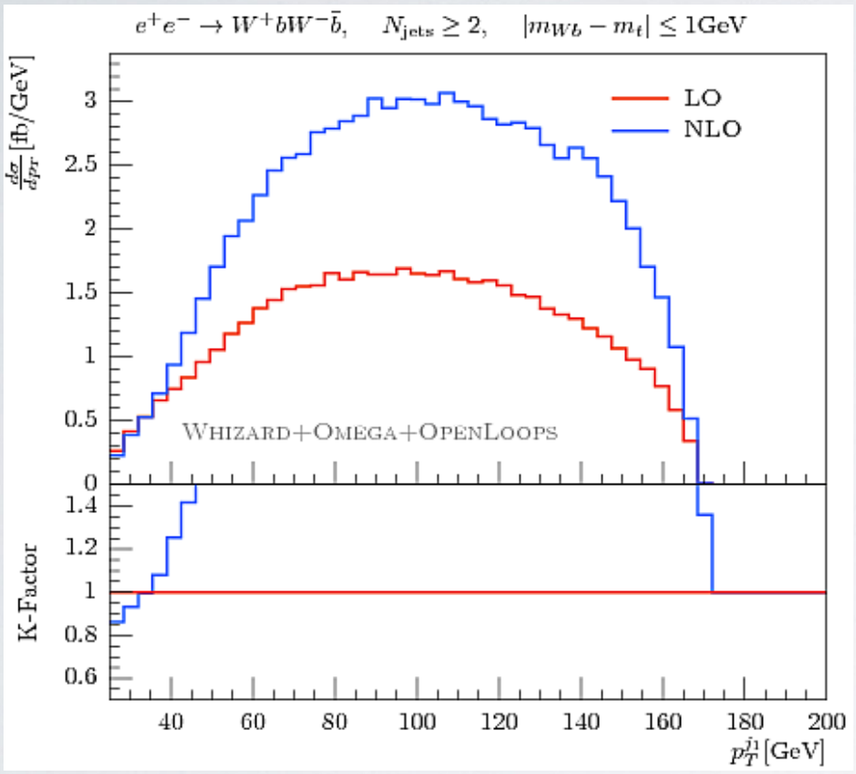


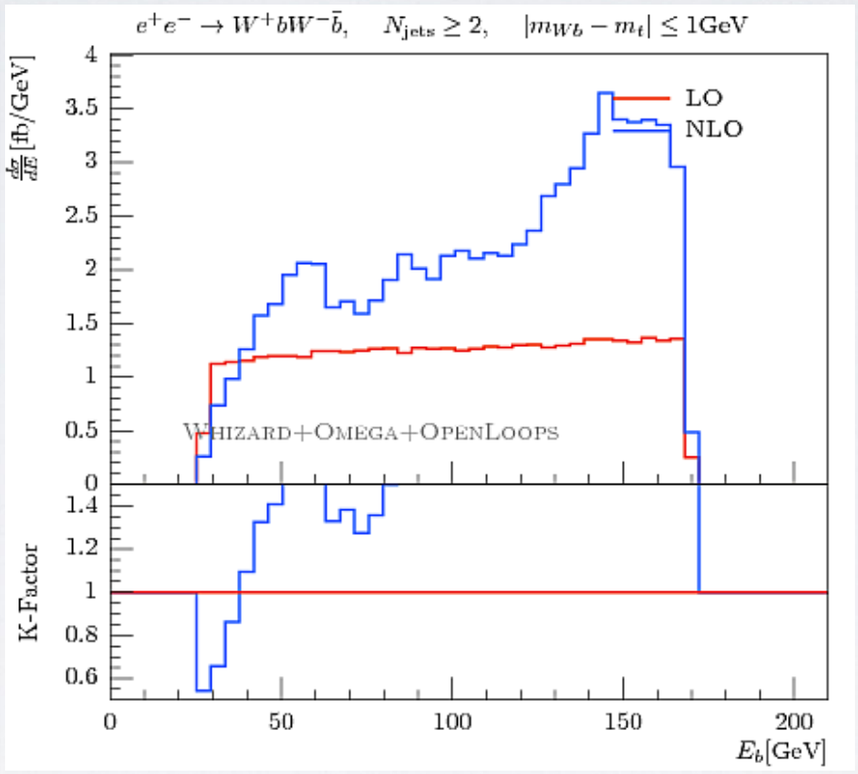


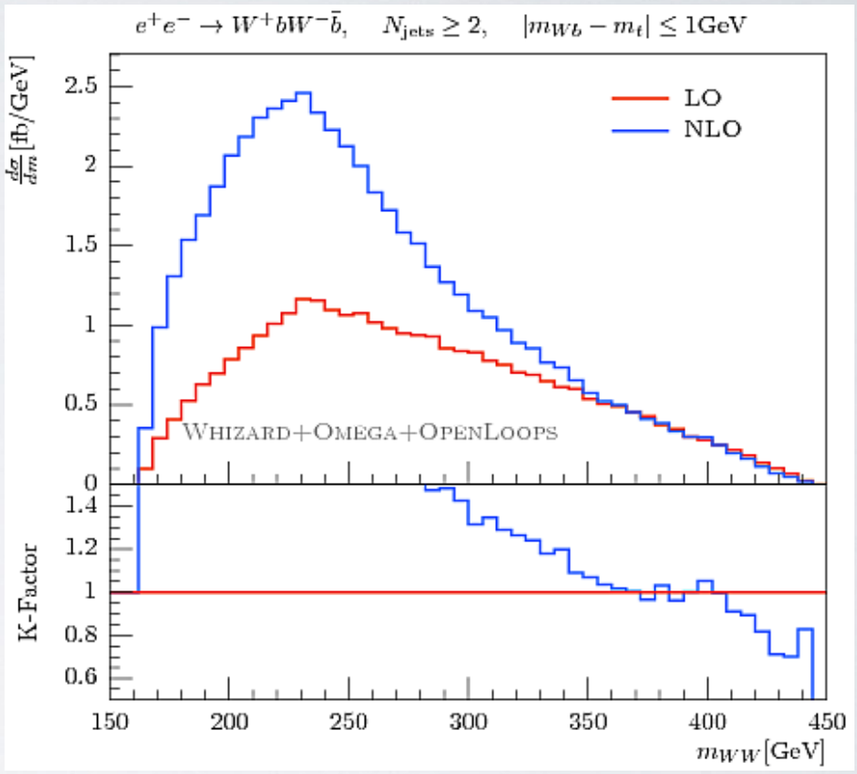

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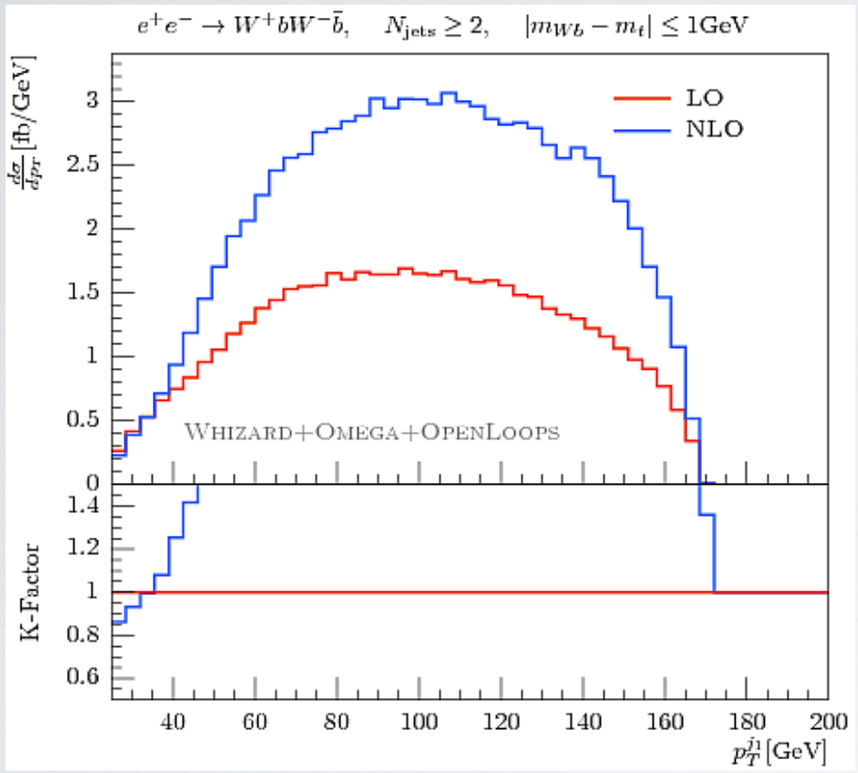
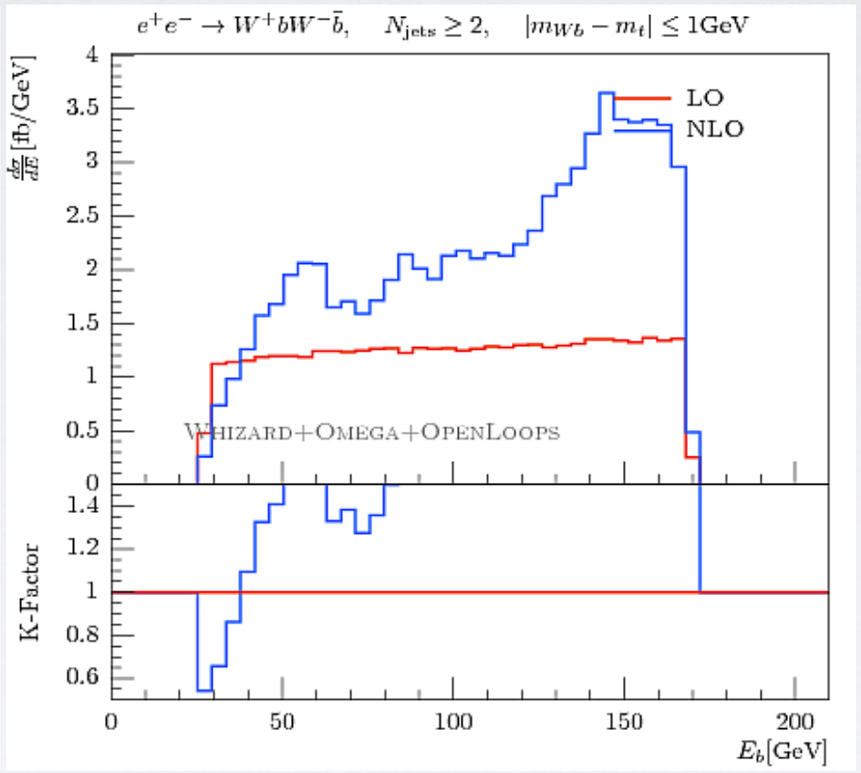
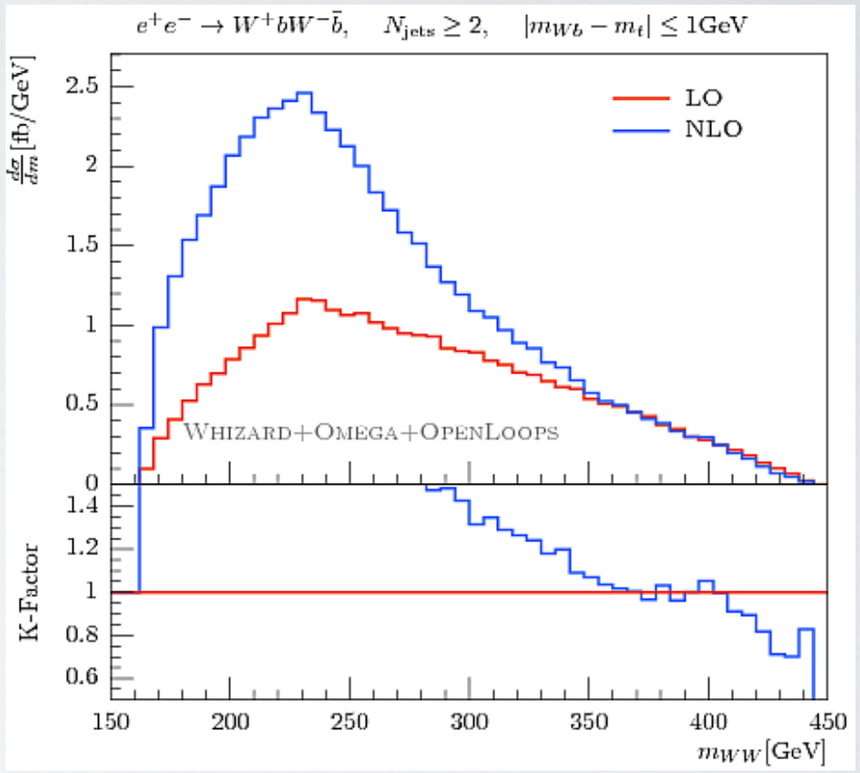


