Automation of NLO processes and decays and POWHEG matching in WHIZARD

ACAT 2016
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Chile/Continental timezone

Jürgen R. Reuter, DESY

Mi primera vez en Chile

Felicitaciones para los ganadores de Copa 2015

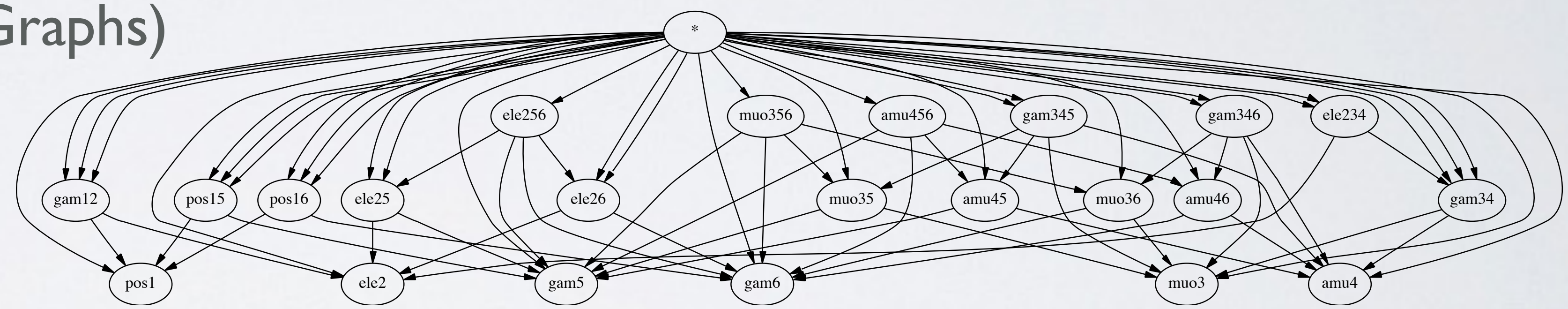
WHIZARD: Introduction

WHIZARD v2.2.8 (22.11.2015) http://whizard.hepforge.org <whizard@desy.de>

WHIZARD Team: *Wolfgang Kilian, Thorsten Ohl, JRR, Simon Braß/Bijan Chokoufé/Marco Sekulla/Soyoung Shim/Florian Staub/Christian Weiss/Zhijie Zhao* + *2 Master*

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)

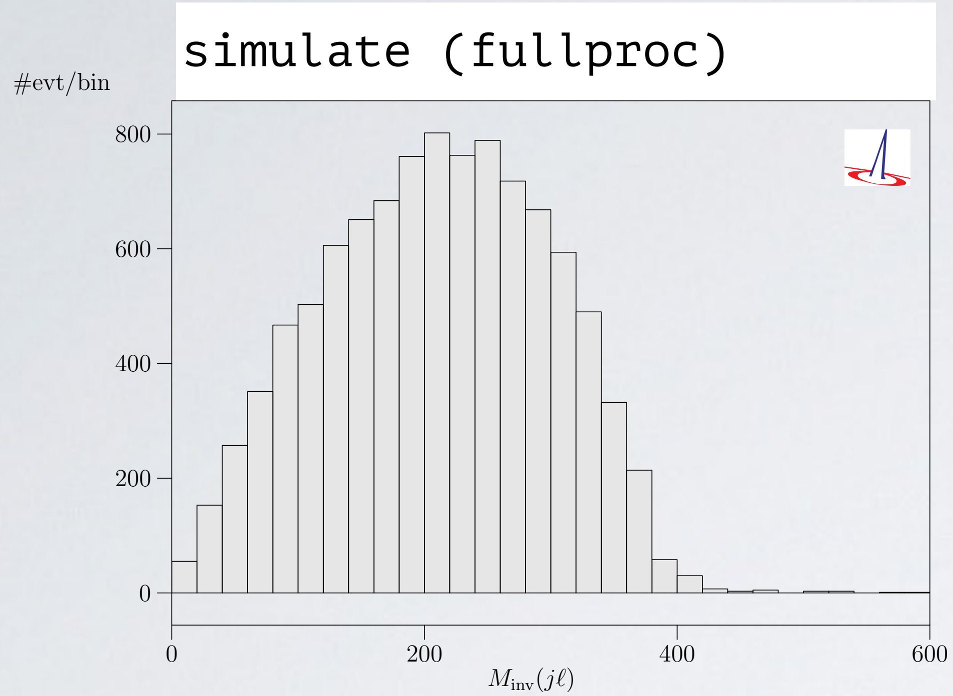


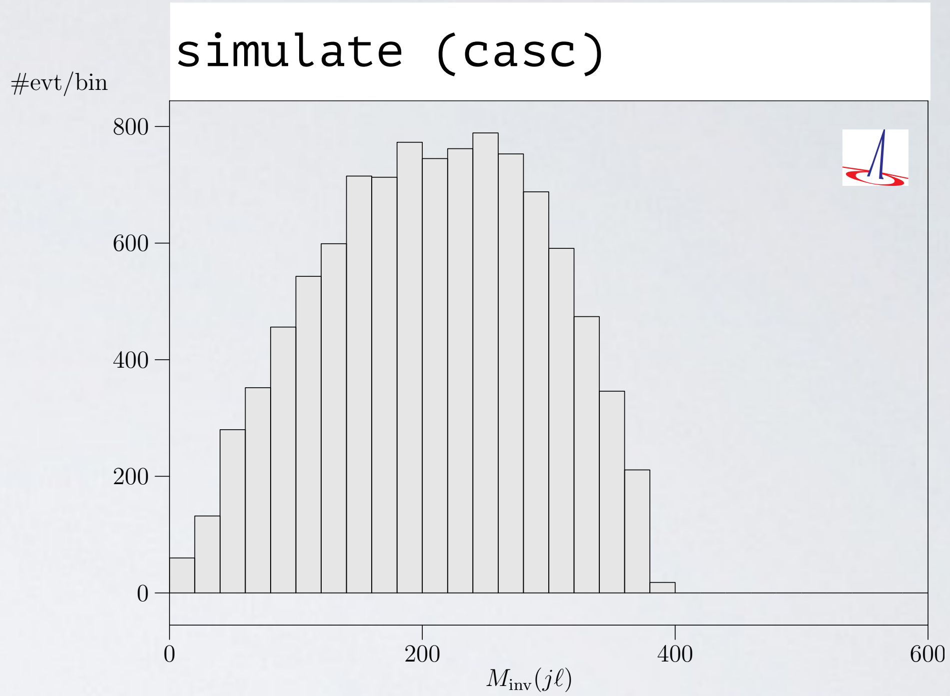
  - VAMP: adaptive multi-channel Monte Carlo integrator
  - CIRCE1/2: generator/simulation tool for lepton collider beam spectra
  - Lepton beam ISR Kuraev/Fadin, 2003; Skrzypek/Jadach, 1991
  - Color flow formalism Stelzer/Willenbrock, 2003; Kilian/Ohl/JRR/Speckner, 2011

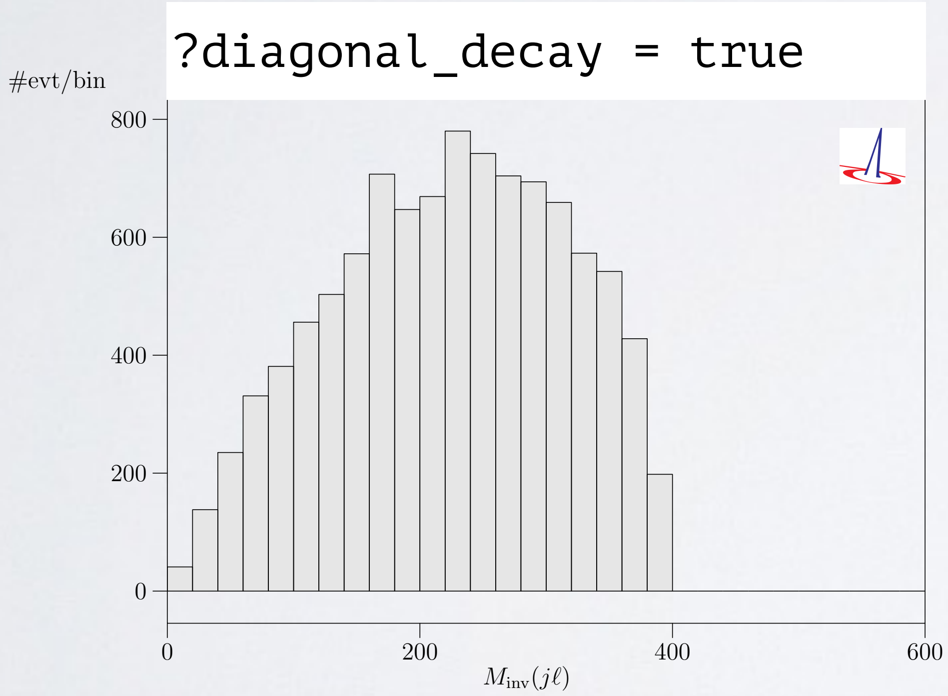
- Interfaces to external packages for Feynman rules, hadronization, tau decays, event formats, analysis, jet clustering etc.: `FastJet, GoSam, GuineaPig(++), HepMC, HOPPET, LCIO, LHAPDF(4/5/6), LoopTools, OpenLoops, PYTHIA6, [PYTHIA8], StdHep [internal]`

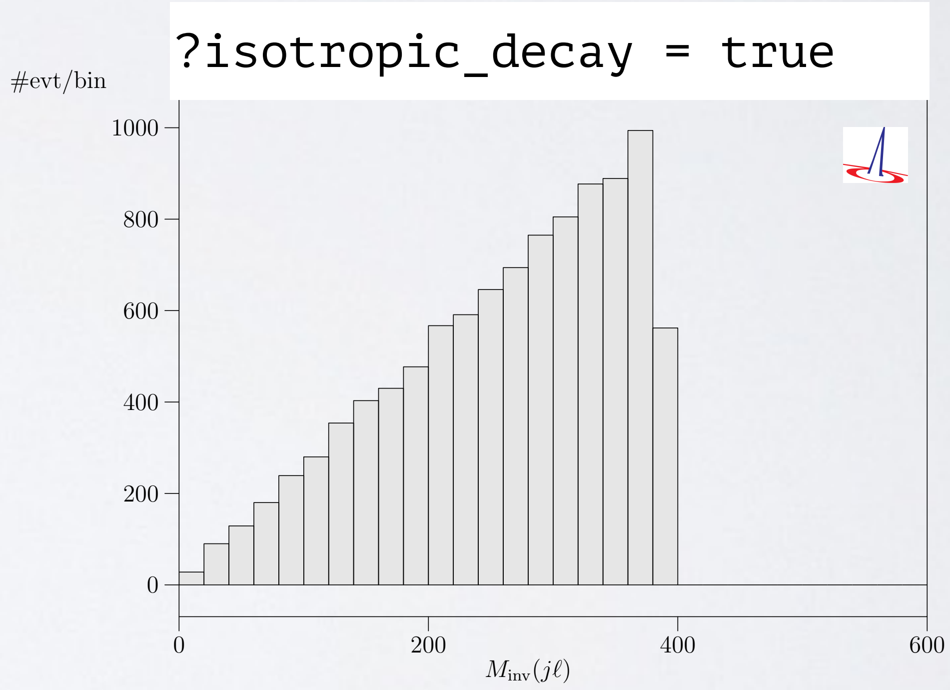
Spin Correlation and Polarization in Cascades

Cascade decay, factorize production and decay









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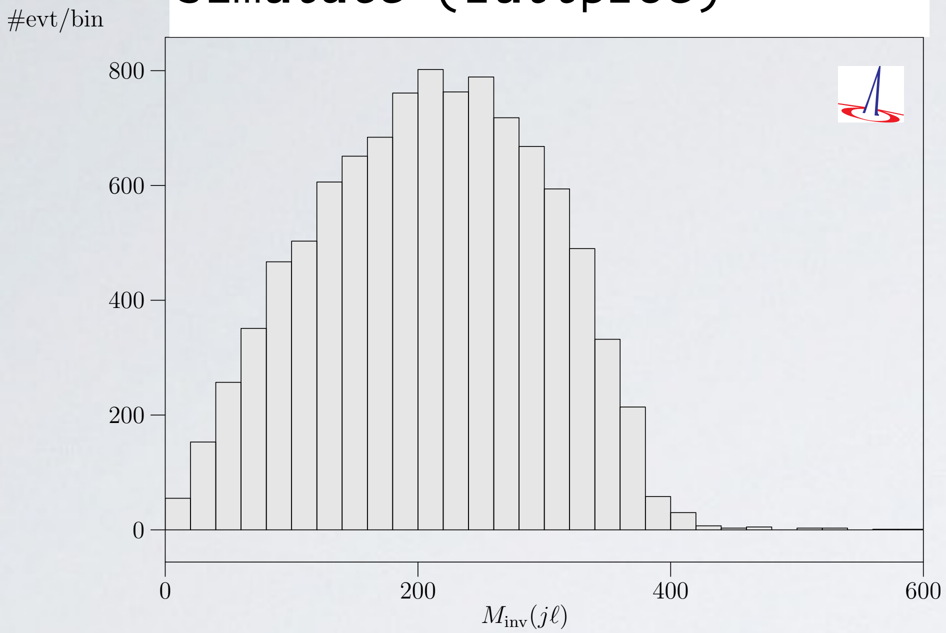
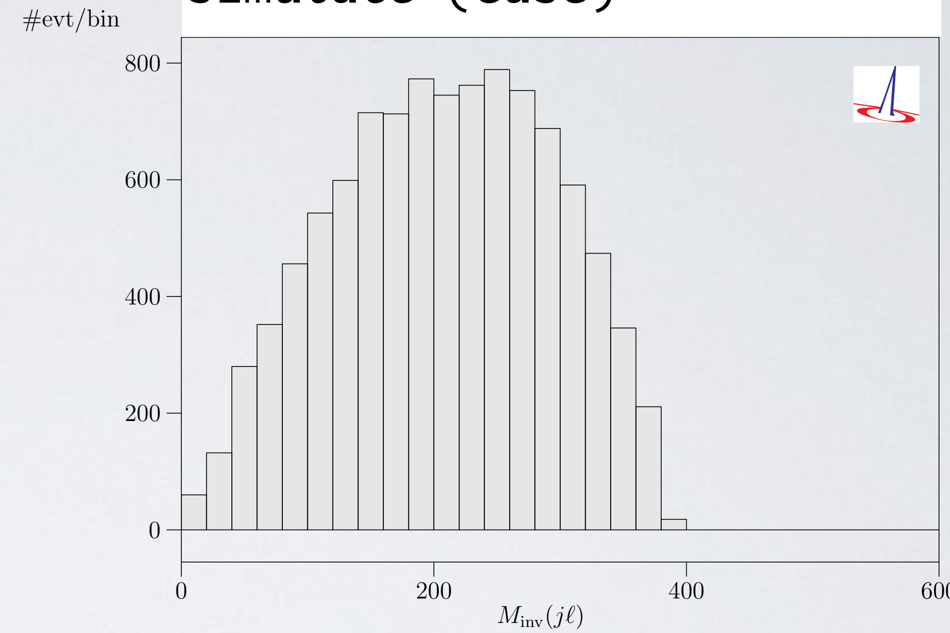
Cascade decay, factorize production and decay

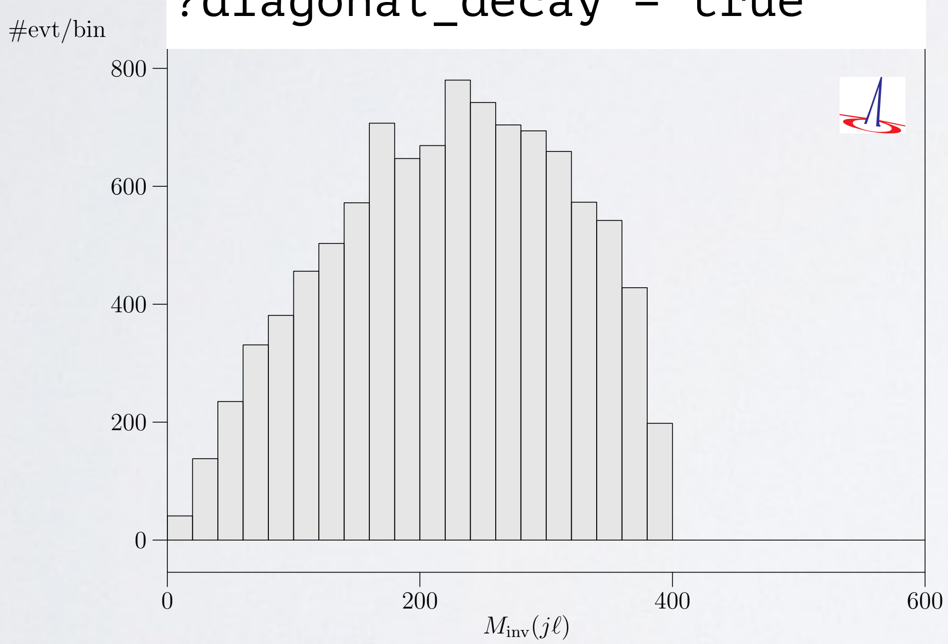
`simulate (fullproc)`



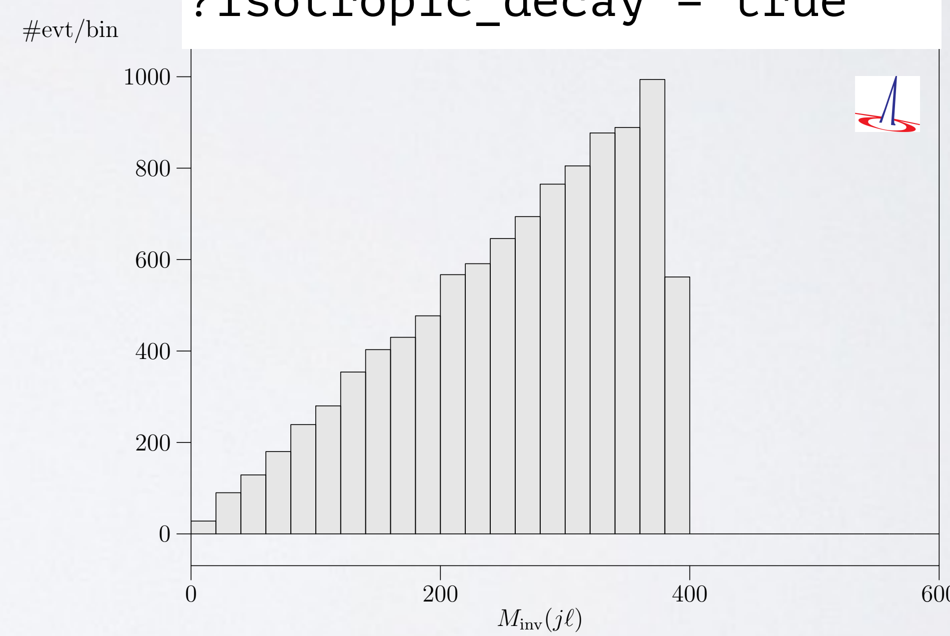
`simulate (casc)`



`?diagonal_decay = true`



`?isotropic_decay = true`



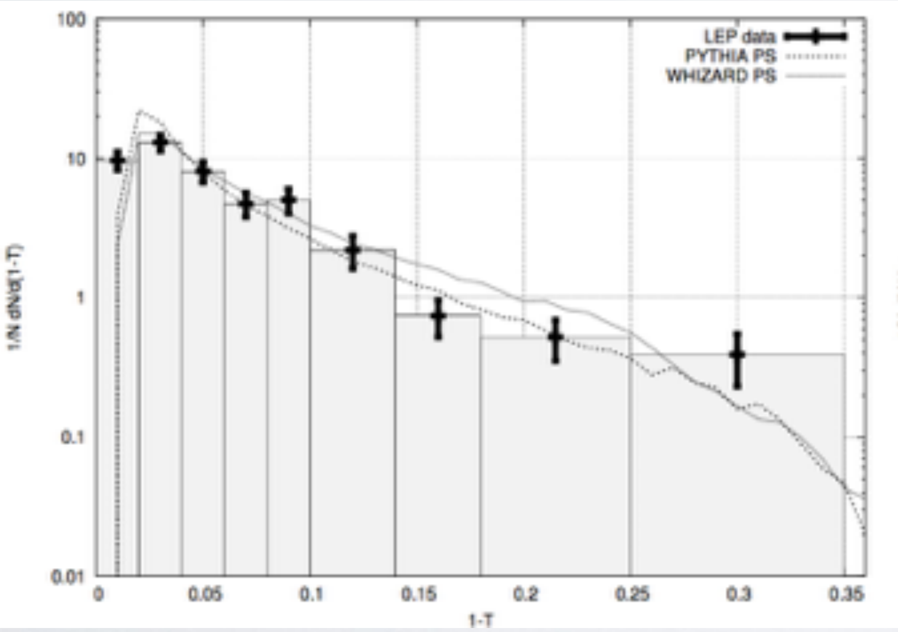
NEW: possibility to select specific helicity in decays!

