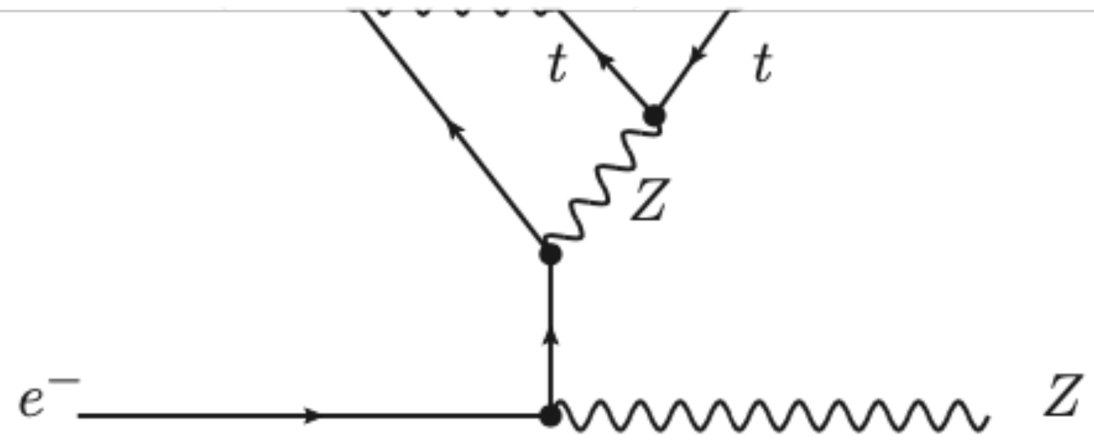
The WHIZARD generator: Status report, News and Plans

LCWS2023
INTERNATIONAL WORKSHOP ON LINEAR COLLIDERS



HELMHOLTZ

Universität Hamburg
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CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

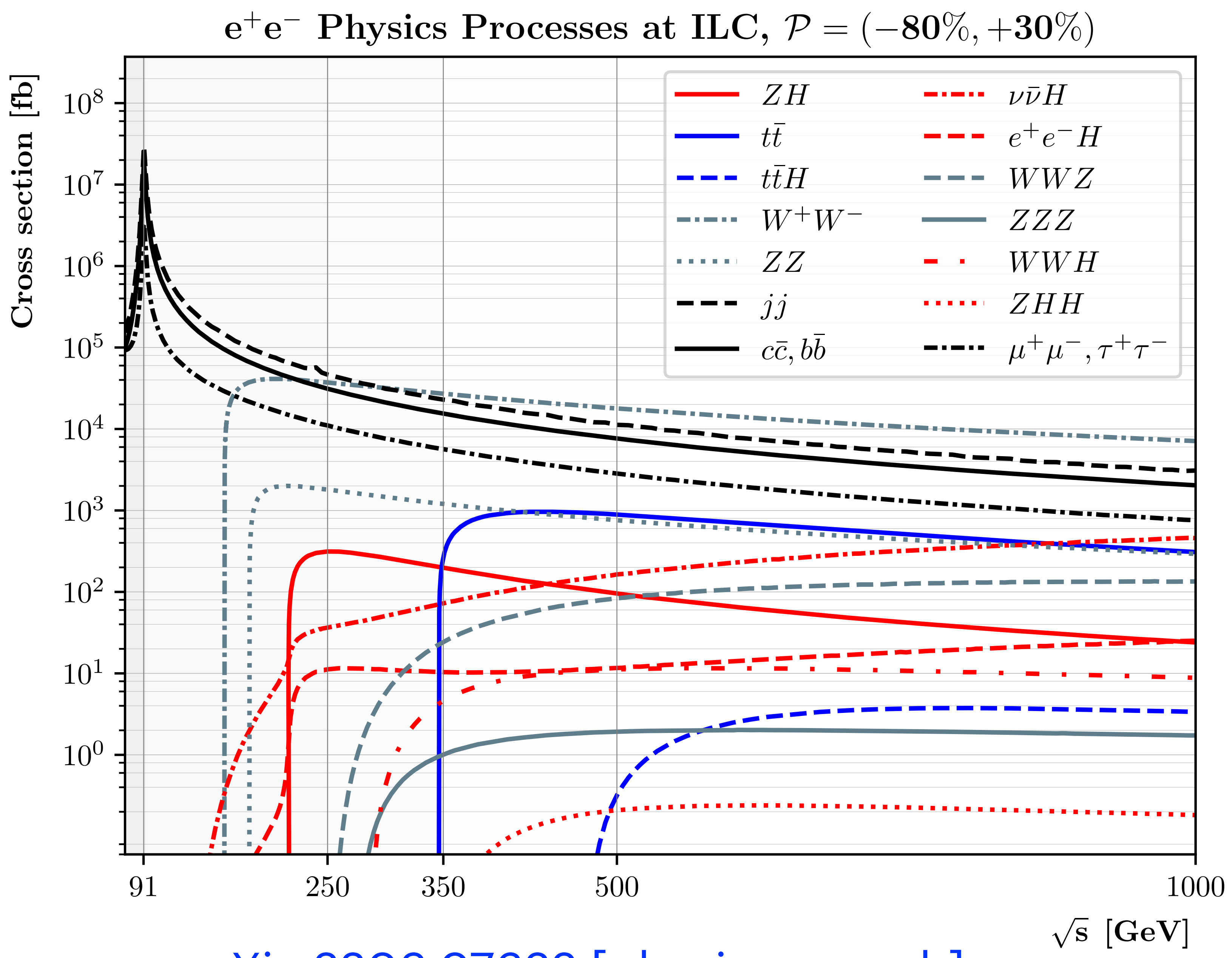
BASED UPON: hep-ph/9607454 ; hep-ph/9806432 ; hep-ph/0102195 ; 0708.4241 ; 1112.1039 ; 1206.3700 ; 1411.3834; 1510.02739 ; 1609.03390 ; 1811.09711; 2108.05362; 2208.09438; 2304.09883

IN COLLABORATION WITH: P. Bredt / W. Kilian / K. Mękała / T. Ohl / T. Striegl / A.F. Żarnecki

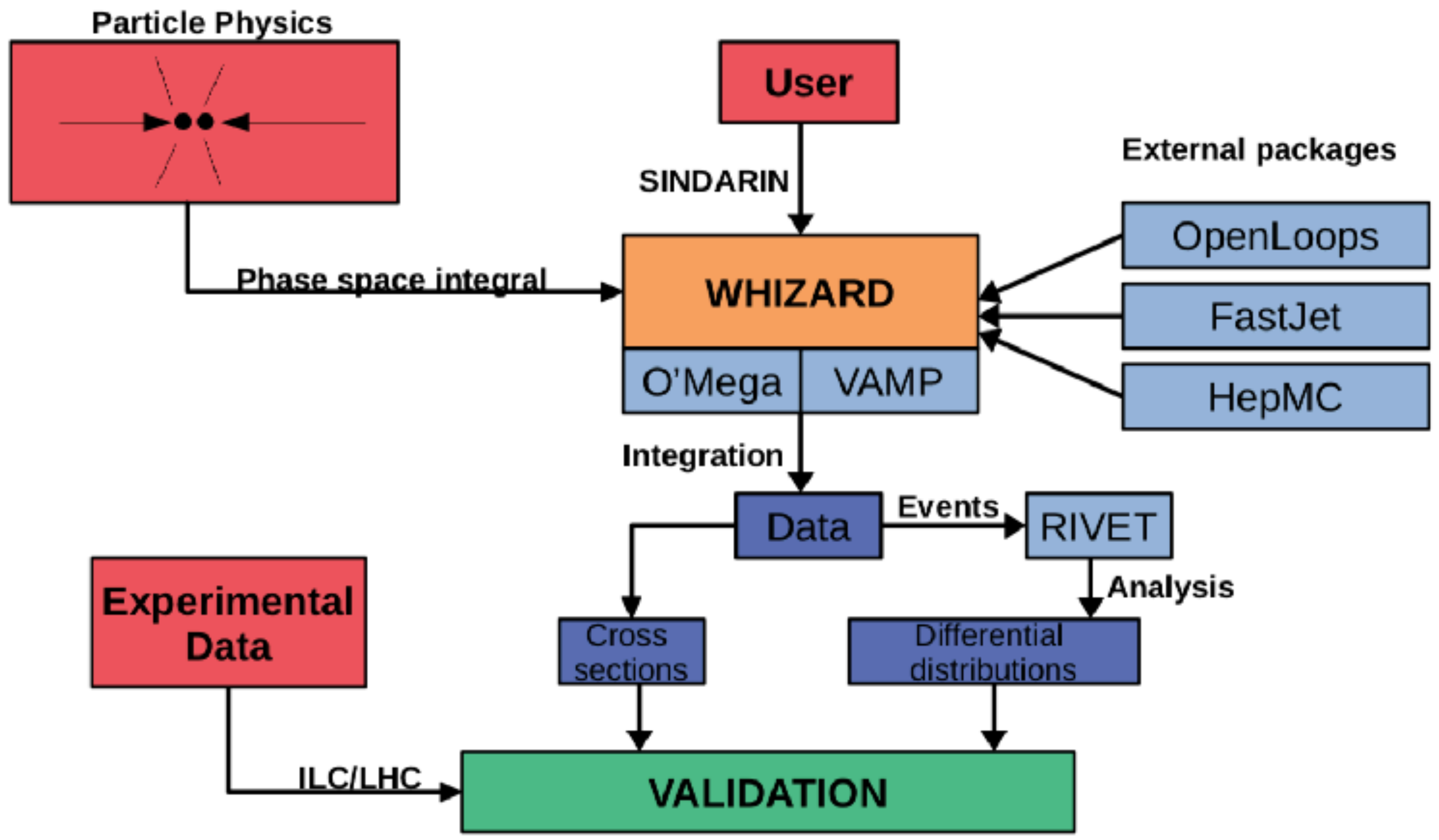
Jürgen R. Reuter

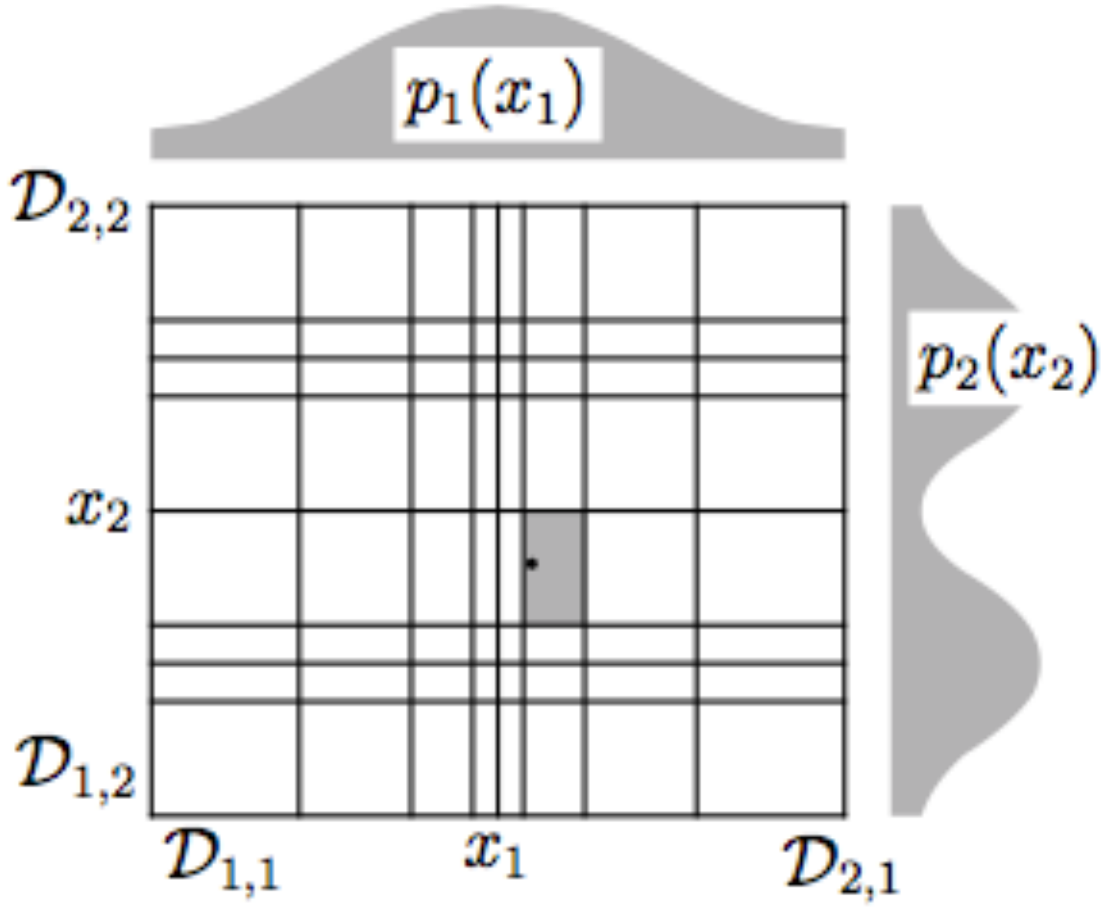
WHIZARD **Overview (I)**

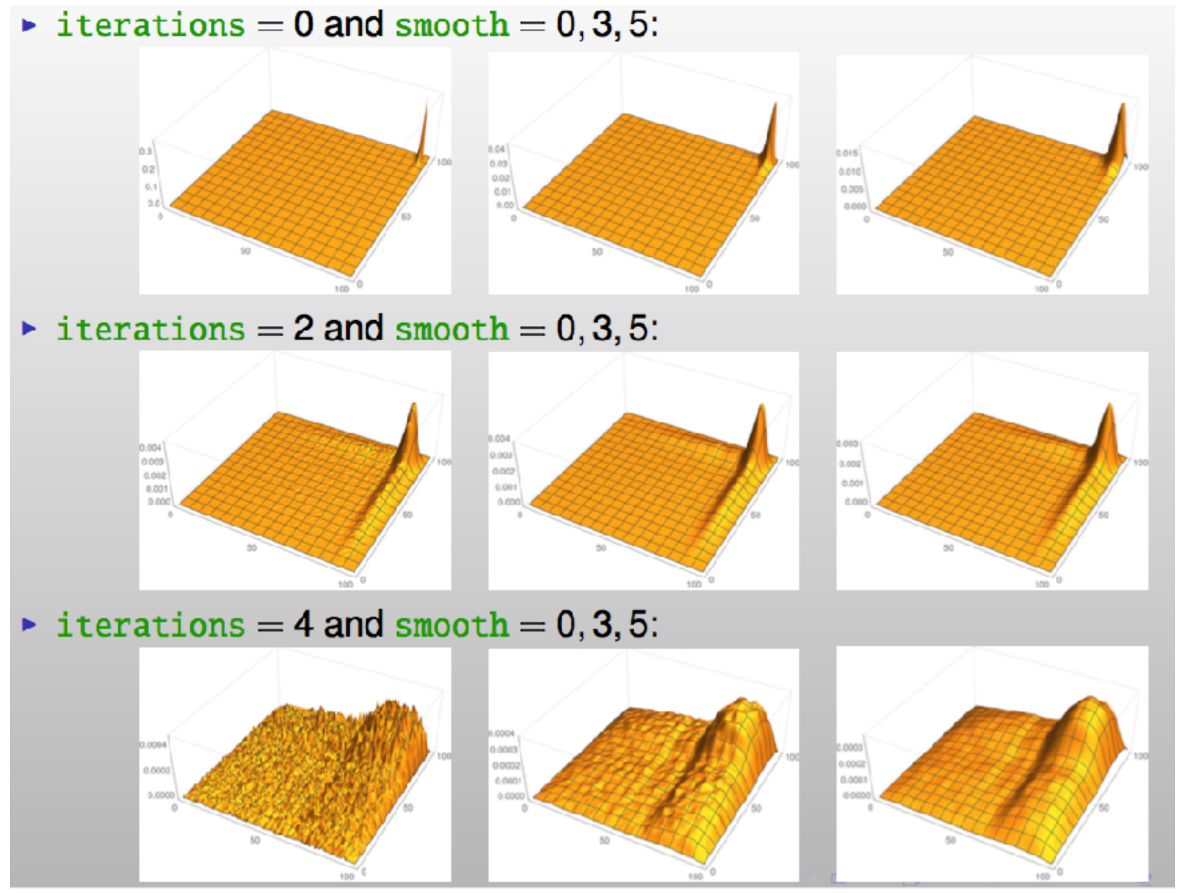
- Complete MC event generator for all colliders: `v3` released 27.4.2021
- Hard matrix elements @ LO internally (`O'Mega`),
- Hard matrix elements @ NLO externally (`OpenLoops`, `Recola`, `Gosam`, ...)
- Parton shower internal+external, hadronization external
- Dedicated interfaces to `Pythia6`, `Pythia8`, `Tauola`, ...
- Lepton collider beam simulations (Gaussian spread, parameterized fit, beam event files, 2d-histogram adapted, smoothened):



arXiv:2203.07622 [physics.acc-ph]