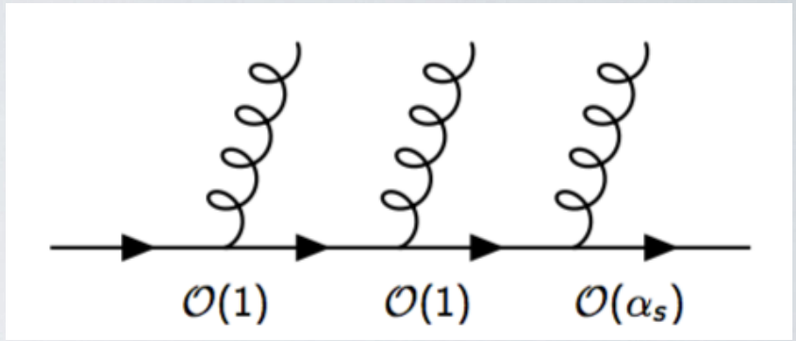




- Next steps: produce polarized results (remember: ILC will always run with polarization)
- Produce also plots including complete ISR photon radiation and beamstrahlung
- Investigate the full 2 → 6 process: e+e- → bbeμνν [Chokoufé/Lindert/JRR/Pozzorini/Weiss]

# Automated POWHEG Matching in WHIZARD

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



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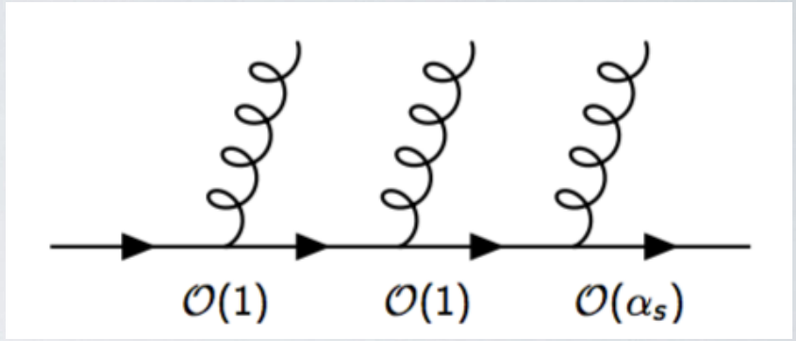


- Complete NLO events

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

- 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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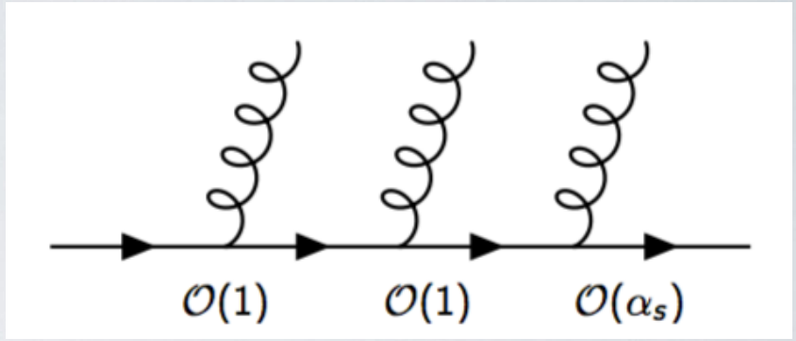


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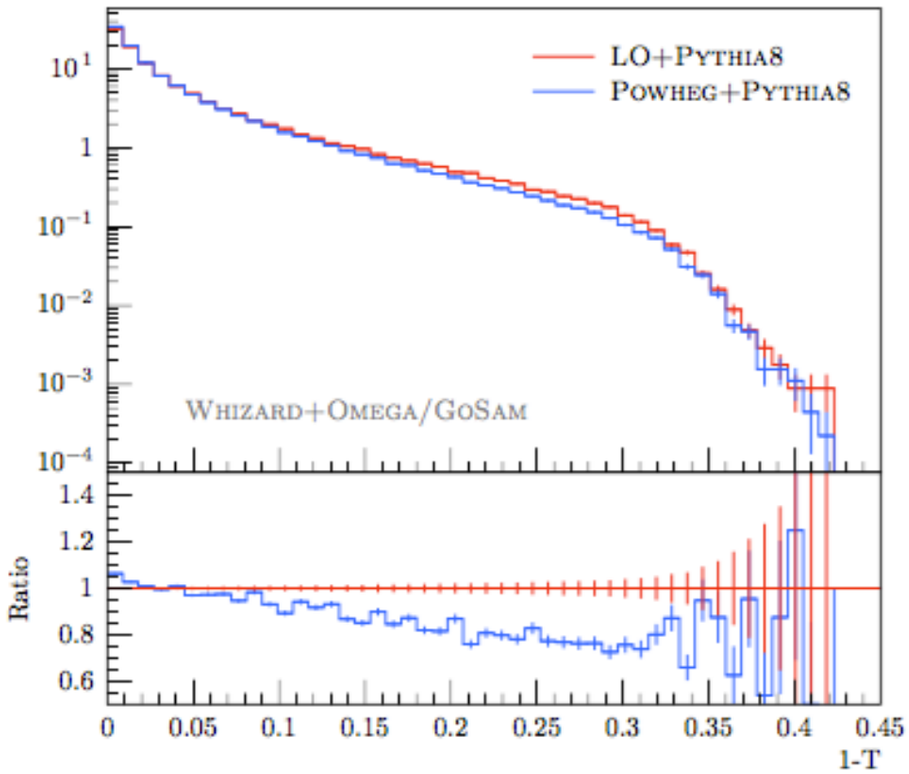
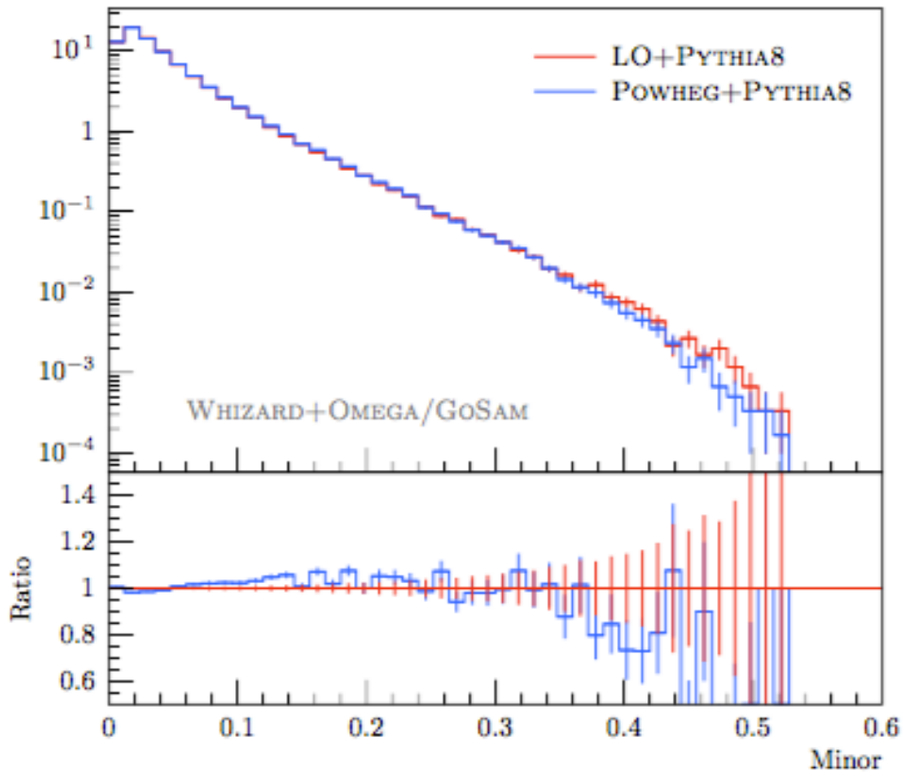
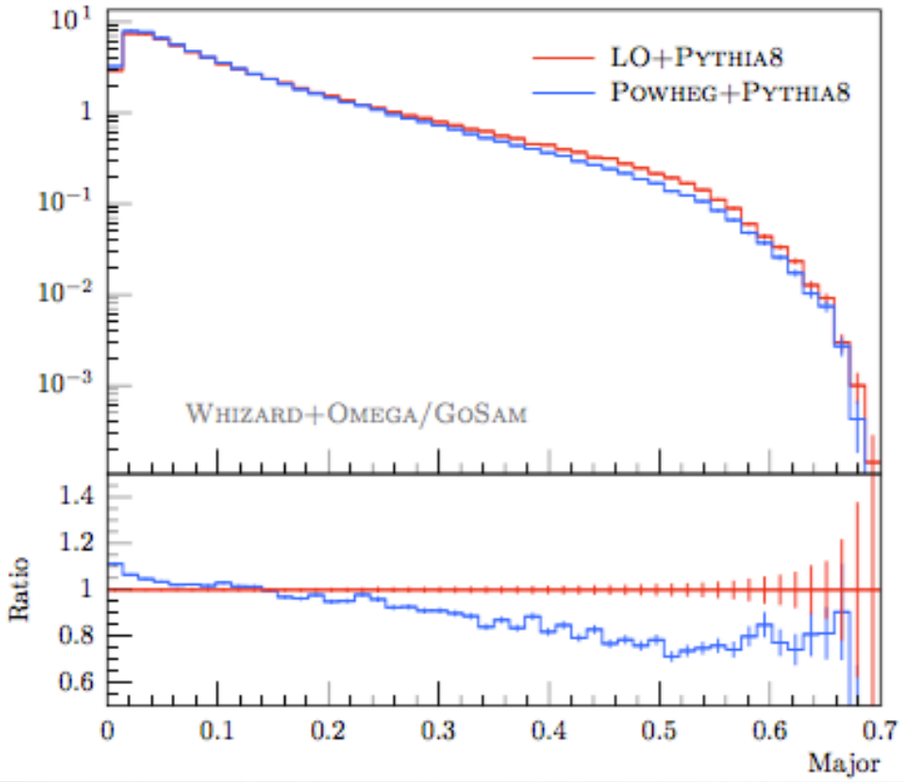
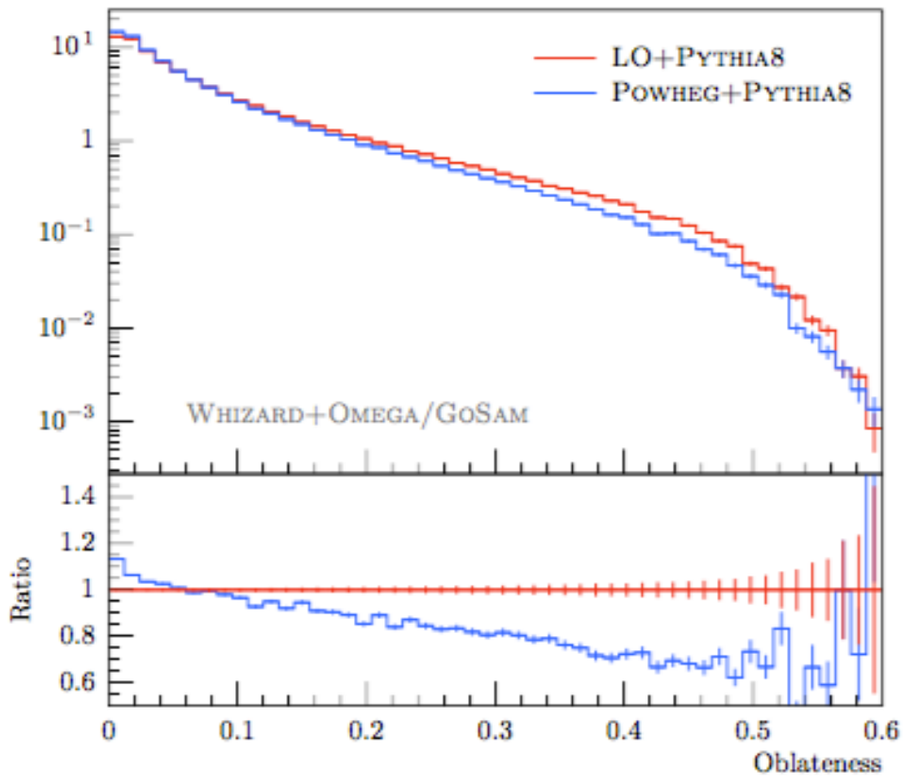
- Hardest emission: $k_T^{\rm max}$ ; shower with imposing a veto
- $\overline{B} < 0$ if virtual and real terms larger than Born: shouldn't happen in perturbative regions
- Reweighting such that $\overline{B} > 0$ for all events
- POWHEG: Positive Weight Hardest Emission Generator own implementation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