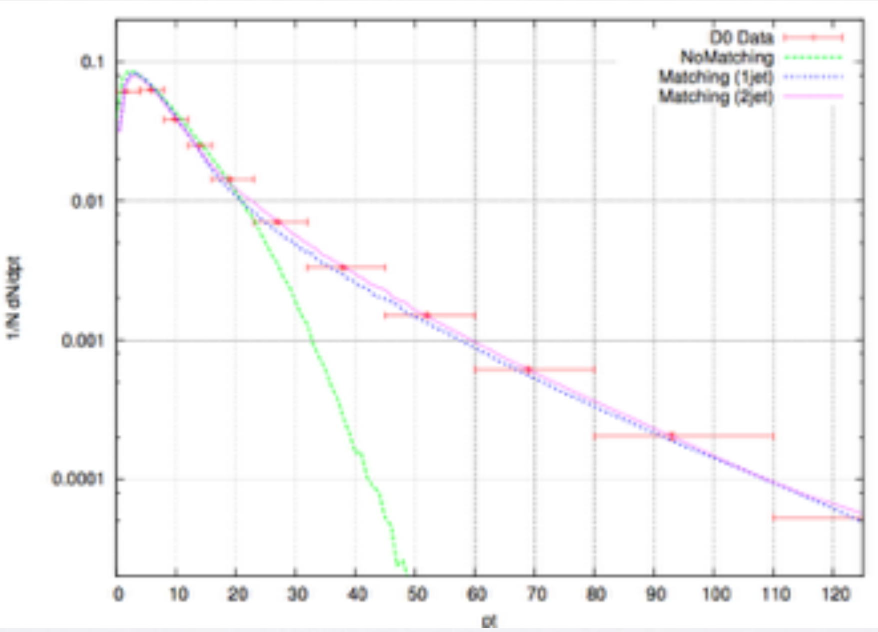
```
unstable “W+” { decay_helicity = 0 }
```

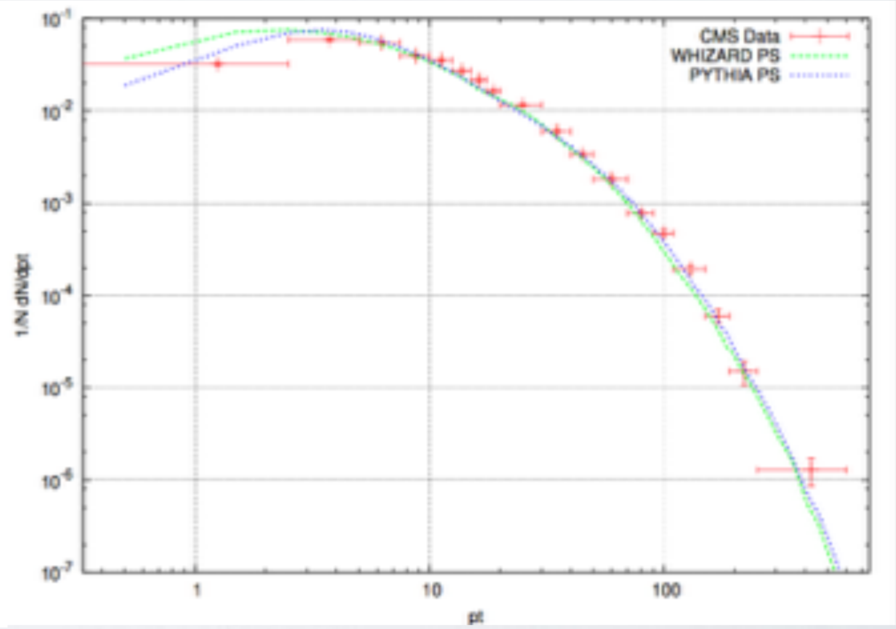
WHIZARD Parton Shower

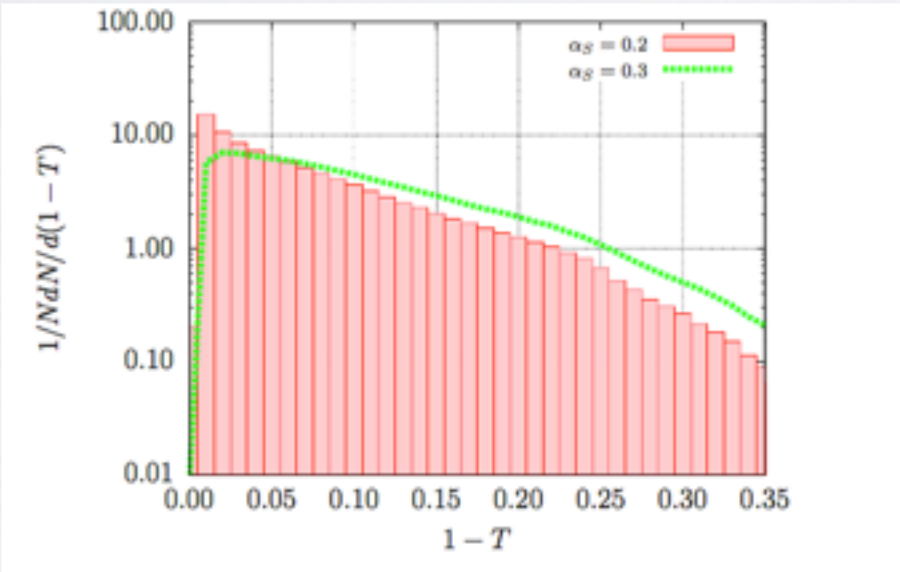
- Two independent implementations: kT-ordered QCD and Analytic QCD shower
- Analytic shower: no shower veto ⇒ exact shower history known, allows reweighting

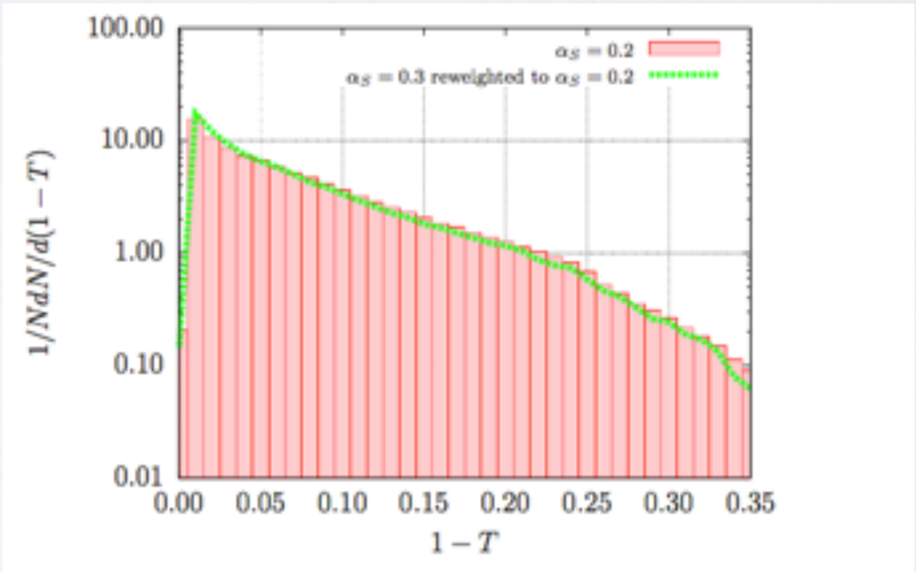
Kilian/JRR/Schmidt/Wiesler, JHEP **1204** 013 (2012)







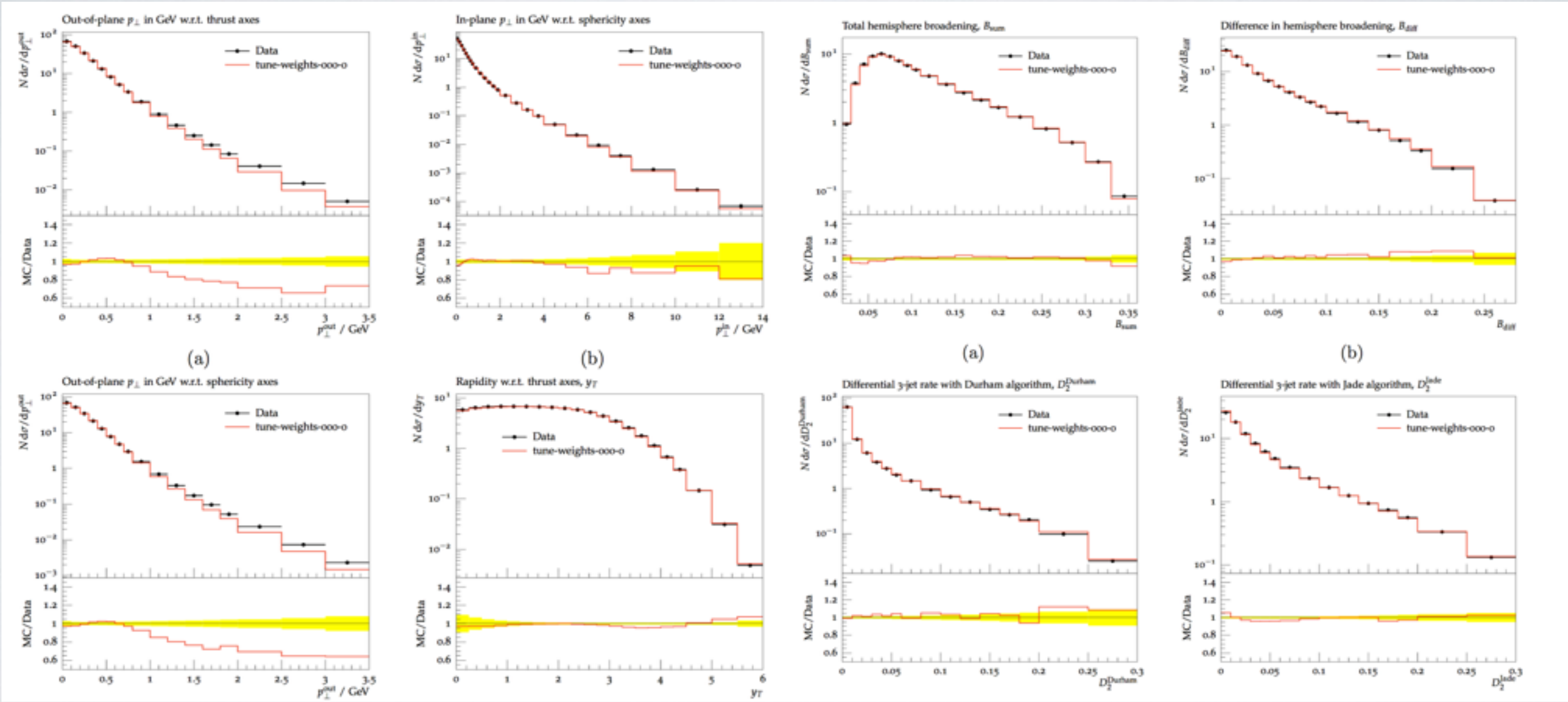




- Technical overhaul of the shower / merging part
- Plans: implement GKS matching, QED shower (also interleaved, infrastructure ready)

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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WHIZARD v2.2.6 contains alpha version