↪ Talk by Thorsten Ohl 06/2023: https://indico.cern.ch/event/1266492/

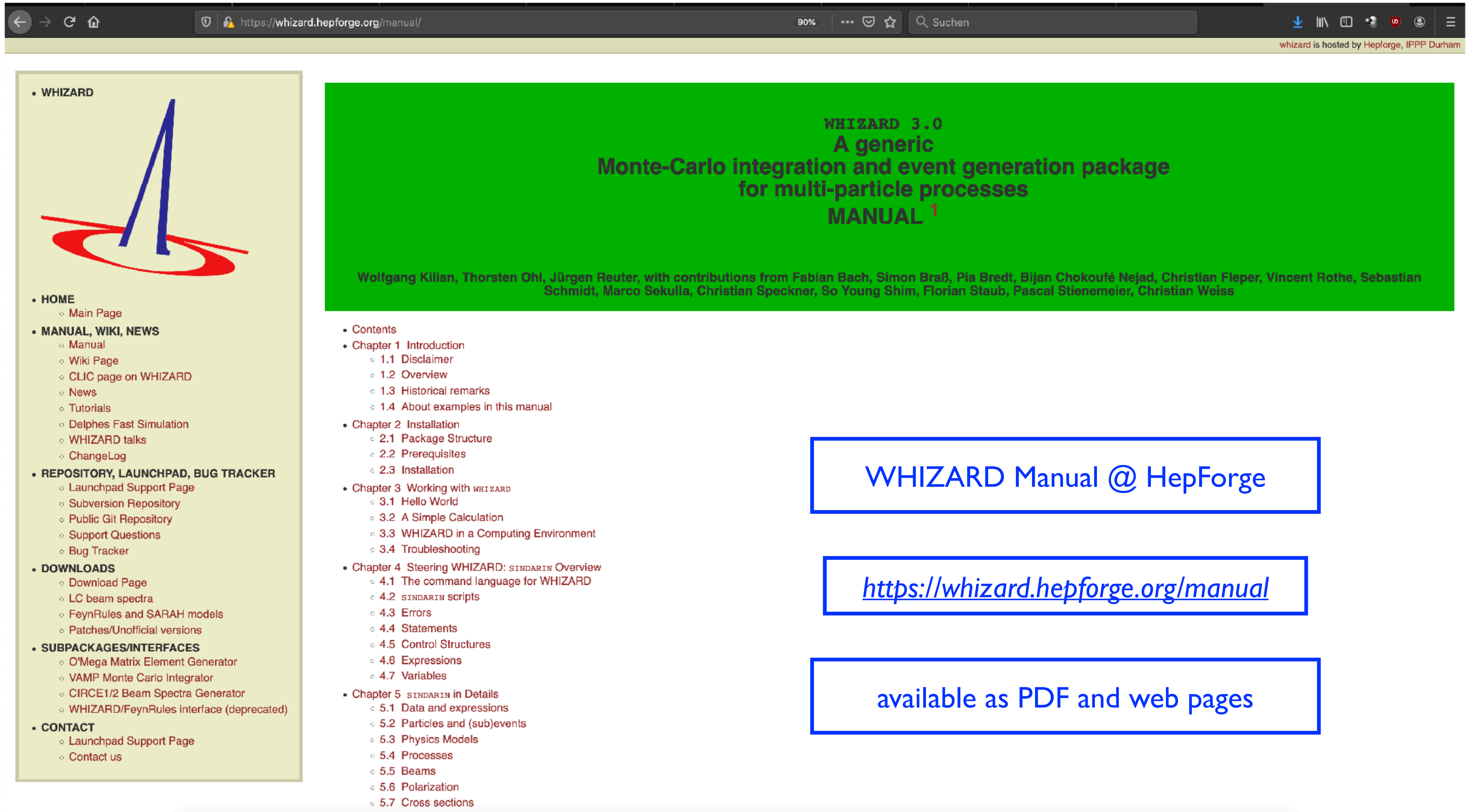
WHIZARD **Overview (II)**


```
model = NMSSM
process susyprod = e1, E1 => stau1, Stau1
process staudec = stau1 => neu1, e3

sqrts = 250 GeV
beams = e1, E1 => circe2 => isr
beams_pol_density = @(-1), @(+1)
beams_pol_fraction = 80%, 30%

n_events = 10000
sample_format = lhef, stdhep, hepmc
simulate (susyprod)
```

- Collider setup: Polarized beams, crossing angle, asymmetric beams
- Event formats available: `LHA,LHE(v1-3),HepMC2/3(RootIO),LCIO`
- Versatile scripting language `SINDARIN`: arbitrary cuts & selections, scale expressions etc. etc.
- Factorized processes (`unstable` feature, NWA, specific decay helicity, polarized resonance decays)
- Automated calculation of BRs of unstable particles, BRs can be set explicitly, e.g. to (N)NLO values
- BSM models through UFO interface (cf. later)
- Special treatment of top threshold physics (cf. later)
- Reweighting / recasting processes + multiple weights/observables
- `WHIZARD` API: callable as a library from any `C/C++/Fortran/Python` program / `Jupyter`
- **Focus here new developments: Completion NLO automation, NLO matching, high-performance, revalidations, new physics implementations: long-lived particles, initial-state QED treatment, EW PDFs etc.**

WHIZARD: User support / bug tracker

WHIZARD v3.1.2 (21.03.2023) https://launchpad.net/whizard whizard@desy.de



WHIZARD Manual @ HepForge

https://whizard.hepforge.org/manual

available as PDF and web pages

WHIZARD Tutorial

e.g. for Snowmass, 20.9.2020: https://indico.fnal.gov/event/45413/

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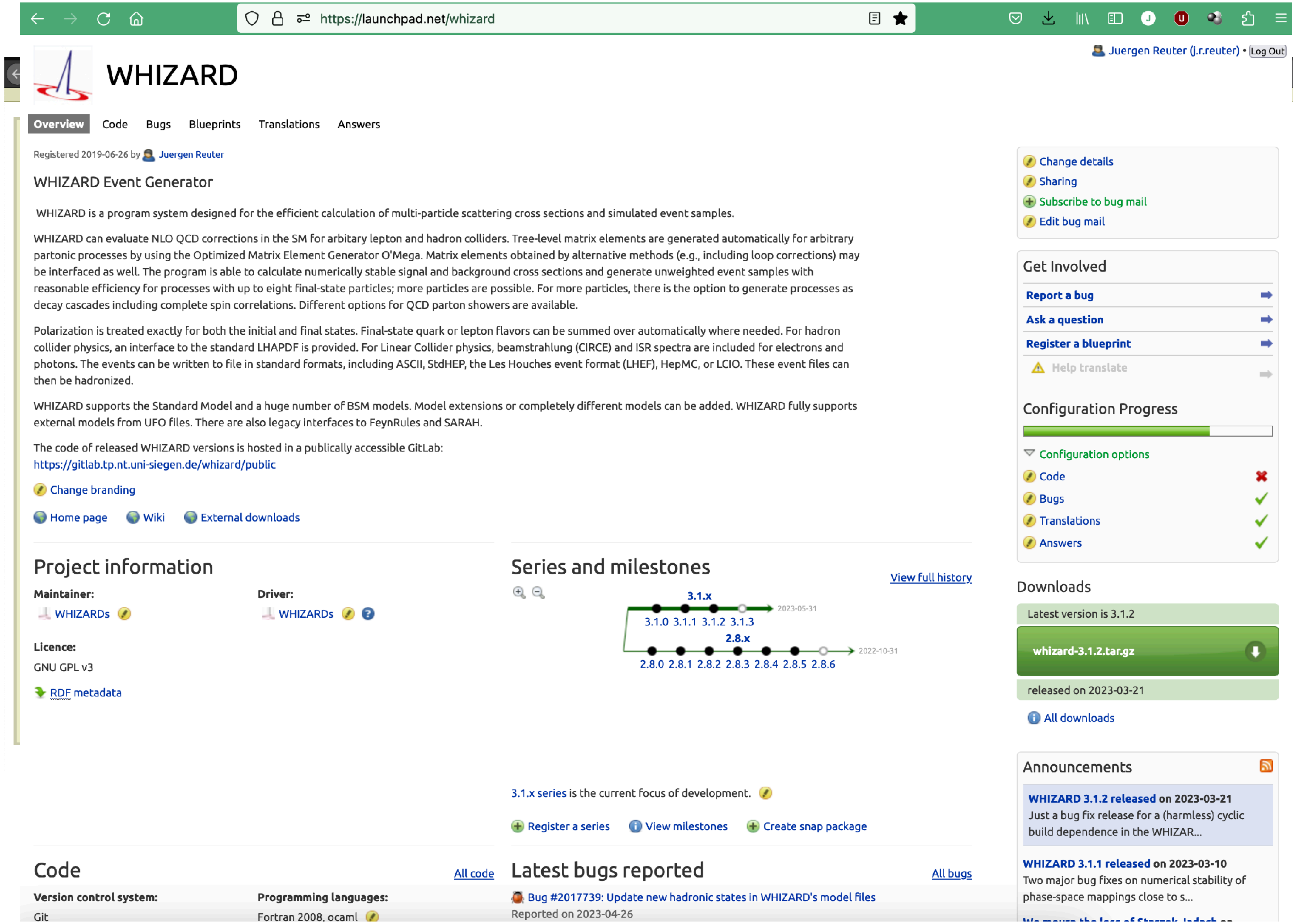


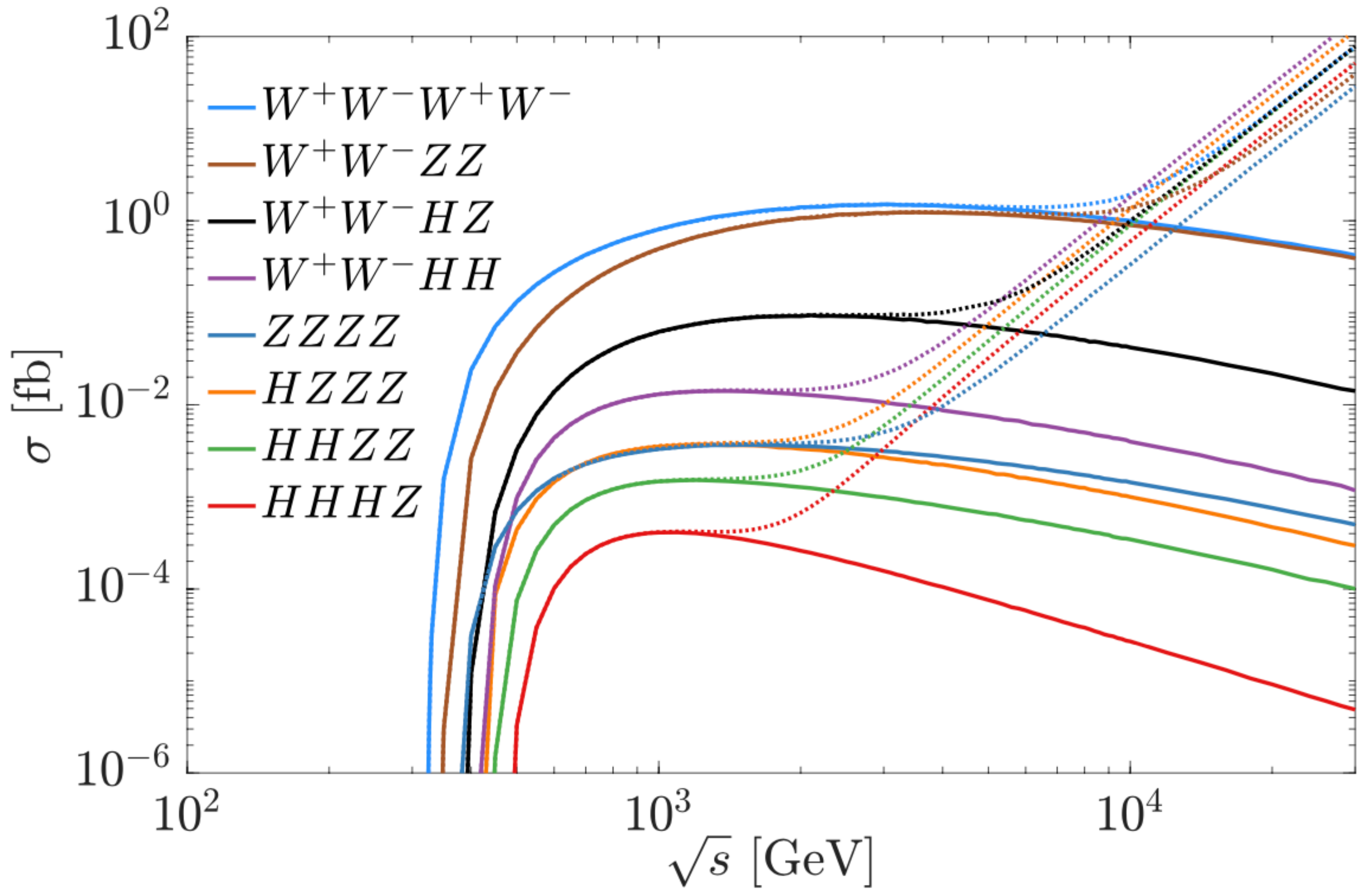
- 706468 Gaussian or Breit wigner distribution
- 706412 Syntax for forcing two identical particles to different final states
- 706411 Various errors when generating events with (b) jets in the final state
- 706291 Error while generating NLO events with polarized e+ e- beams
- 706197 how to uninstall whizard
- 706070 default cuts
- 706008 issues with installing whizard with openloops