# POWHEG Matching, example: e+e- to dijets



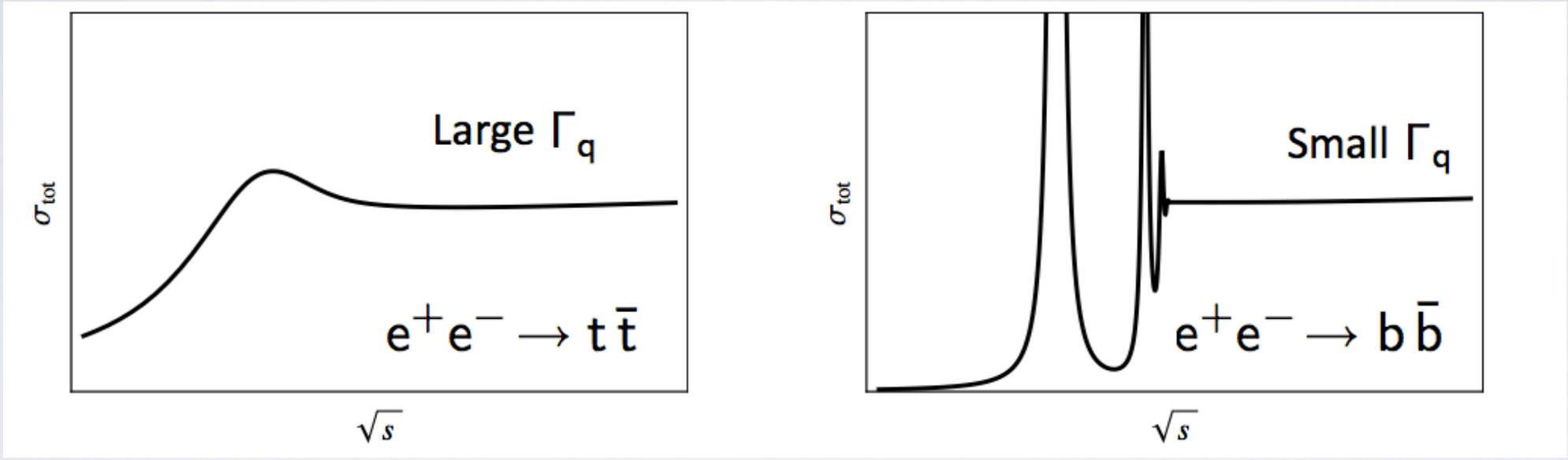



# 3) Top threshold in (N)LL (p)NRQCD matched to (N)LO QCD in WHIZARD

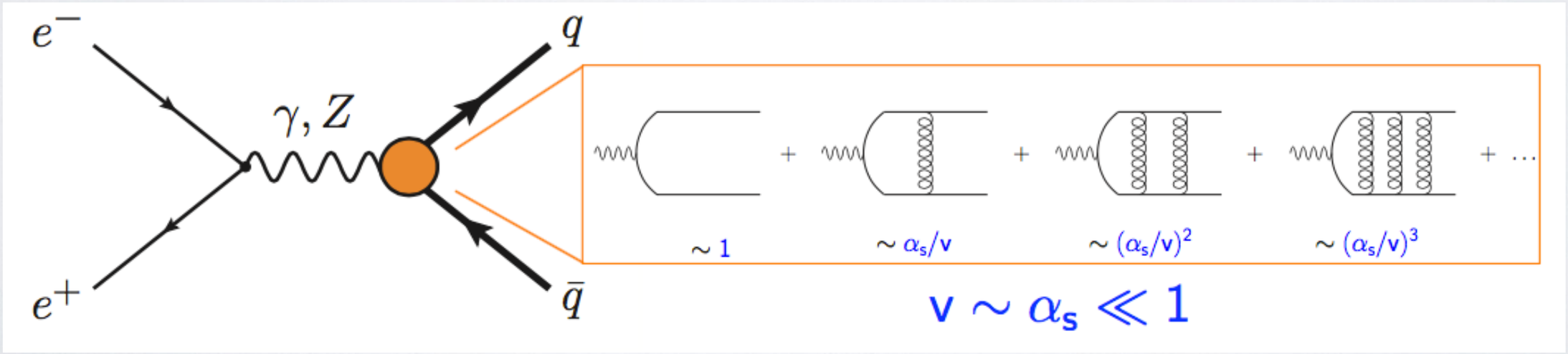
# Top Threshold at lepton colliders

ILC top threshold scan best-known method to measure top quark mass, $\Delta M \sim 30\text{-}50$ MeV

Heavy quark production at lepton colliders, qualitatively:




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



# 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. (for more details: Talk by P. Marquard )
- Resummation of singular terms close to threshold (v = 0) Hoang/Teubner, 1999; Hoang et al., 2001

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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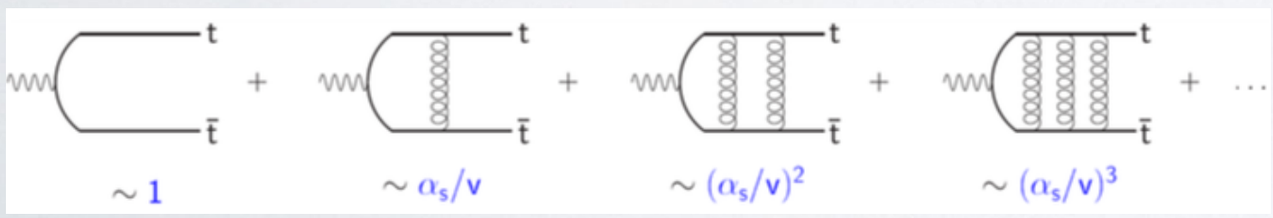
Coulomb potential gluon ladder resumption



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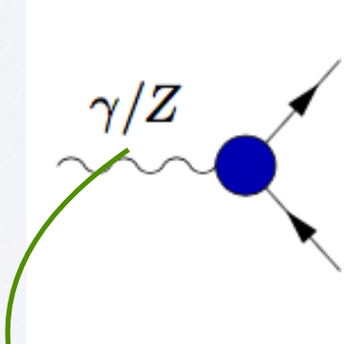
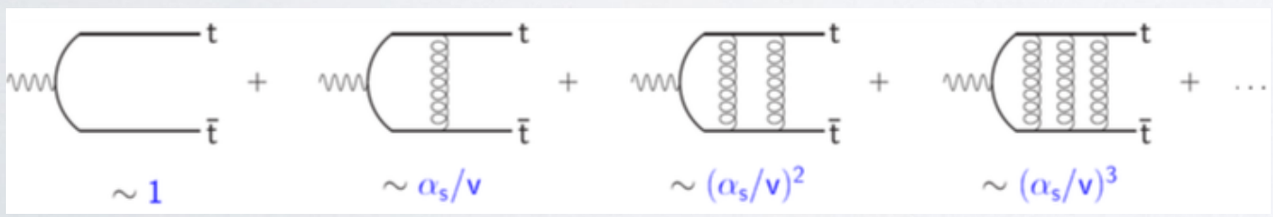
can be mapped onto effective *ttV* vertex




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

far away from threshold

Coulomb potential gluon ladder resumption



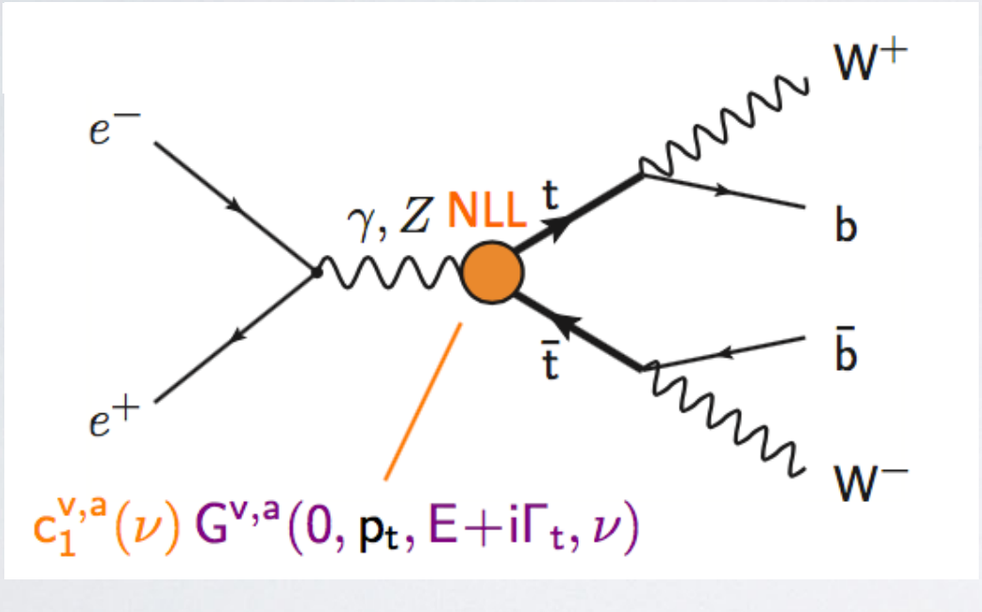

$$\mathbb{C} \ni \mathcal{G}^{v/a}_{(\mathrm{N})\mathrm{LL}} = \mathcal{G}^{v/a}_{(\mathrm{N})\mathrm{LL}}(\alpha_s, M_t^{\mathrm{pole}}, \sqrt{s}, |\vec{p}_t|, \Gamma_t)$$

differential in off-shell *tt* phase space

# Top Threshold in WHIZARD

with F. Bach/A. Hoang/M. Stahlhofen

- 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:

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

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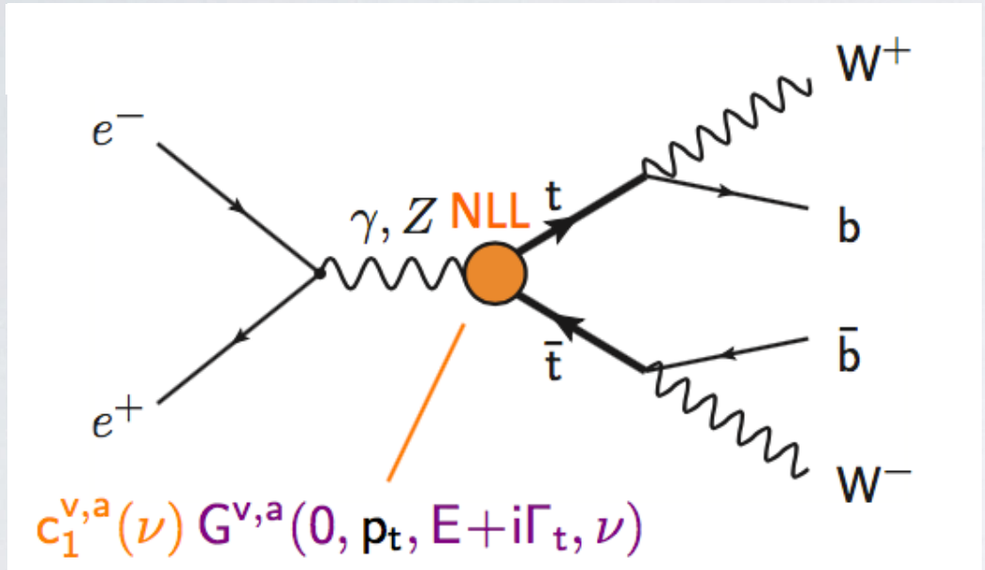


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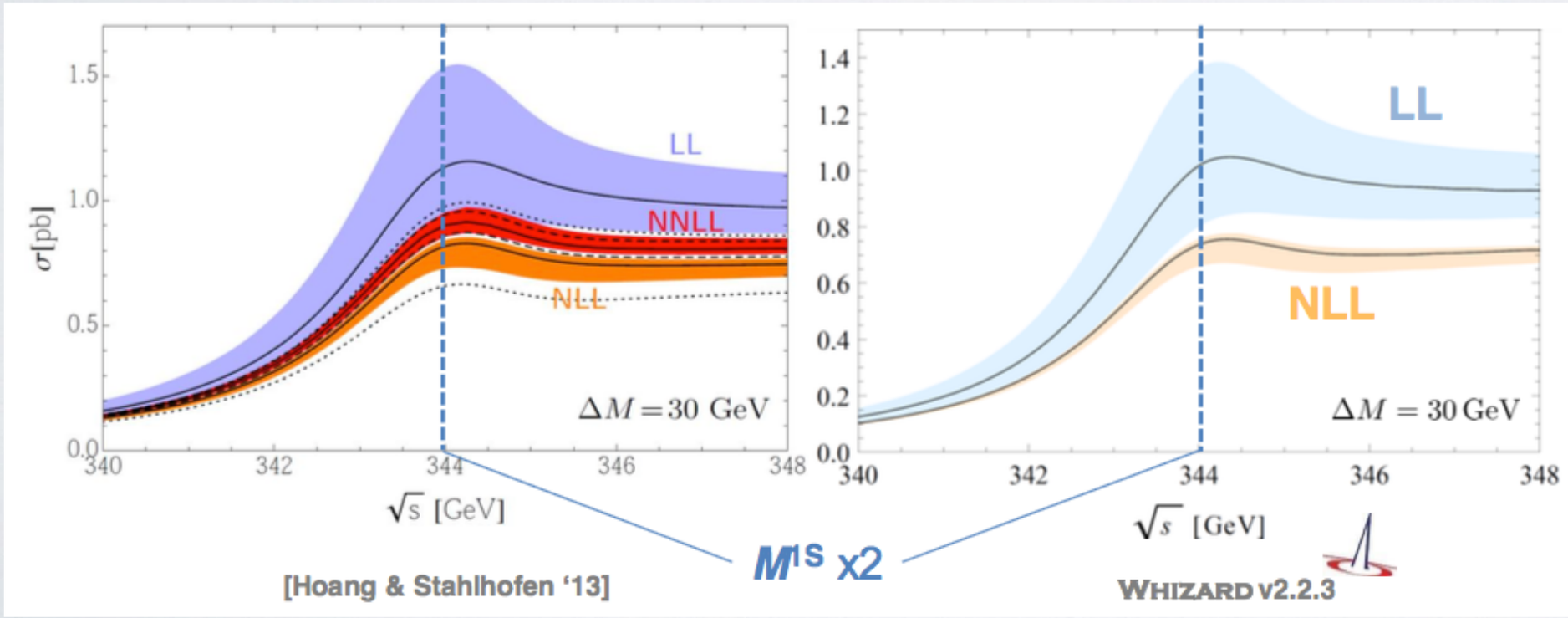

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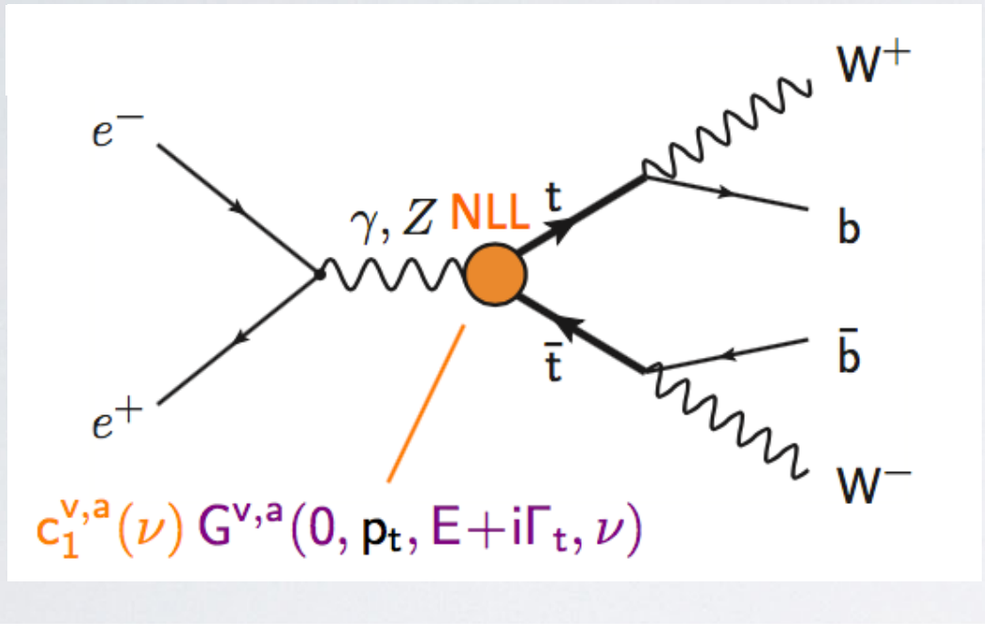


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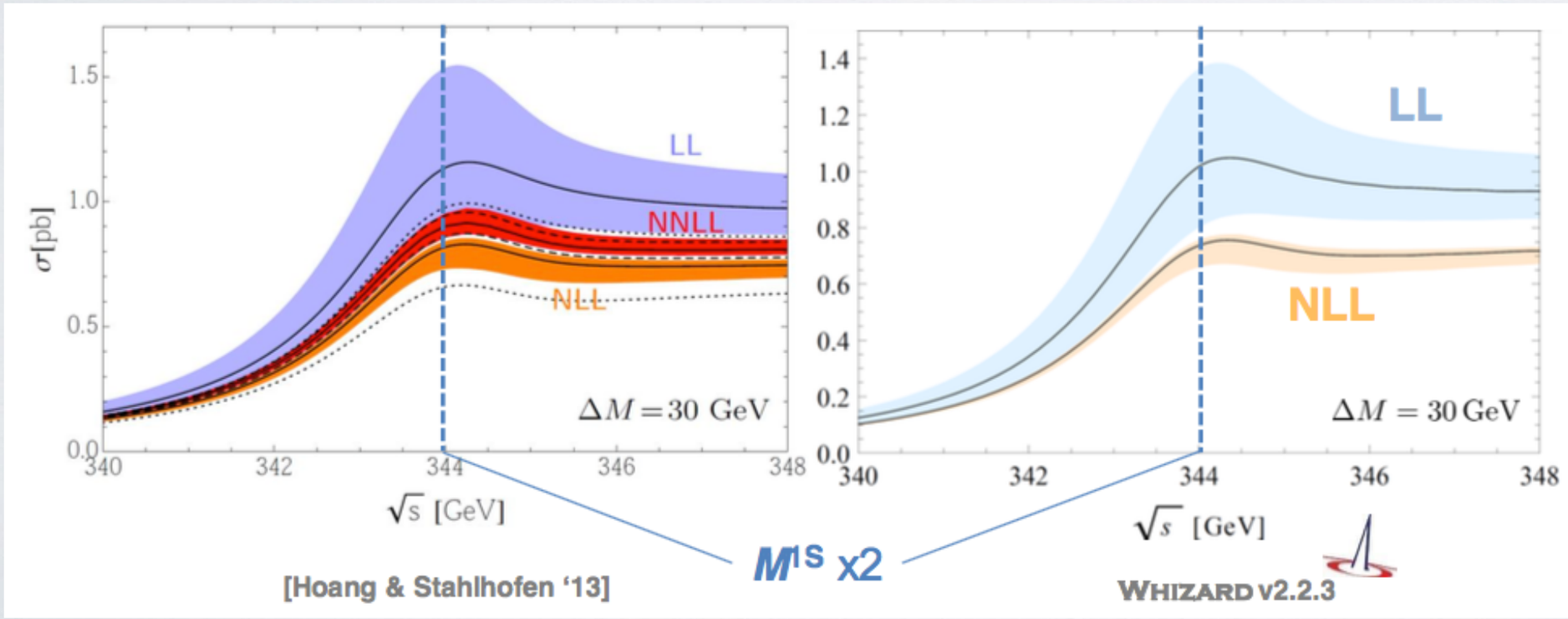
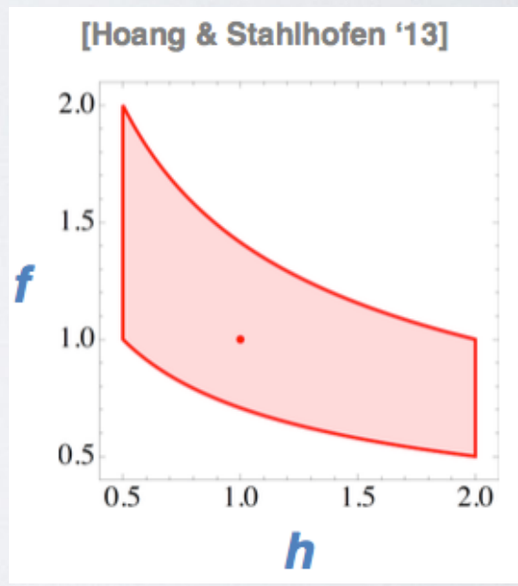
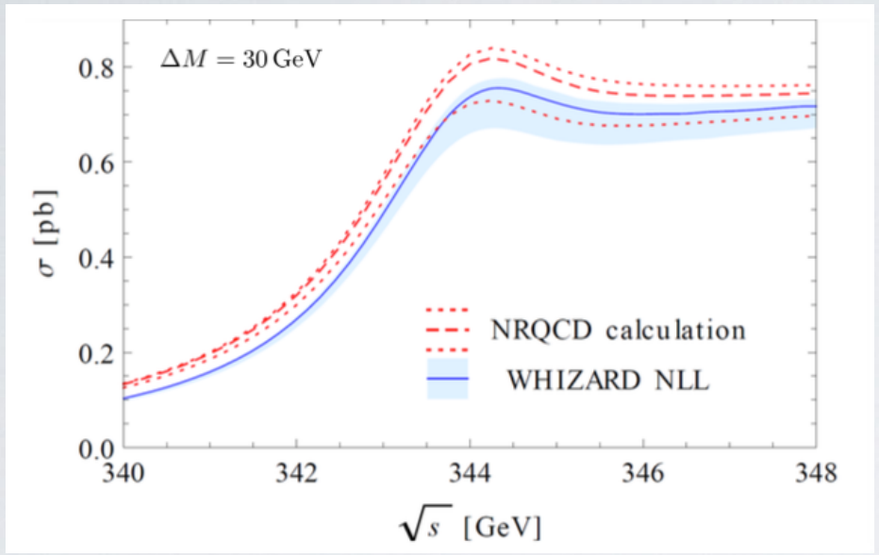
Theory uncertainties from scale variations:
hard and soft scale