QCD corrections (massless and massive emitters)

```
alpha_power = 2
alphas_power = 0

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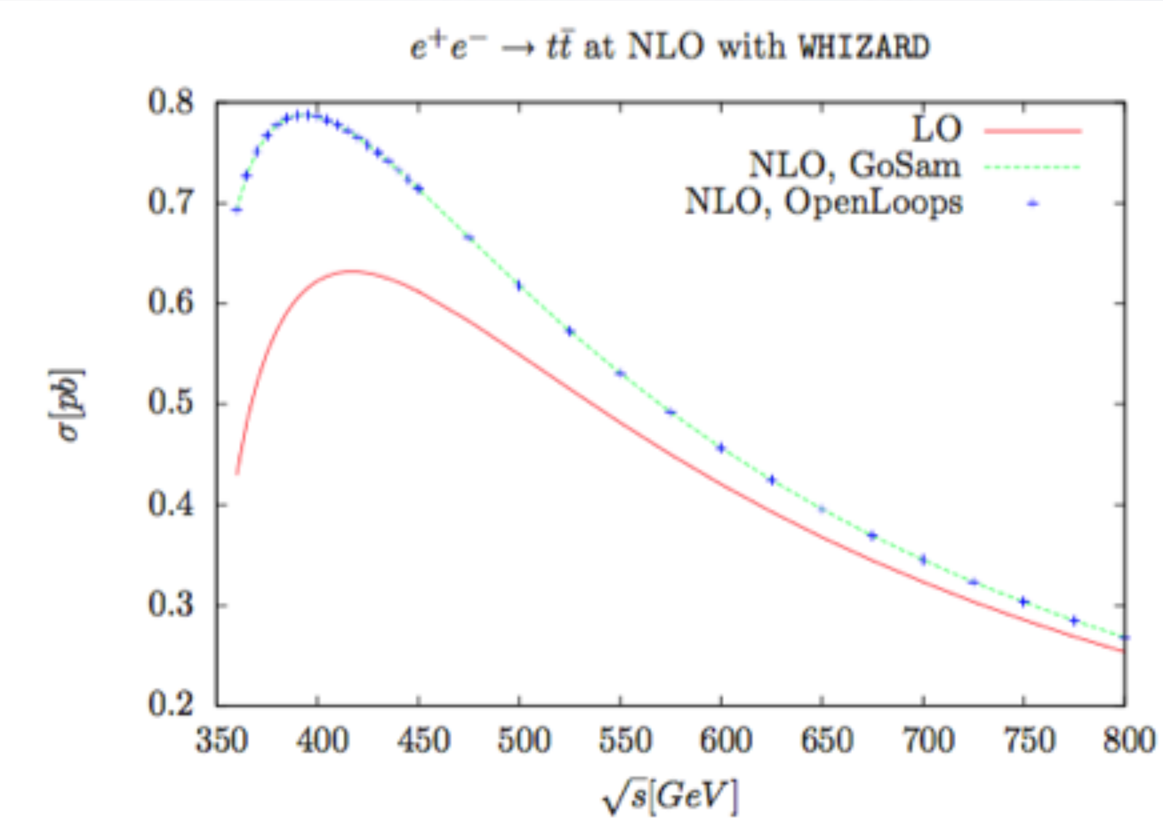

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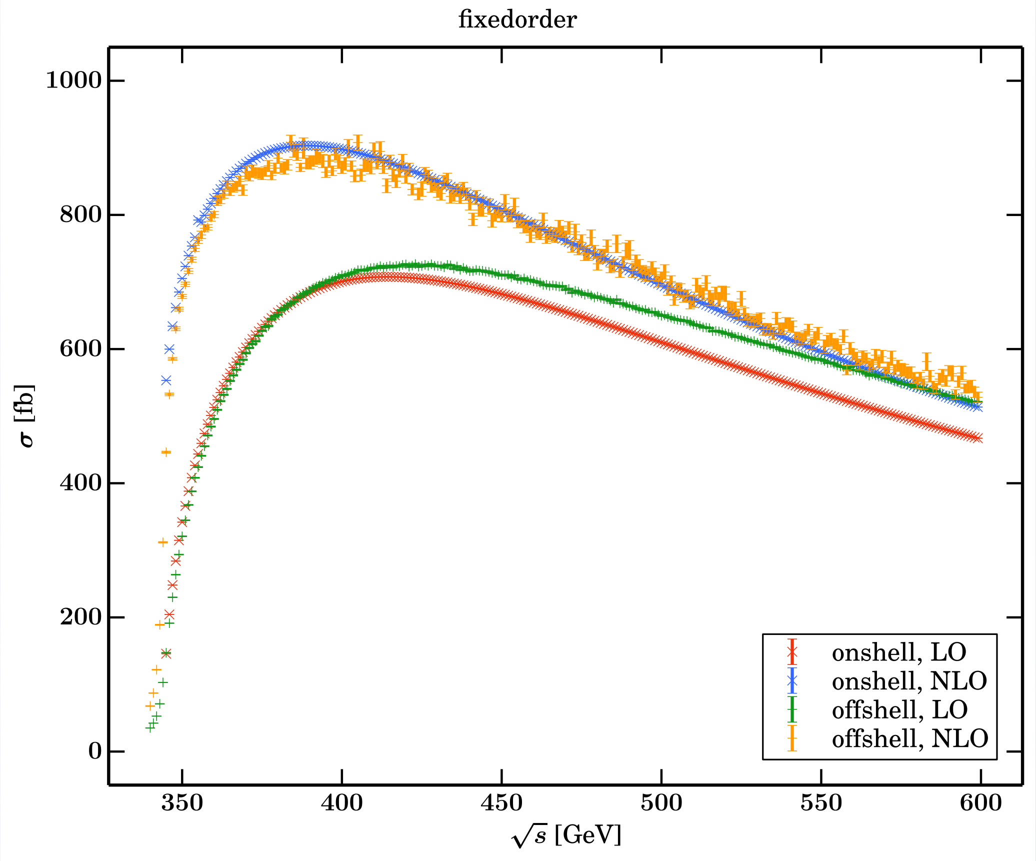

FKS Subtraction (Frixione/Kunszt/Signer)

Subtraction formalism to make real and virtual contributions separately finite

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

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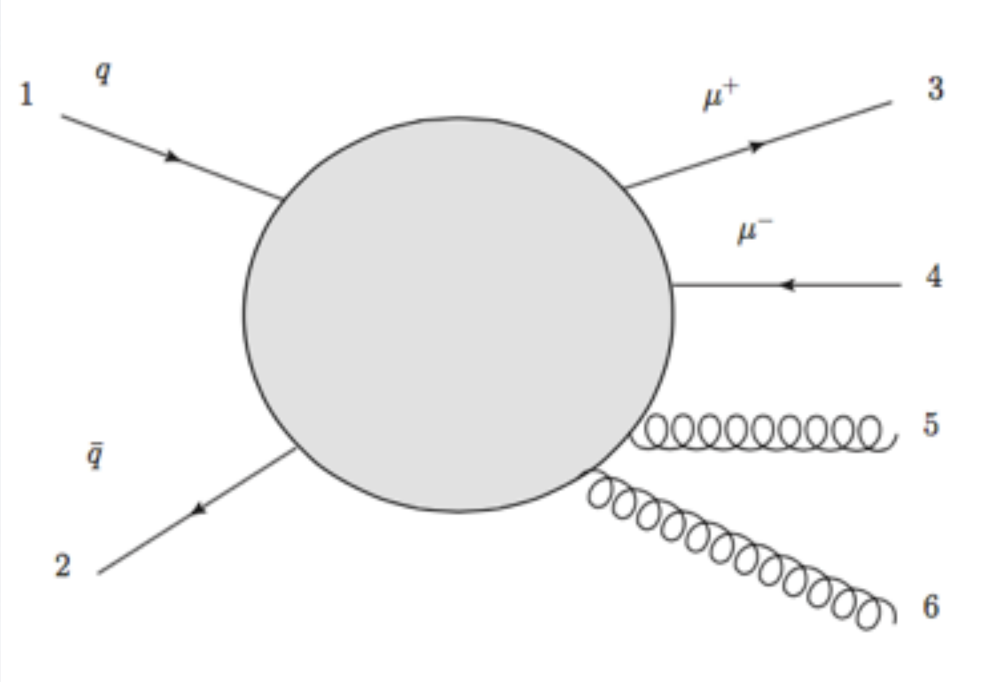

Automated subtraction terms in `WHIZARD`, algorithm:

- 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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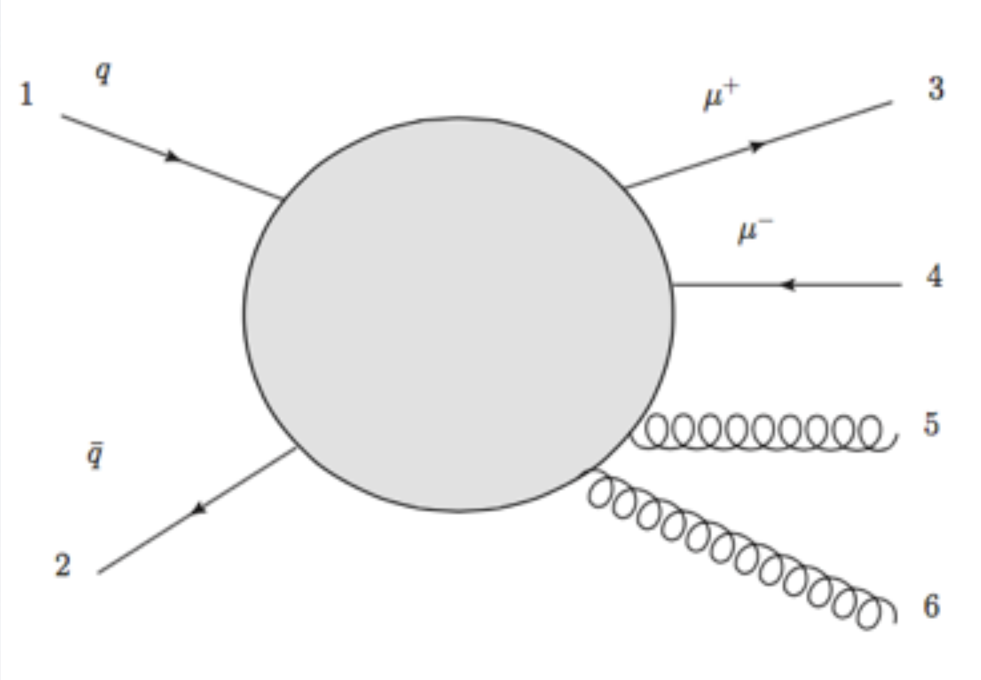

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* Generate subtraction terms for singular regions

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:

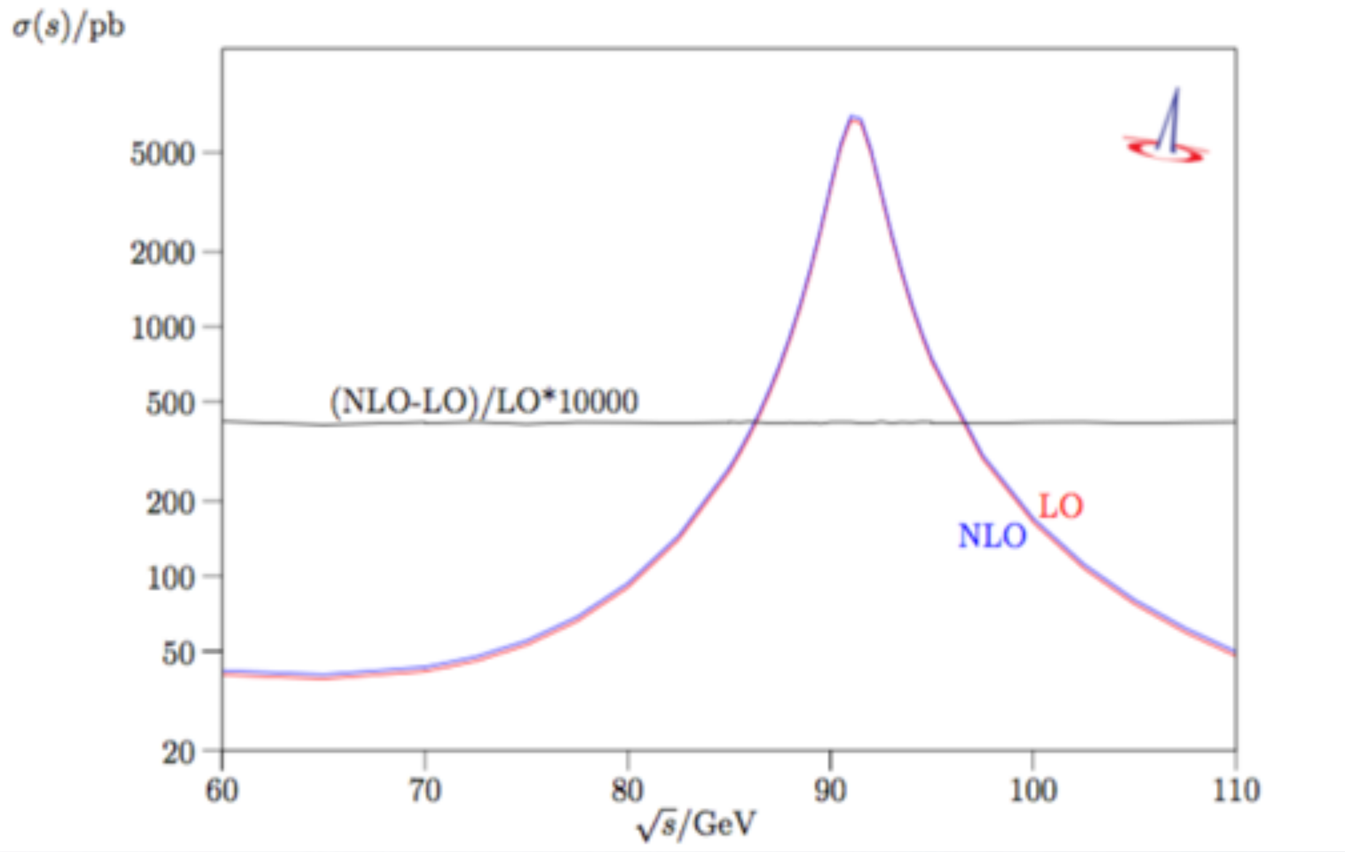
$$\mathcal{B}_{+-} \sim Re \left\{ \frac{\langle k_{\mathrm{em}} k_{\mathrm{rad}} \rangle}{[k_{\mathrm{em}} k_{\mathrm{rad}}]} \sum_{\substack{\text{color}\\ \text{spin}}} \mathcal{A}_+^{(n)} \mathcal{A}_-^{(n)*} \right\}$$

First 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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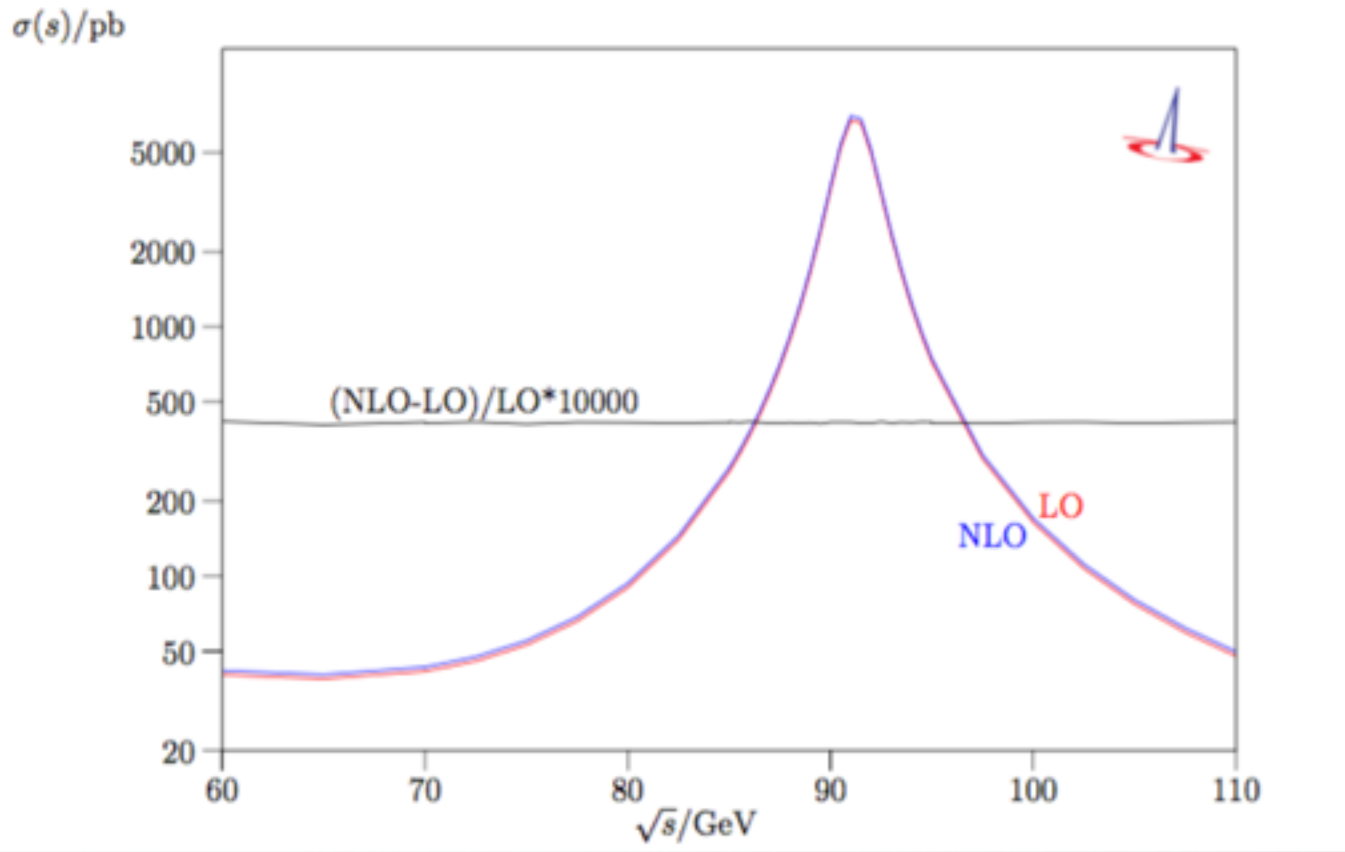

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- $e^+e^- \to t\bar{t}H$

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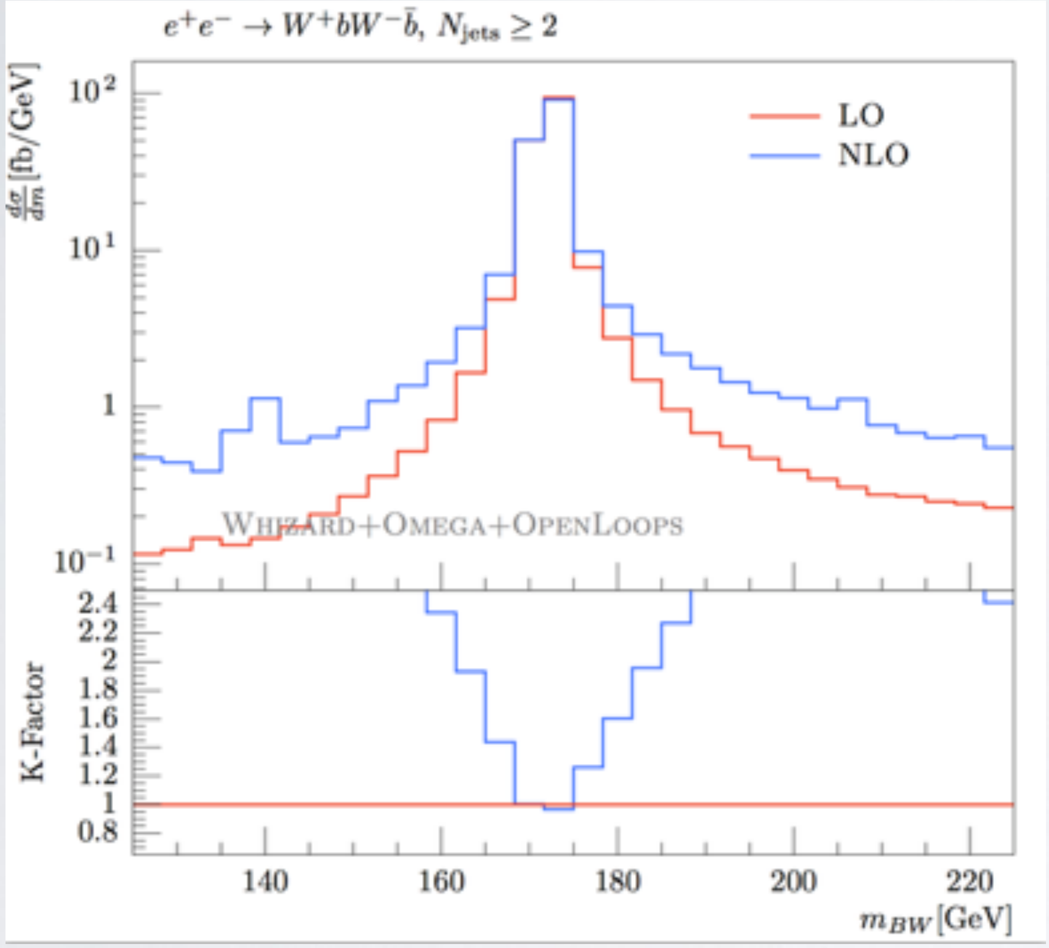
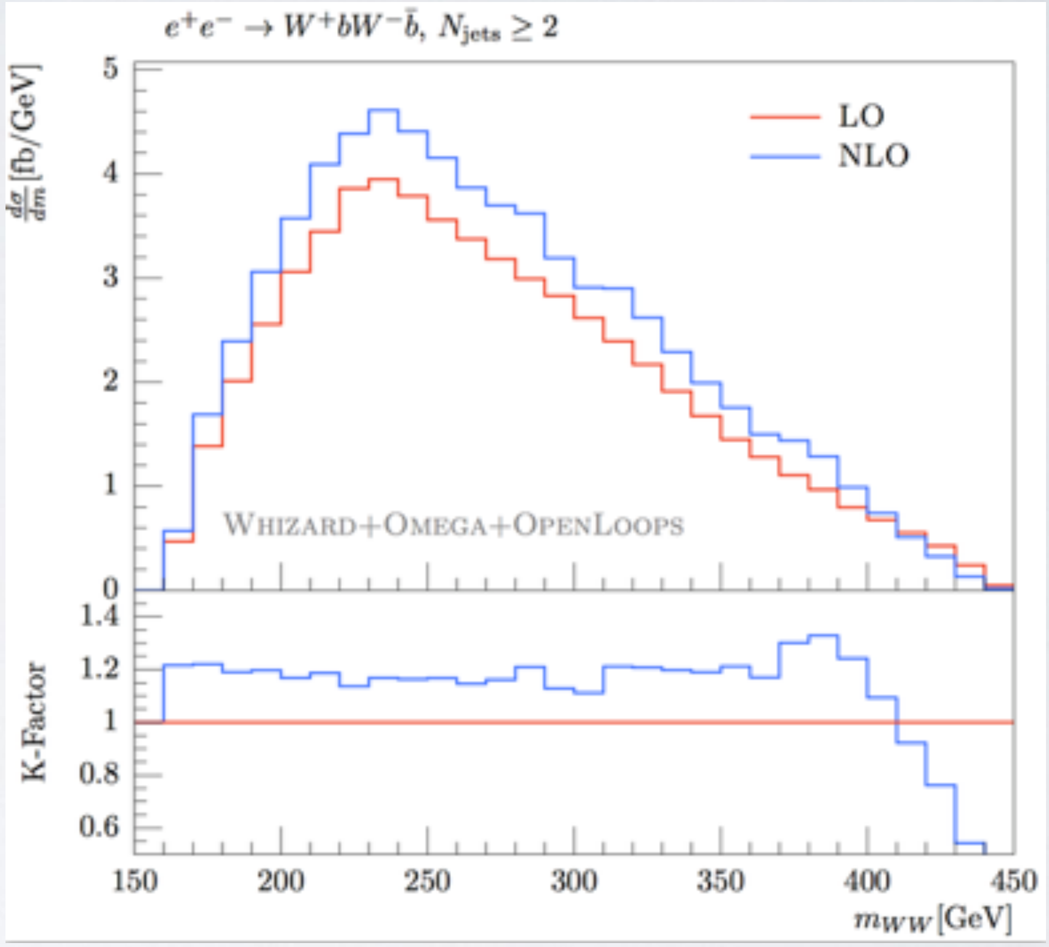
✦ QCD NLO infrastructure in pp complete

✦ 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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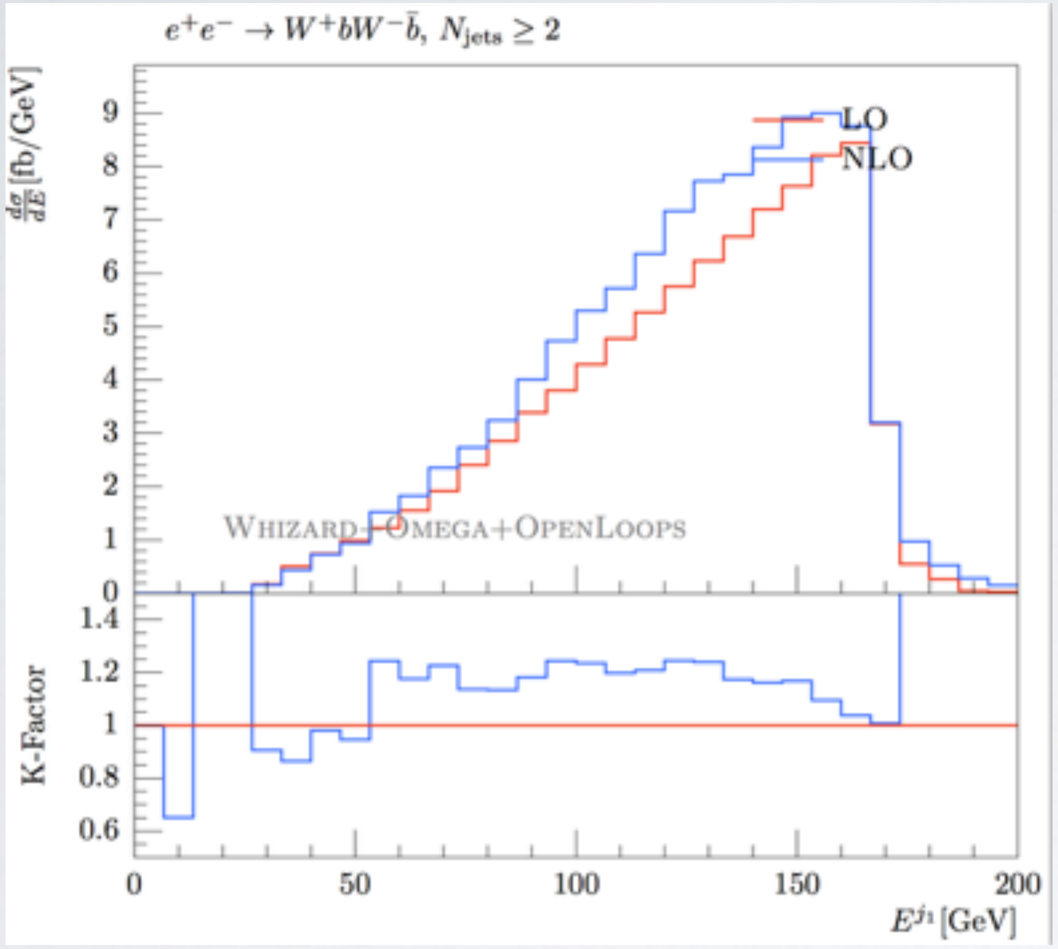

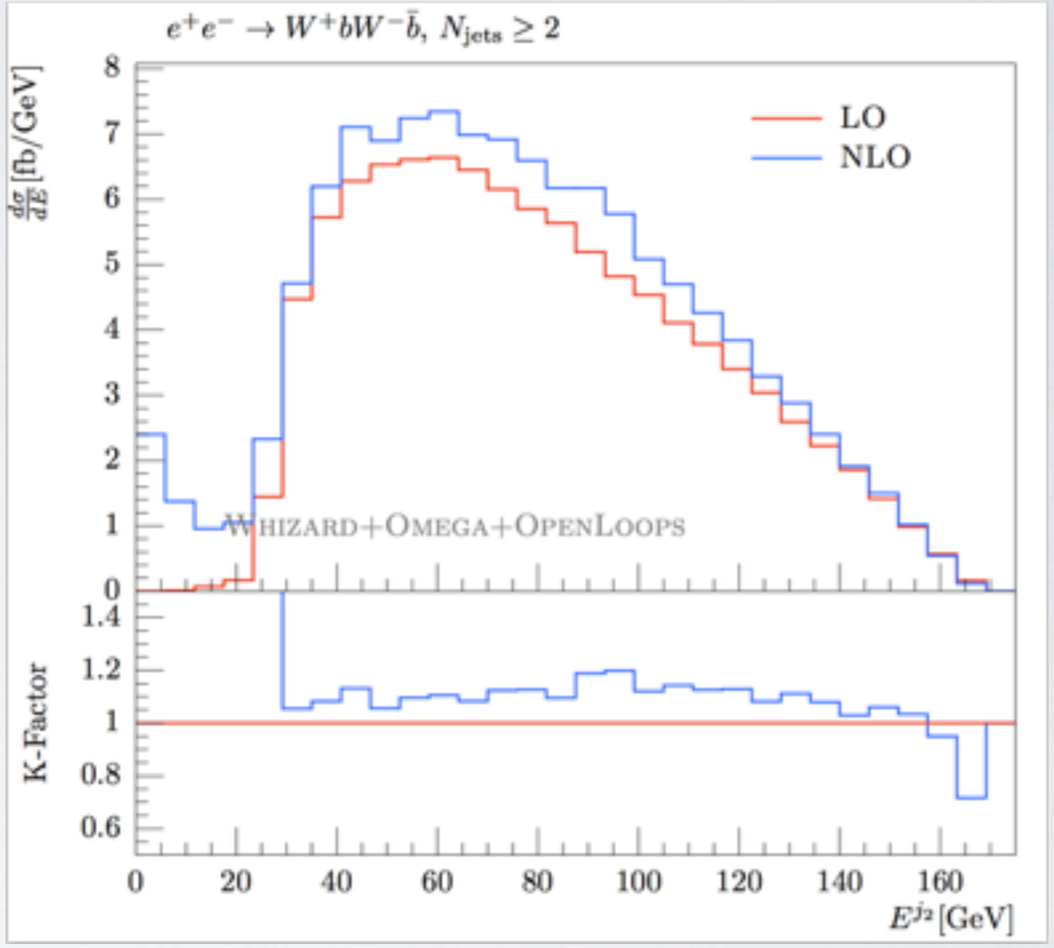

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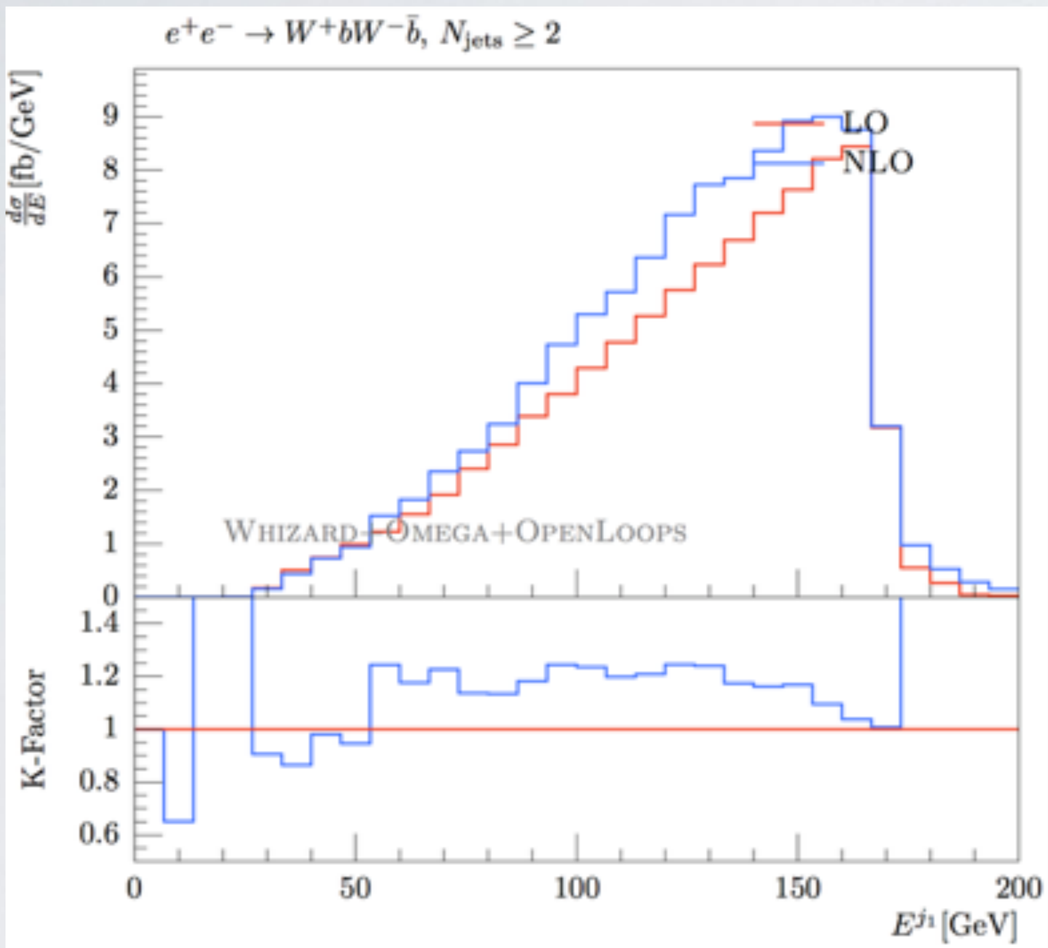
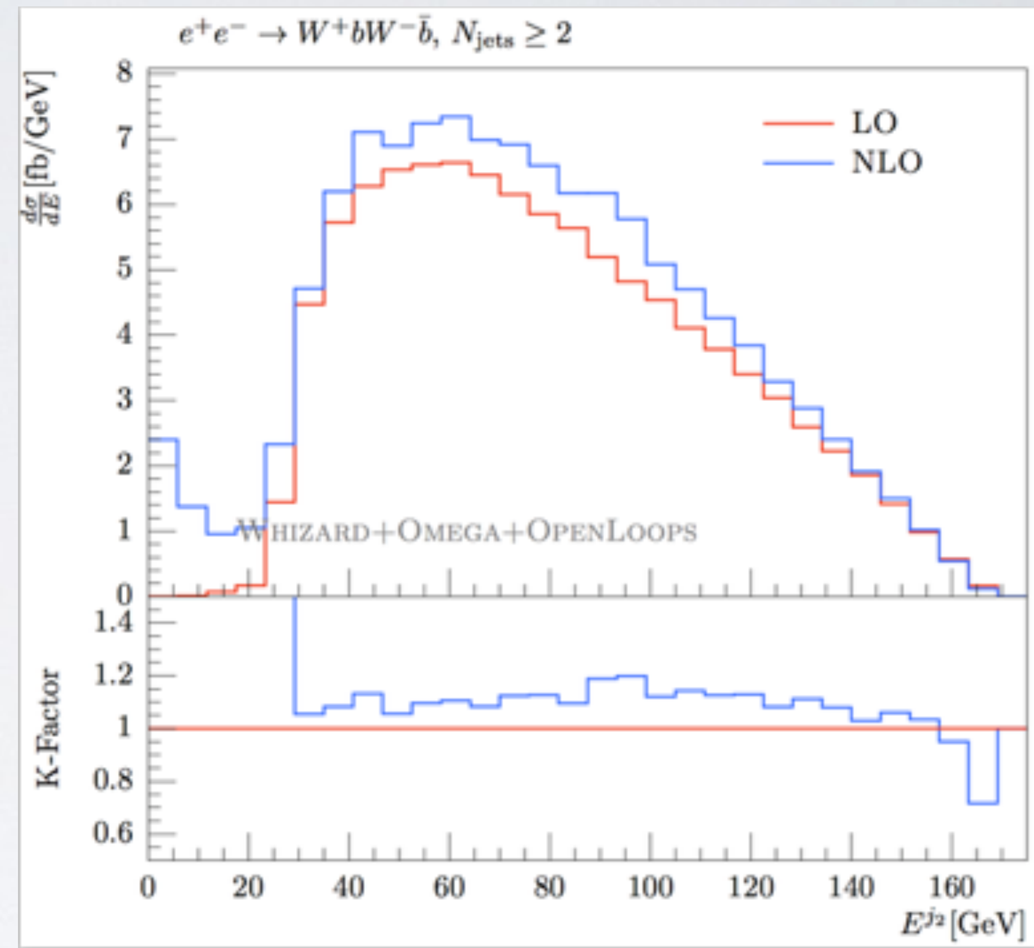
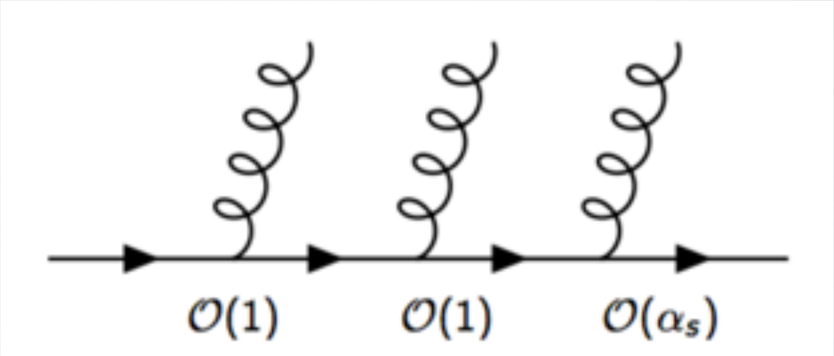




- Completed: polarized NLO results (remember: ILC will always run with polarization)
- Produce also plots including complete ISR photon radiation and beamstrahlung
- NLO decays also available (Initial state Jacobian, important for consistent widths)
- Investigate the full 2 → 6 process: e+e- → bbeμνν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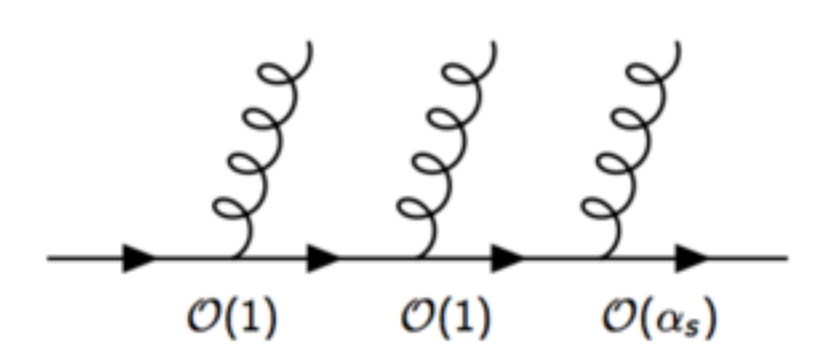