News on the UFO / BSM in WHIZARD

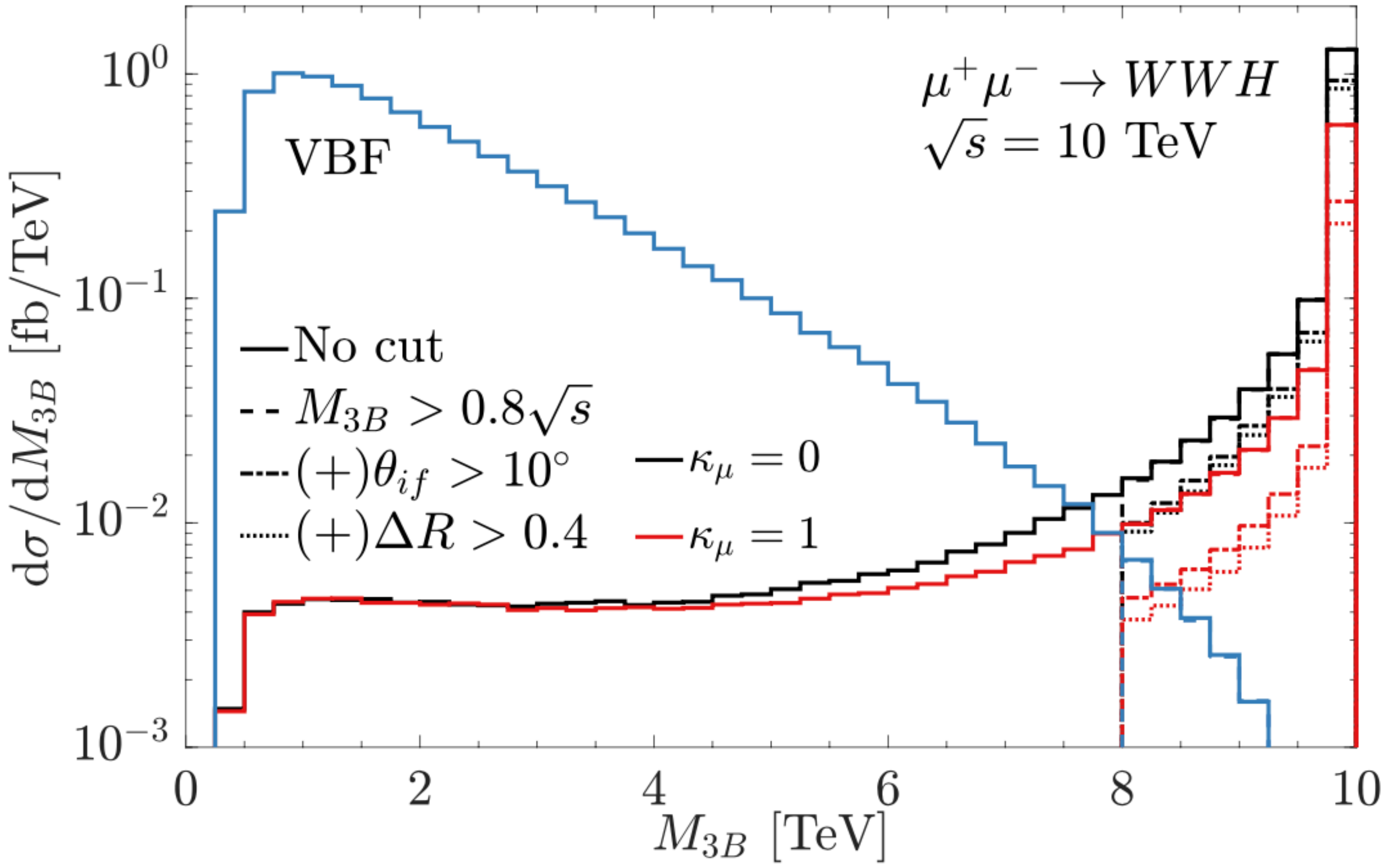
```
model = SM  (ufo)
model = SM  (ufo ("<my UFO path>"))
```

Old FeynRules / SARAH interface **is deprecated**

backwards validation possible via v3.0.0



- [x] WHIZARD 2.8.3: Full UFO (I) support
- [x] Majorana statistics (3.0.0) cf. Talk by Krzysztof Mękała
- [x] LO matrix elements from externals UFO models (particularly SMEFTSim v3.x)
- [x] Customized propators
- [x] Spin 0, 1/2, 1, [3/2, 2] supported [3.2.x]
- [x] Arbitrary Lorentz structures supported
- [x] 5-, 6-, 7-, 8-, ... point vertices (optimization for code generation pending)
- [x] BSM SLHA input (2.8.3)
- [x] Lots of bug reports and constructive feedback from many different users
- [ ] Crazy color structures (sextets, decuplets, epsilon structures) (3.2.0)
- [ ] NLO (QCD) matrix elements from external UFO models with GoSam (3.2.x)



New paper on UFO 2.0: Darmé et al. arXiv: 2304.09883

MuC example for SMEFT/HEFT UFO, from: T. Han et al. arXiv:2108.05362

WHIZARD NLO Automation: Loops & Legs

Getty Villa, Pacific Palisades, Etruscan, 525 BC

WHIZARD NLO Automation: Loops & Legs

- NLO SM automation for lepton-/hadron colliders completed 2022 Chokoufé 2017; Weiss 2017; Rothe 2021; Stienemeier 2022; Bredt 2022
- FKS subtraction, NLO matrix elements from OpenLoops/Recola/GoSam/...
- also: resonance-aware FKS subtraction cf. Ježo/Nason, arXiv:1509.09071; Chokoufé, 2017
- Setup for automatic differential fixed-order results (histogrammed distributions)
- Photon isolation, photon recombination, light-, b-, c-jet selection
- New: loop-induced processes supported

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ee @ 1 TeV, NLO QCD

Process	WHIZARD+OpenLoops $\sigma_{\rm LO}$[fb]	$\sigma_{\rm NLO}$[fb]	K
$e^+e^- \to jj$	622.737(8)	639.39(5)	1.03
$e^+e^- \to jjj$	340.6(5)	317.8(5)	0.93
$e^+e^- \to jjjj$	105.0(3)	104.2(4)	0.99
$e^+e^- \to jjjjj$	22.33(5)	24.57(7)	1.10
$e^+e^- \to t\bar{t}$	166.37(12)	174.55(20)	1.05
$e^+e^- \to t\bar{t}j$	48.12(5)	53.41(7)	1.11
$e^+e^- \to t\bar{t}jj$	8.592(19)	10.526(21)	1.23
$e^+e^- \to t\bar{t}jjj$	1.035(4)	1.405(5)	1.36
$e^+e^- \to t\bar{t}t\bar{t}$	$0.6388(8) \cdot 10^{-3}$	$1.1922(11) \cdot 10^{-3}$	1.87
$e^+e^- \to t\bar{t}t\bar{t}j$	$2.673(7) \cdot 10^{-5}$	$5.251(11) \cdot 10^{-5}$	1.96
$e^+e^- \to t\bar{t}H$	2.020(3)	1.912(3)	0.95
$e^+e^- \to t\bar{t}Hj$	$2.536(4) \cdot 10^{-1}$	$2.657(4) \cdot 10^{-1}$	1.05
$e^+e^- \to t\bar{t}Hjj$	$2.646(8) \cdot 10^{-2}$	$3.123(9) \cdot 10^{-2}$	1.18
$e^+e^- \to t\bar{t}Z$	4.638(3)	4.937(3)	1.06
$e^+e^- \to t\bar{t}Zj$	$6.027(9) \cdot 10^{-1}$	$6.921(11) \cdot 10^{-1}$	1.15
$e^+e^- \to t\bar{t}Zjj$	$6.436(21) \cdot 10^{-2}$	$8.241(29) \cdot 10^{-2}$	1.28
$e^+e^- \to t\bar{t}W^\pm jj$	$2.387(8) \cdot 10^{-4}$	$3.716(10) \cdot 10^{-4}$	1.56
$e^+e^- \to t\bar{t}HZ$	$3.623(19) \cdot 10^{-2}$	$3.584(19) \cdot 10^{-2}$	0.99
$e^+e^- \to t\bar{t}ZZ$	$3.788(6) \cdot 10^{-2}$	$4.032(7) \cdot 10^{-2}$	1.06
$e^+e^- \to t\bar{t}HH$	$1.3650(15) \cdot 10^{-2}$	$1.2168(16) \cdot 10^{-2}$	0.89
$e^+e^- \to t\bar{t}W^+W^-$	$1.3672(21) \cdot 10^{-1}$	$1.5385(22) \cdot 10^{-1}$	1.13

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pp @ 13 TeV, NLO QCD

Process	$\sigma_{\rm LO}$[fb] (WHIZARD+OpenLoops)	$\sigma_{\rm NLO}$[fb] (WHIZARD+OpenLoops)	K
$pp \to jj$	$1.162(4) \cdot 10^9$	$1.601(5) \cdot 10^9$	1.38
$pp \to jjj$	$9.01(4) \cdot 10^7$	$7.46(9) \cdot 10^7$	0.83
$pp \to t\bar{t}$	$4.589(9) \cdot 10^5$	$6.740(10) \cdot 10^5$	1.47
$pp \to t\bar{t}j$	$3.123(6) \cdot 10^5$	$4.087(9) \cdot 10^5$	1.31
$pp \to t\bar{t}jj$	$1.360(4) \cdot 10^5$	$1.775(7) \cdot 10^5$	1.31
$pp \to t\bar{t}t\bar{t}$	4.485(6)	9.070(9)	2.02
$pp \to W^\pm$	$1.3749(8) \cdot 10^8$	$1.7696(10) \cdot 10^8$	1.29
$pp \to W^\pm j$	$2.046(3) \cdot 10^7$	$2.854(5) \cdot 10^7$	1.39
$pp \to W^\pm jj$	$6.856(12) \cdot 10^6$	$7.814(27) \cdot 10^6$	1.14
$pp \to W^\pm jjj$	$1.840(5) \cdot 10^6$	$1.978(7) \cdot 10^6$	1.07
$pp \to Z$	$4.2541(3) \cdot 10^7$	$5.4086(16) \cdot 10^7$	1.27
$pp \to Zj$	$7.215(4) \cdot 10^6$	$9.733(10) \cdot 10^6$	1.35
$pp \to Zjj$	$2.364(5) \cdot 10^6$	$2.676(7) \cdot 10^6$	1.13
$pp \to Zjjj$	$6.381(23) \cdot 10^5$	$6.85(3) \cdot 10^5$	1.07
$pp \to W^+W^+jj$	$1.506(5) \cdot 10^2$	$2.235(7) \cdot 10^2$	1.48
$pp \to W^-W^-jj$	$6.772(24) \cdot 10^1$	$9.982(28) \cdot 10^1$	1.47
$pp \to ZW^\pm$	$2.780(5) \cdot 10^4$	$4.488(4) \cdot 10^4$	1.61
$pp \to ZW^\pm j$	$1.609(4) \cdot 10^4$	$2.0940(28) \cdot 10^4$	1.30
$pp \to ZW^\pm jj$	$8.06(3) \cdot 10^3$	$9.02(4) \cdot 10^3$	1.12
$pp \to ZZ$	$1.0969(10) \cdot 10^4$	$1.4183(11) \cdot 10^4$	1.29
$pp \to ZZj$	$3.667(9) \cdot 10^3$	$4.807(8) \cdot 10^3$	1.31
$pp \to ZZjj$	$1.356(6) \cdot 10^3$	$1.684(8) \cdot 10^3$	1.24

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$pp \to Z$	$4.2541(3) \cdot 10^7$	$5.4086(16) \cdot 10^7$	1.27
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$pp \to ZW^\pm j$	$1.609(4) \cdot 10^4$	$2.0940(28) \cdot 10^4$	1.30
$pp \to ZW^\pm jj$	$8.06(3) \cdot 10^3$	$9.02(4) \cdot 10^3$	1.12
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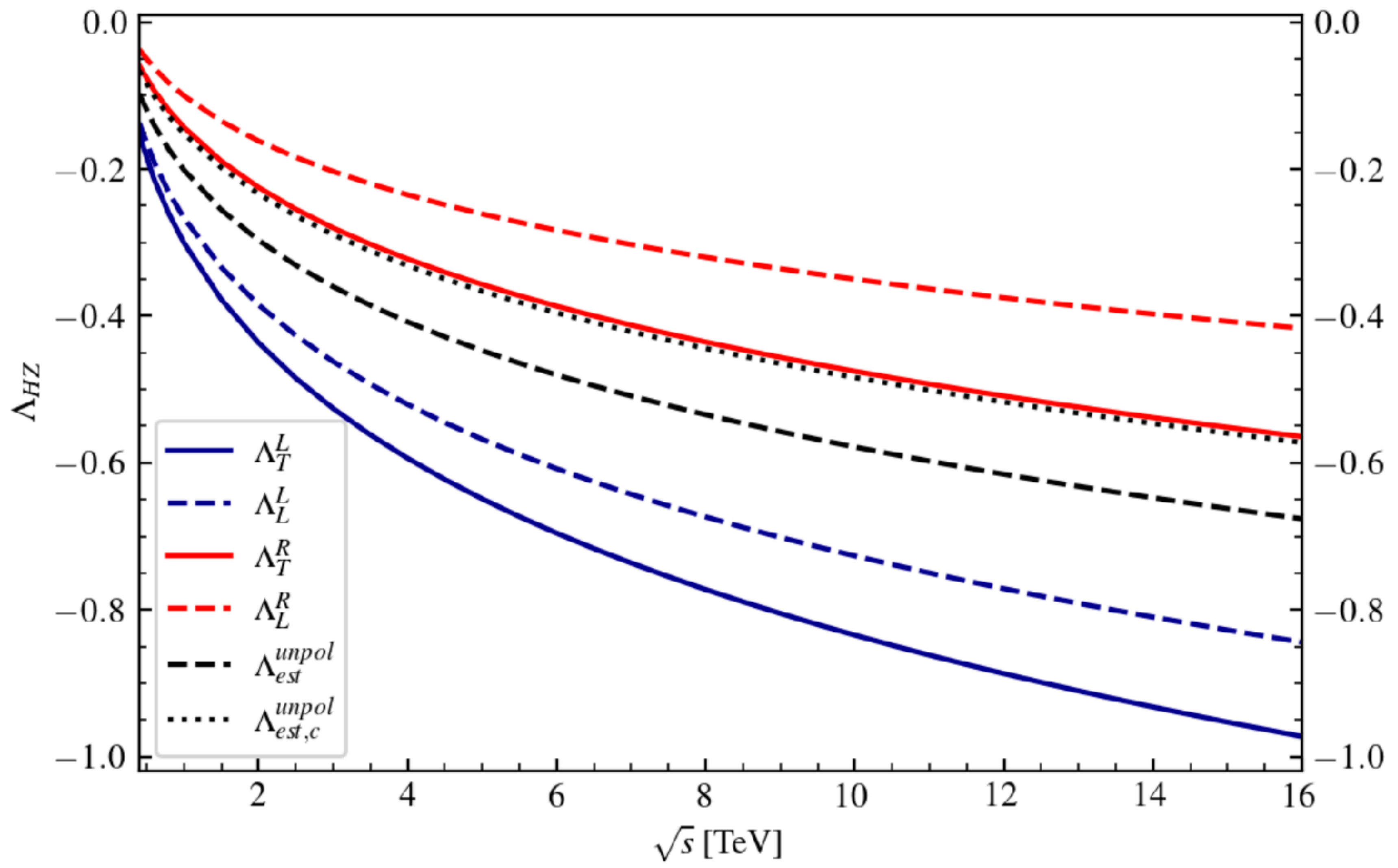
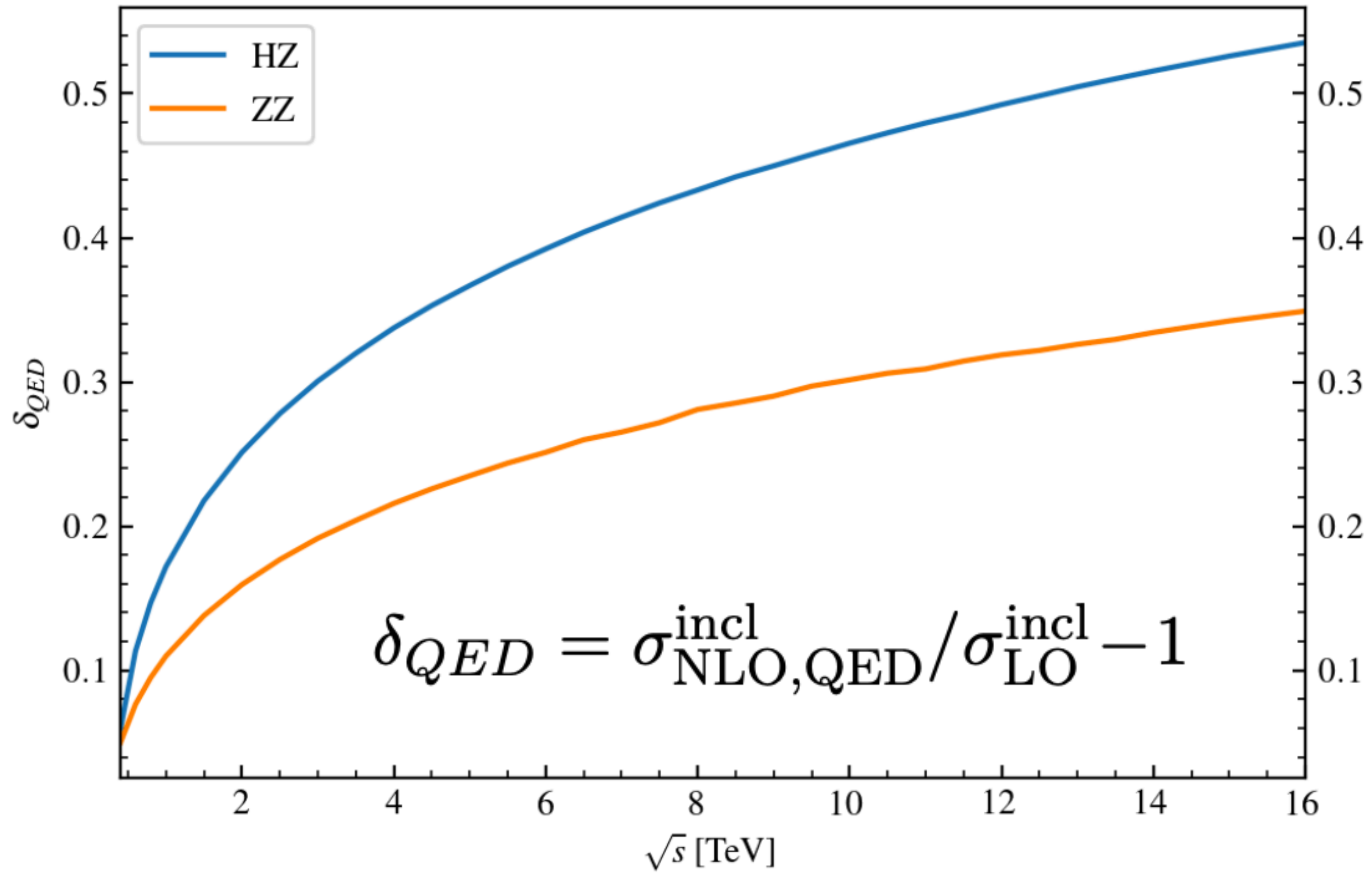
$\mu\mu$ @ 3 TeV, NLO EW