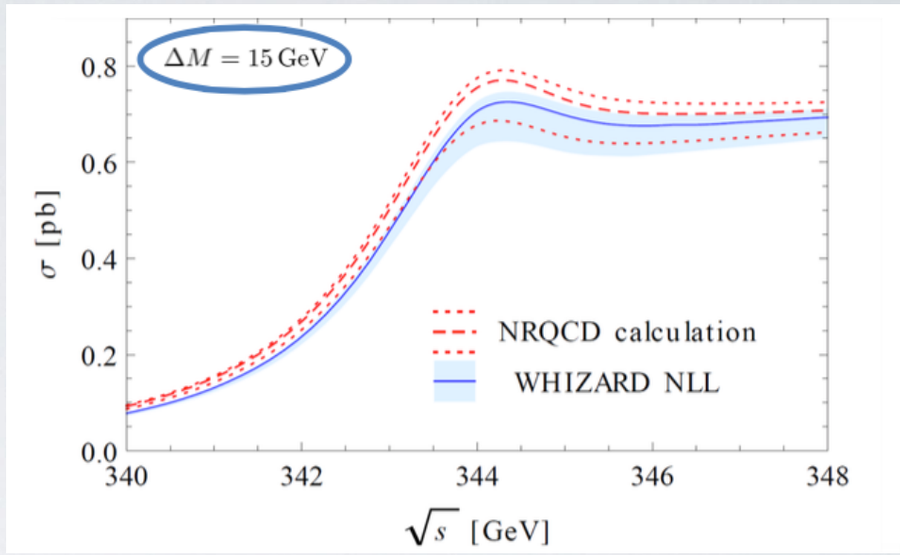
$$\mu_h = h \cdot m_t \qquad \mu_s = f \cdot m_t v$$



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

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

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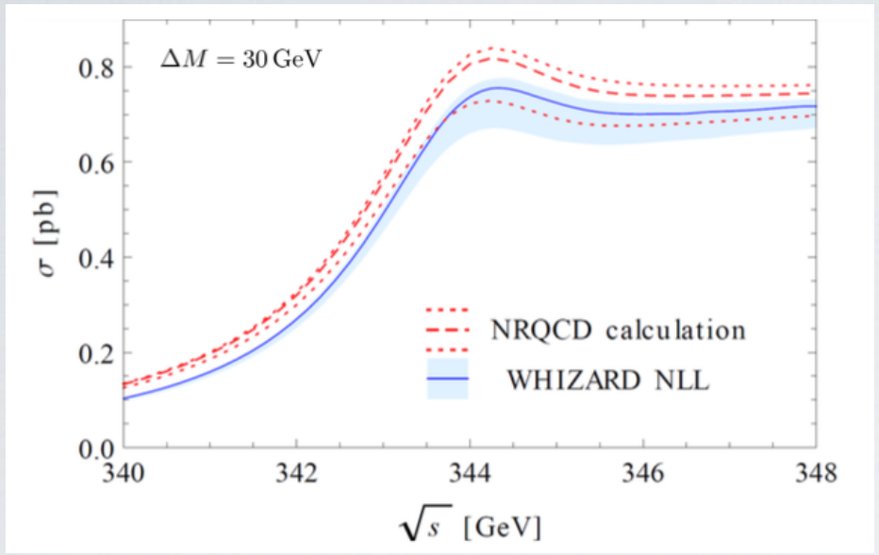


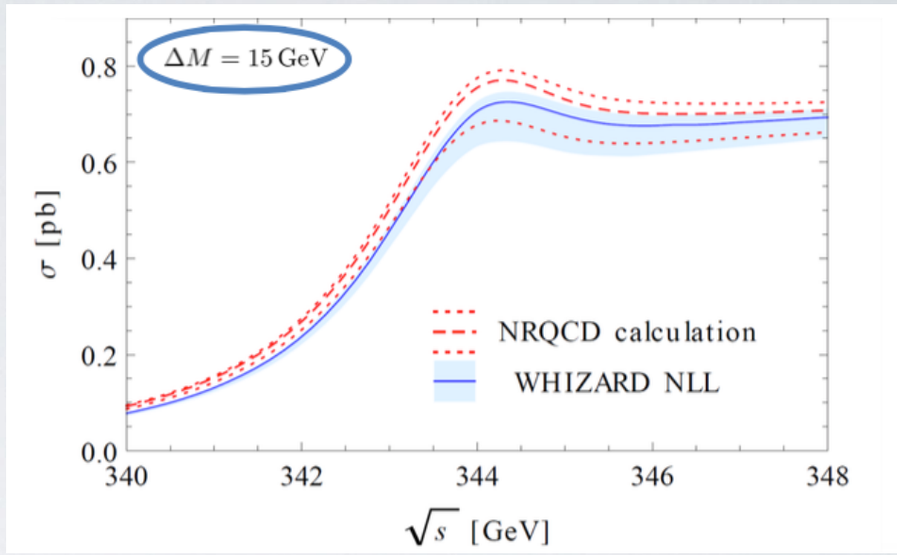


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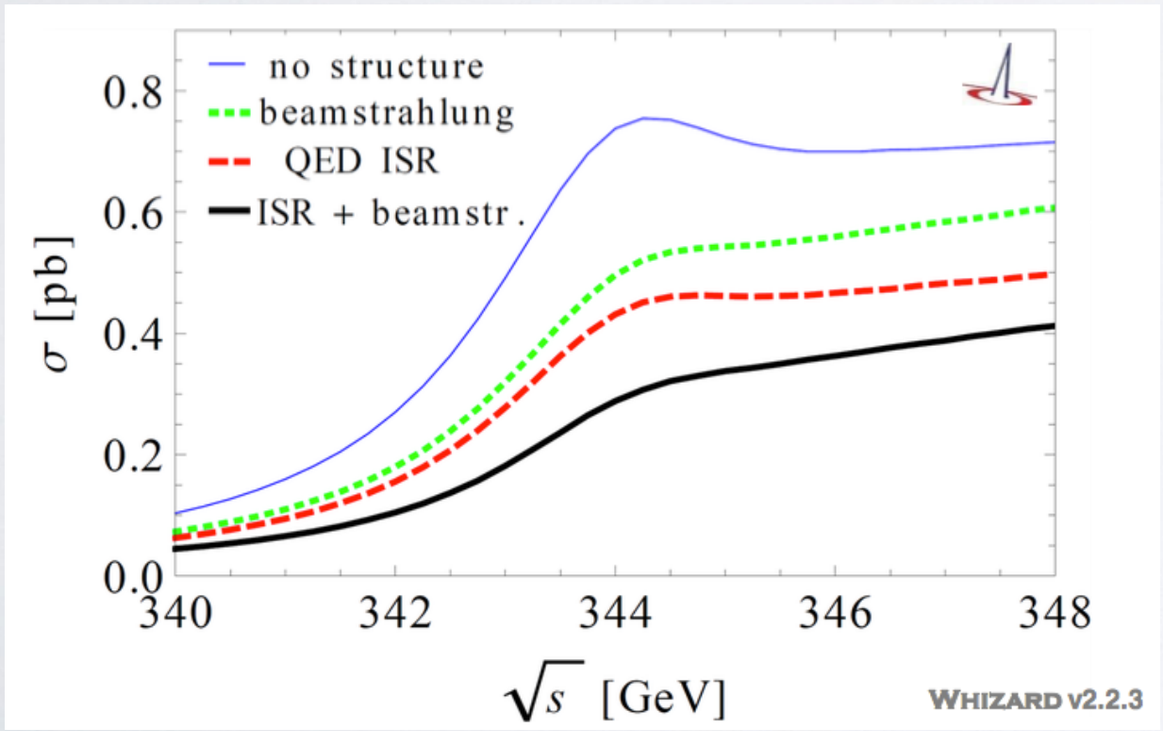

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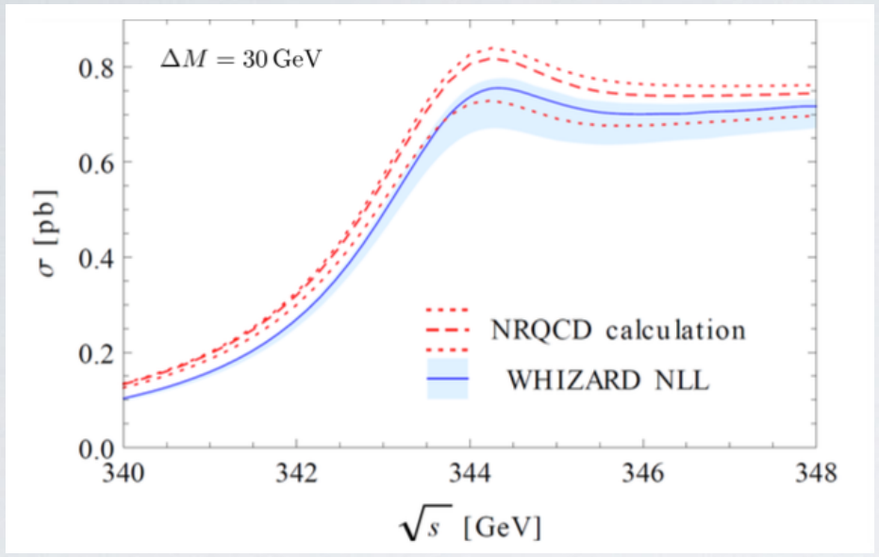