- Complete NLO events

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

- POWHEG generate events according to the formula:

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

- 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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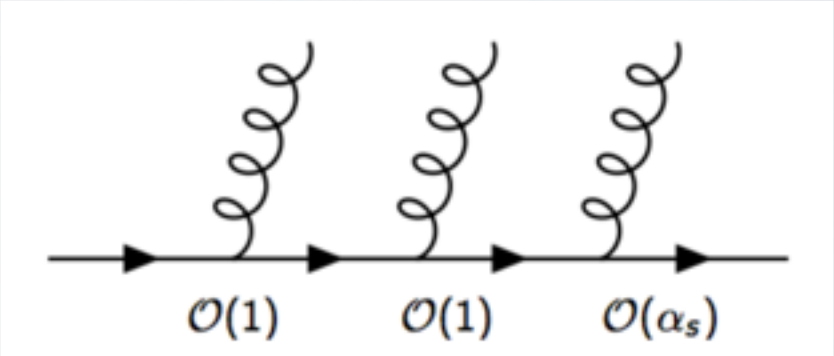

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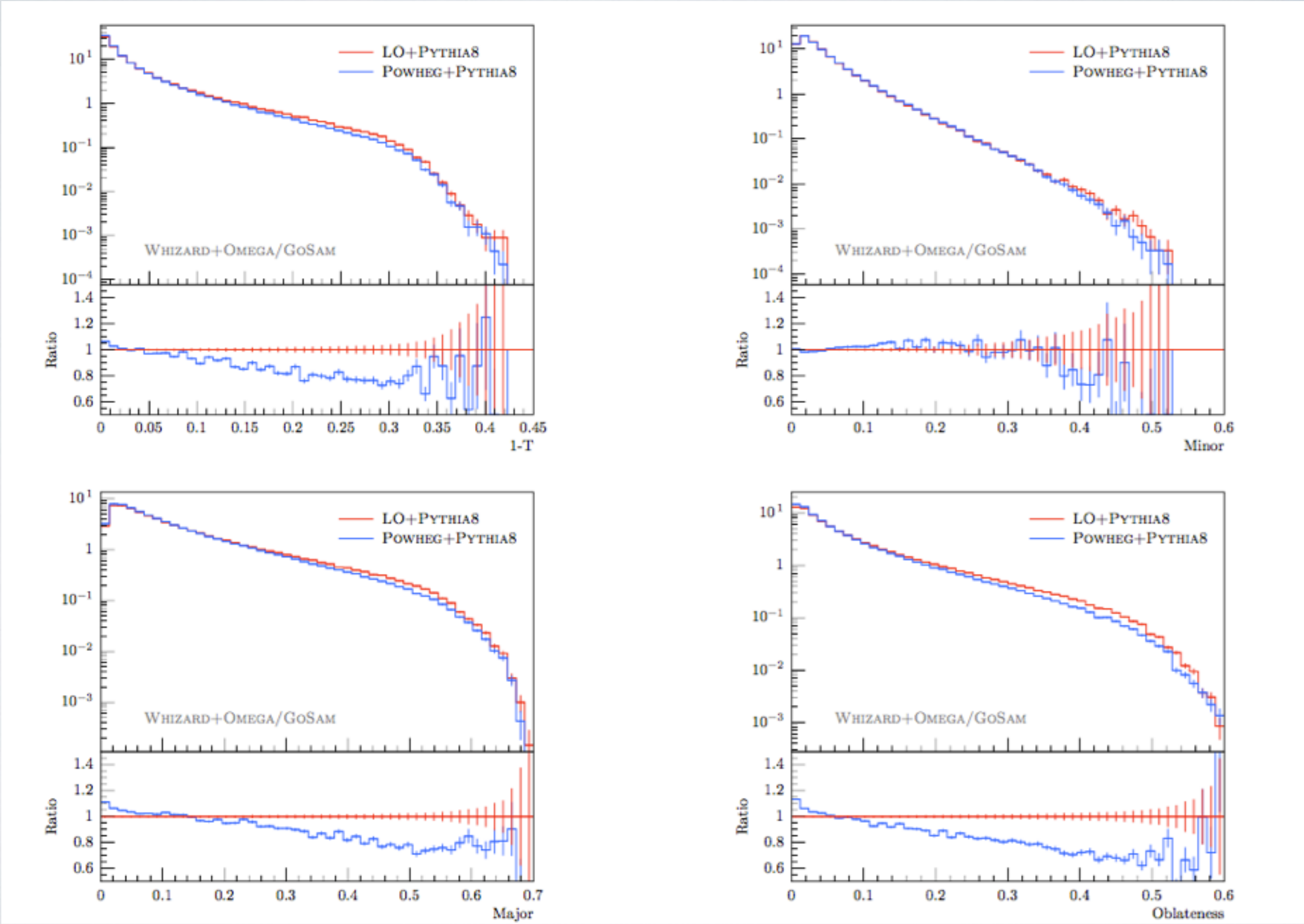
- Hardest emission: $k_T^{\rm max}$; shower with imposing a veto
- $\overline{B} < 0$ if virtual and real terms larger than Born: shouldn't happen in perturbative regions
- Reweighting such that $\overline{B} > 0$ for all events
- POWHEG: Positive Weight Hardest Emission Generator own implementation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

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



Resonance mappings for NLO processes

- Amplitudes (except for pure QCD/QED) contain resonances (*Z*, *W*, *H*, *t*)
- In general: resonance masses *not* respected by modified kinematics of subtraction terms
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- Algorithm to include resonance histories [Ježo/Nason, 1509.09071]
- Avoids double logarithms in the resonances' width
- Most important for narrow resonances ($H \to bb$)
- Separate treatment of Born and real terms,
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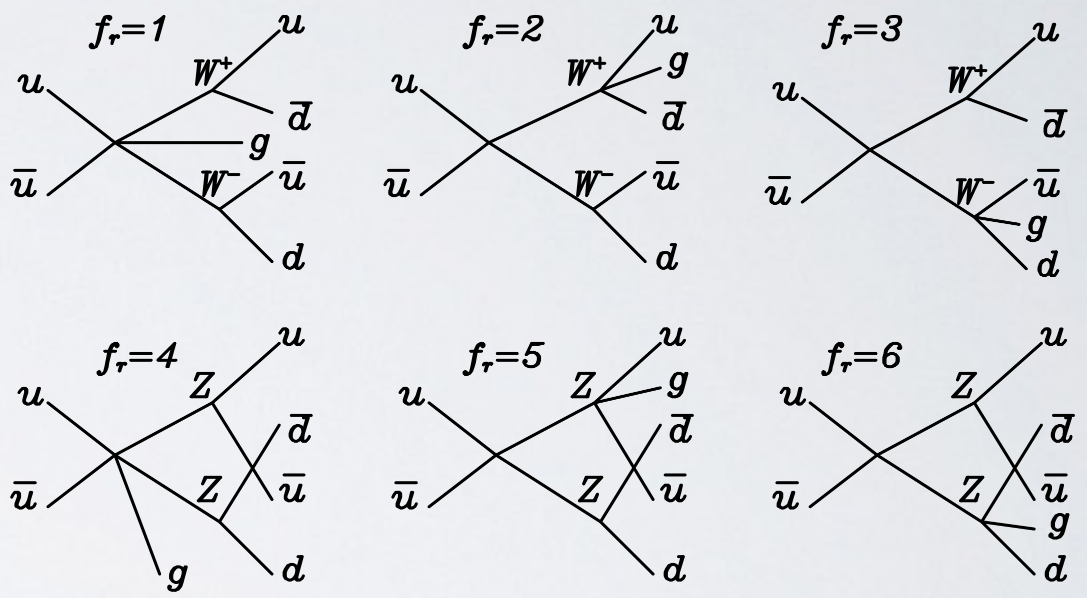

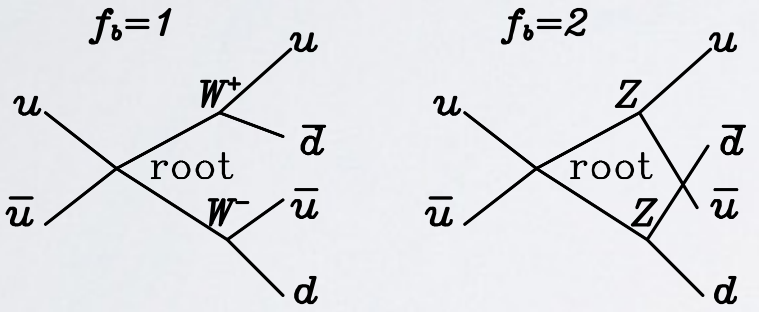

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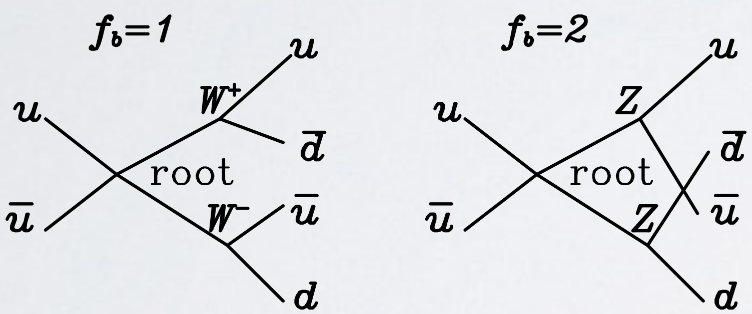
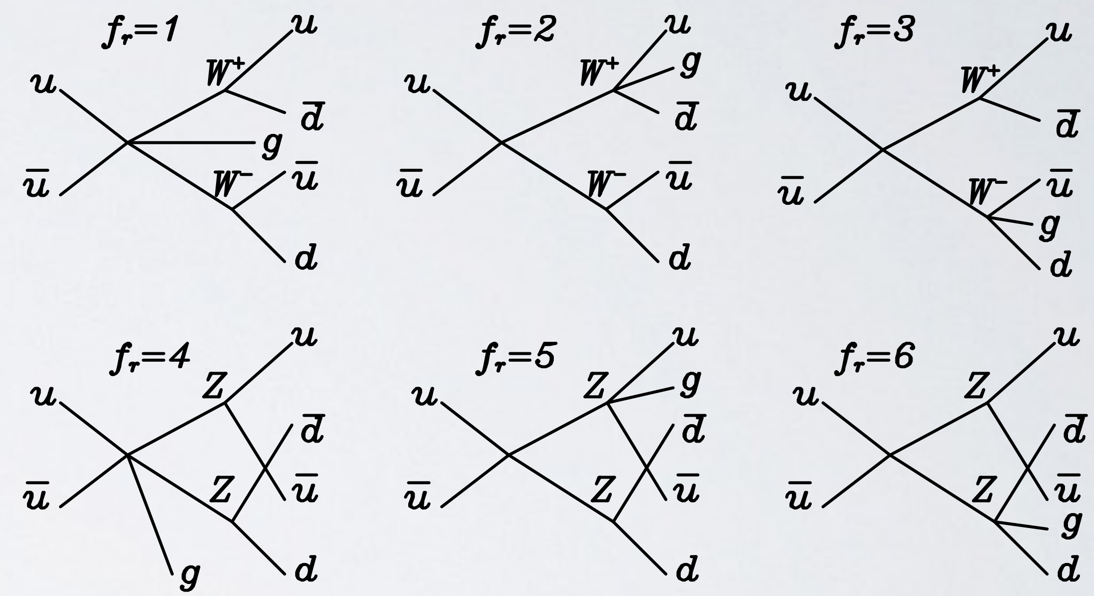




- WHIZARD complete automatic mplementation: example $e^+ e^- \to \mu\mu bb$ (*ZZ*, *ZH* histories)

It	Calls	Integral[fb]	Error[fb]	Err[%]	Acc	Eff[%]	Chi2	N[It]
1	11988	9.6811847E+00	6.42E+00	66.30	72.60*	0.65		
2	11959	2.8539703E+00	2.35E-01	8.25	9.02*	0.69		
3	11936	2.4907574E+00	6.54E-01	26.25	28.68	0.35		
4	11908	2.7695559E+00	9.67E-01	34.91	38.09	0.30		
5	11874	2.4346151E+00	4.82E-01	19.80	21.57*	0.74		
5	59665	2.7539078E+00	1.97E-01	7.15	17.47	0.74	0.49	5

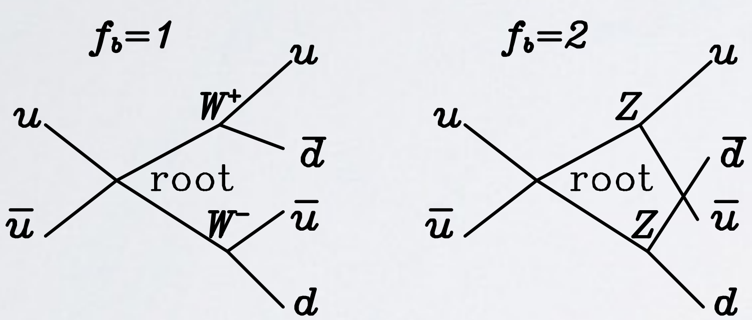
standard FKS

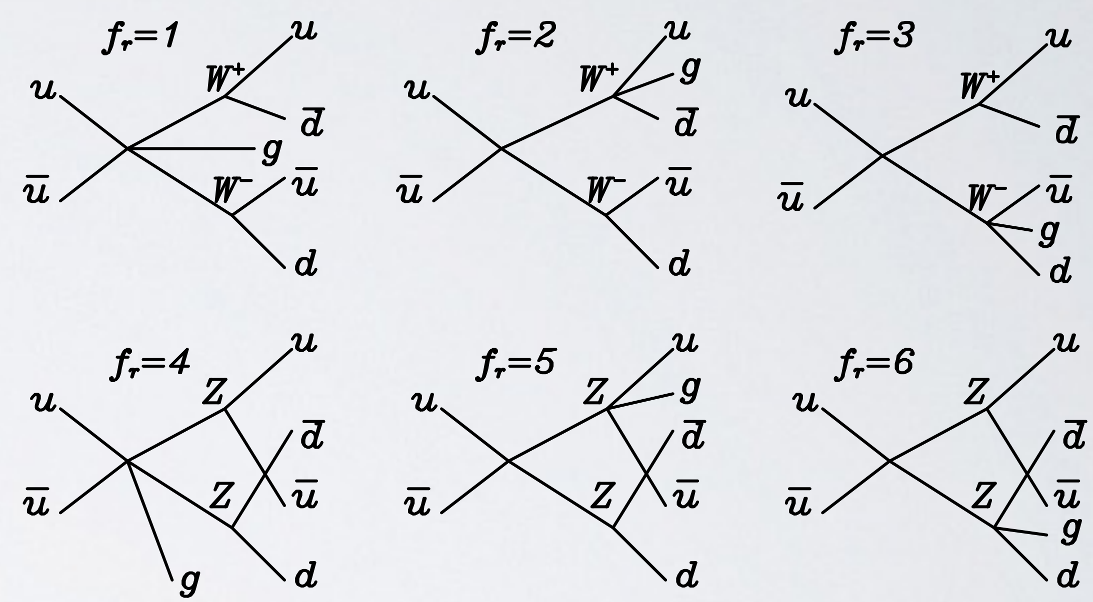
Resonance mappings for NLO processes

- Amplitudes (except for pure QCD/QED) contain resonances (*Z*, *W*, *H*, *t*)
- In general: resonance masses *not* respected by modified kinematics of subtraction terms