$\mu^+\mu^- \to X, \sqrt{s} =$	$\sigma^{\rm incl}_{\rm LO}$ [fb]	$\sigma^{\rm incl}_{\rm NLO}$ [fb]	$\delta_{\rm EW}$ [%]
W^+W^-	$4.6591(2) \cdot 10^2$	$4.847(7) \cdot 10^2$	+4.0(2)
ZZ	$2.5988(1) \cdot 10^1$	$2.656(2) \cdot 10^1$	+2.19(6)
HZ	$1.3719(1) \cdot 10^0$	$1.3512(5) \cdot 10^0$	−1.51(4)
HH	$1.60216(7) \cdot 10^{-7}$	$5.66(1) \cdot 10^{-7}$ *	
W^+W^-Z	$3.330(2) \cdot 10^1$	$2.568(8) \cdot 10^1$	−22.9(2)
W^+W^-H	$1.1253(5) \cdot 10^0$	$0.895(2) \cdot 10^0$	−20.5(2)
ZZZ	$3.598(2) \cdot 10^{-1}$	$2.68(1) \cdot 10^{-1}$	−25.5(3)
HZZ	$8.199(4) \cdot 10^{-2}$	$6.60(3) \cdot 10^{-2}$	−19.6(3)
HHZ	$3.277(1) \cdot 10^{-2}$	$2.451(5) \cdot 10^{-2}$	−25.2(1)
HHH	$2.9699(6) \cdot 10^{-8}$	$0.86(7) \cdot 10^{-8}$ *	
$W^+W^-W^+W^-$	$1.484(1) \cdot 10^0$	$0.993(6) \cdot 10^0$	−33.1(4)
W^+W^-ZZ	$1.209(1) \cdot 10^0$	$0.699(7) \cdot 10^0$	−42.2(6)
W^+W^-HZ	$8.754(8) \cdot 10^{-2}$	$6.05(4) \cdot 10^{-2}$	−30.9(5)
W^+W^-HH	$1.058(1) \cdot 10^{-2}$	$0.655(5) \cdot 10^{-2}$	−38.1(4)
$ZZZZ$	$3.114(2) \cdot 10^{-3}$	$1.799(7) \cdot 10^{-3}$	−42.2(2)
$HZZZ$	$2.693(2) \cdot 10^{-3}$	$1.766(6) \cdot 10^{-3}$	−34.4(2)
$HHZZ$	$9.828(7) \cdot 10^{-4}$	$6.24(2) \cdot 10^{-4}$	−36.5(2)
$HHHZ$	$1.568(1) \cdot 10^{-4}$	$1.165(4) \cdot 10^{-4}$	−25.7(2)

Validation of the Sudakov regime

$\mu^+\mu^- \to X, \sqrt{s} = 10$ TeV	$\sigma^{\rm incl}_{\rm LO}$ [fb]	$\sigma^{\rm incl}_{\rm NLO}$ [fb]	$\delta_{\rm EW}$ [%]
W^+W^-	$5.8820(2) \cdot 10^1$	$6.11(1) \cdot 10^1$	$+3.9(2)$
ZZ	$3.2730(4) \cdot 10^0$	$3.401(4) \cdot 10^0$	$+3.9(1)$
HZ	$1.22929(8) \cdot 10^{-1}$	$1.0557(8) \cdot 10^{-1}$	$-14.12(7)$
HH	$1.31569(5) \cdot 10^{-9}$	$42.9(4) \cdot 10^{-9}$ *	
W^+W^-Z	$9.609(5) \cdot 10^0$	$5.86(4) \cdot 10^0$	$-39.0(2)$
W^+W^-H	$2.1263(9) \cdot 10^{-1}$	$1.31(1) \cdot 10^{-1}$	$-38.4(5)$
ZZZ	$8.565(4) \cdot 10^{-2}$	$5.27(8) \cdot 10^{-2}$	$-38.5(9)$
HZZ	$1.4631(6) \cdot 10^{-2}$	$0.952(6) \cdot 10^{-2}$	$-34.9(4)$
HHZ	$6.083(2) \cdot 10^{-3}$	$2.95(3) \cdot 10^{-3}$	$-51.6(5)$
HHH	$2.3202(4) \cdot 10^{-9}$	$-1.0(2) \cdot 10^{-9}$ *	





$\mu^+\mu^- \to X, \sqrt{s} = 10$ TeV	$\sigma^{\rm incl}_{\rm LO}$ [fb]	$\sigma^{\rm incl}_{\rm LO+ISR}$ [fb]	$\delta_{\rm ISR}$ [%]
W^+W^-	$5.8820(2) \cdot 10^1$	$7.295(7) \cdot 10^1$	$+24.0(1)$
ZZ	$3.2730(4) \cdot 10^0$	$4.119(4) \cdot 10^0$	$+25.8(1)$
HZ	$1.22929(8) \cdot 10^{-1}$	$1.8278(5) \cdot 10^{-1}$	$+48.69(4)$
W^+W^-Z	$9.609(5) \cdot 10^0$	$10.367(8) \cdot 10^0$	$+7.9(1)$
W^+W^-H	$2.1263(9) \cdot 10^{-1}$	$2.410(2) \cdot 10^{-1}$	$+13.3(1)$
ZZZ	$8.565(4) \cdot 10^{-2}$	$9.431(7) \cdot 10^{-2}$	$+10.1(1)$
HZZ	$1.4631(6) \cdot 10^{-2}$	$1.677(1) \cdot 10^{-2}$	$+14.62(8)$
HHZ	$6.083(2) \cdot 10^{-3}$	$6.916(3) \cdot 10^{-3}$	$+13.68(6)$

arXiv: 2208.09438

Some examples for NLO results

ee @ 1 TeV, NLO QCD

Process	WHIZARD+OpenLoops $\sigma_{\rm LO}$ [fb]	$\sigma_{\rm NLO}$ [fb]
$e^+e^- \to jj$	622.737(8)	639.39(5)
$e^+e^- \to jjj$	340.6(5)	317.8(5)
$e^+e^- \to jjjj$	105.0(3)	104.2(4)
$e^+e^- \to jjjjj$	22.33(5)	24.57(7)
$e^+e^- \to jjjjjj$	3.583(17)	4.46(4)

pp @ 13 TeV, NLO QCD/EW mixed

process $pp \to$	$\alpha^n \alpha_s^m$	MG5_aMC@NLO $\sigma^{\rm tot}_{\rm NLO}$ [pb] [1804.10017]	WHIZARD $\sigma^{\rm tot}_{\rm NLO}$ [pb]	δ [%]	dev [%]	$\sigma^{\rm sig}_{\rm NLO}$
W^+j	$\alpha\alpha_s$	11552.(4)	11545.(4)	−0.37	0.07	1.26
Zj	$\alpha\alpha_s$	7062.(1)	7064.(3)	−0.80	0.03	0.77
$t\bar{t}$	α_s^2	432.90(6)	432.99(5)	−1.15	0.02	1.16
$t\bar{t}W^+$	$\alpha\alpha_s^2$	0.23025(3)	0.23017(5)	−4.53	0.03	1.28
$t\bar{t}Z$	$\alpha\alpha_s^2$	0.50033(7)	0.50041(10)	−0.84	0.02	0.67

ee @ .25 TeV, NLO EW, pol.av. + pol.

$\sqrt{s}$ [GeV]	MCSANCee[37] $\sigma^{\rm tot}_{\rm LO}$ [fb]	MCSANCee[37] $\sigma^{\rm tot}_{\rm NLO}$ [fb]	WHIZARD+RECOLA $\sigma^{\rm tot}_{\rm LO}$ [fb]	WHIZARD+RECOLA $\sigma^{\rm tot}_{\rm NLO}$ [fb]	$\delta_{\rm EW}$ [%]	$\sigma^{\rm sig}$ (LO/NLO)
250	225.59(1)	206.77(1)	225.60(1)	207.0(1)	−8.25	0.4/2.1
500	53.74(1)	62.42(1)	53.74(3)	62.41(2)	+16.14	0.2/0.3
1000	12.05(1)	14.56(1)	12.0549(6)	14.57(1)	+20.84	0.5/0.5

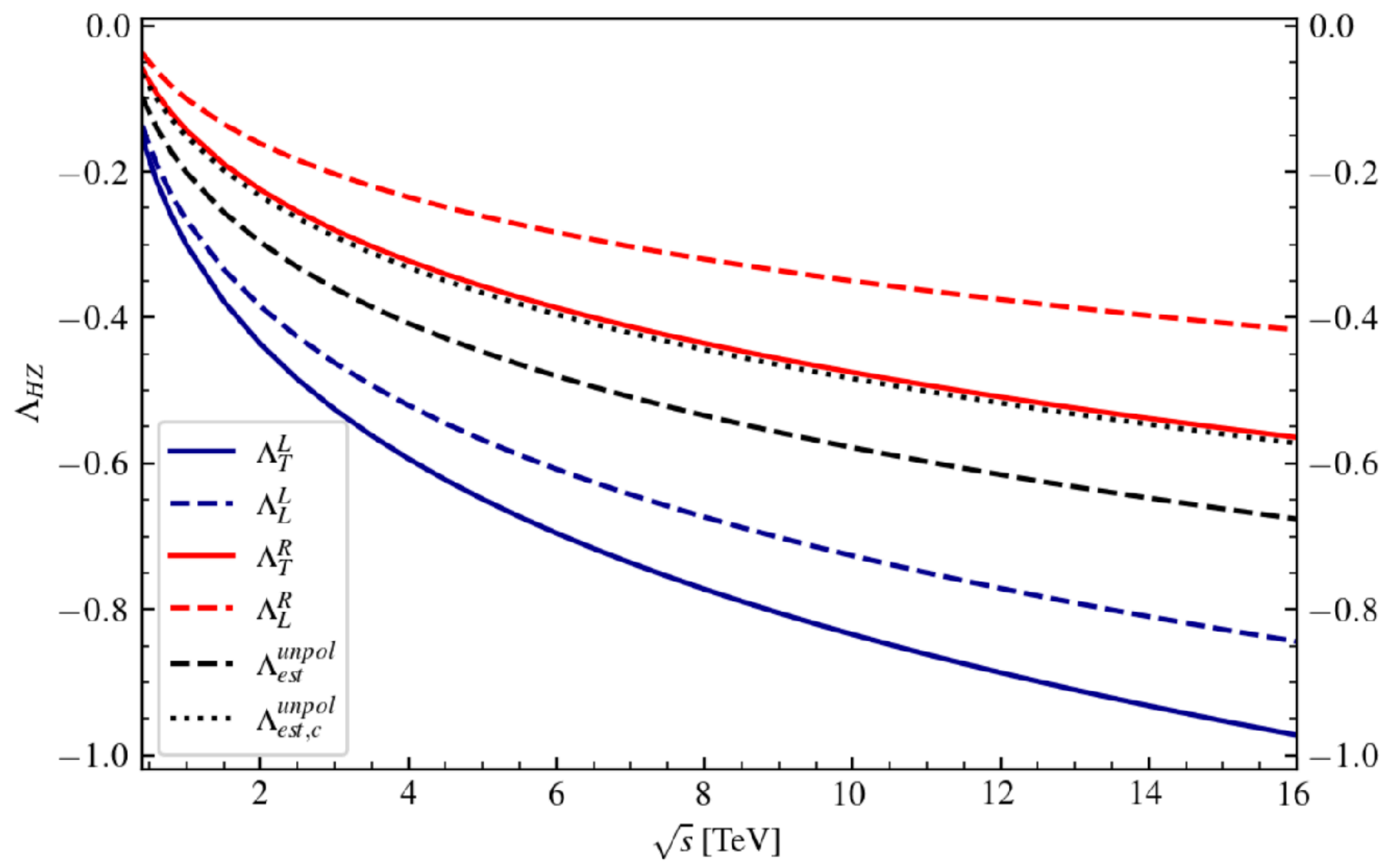
Cross-validation of WHIZARD and MUNICH orig. ref. [Kallweit *et. al.*: 1412.5157]

process $pp \to$	α^n	MUNICH +OpenLoops $\sigma^{\rm tot}_{\rm NLO}$ [fb]	WHIZARD +OpenLoops $\sigma^{\rm tot}_{\rm NLO}$ [fb]	δ [%]	dev [%]	$\sigma^{\rm sig}_{\rm NLO}$
ZZ	α^2	$1.05729(1) \cdot 10^4$	$1.05729(11) \cdot 10^4$	−4.20	0.0001	0.01
W^+Z	α^2	$1.71505(2) \cdot 10^4$	$1.71507(2) \cdot 10^4$	−0.15	0.001	0.88
W^-Z	α^2	$1.08576(1) \cdot 10^4$	$1.08574(1) \cdot 10^4$	+0.07	0.001	0.90
W^+W^-	α^2	$7.93106(7) \cdot 10^4$	$7.93087(21) \cdot 10^4$	+4.55	0.002	0.89
ZH	α^2	$6.18523(6) \cdot 10^2$	$6.18533(6) \cdot 10^2$	−5.29	0.002	1.17
W^+H	α^2	$7.18070(7) \cdot 10^2$	$7.18072(9) \cdot 10^2$	−2.31	0.0003	0.18
W^-H	α^2	$4.59289(4) \cdot 10^2$	$4.59299(5) \cdot 10^2$	−2.15	0.002	1.62
ZZZ	α^3	$9.7429(2) \cdot 10^0$	$9.7417(11) \cdot 10^0$	−9.47	0.012	1.01
W^+W^-Z	α^3	$1.08288(2) \cdot 10^2$	$1.08293(10) \cdot 10^2$	+7.67	0.004	0.45
W^+ZZ	α^3	$2.0188(4) \cdot 10^1$	$2.0188(23) \cdot 10^1$	+1.58	0.0001	0.01
W^-ZZ	α^3	$1.09844(2) \cdot 10^1$	$1.09838(12) \cdot 10^1$	+3.09	0.006	0.51
$W^+W^-W^+$	α^3	$8.7979(2) \cdot 10^1$	$8.7991(15) \cdot 10^1$	+6.18	0.014	0.79
$W^+W^-W^-$	α^3	$4.9447(1) \cdot 10^1$	$4.9441(2) \cdot 10^1$	+7.13	0.013	2.52
ZZH	α^3	$1.91607(2) \cdot 10^0$	$1.91614(18) \cdot 10^0$	−8.78	0.004	0.39
W^+ZH	α^3	$2.48068(2) \cdot 10^0$	$2.48095(28) \cdot 10^0$	+1.64	0.011	0.96
W^-ZH	α^3	$1.34001(1) \cdot 10^0$	$1.34016(15) \cdot 10^0$	+2.51	0.011	1.02
ZHH	α^3	$2.39350(2) \cdot 10^{-1}$	$2.39337(32) \cdot 10^{-1}$	−11.06	0.005	0.41
W^+HH	α^3	$2.44794(2) \cdot 10^{-1}$	$2.44776(24) \cdot 10^{-1}$	−12.04	0.007	0.74
W^-HH	α^3	$1.33525(1) \cdot 10^{-1}$	$1.33471(19) \cdot 10^{-1}$	−11.53	0.041	2.80