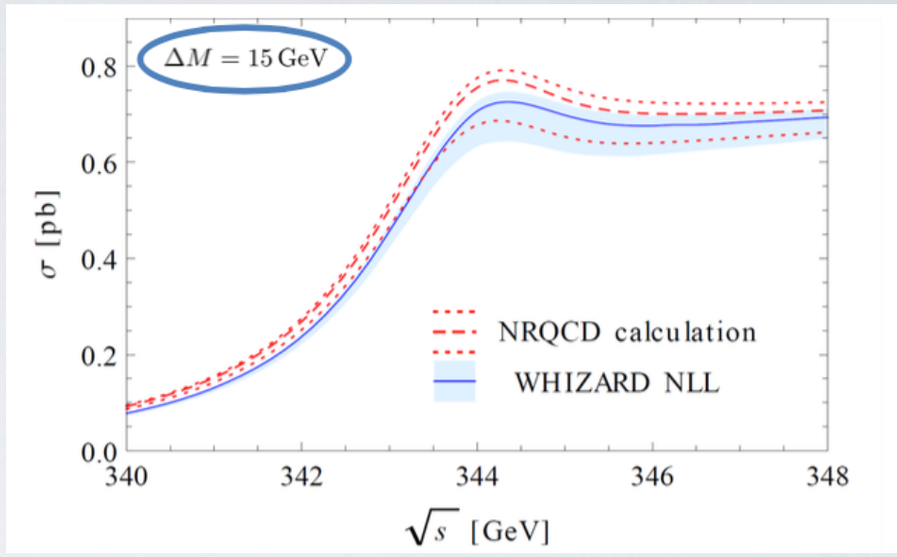


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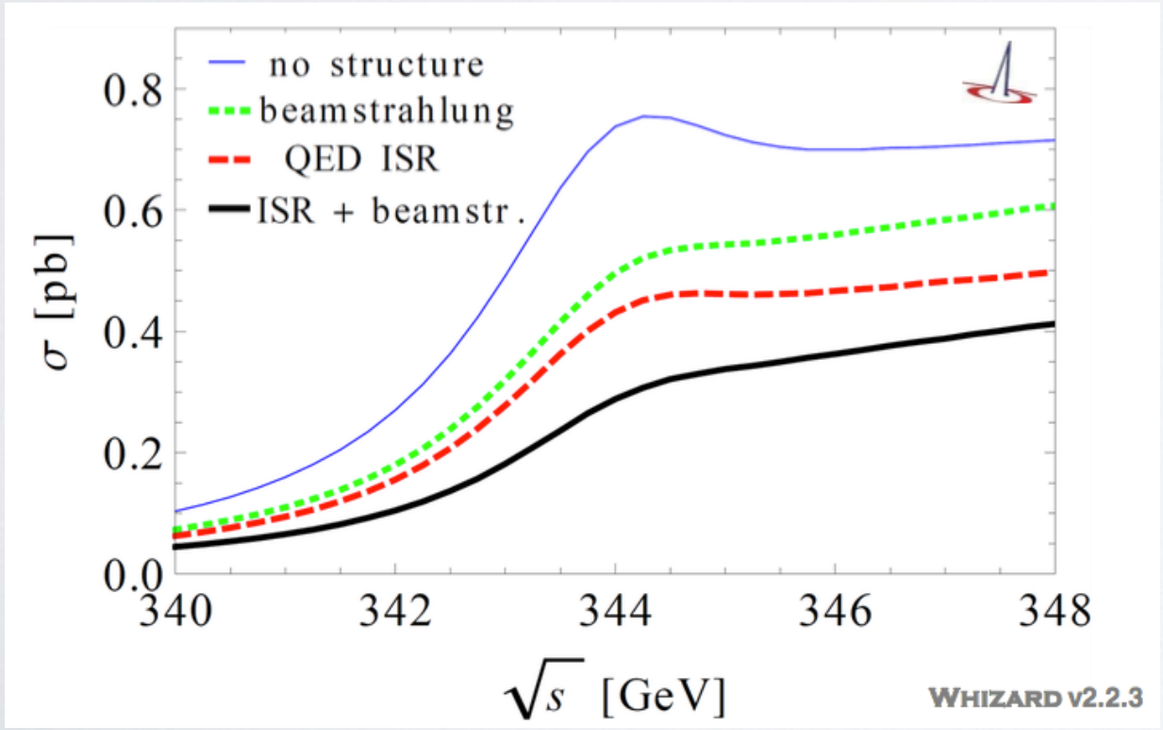
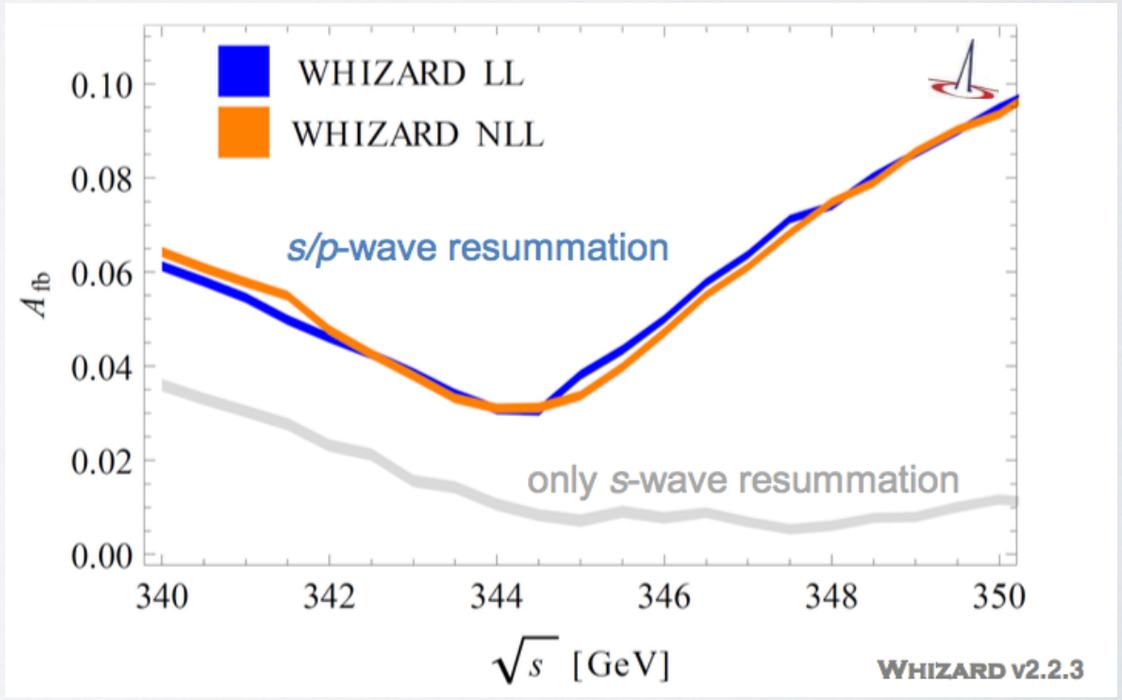
Forward-backward asymmetry (norm. ⇒ good shape stability)

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



# 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

Comparison of different approximations

- Leading order approximation
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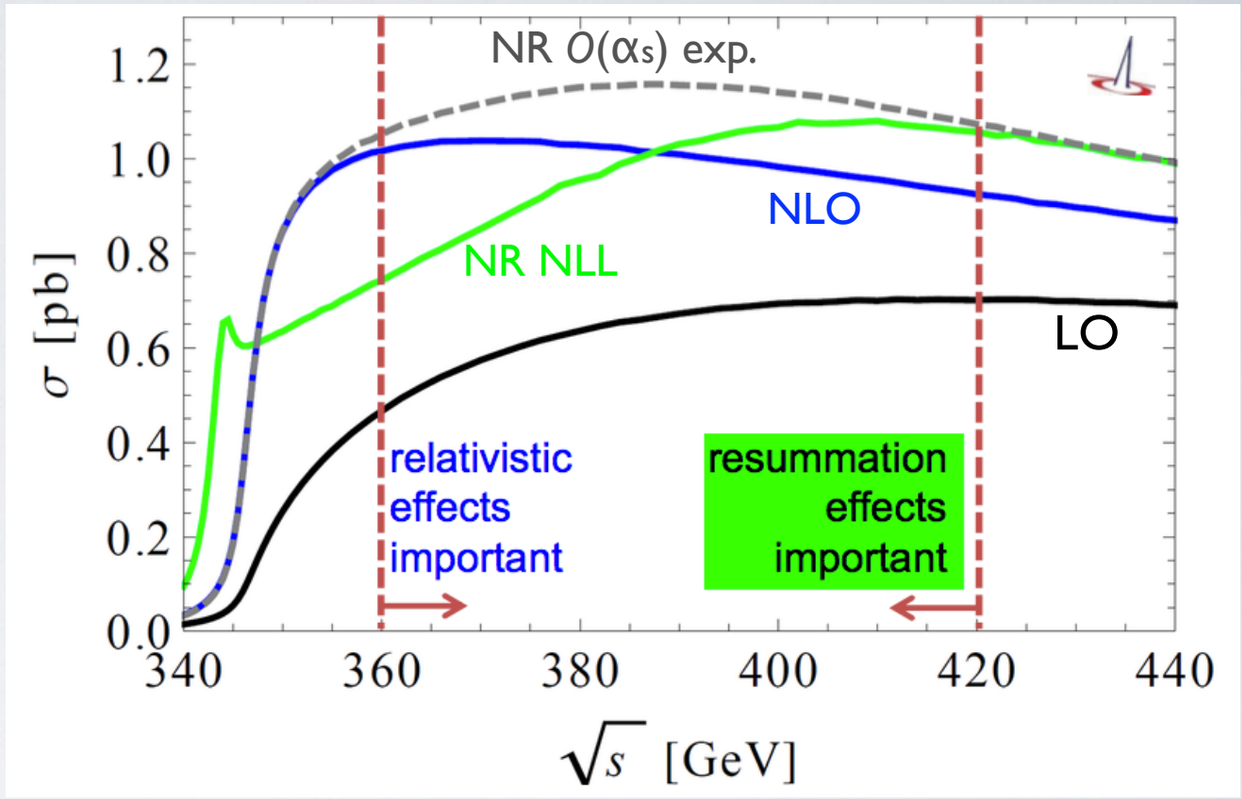