- Collinear (and soft) radiation can lead to mismatch between Born and subtraction terms

- Algorithm to include resonance histories [Ježo/Nason, 1509.09071]
- Avoids double logarithms in the resonances' width
- Most important for narrow resonances ($H \to bb$)
- Separate treatment of Born and real terms,

  soft mismatch





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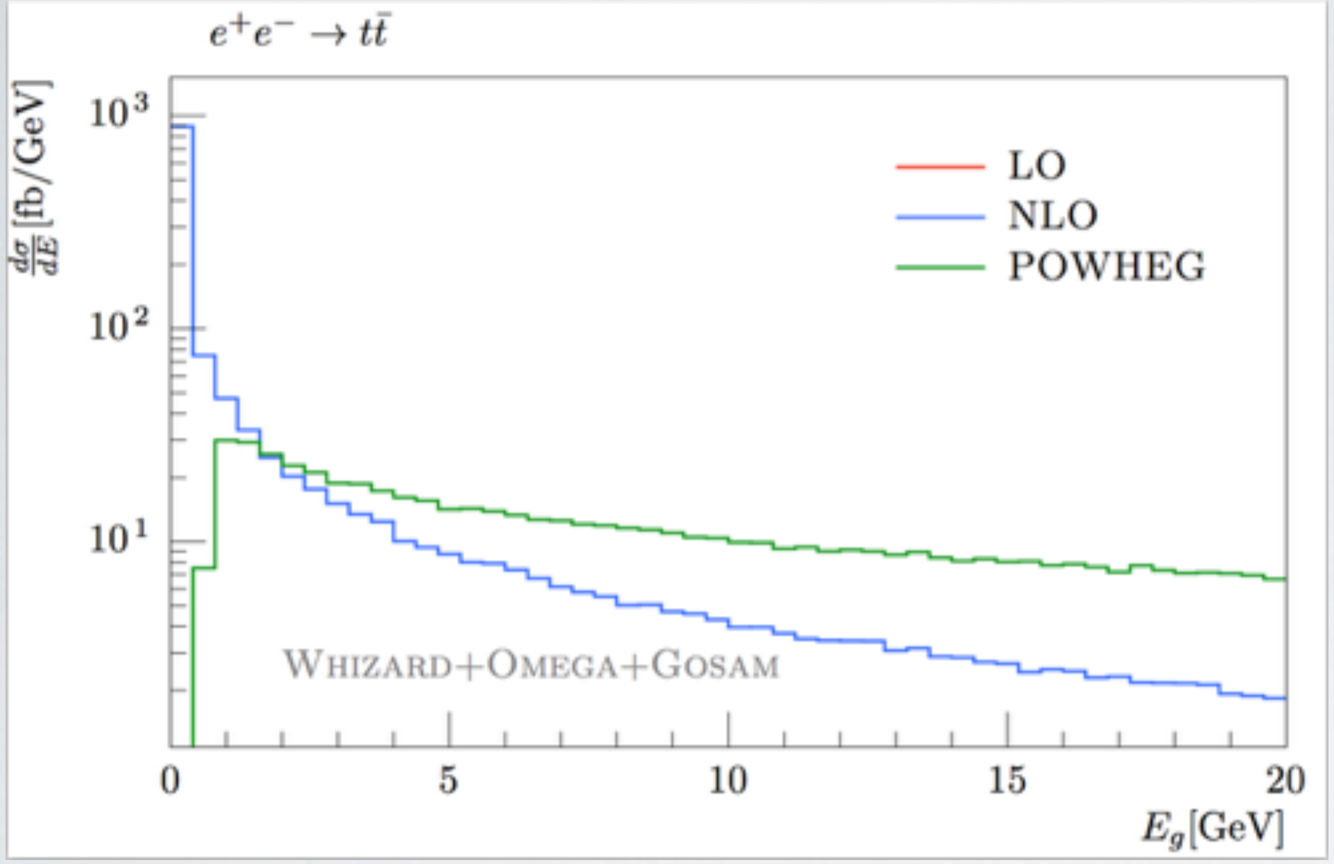
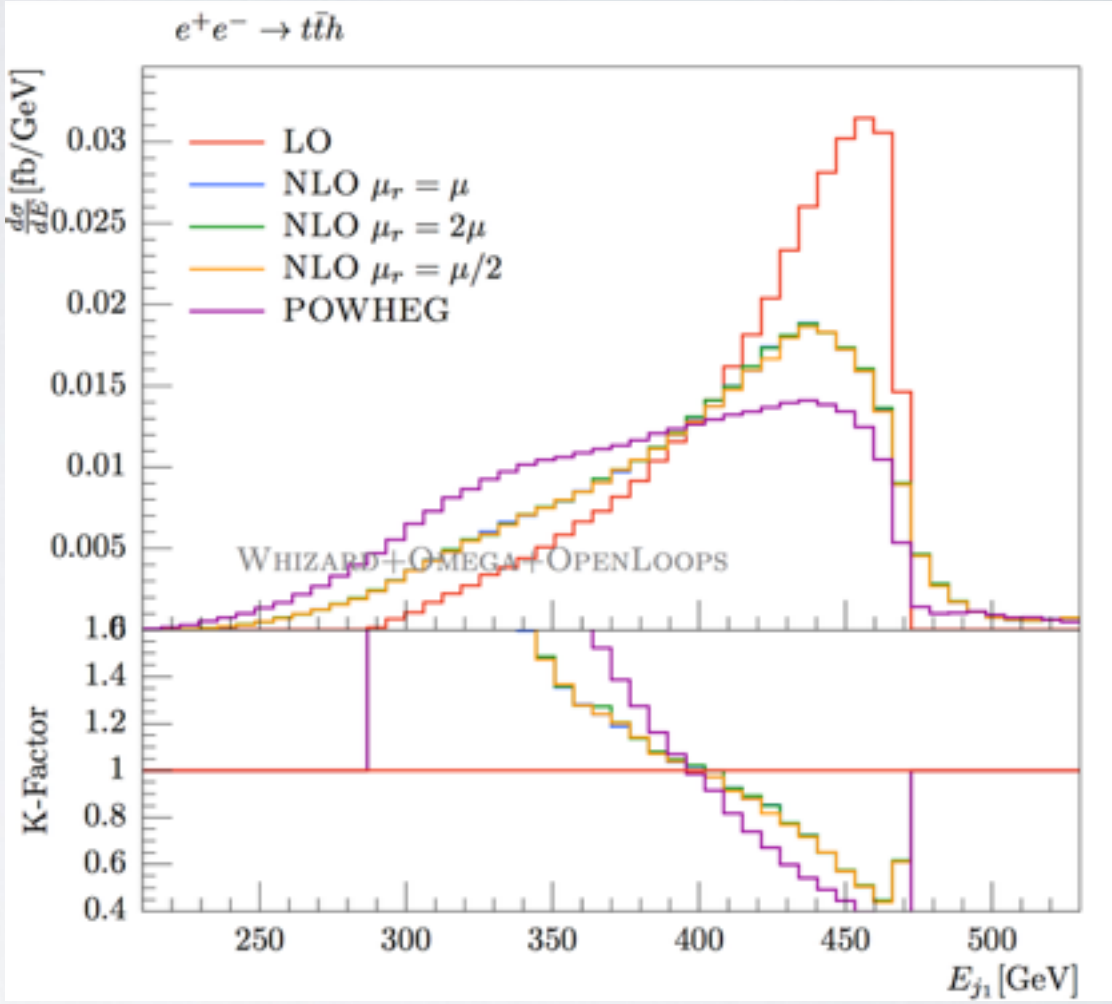
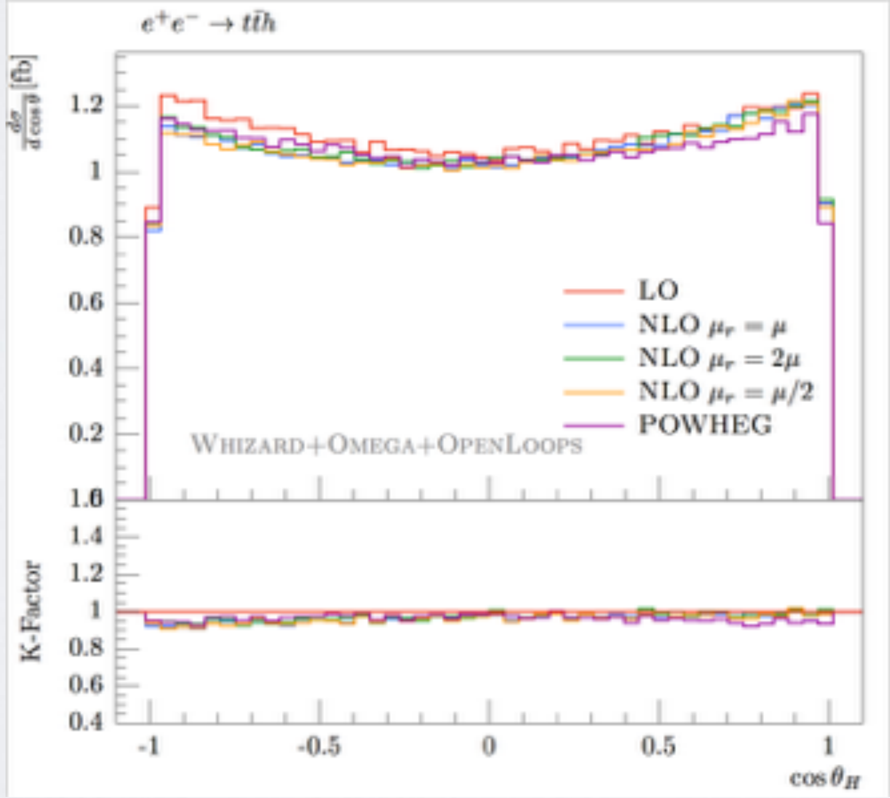
2	11962	2.8591952E+00	5.20E-02	1.82	1.99*	10.91		
3	11936	2.9277880E+00	4.09E-02	1.40	1.52*	14.48		
4	11902	2.8512337E+00	3.98E-02	1.40	1.52*	13.70		
5	11874	2.8855399E+00	3.87E-02	1.34	1.46*	17.15		
5	59662	2.8842006E+00	2.04E-02	0.71	1.72	17.15	0.53	5

FKS with resonance mappings

Examples: Top pairs and *tth* production



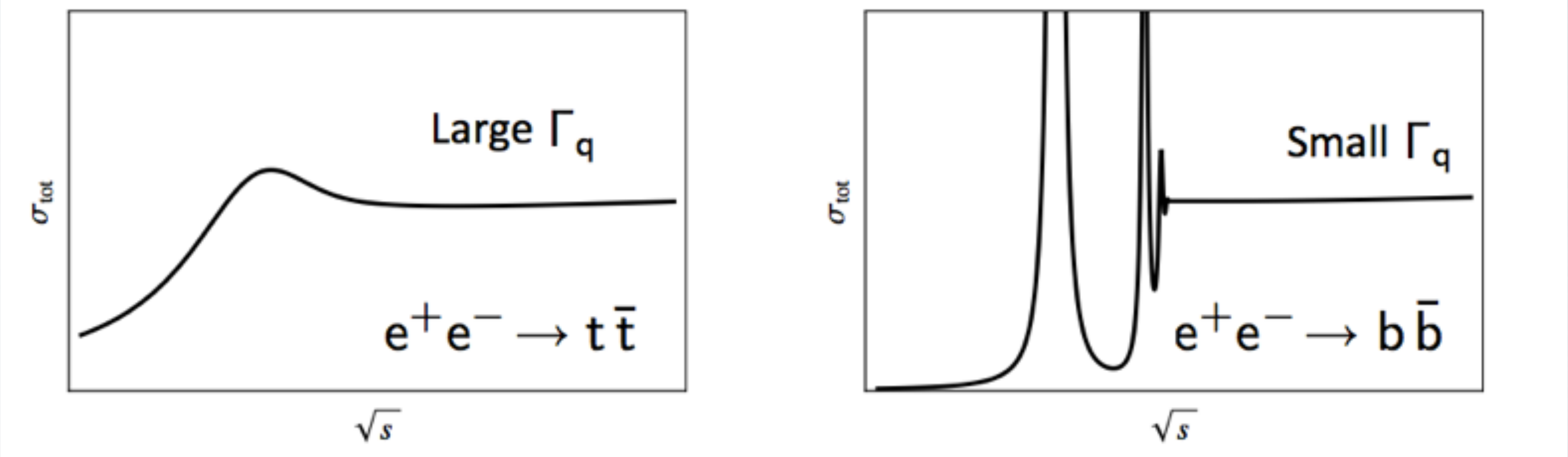




Top Threshold at lepton colliders

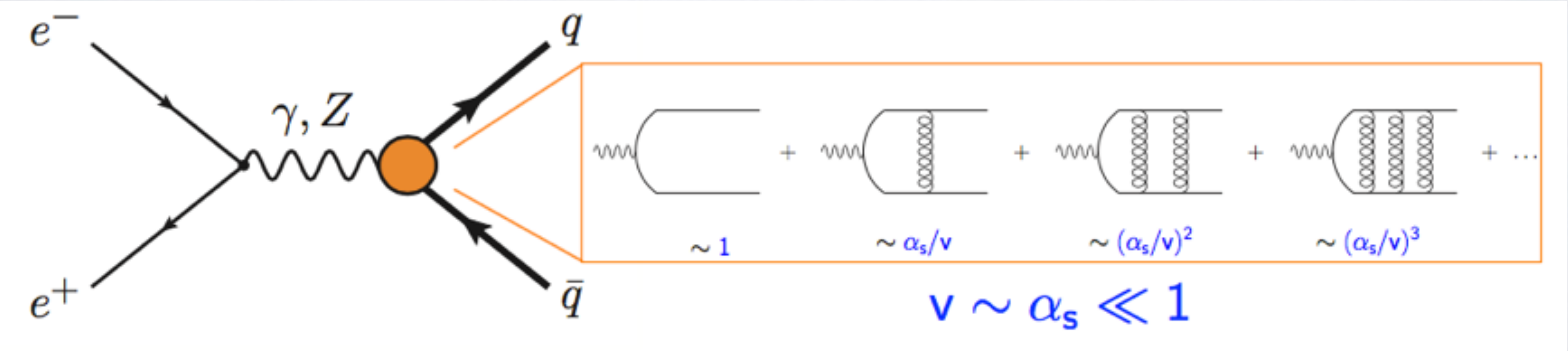
ILC top threshold scan best-known method to measure top quark mass, ΔM ~ 30-50 MeV

Heavy quark production at lepton colliders, qualitatively:



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

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



Top Threshold Resummation in (v)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.: vNRQCD
- Resummation of singular terms close to threshold ($v = 0$) Hoang et al. '99-'01; Beneke et al., '13-'14

Phase space of two massive particles

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

(p/v)NRQCD EFT w/ RG improvement

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

but contributes
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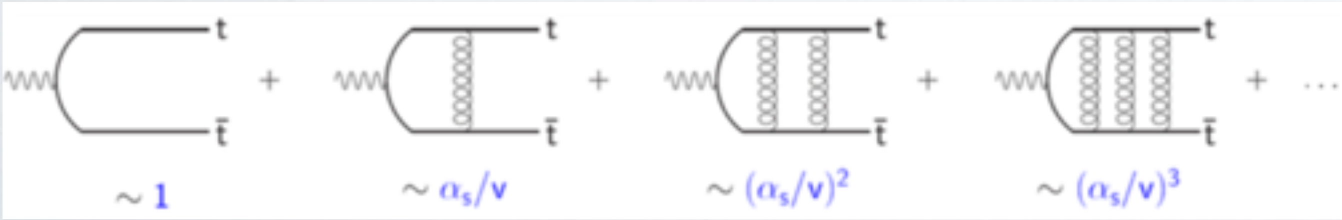
Coulomb potential gluon ladder resummation



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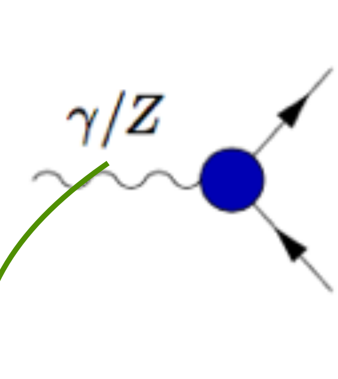
can be mapped onto effective *ttV* vertex



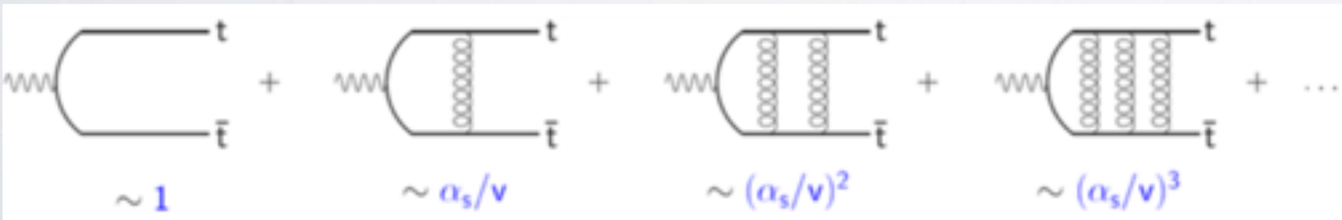
$$\sim \sqrt{R^{v/a}_{\mathrm{(N)LL}}} \sim \frac{\mathcal{G}^{v/a}_{\mathrm{(N)LL}}}{\mathcal{G}^{v/a}\big|_{\alpha_s=0}} \longrightarrow 1$$

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

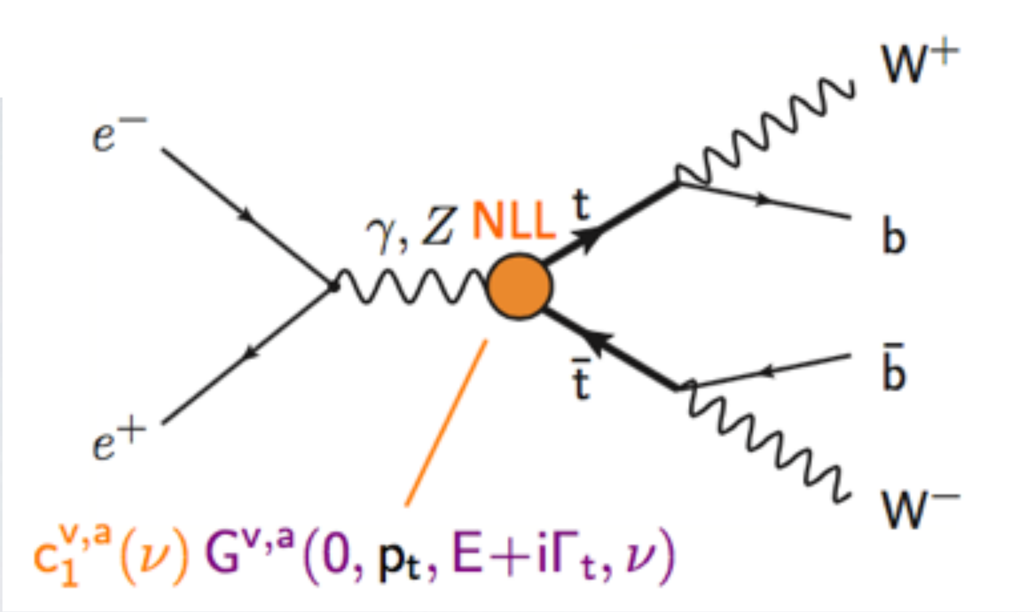
Coulomb potential gluon ladder resummation



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`