pp @ 13 TeV, NLO EW

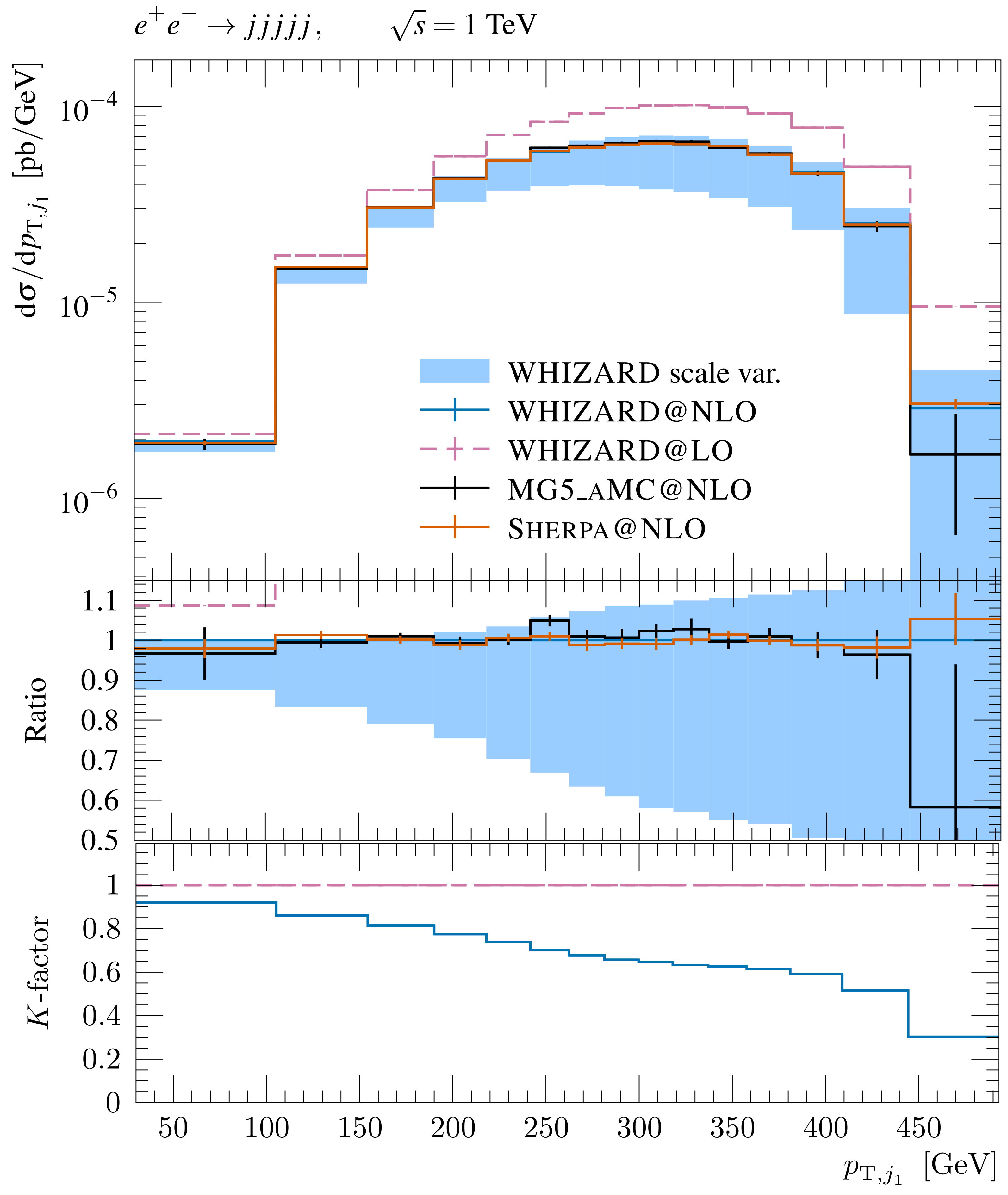
$$\delta \equiv \frac{\sigma^{\rm tot}_{\rm NLO} - \sigma^{\rm tot}_{\rm LO}}{\sigma^{\rm tot}_{\rm LO}} \qquad \text{dev} \equiv \frac{|\sigma^{\rm tot}_{\rm WHIZARD} - \sigma^{\rm tot}_{\rm MUNICH}|}{\sigma^{\rm tot}_{\rm WHIZARD}} \qquad \sigma^{\rm sig} \equiv \frac{|\sigma^{\rm tot}_{\rm WHIZARD} - \sigma^{\rm tot}_{\rm MUNICH}|}{\sqrt{\Delta^2_{\rm err,WHIZARD} + \Delta^2_{\rm err,MUNICH}}}$$

$\mu\mu$ @ 1-16 TeV, Validation of Sudakov regime

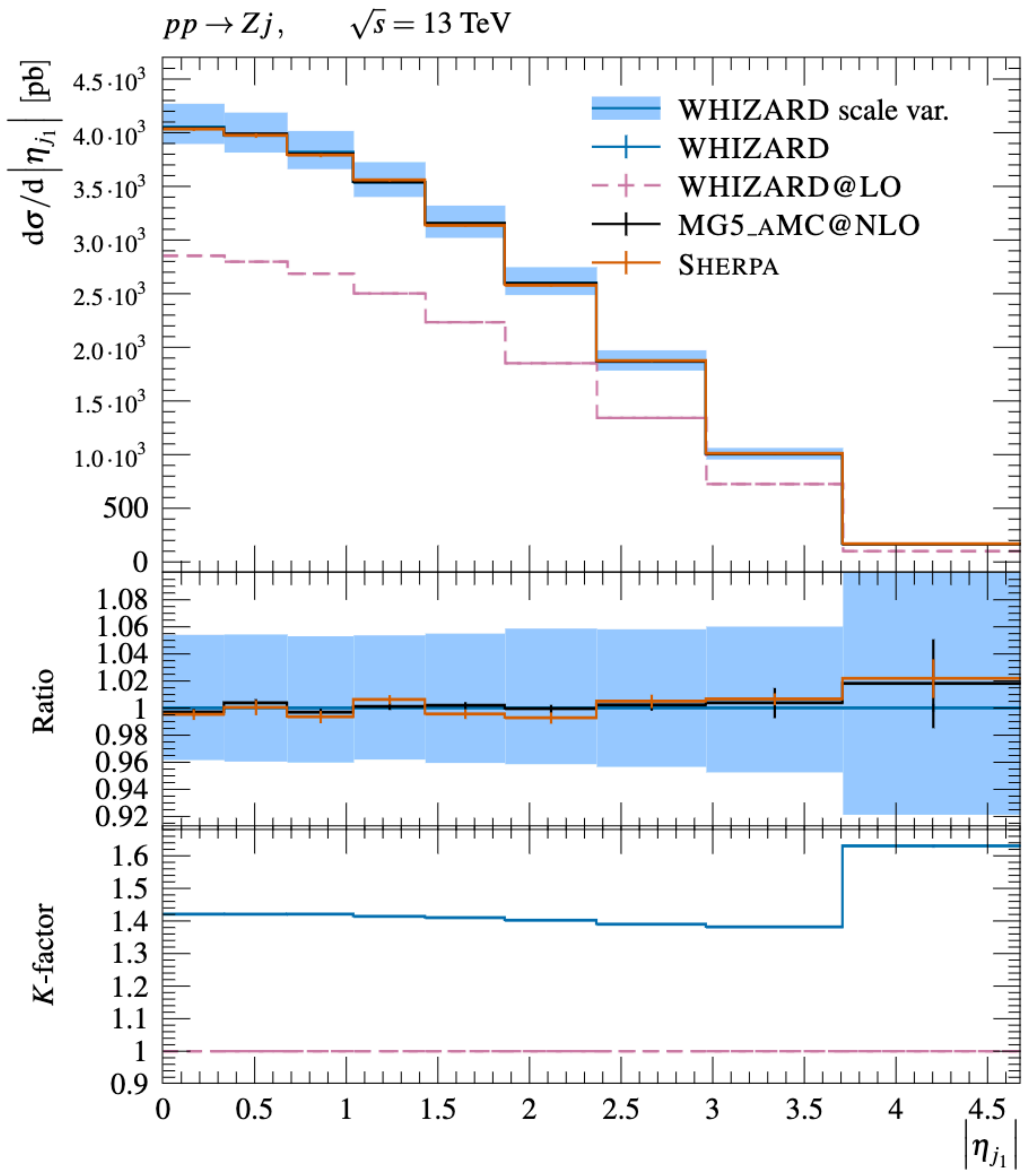


Differential NLO fixed-order distributions

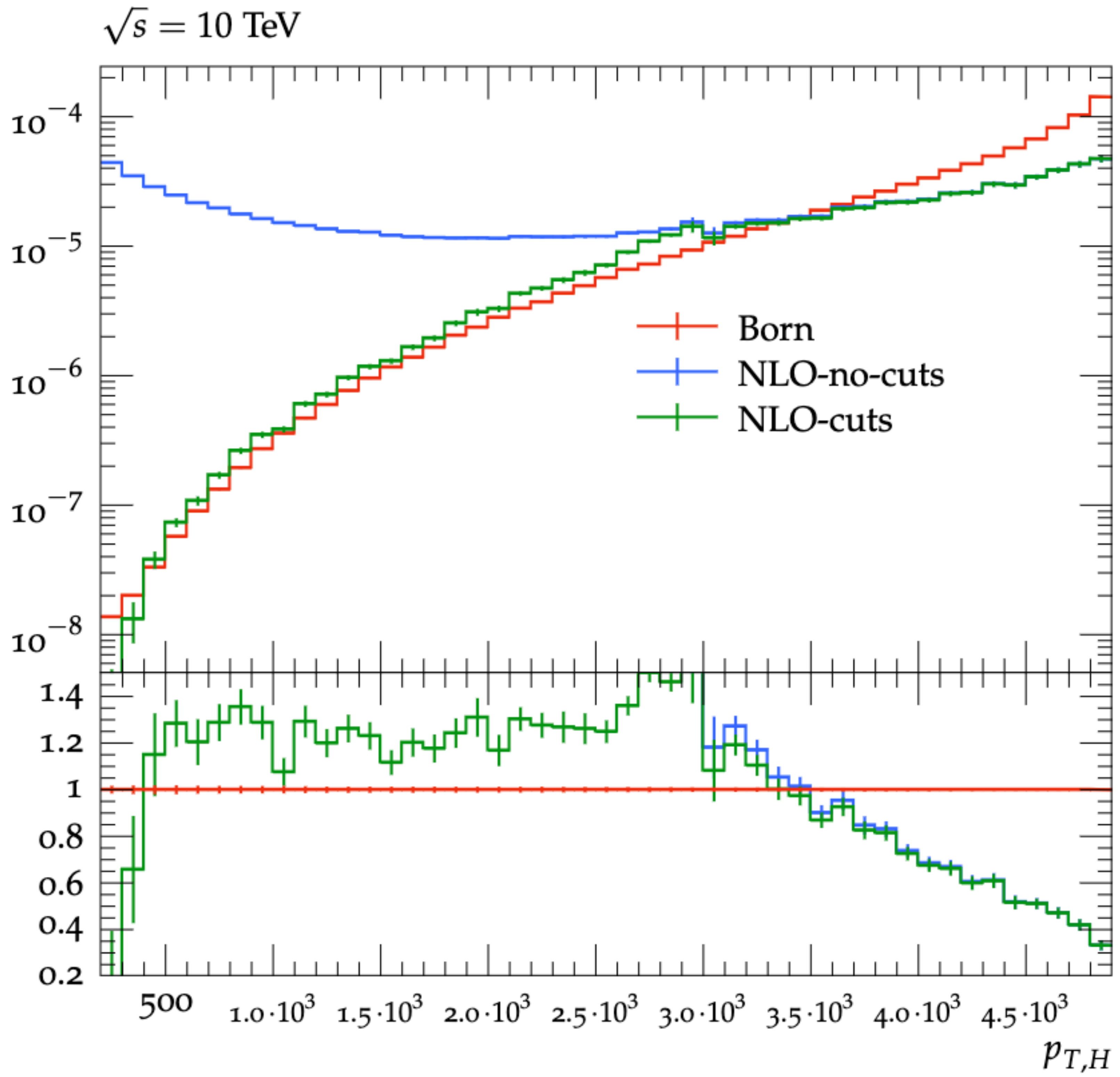
ee @ 1 TeV, NLO QCD



pp @ 13 TeV, NLO QCD



$\mu\mu$ @ 10 TeV, NLO EW



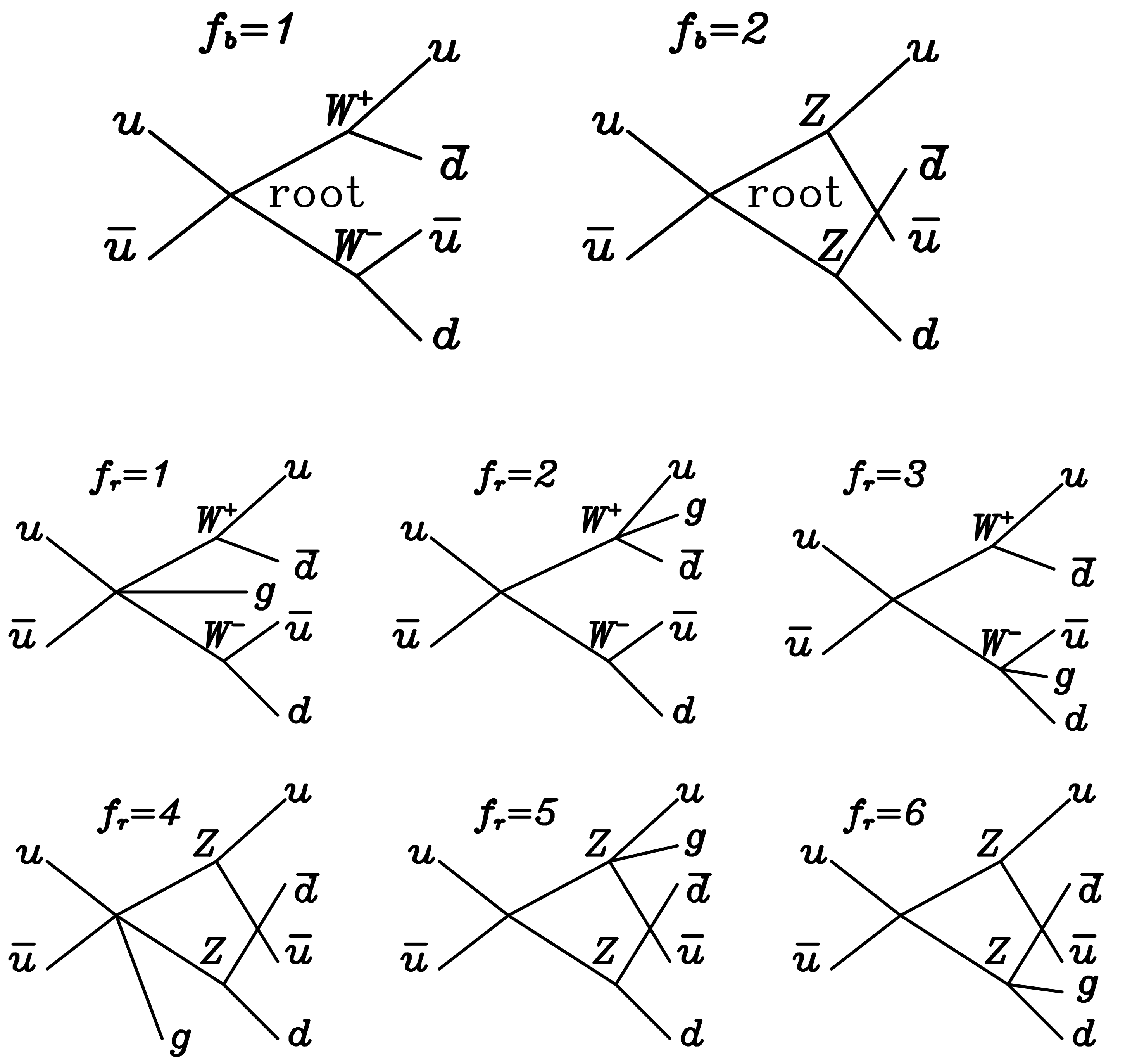
tricky numerics of eikonal terms
at high energies!