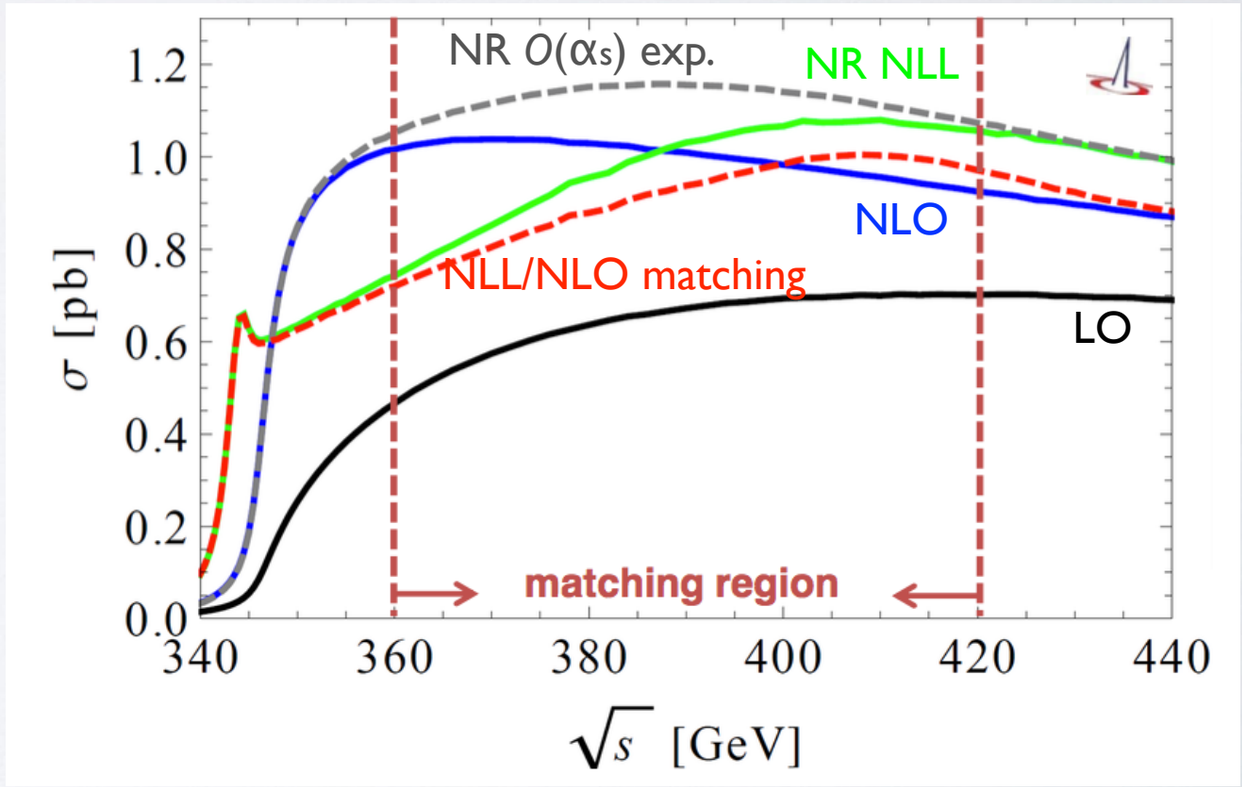

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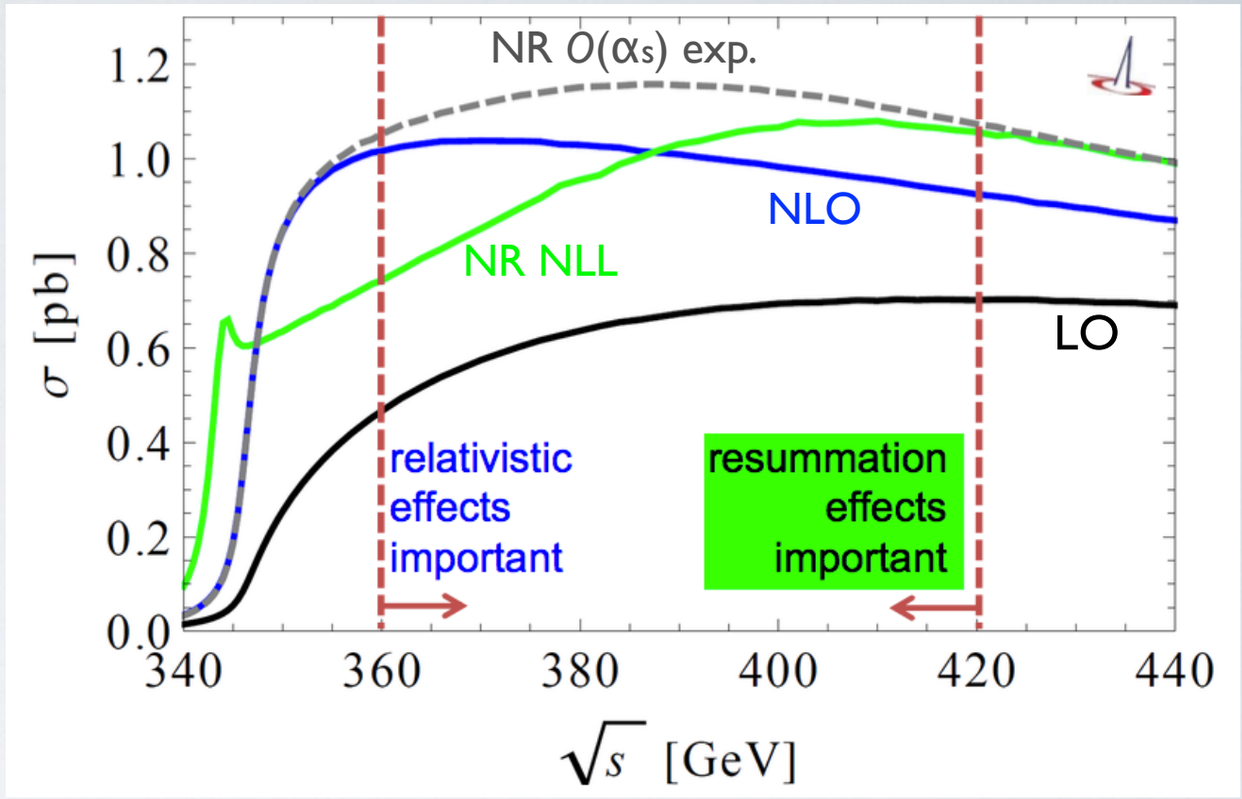


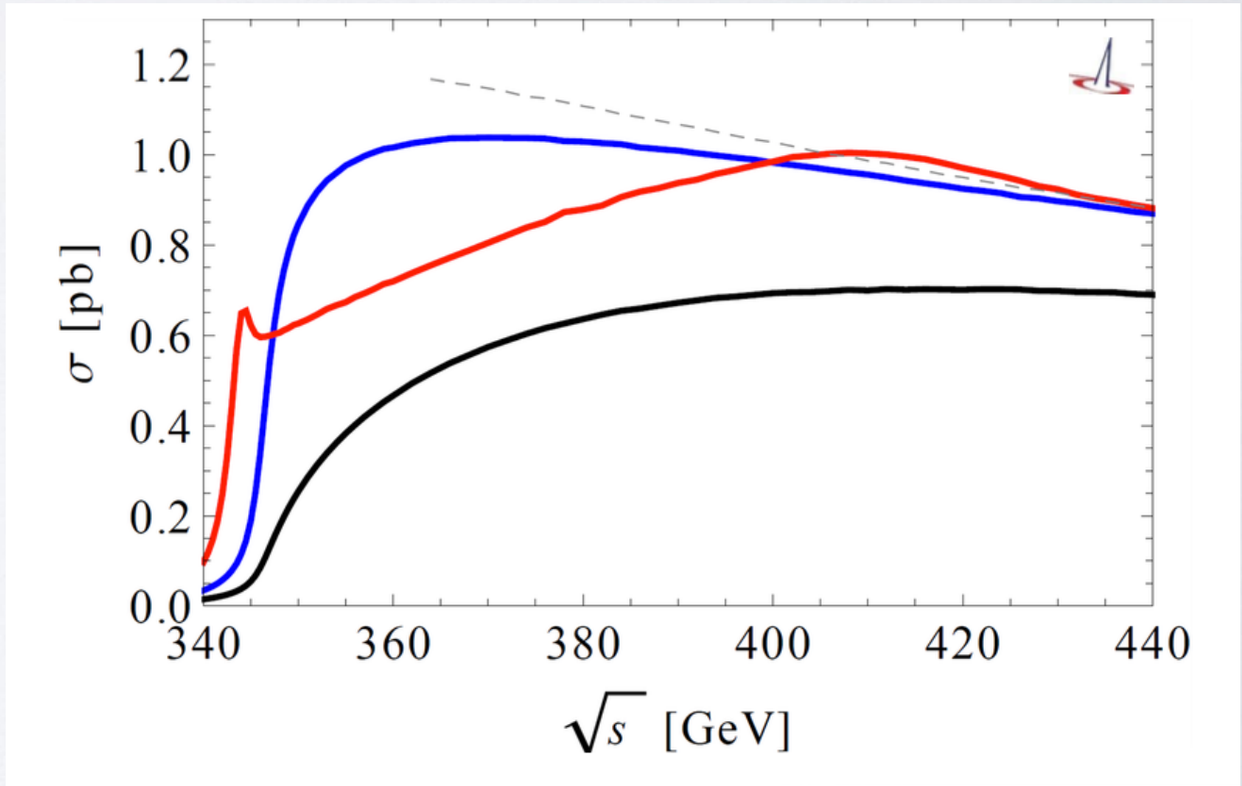

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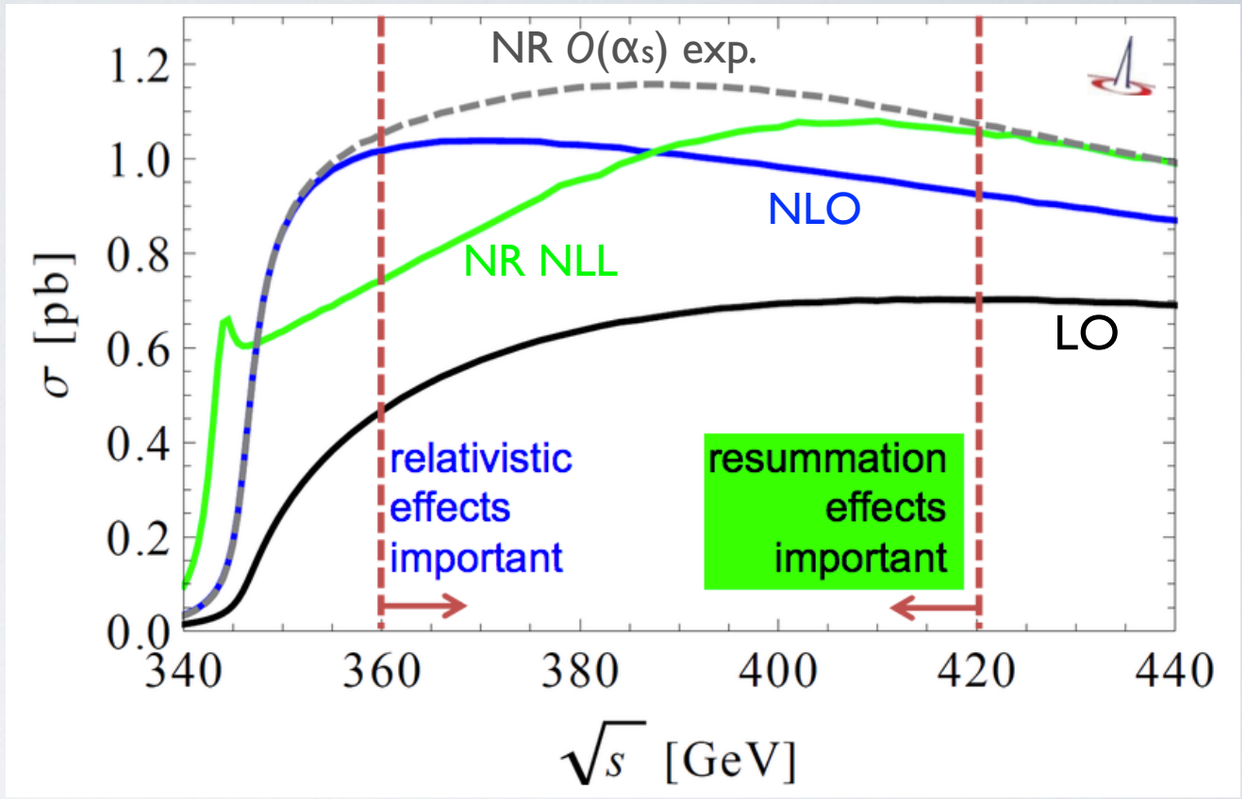
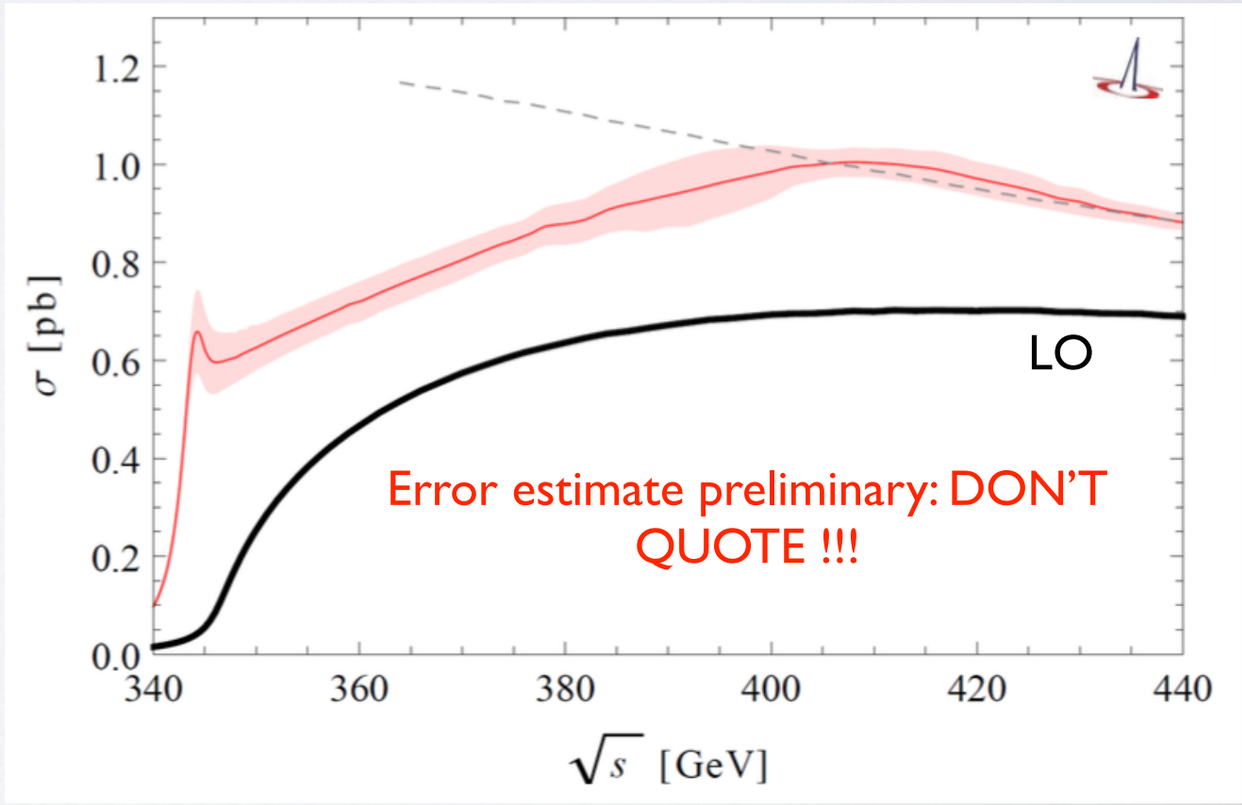
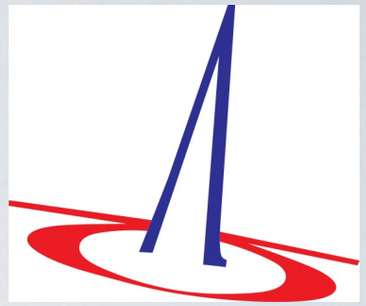
Total uncertainty: **matching and *h-f* variation band**