- $G^{v,a}(0, p_t, E + i\Gamma_t, \nu)$ from TOPPIK code [Jezabek/Teubner], included in `WHIZARD`



- Default parameters:

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

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

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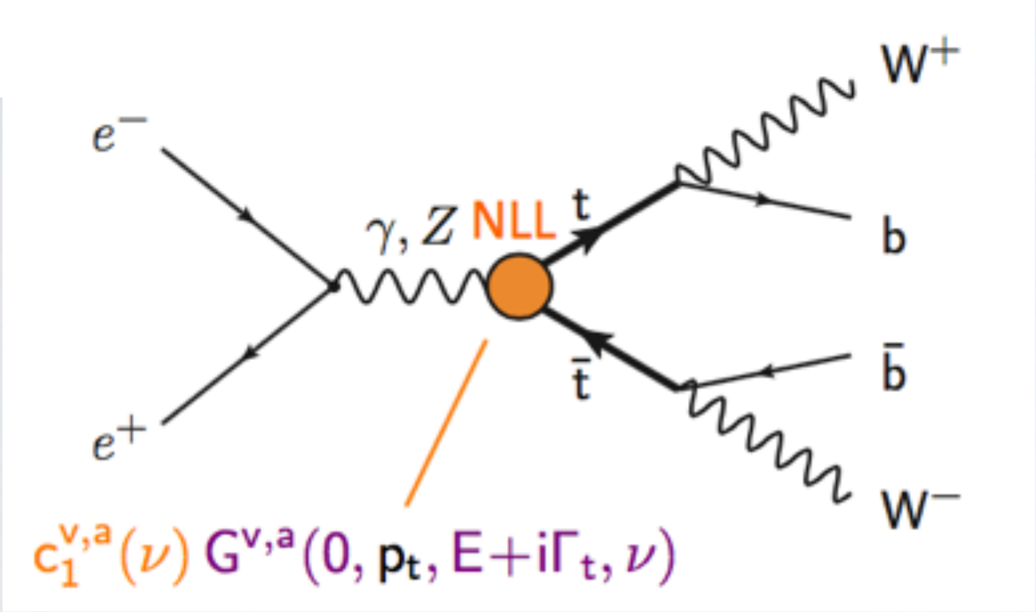

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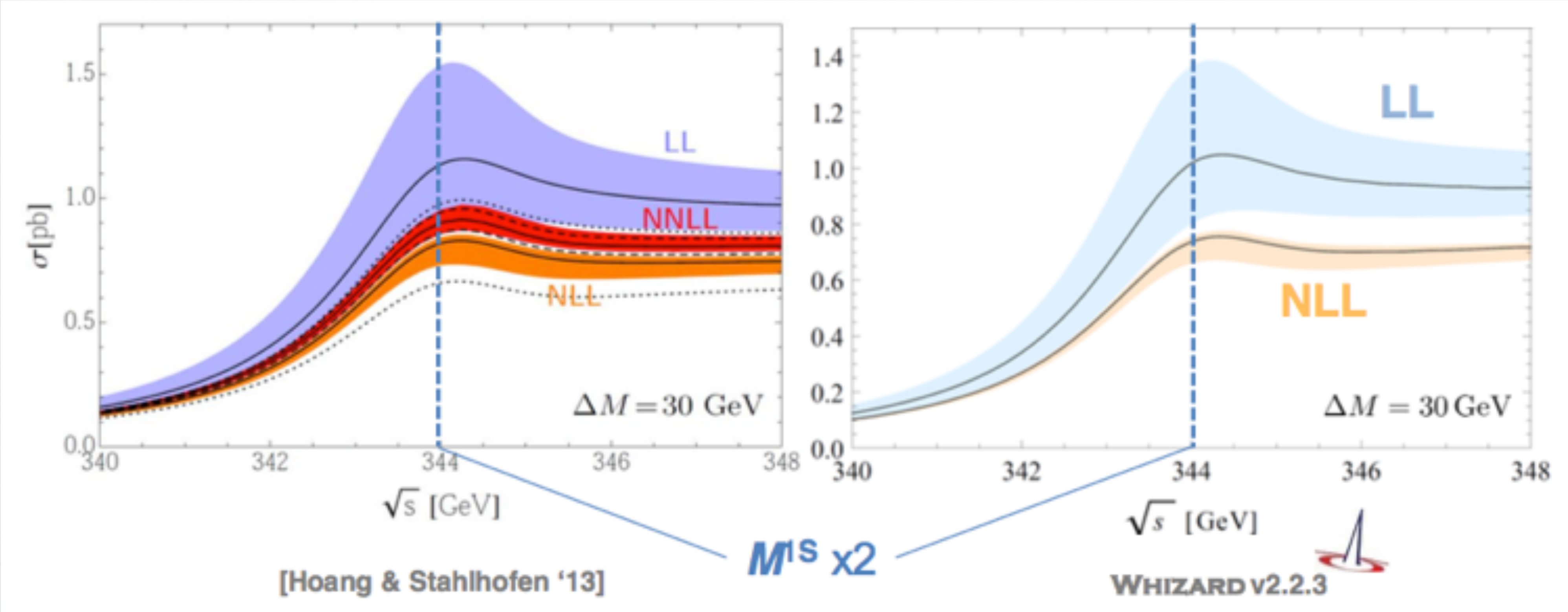

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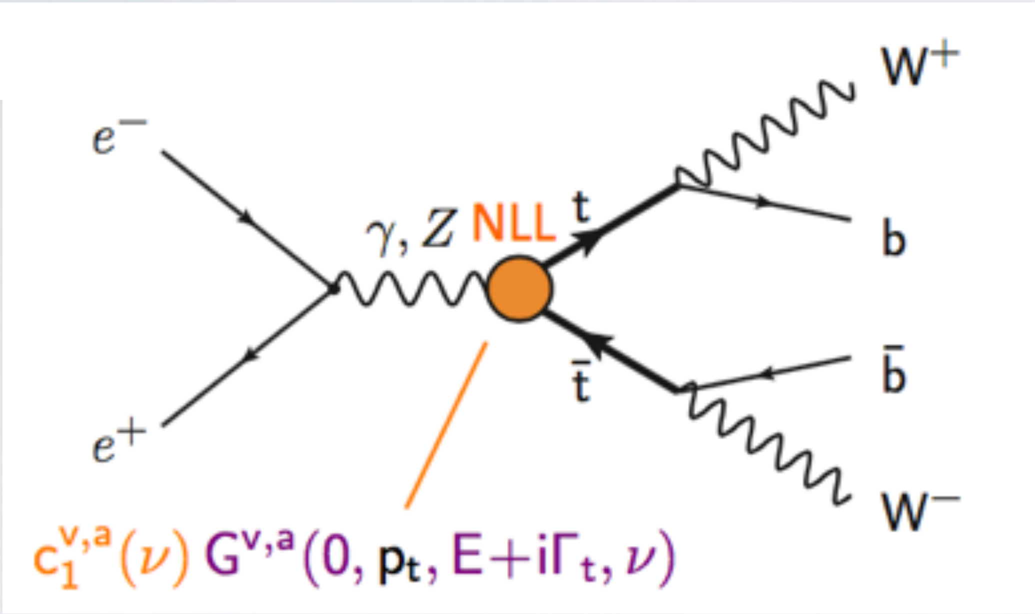

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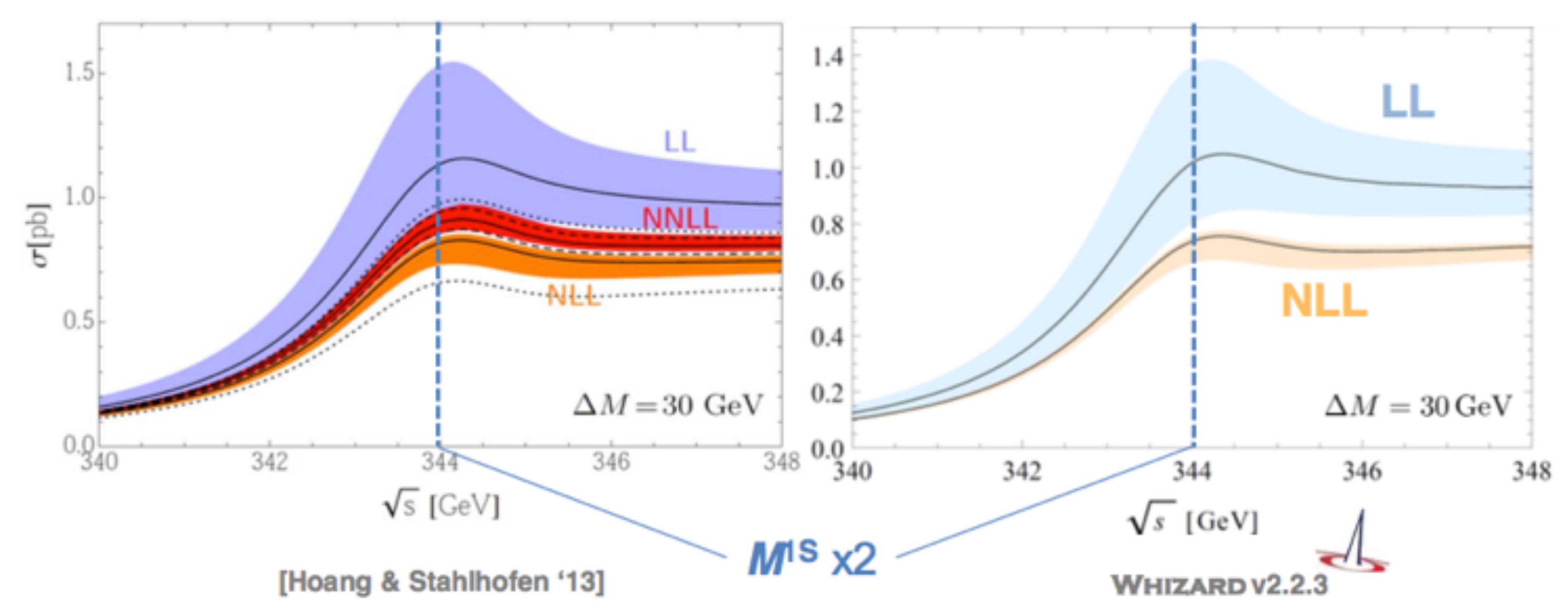
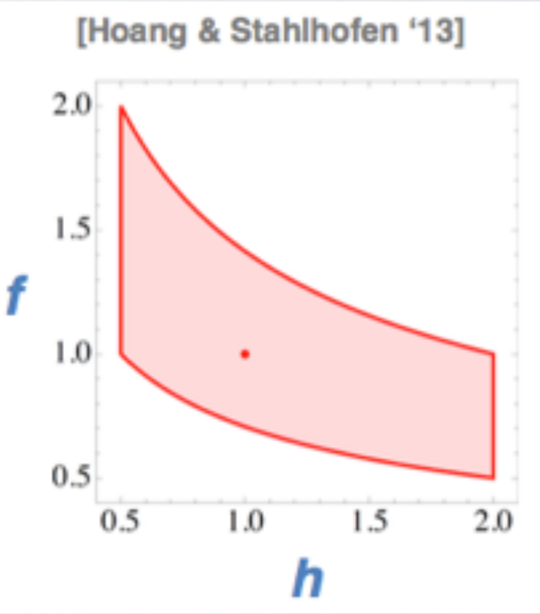
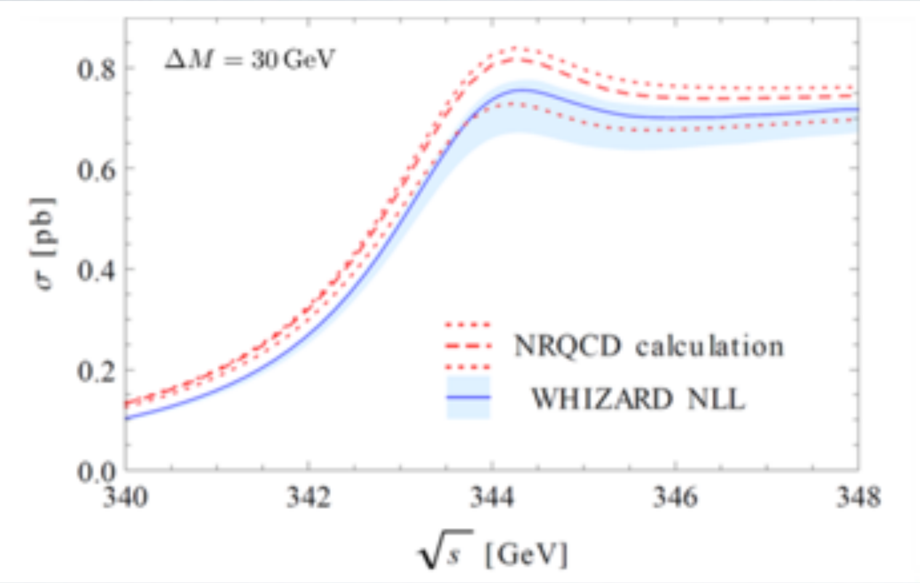
Theory uncertainties from scale variations: hard and soft scale

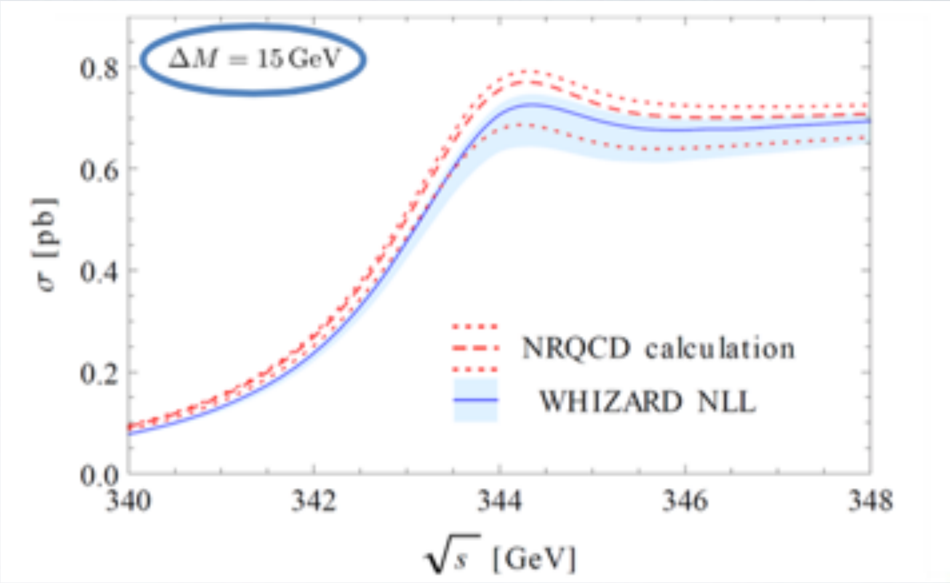
$$\mu_h = h \cdot m_t \qquad \mu_s = f \cdot m_t v$$





▹ 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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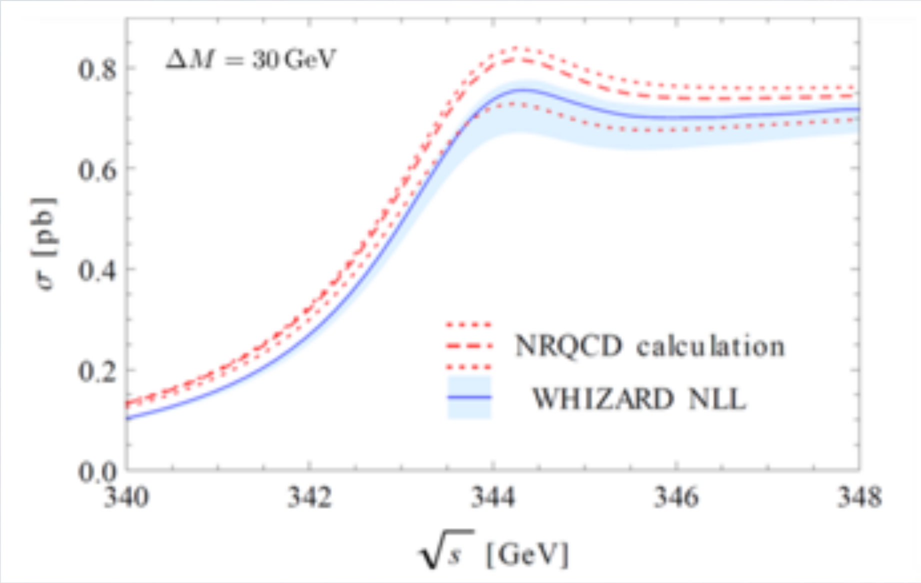

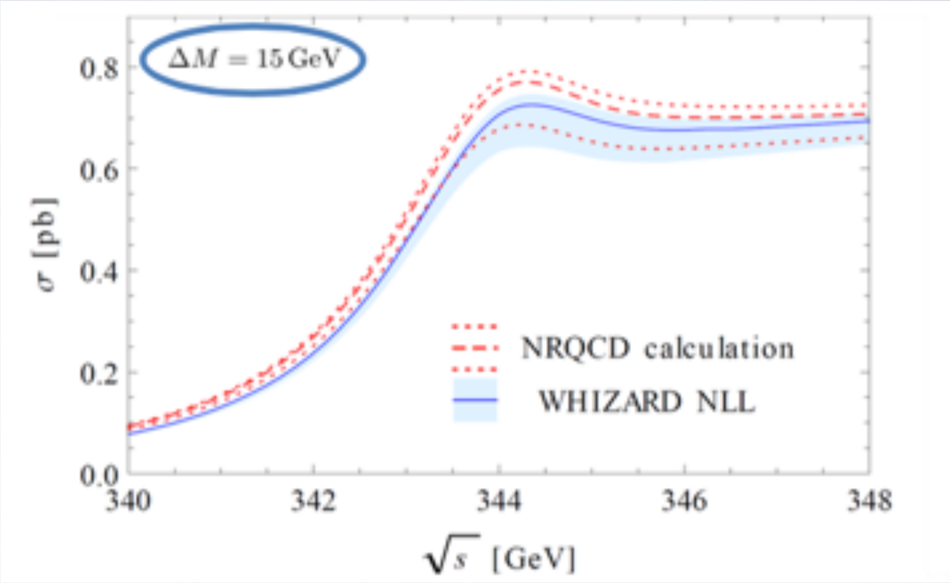

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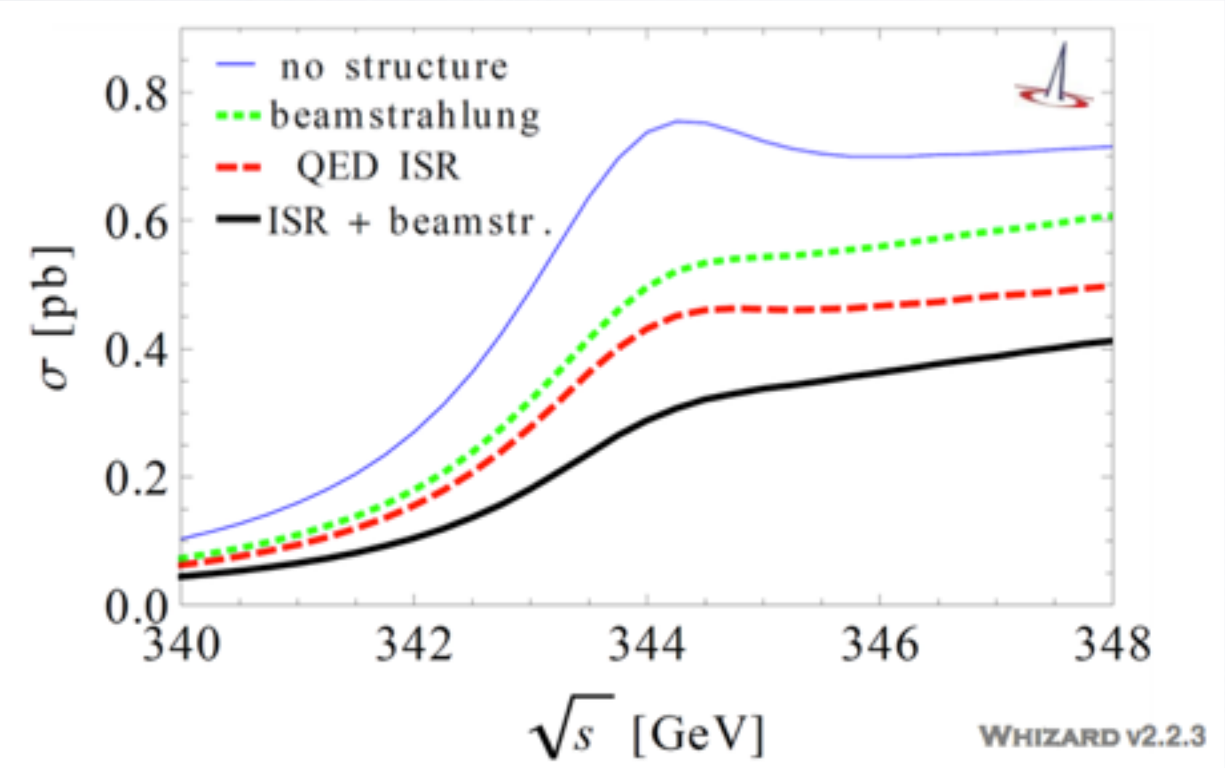

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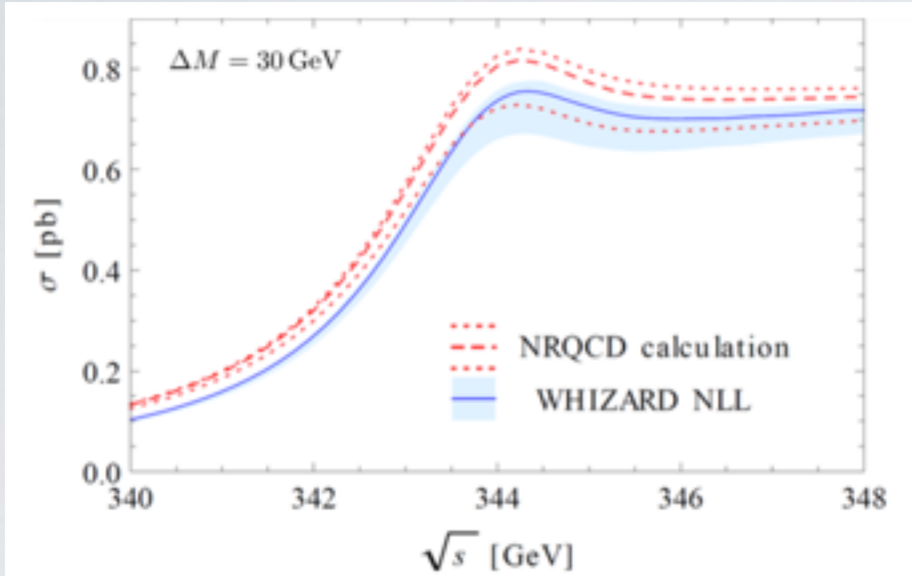

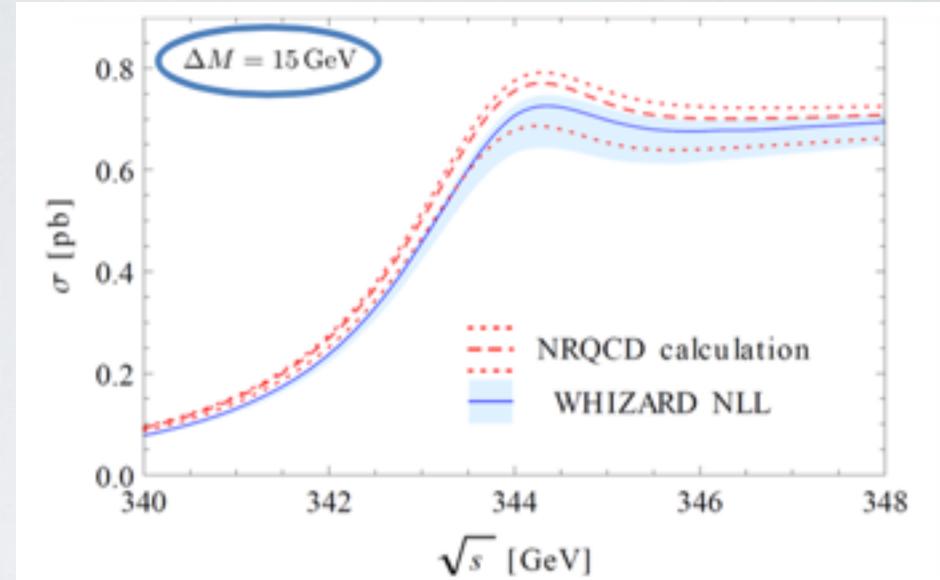

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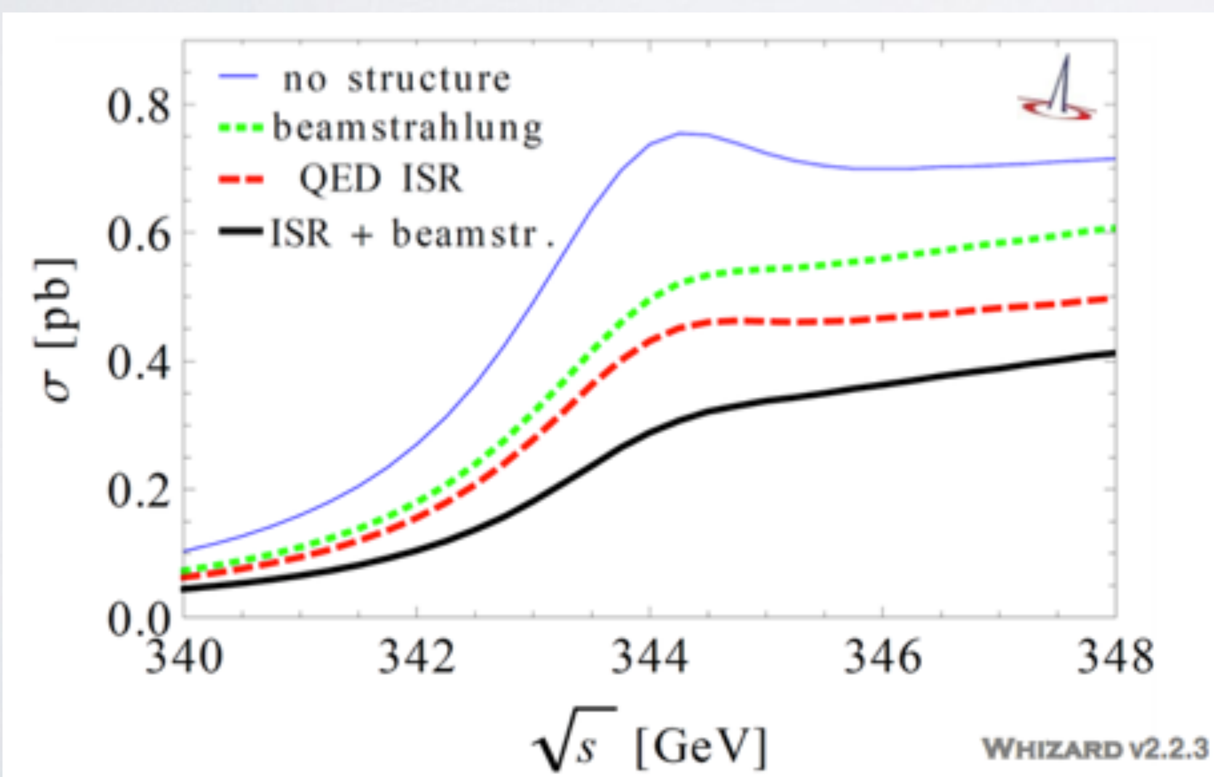
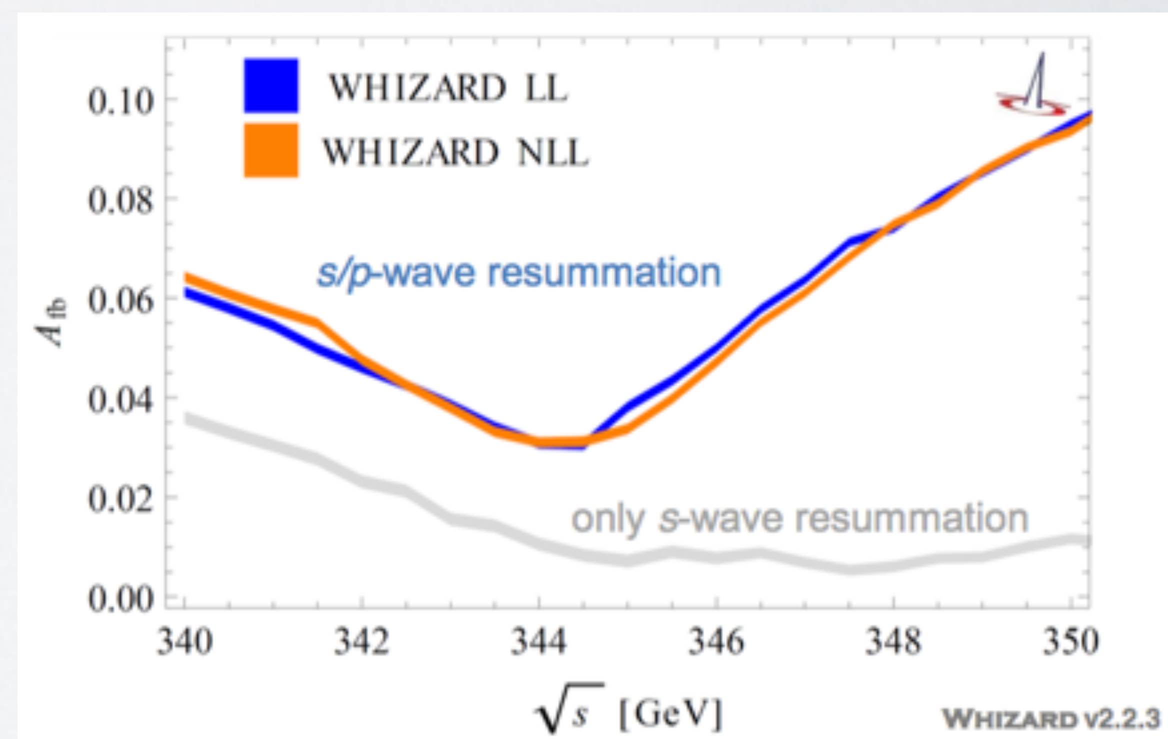
Forward-backward asymmetry (norm. ⇒ good shape stability)

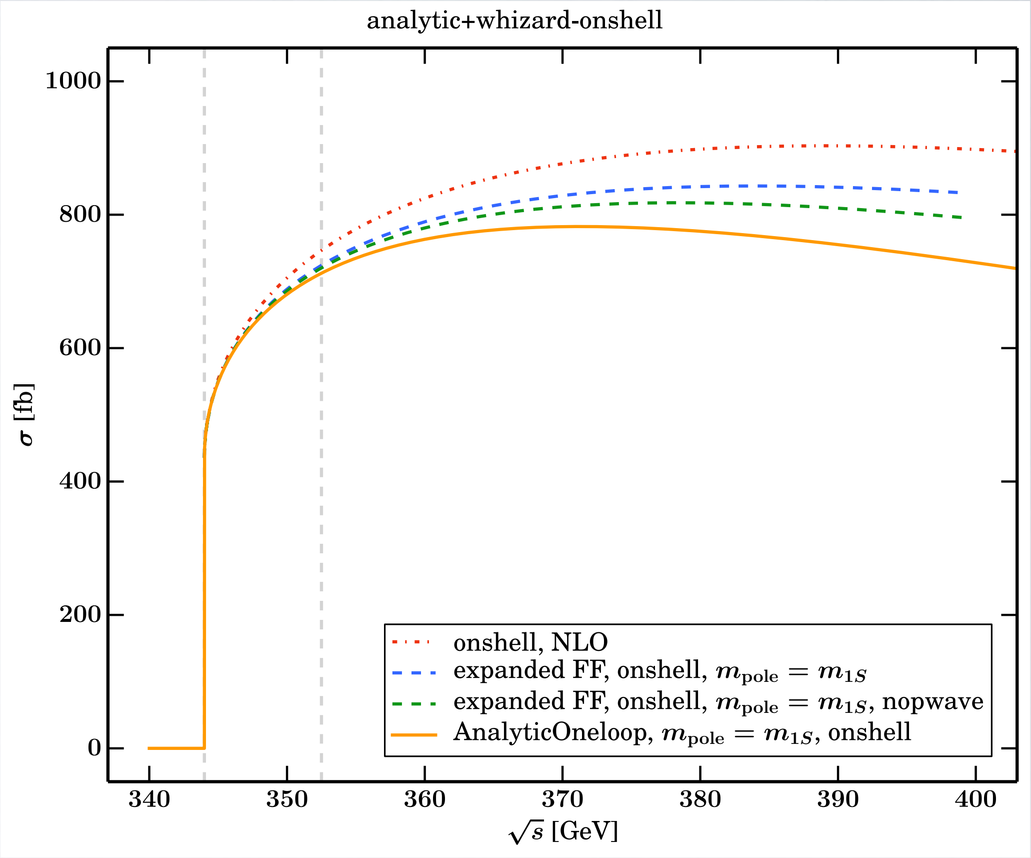
$$A_{fb} := \frac{\sigma(p_z^t > 0) - \sigma(p_z^t) < 0)}{\sigma(p_z^t > 0) + \sigma(p_z^t < 0)}$$





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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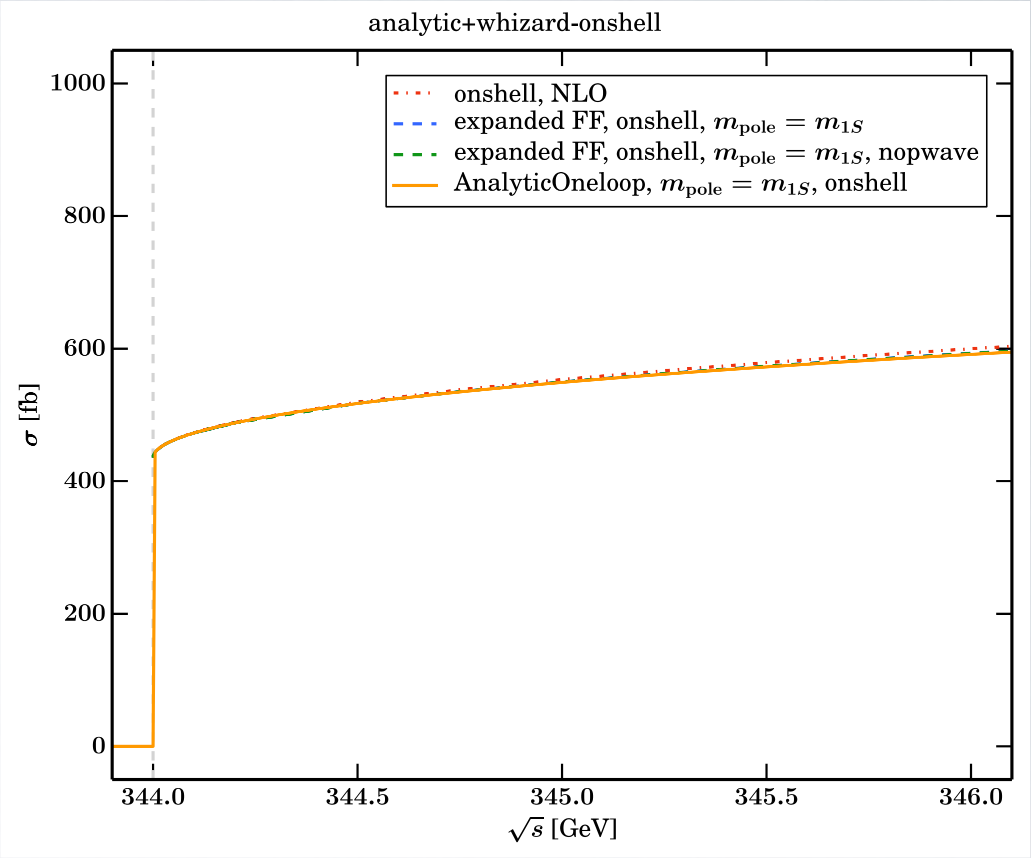

Resummed formfactor, expanded to $\mathcal{O}(\alpha_s)$

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

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

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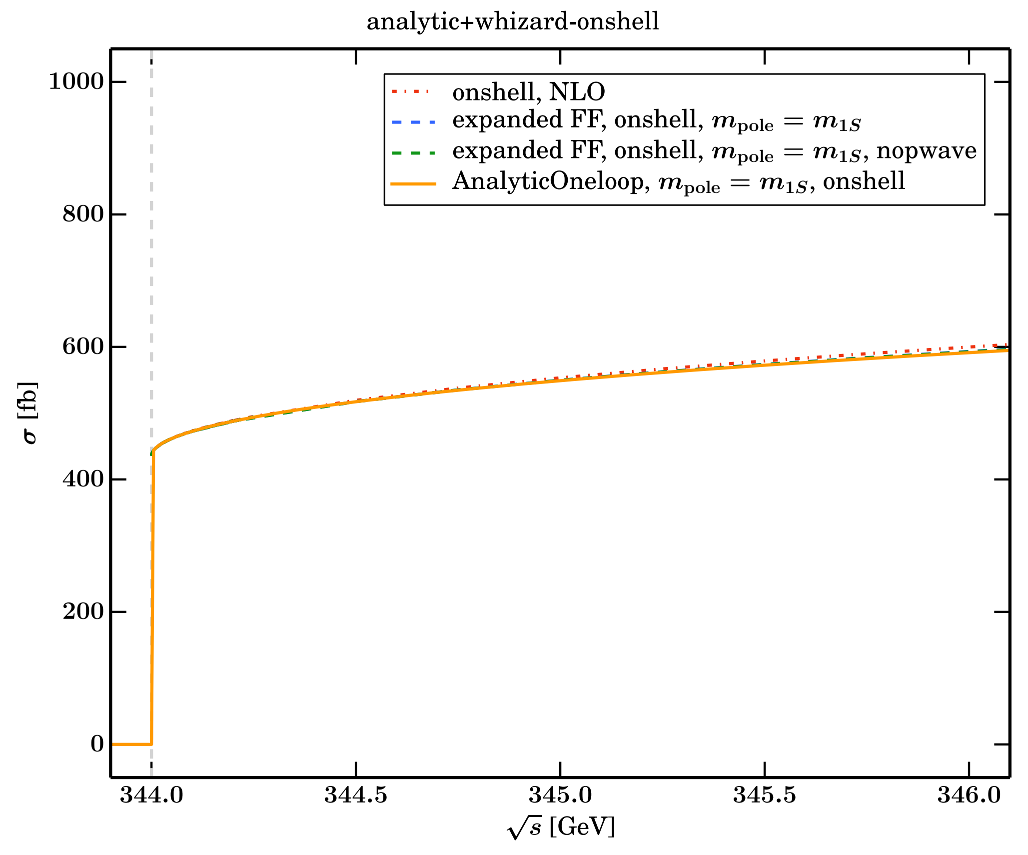

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Matching formula

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

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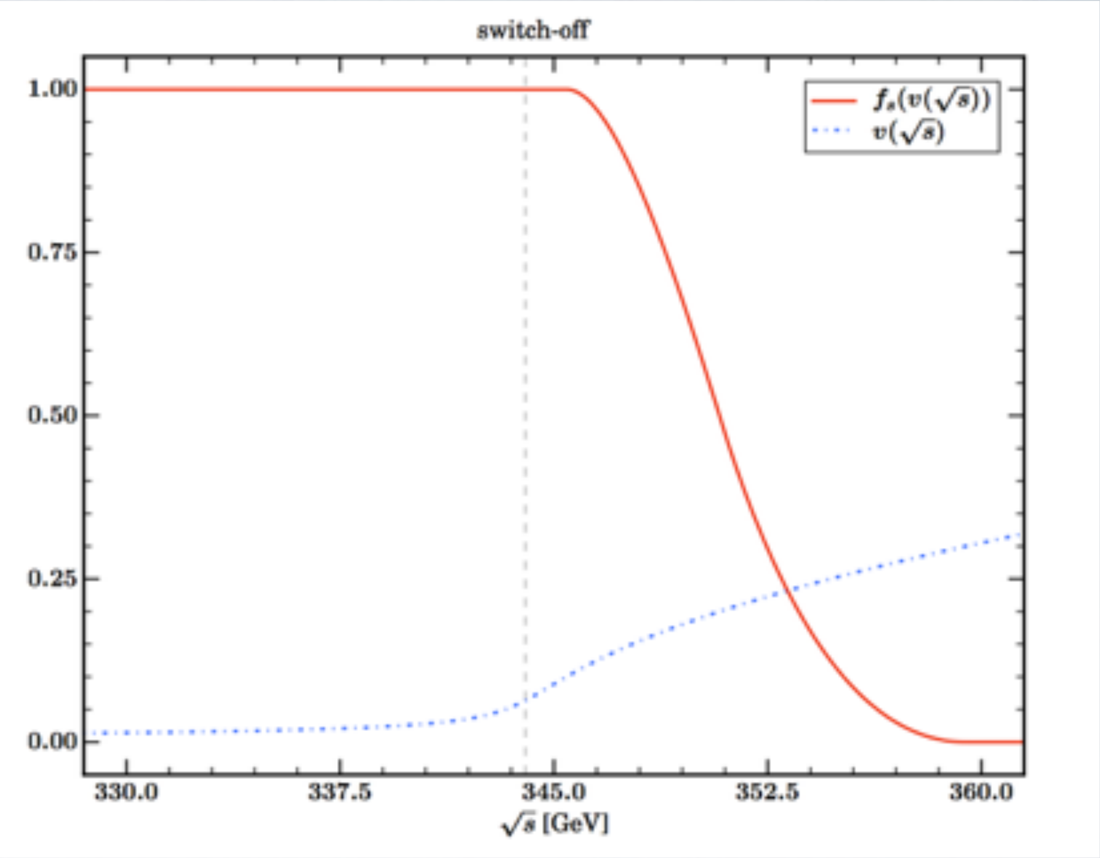

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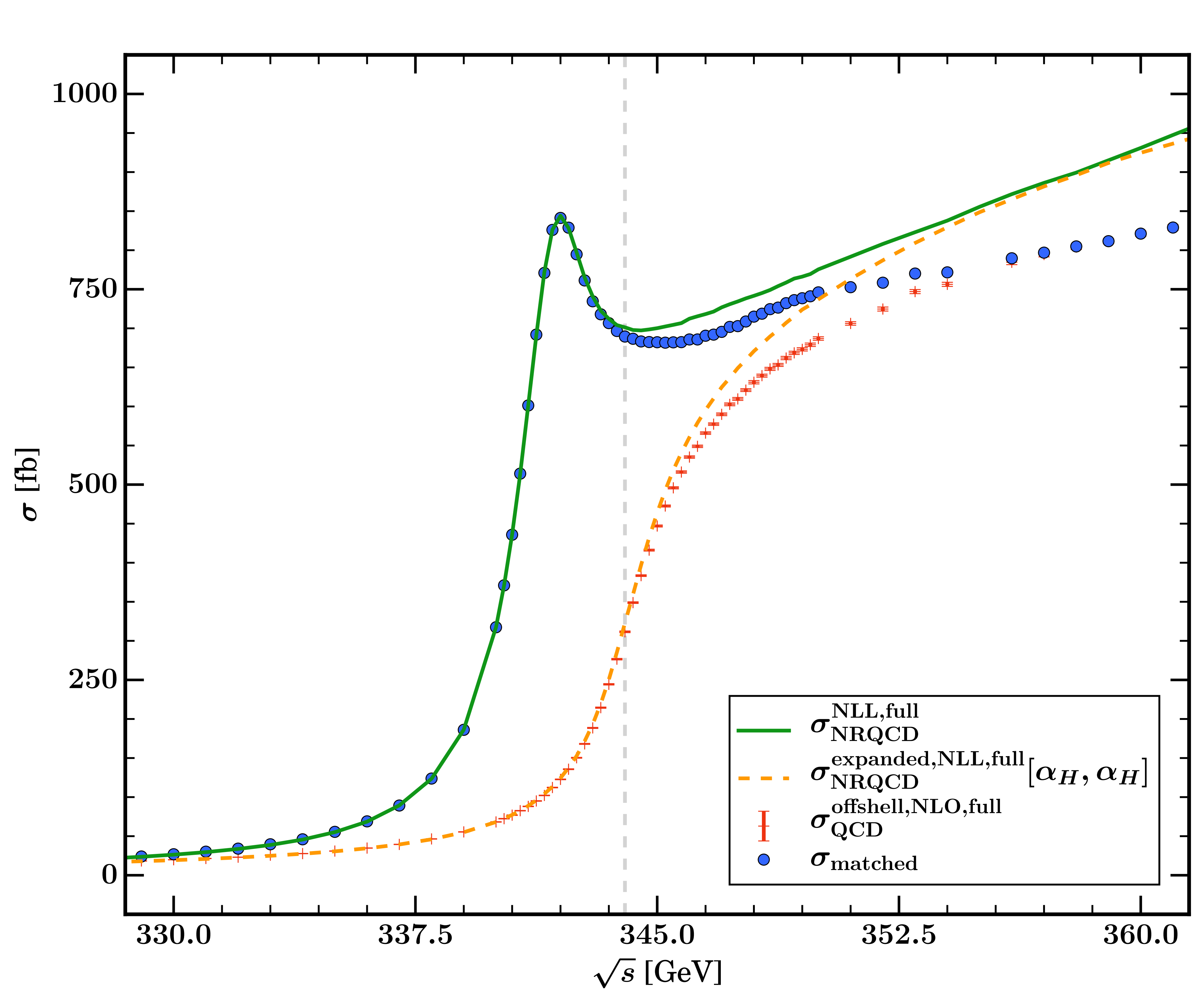
Switch-off function