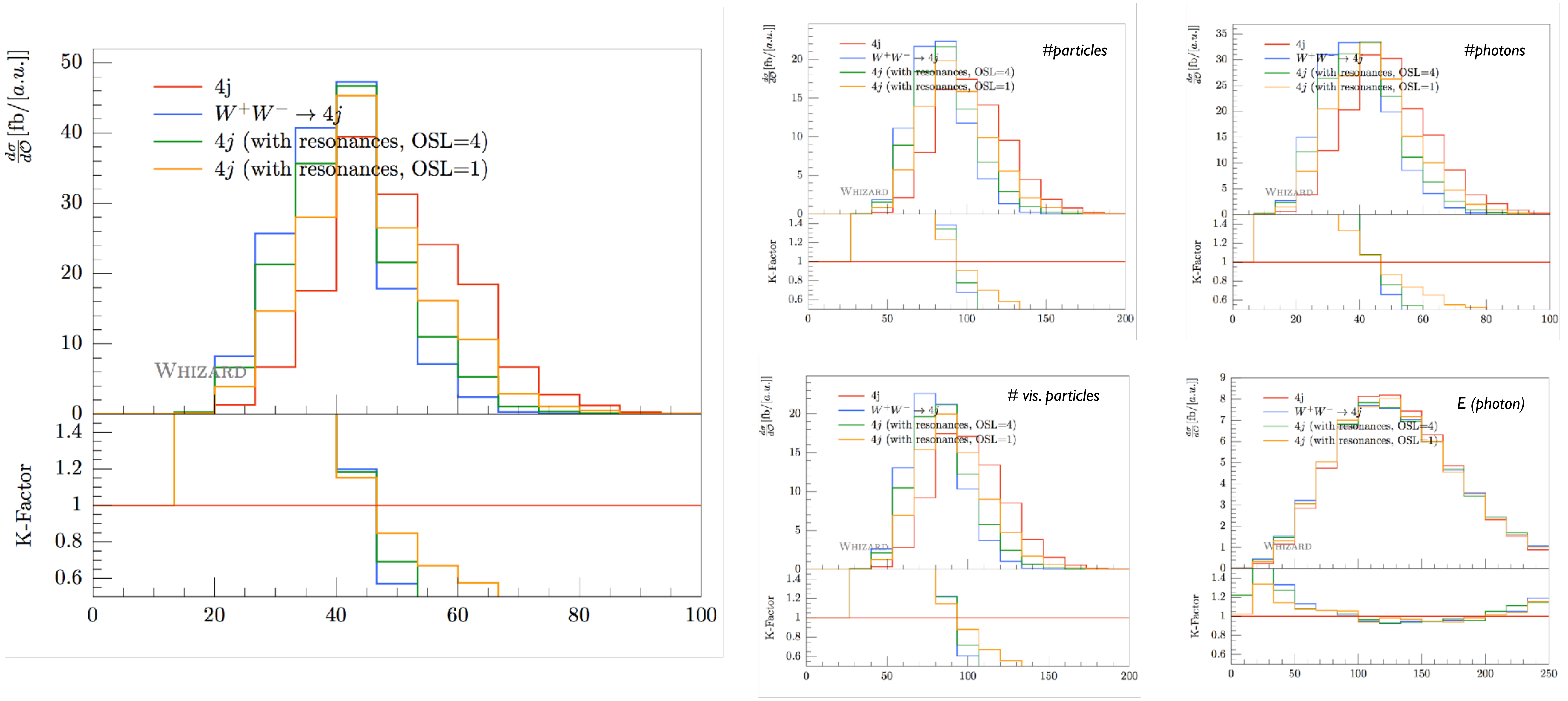
arXiv: 2208.09438

(Resonance) Matching to shower / hadronization


```
?resonance_history = true
resonance_on_shell_limit = 4
resonance_on_shell_turnoff = 1
resonance_background_factor = 1e-10
```

- Problem: $e^+e^- \to jjjj$ not dominated by highest α_s power,
  but by resonances $e^+e^- \to WW/ZZ \to (jj)(jj)$
- Solution: proper merging w/ resonant subprocesses by resonance histories
- `WHIZARD v2.6.0`: option to set resonance histories

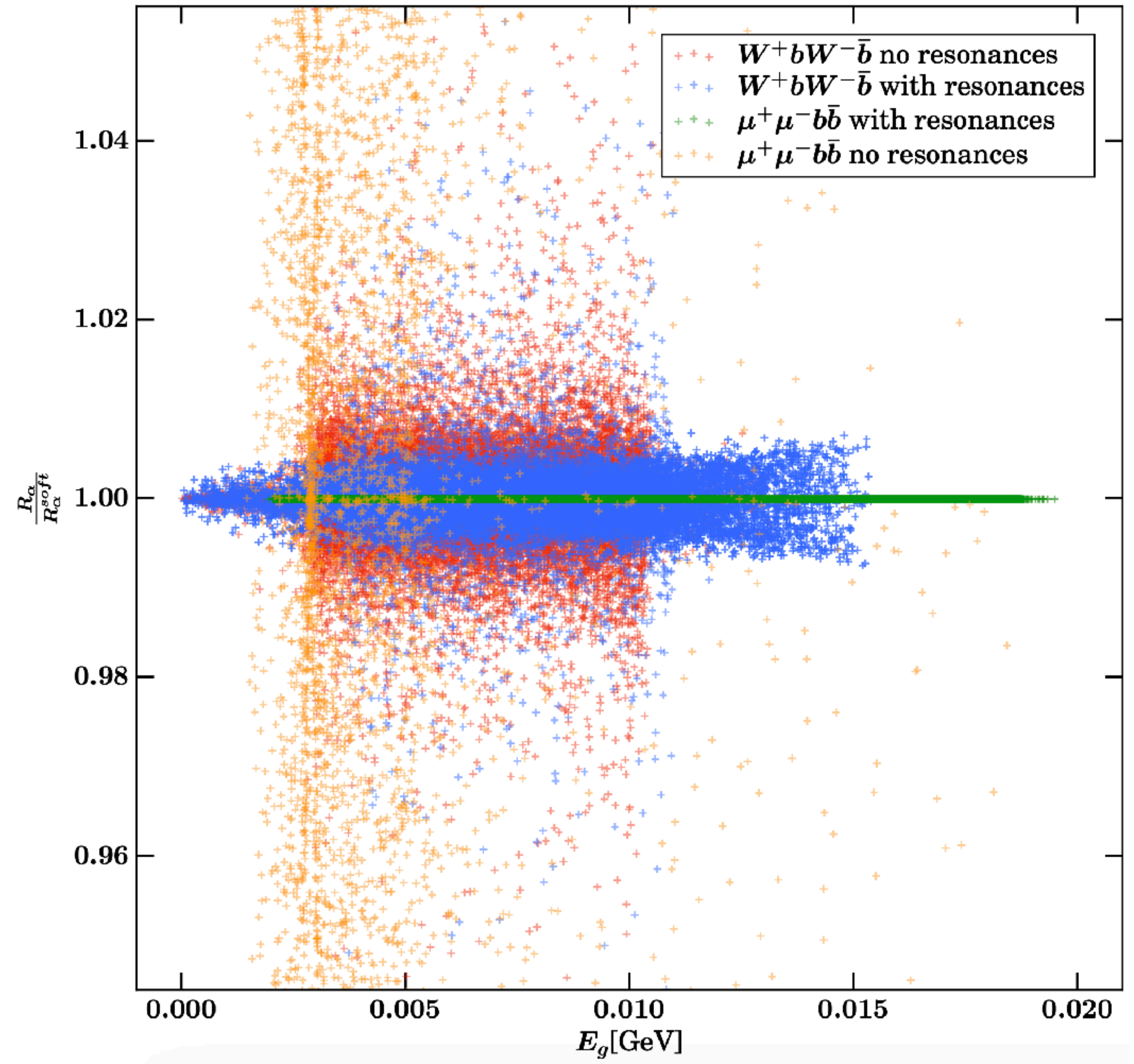




↪ Talk by Zhijie Zhao on corresponding matching with PYTHIA8

NLO QCD (+EW?) matching (and resonances)

- Matching between NLO real emission from hard ME and parton shower (PS)
- Perturbative α_s : $\left|\mathcal{M}_{\text{soft}}\right|^2 \sim \frac{1}{k_T^2} \longrightarrow \log \frac{k^T_{\text{max}}}{k^T_{\text{min}}}$
- POWHEG method: hardest emission first [Frixione/Nason et al.]
- Process-independent NLO matching in WHIZARD
- Massive/massless emitters, back-to-pack kinematics, running α_s
- Real partitioning of phase space into singular and finite regions
- Resonance-aware subtraction: Intermediate resonances handled
- At the moment: NLO QCD; straightforward EW generalization



- Complete NLO events

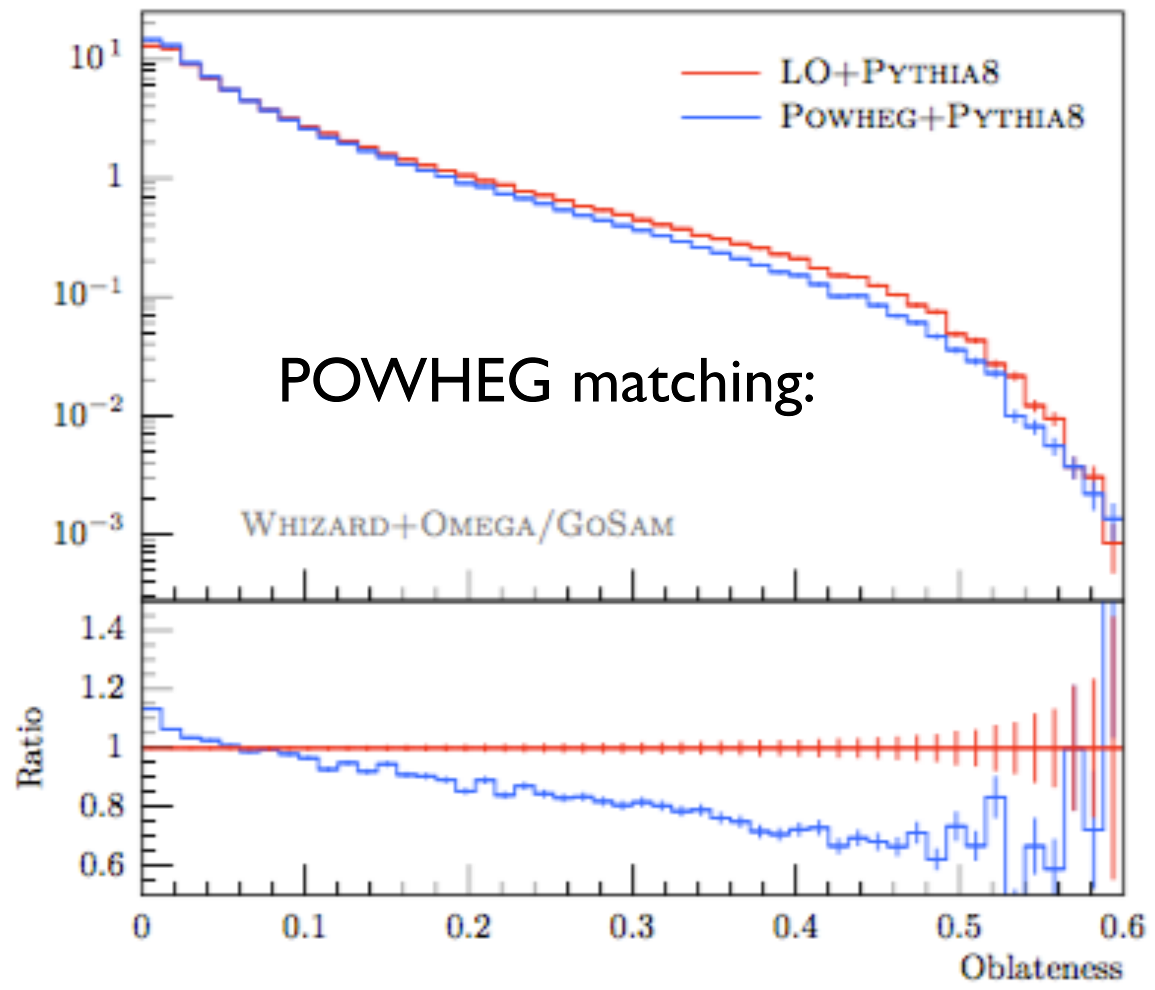
$$\overline{B}(\Phi_n) = B(\Phi_n) + V(\Phi_n) + \int d\Phi_{\text{rad}} R(\Phi_{n+1})$$

- POWHEG generate events according to the formula:

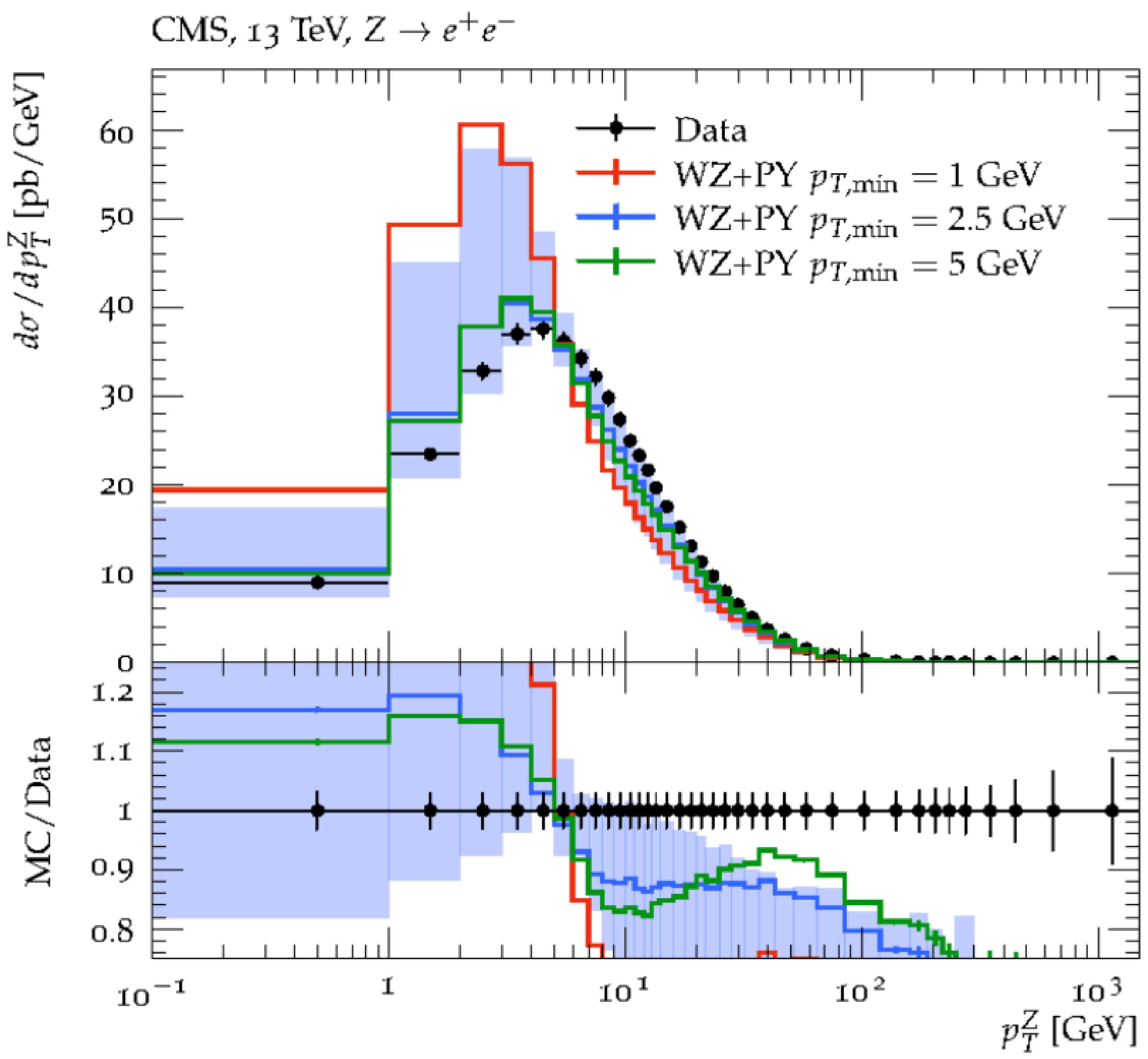
$$d\sigma = \overline{B}(\Phi_n)\left[\Delta_R^{\text{NLO}}(k_T^{\text{min}}) + \Delta_R^{\text{NLO}}(k_T)\frac{R(\Phi_{n+1})}{B(\Phi_n)} d\Phi_{\text{rad}}\right]$$