# Conclusions & Outlook



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- NLO automation: reals and subtraction terms (FKS) [+ virtuals externally] → WHIZARD 3.0
- allows to produce NLO fixed-order histograms
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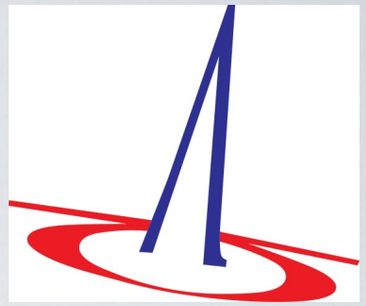

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# Pictorial summary: loops, legs, and subtractions

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# BACKUP SLIDES:

# Phase Space Setup

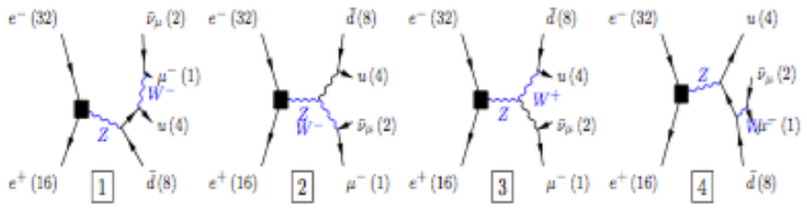
WHIZARD algorithm: heuristics to classify phase-space topology, adaptive multi-channel mapping $\Longrightarrow$ `resonant, t-channel, radiation, infrared, collinear, off-shell`

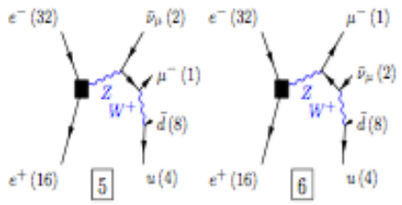
**WHIZARD phase space channels**

**Process:** `cc10` ($e^-e^+ \to \mu^-\bar{\nu}_\mu u\bar{d}$)
**Color code:** resonance, t-channel, radiation, infrared, collinear, external/off-shell

**Grove 1**

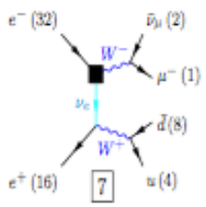
Multiplicity: 1
Resonances: 2
Log-enhanced: 0
t-channel: 0



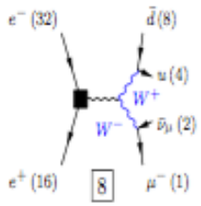

**Grove 2**

Multiplicity: 2
Resonances: 2
Log-enhanced: 1
t-channel: 1




**Grove 3**

Multiplicity: 2
Resonances: 2
Log-enhanced: 0
t-channel: 0

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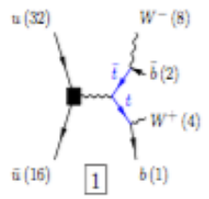
**Color code:** resonance, t-channel, radiation, infrared, collinear, external/off-shell

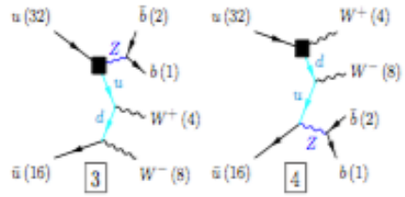
**Grove 1**

Multiplicity: 2
Resonances: 2
Log-enhanced: 0
t-channel: 0



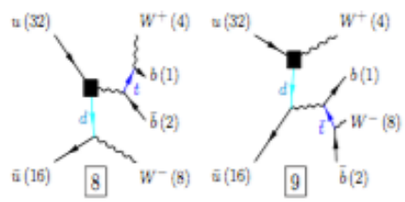

**Grove 3**

Multiplicity: 3
Resonances: 1
Log-enhanced: 2
t-channel: 2



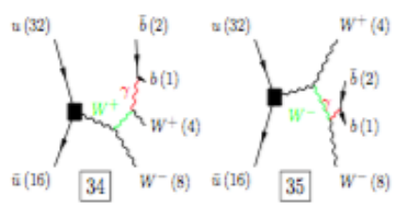

**Grove 6**

Multiplicity: 3
Resonances: 1
Log-enhanced: 1
t-channel: 1



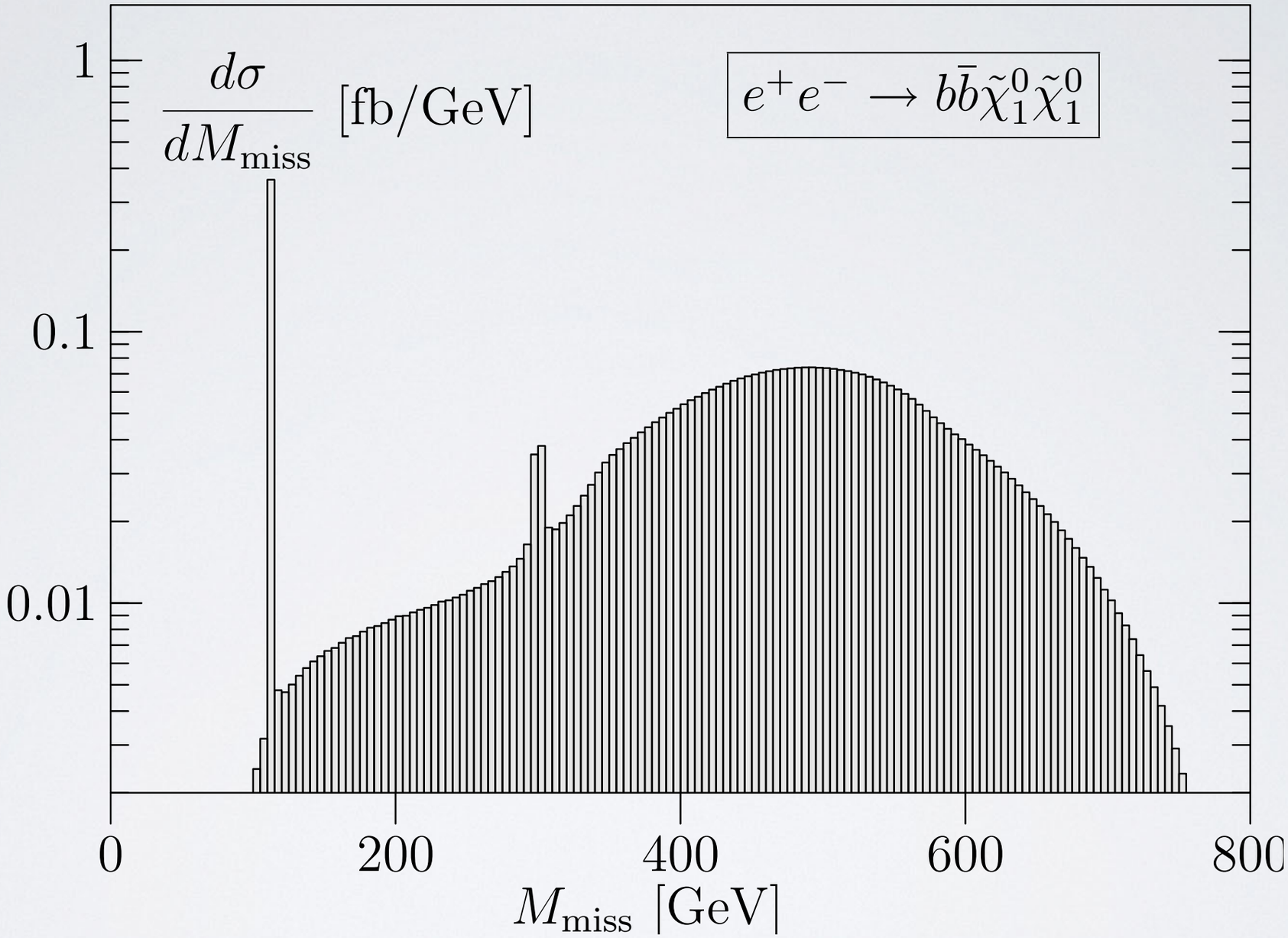

**Grove 19**

Multiplicity: 4
Resonances: 0
Log-enhanced: 2
t-channel: 0




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

# Why care about beamstrahlung / ISR ?



# Why care about beamstrahlung / ISR ?