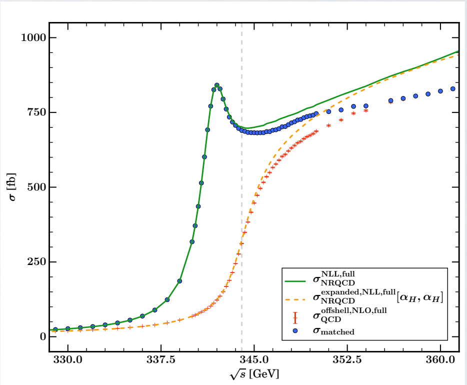
$$f_s(v) = \begin{cases} 1 & v < v_1 \\ 1 - 2\frac{(v-v_1)^2}{(v_2-v_1)^2} & v_1 < v < \frac{v_1+v_2}{2} \\ 2\frac{(v-v_2)^2}{(v_2-v_1)^2} & \frac{v_1+v_2}{2} < v < v_2 \\ 0 & v > v_2 \end{cases}$$

Threshold-continuum matching



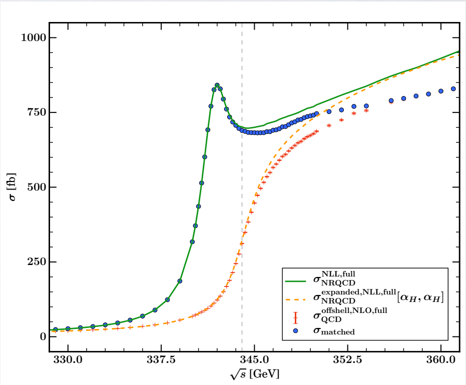
Conclusions & Outlook

- `WHIZARD 2.2` event generator for collider physics (ee, pp, ep)
- (QCD) NLO automation: reals and subtraction terms (FKS) [+ virtuals externally] → `WHIZARD 3.0`
- Automated POWHEG matching (other schemes in progress)
- Automated Resonance Mapping in Subtractions / Resonance History
- Polarized results and decays available at NLO (QCD)
- allows to produce NLO fixed-order histograms
- Top threshold in e+e-: NLL NRQCD threshold / NLO continuum matching



Conclusions & Outlook

- `WHIZARD 2.2` event generator for collider physics (ee, pp, ep)
- (QCD) NLO automation: reals and subtraction terms (FKS) [+ virtuals externally] → `WHIZARD 3.0`
- Automated POWHEG matching (other schemes in progress)
- Automated Resonance Mapping in Subtractions / Resonance History
- Polarized results and decays available at NLO (QCD)
- allows to produce NLO fixed-order histograms
- Top threshold in e+e-: NLL NRQCD threshold / NLO continuum matching



- Near Future projects: QCD in hadron collisions (fixed-order)
- Mid-term project: inclusion of *tth* threshold (resummation/threshold)
- Long term: QED/EW NLO, QED Shower, NNLO QCD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  - Contact us
- **INTERNAL WHIZARD PAGE**
  - You Shall Not Pass!

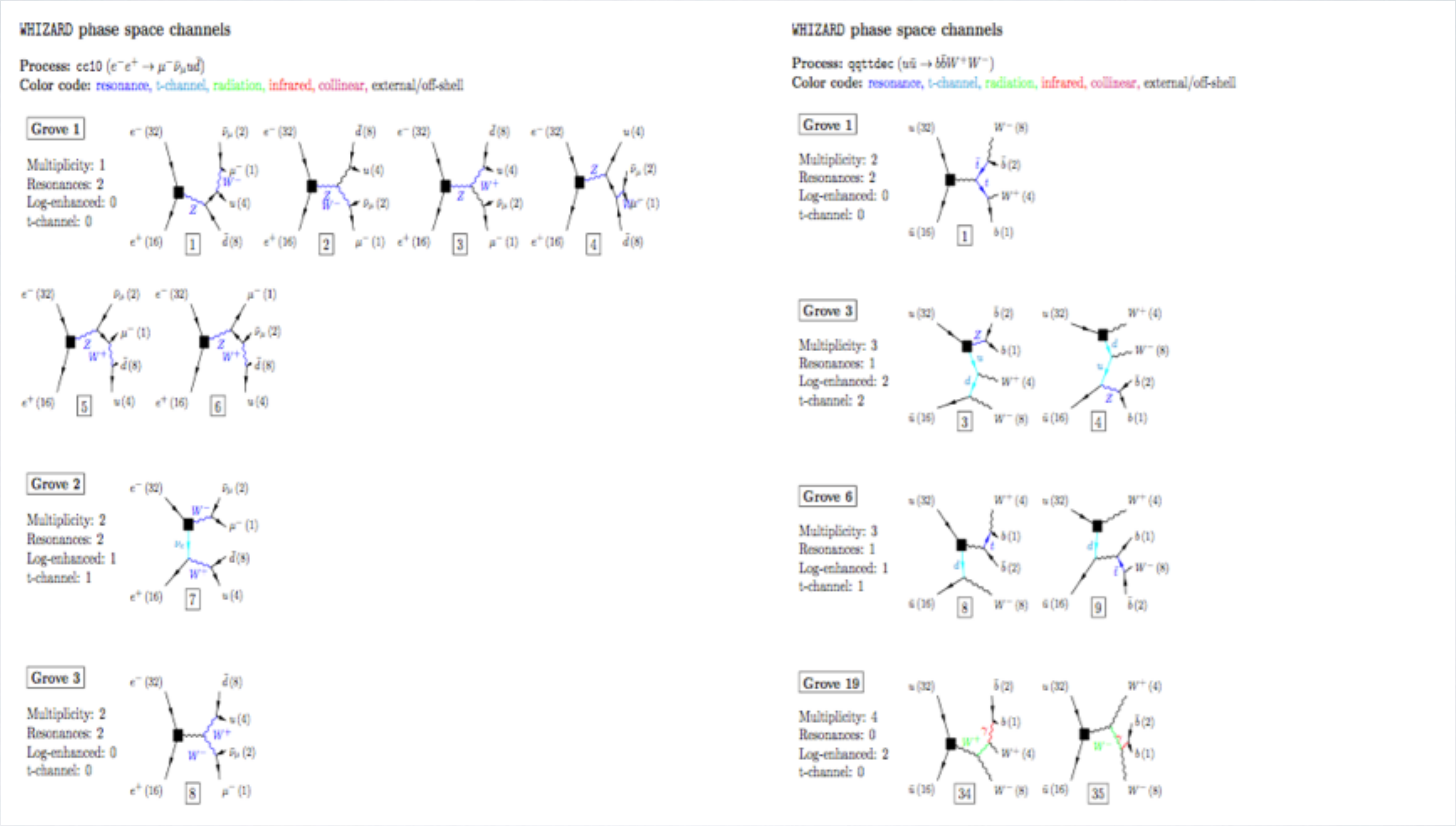
WHIZARD 2.2
A generic Monte-Carlo integration and event generation package for multi-particle processes
MANUAL [1]

Wolfgang Kilian,[2] Thorsten Ohl,[3] Jürgen Reuter,[4] with contributions from Fabian Bach, [5] Bijan Chokoufé Nejad, [6] Sebastian Schmidt, Christian Speckner [7], Florian Staub [8]

WHIZARD Manual @ HepForge

Phase Space Setup

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



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

Decay processes / auto_decays

WHIZARD cannot only do scattering processes, but also decays

Example Energy distribution electron in muon decay:

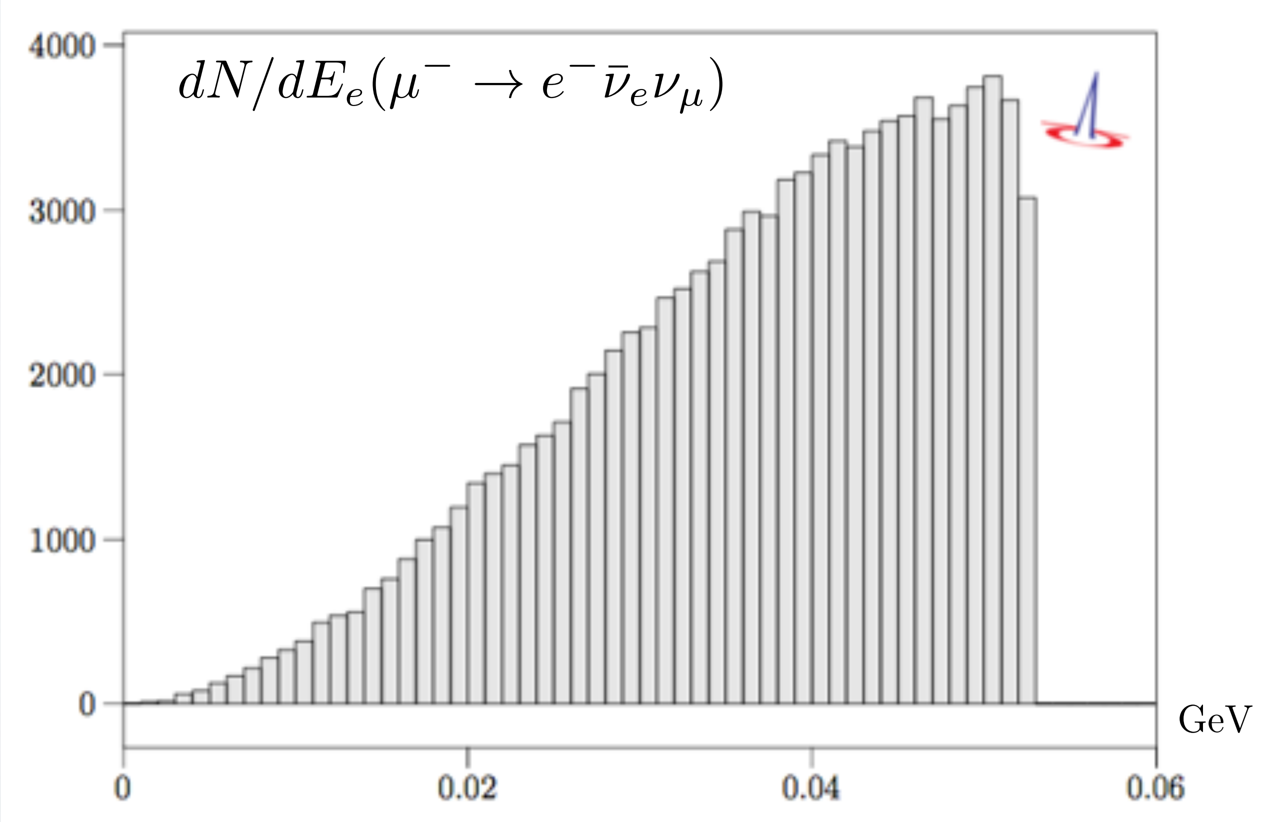
```
model = SM
process mudec = e2 => e1, N1, n2
integrate (mudec)