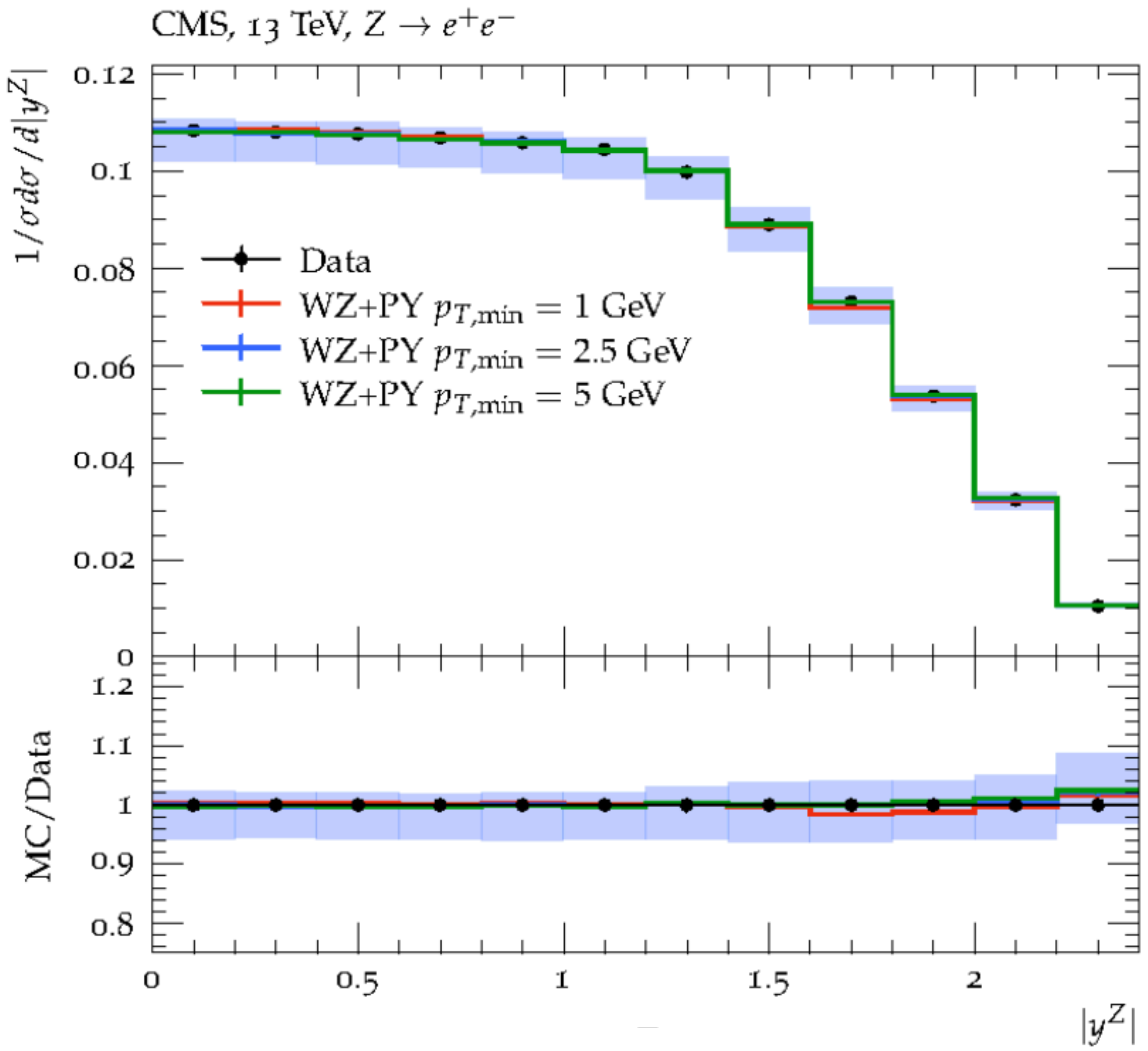
- Uses the modified Sudakov form factor:

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



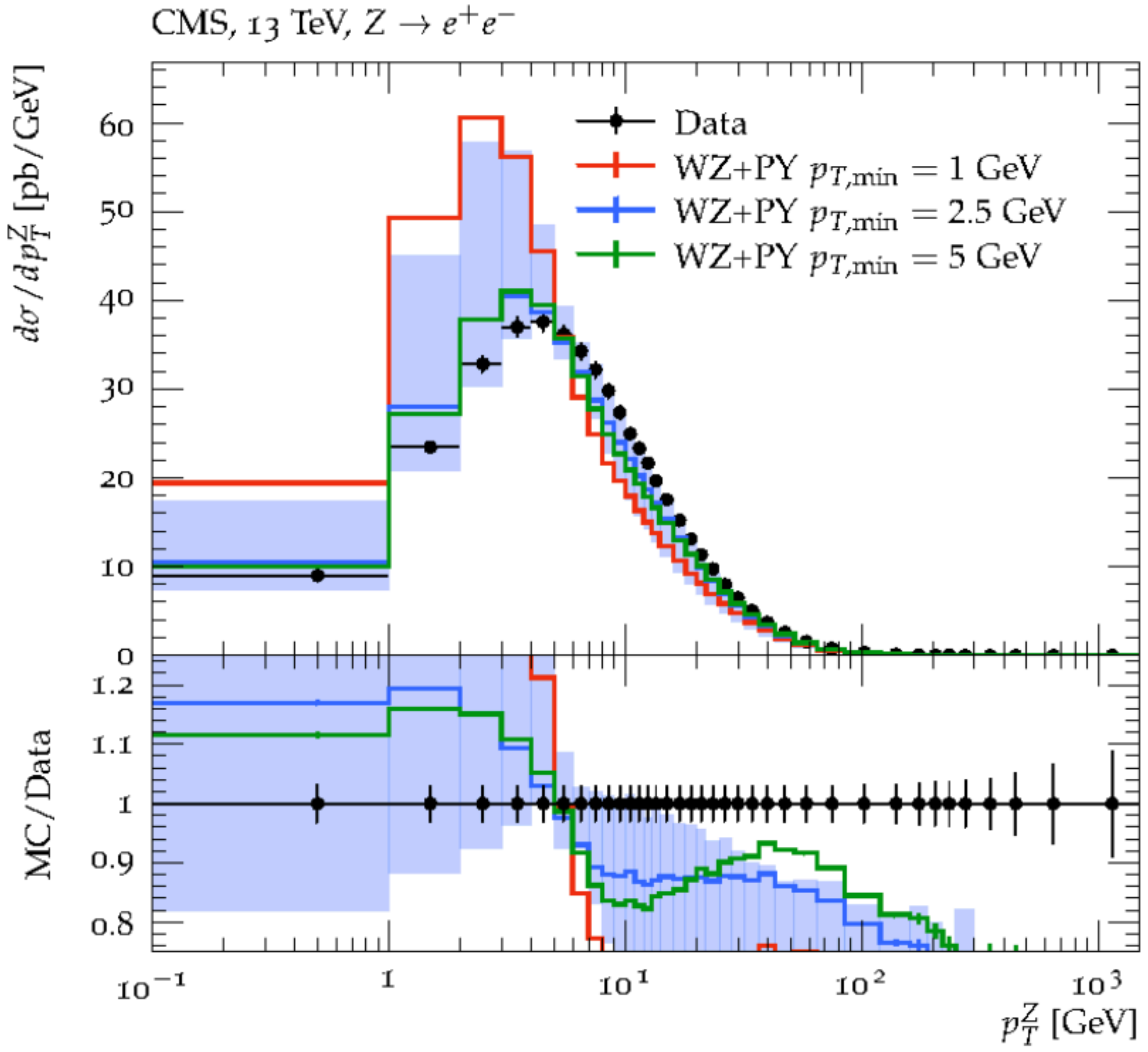
NLO QCD (+EW?) matching (and resonances)





LHC 13 TeV: Drell-Yan $pp \to \ell^+\ell^-$
compared to CMS data

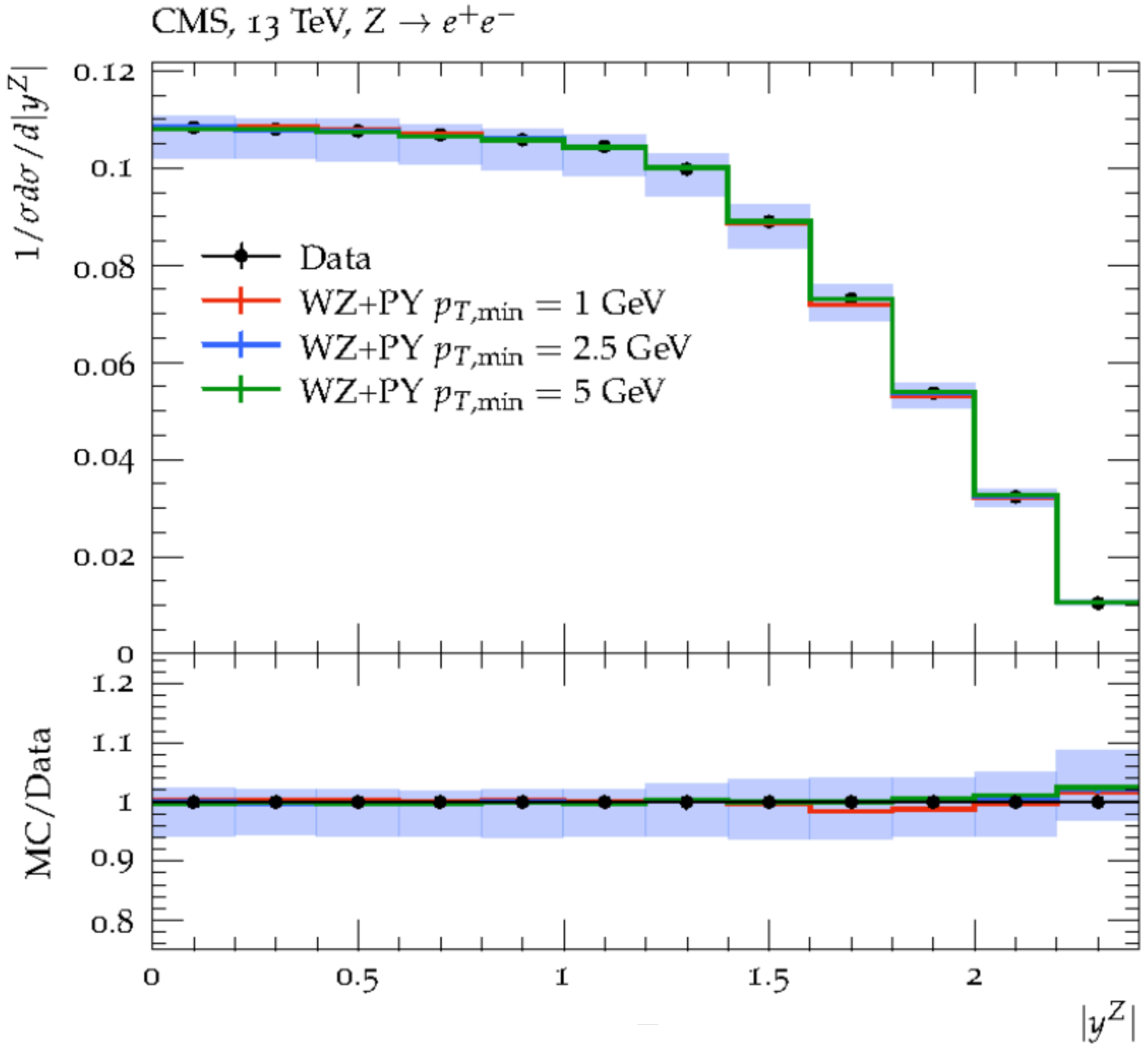
NLO QCD (+EW?) matching (and resonances)

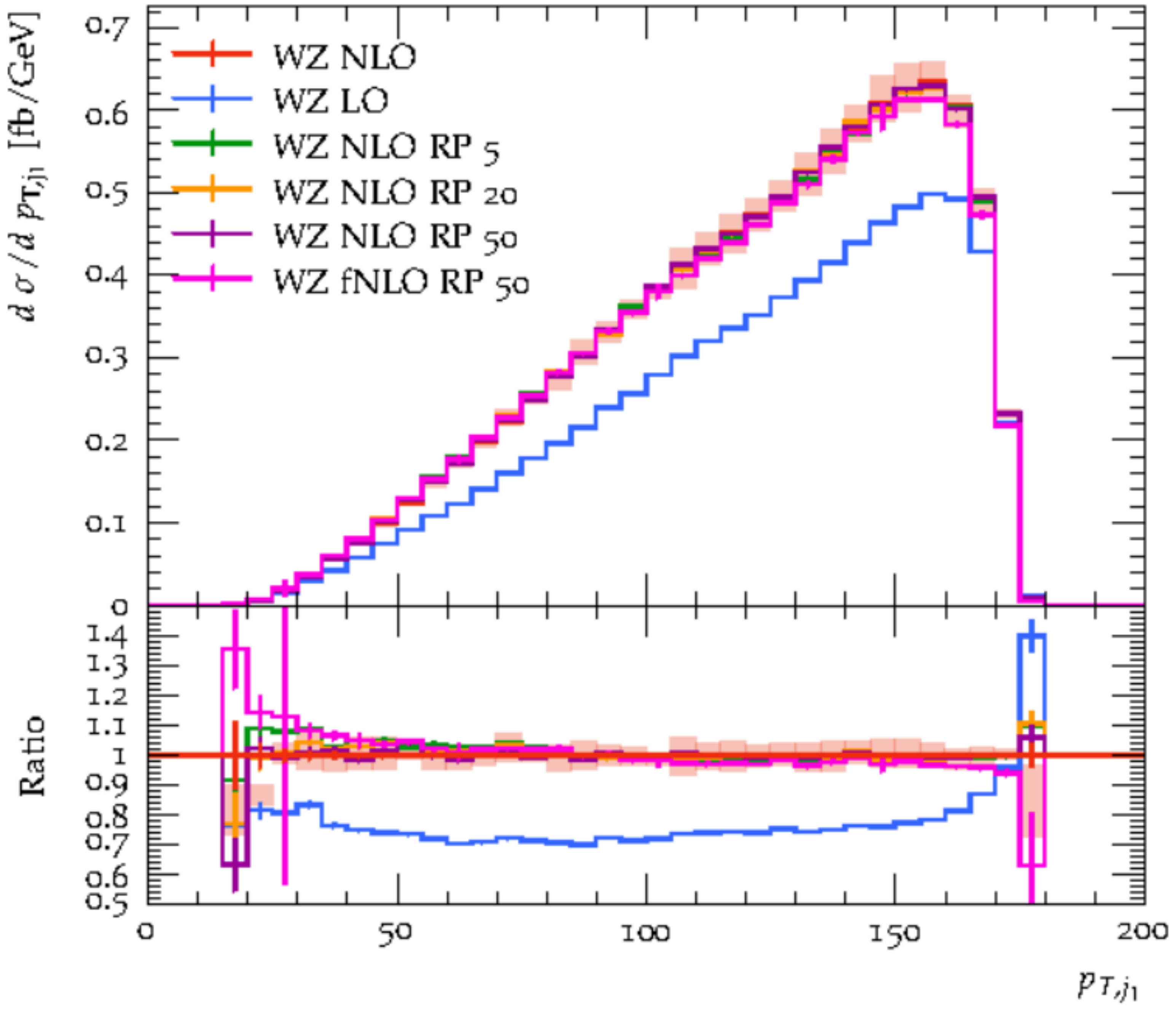


LHC 13 TeV: Drell-Yan $pp \to \ell^+\ell^-$
compared to CMS data

ILC 500: $e^+e^- \to t\bar{t}j$

$$\mu_R = {}^{H_T}/_2 \quad \text{with} \quad H_T := \sum_i \sqrt{p_{T,i}^2 + m_i^2}$$