histogram e_e1 (0, 60 MeV, 1 MeV)
analysis = record e_e1 (eval E [e1])

n_events = 100000

simulate (mudec)

compile_analysis { $out_file = "test.dat" }
```



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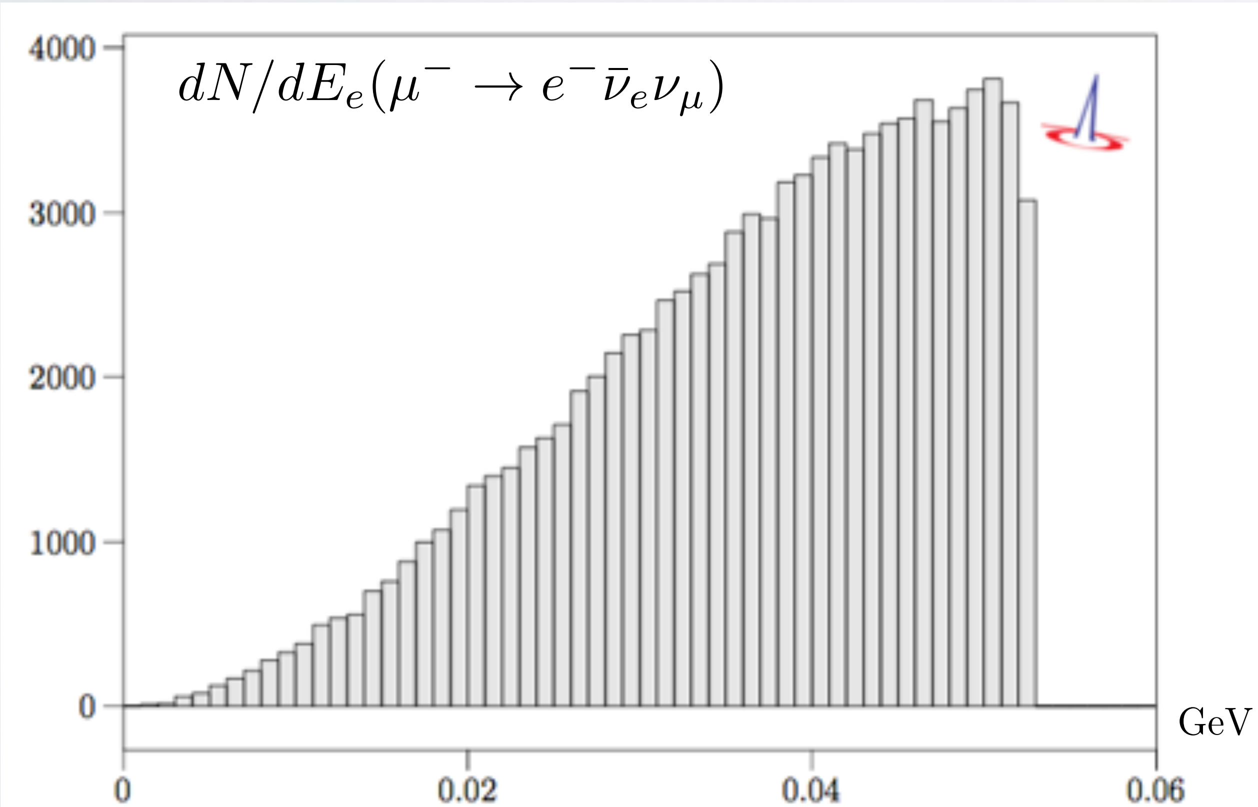

Automatic integration of particle decays

```
auto_decays_multiplicity = 2
?auto_decays_radiative = false

unstable Wp () { ?auto_decays = true }
```

```
|=============================================================
| It      Calls  Integral[GeV] Error[GeV]  Err[%]    Acc
|=============================================================
   1        100  2.2756406E-01  0.00E+00    0.00    0.00*
|-------------------------------------------------------------
   1        100  2.2756406E-01  0.00E+00    0.00    0.00
|=============================================================
| Unstable particle W+: computed branching ratios:
|   decay_p24_1: 3.3337068E-01   dbar, u
|   decay_p24_2: 3.3325864E-01   sbar, c
|   decay_p24_3: 1.1112356E-01   e+, nue
|   decay_p24_4: 1.1112356E-01   mu+, numu
|   decay_p24_5: 1.1112356E-01   tau+, nutau
|   Total width = 2.0478471E+00 GeV (computed)
|               = 2.0490000E+00 GeV (preset)
|   Decay options: helicity treated exactly
```