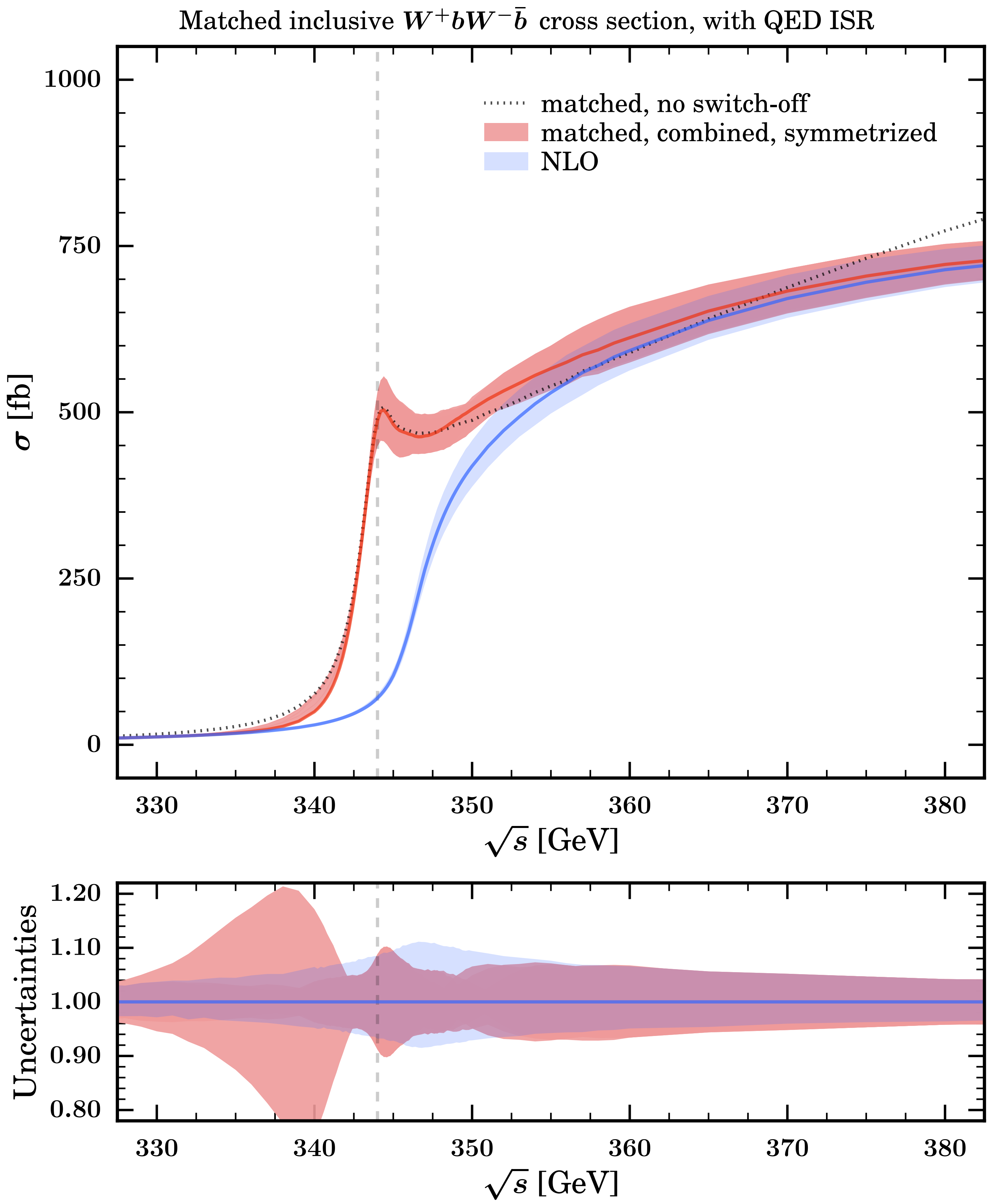


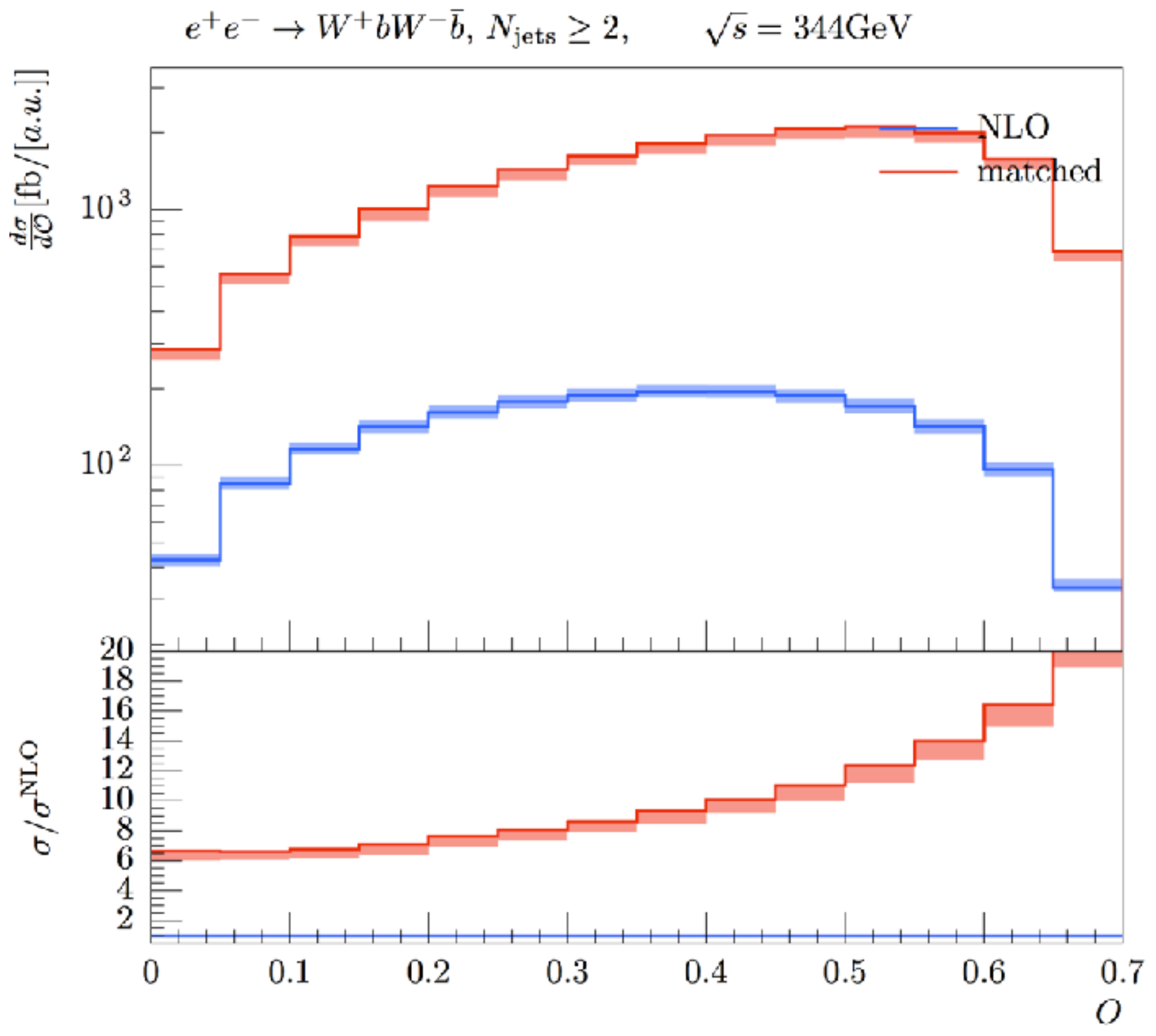


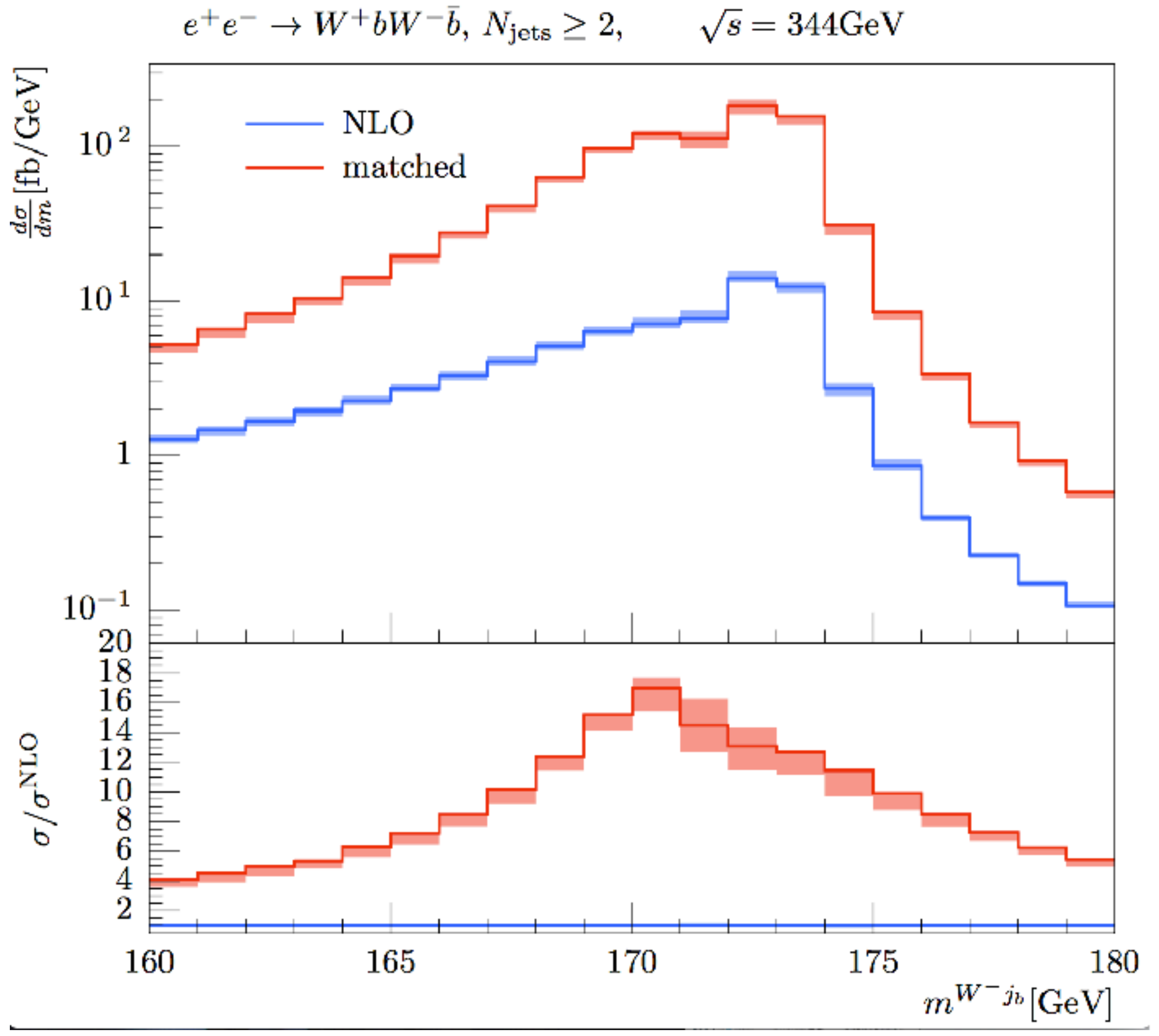
New features, ongoing development

Quick note on the top threshold

- Exclusive Top threshold NLL-NLO QCD matched available
- Implemented for v2.5.1, revalidated in v3.0 parallelized
- Recent improvement in axial form factor matching
- Started to work on this implementation again








```
model = SM_tt_threshold

nrqcd_order = 1
FF = 1    ! NLL resummed
mpole_fixed = 1
Vtb = 1
m1S = 172 GeV
scale = m1S

$method = "threshold"
process eett_threshold = E1, e1 => Wp, Wm, b, B {
  $restrictions = "3+5~t && 4+6~tbar" nlo_calculation = real }

sqrts = 350 GeV
integrate (eett_threshold)
```

Chokoufé/Hoang/Kilian/JRR/Stahlhofen/Teubner/Weiss, 1712.02220

Further work on QED: ePDFs, EW PDFs, QED shower

QED ISR, inclusive part

- Collinear resummation LO/LL — Gribov/Lipatov, 1972; Kuraev/Fadin, 1985; Skrzypek/Jadach, 1992; Cacciari/Deandrea/Montagna/Nicrosini, 1992
- NLO QED PDFs, collinear evolution @ NLL — Frixione, 1909.0388; Bertone/Cacciari/Frixione/Stagnitto, 1911.12040 + 2207.03265; Bertone et al., 2110.xxxxx
- Status in WHIZARD: LO+LL ePDFs fully functional, NLO+NLL ePDFs implemented (incl. NLO QED evol.), validated, functional for Born processes
- Crucial: numerical stability at kinematically peaked limit $z \to 1$
- *Also:* fast interpolation (CTEQ-like) grids available, final infrastructure done, mapping for real radiation component (⇒ no plots yet ☹)

$$d\sigma_{kl}(p_k,p_l) = \sum_{ij=e^+,e^-,\gamma} \int dz_+ dz_- \, \Gamma_{i/k}(z_+,\mu^2,m^2)\,\Gamma_{j/l}(z_-,\mu^2,m^2) \times d\hat\sigma_{ij}(z_+p_k, z_-p_l,\mu^2) + \mathcal{O}\left(\left(\frac{m^2}{s}\right)^p\right)$$

$$\mathbb{P}_{\rm S} = \begin{pmatrix} P_{\Sigma\Sigma} & P_{\Sigma\gamma} \\ P_{\gamma\Sigma} & P_{\gamma\gamma} \end{pmatrix},$$

$$P_{\rm NS} = P_{e^\pm e^\pm} - P_{e^\pm e^\mp} \equiv P^{\rm V}_{ee} - P^{\rm V}_{e\bar e}\,.$$

```
Q = 10 GeV, NLL, alpha running:

ePDF (x = 0.900, S/GAM/NS) =     0.460772     0.023594     0.460727
ePDF (x = 0.950, S/GAM/NS) =     0.986551     0.021590     0.986529
ePDF (x = 0.990, S/GAM/NS) =     5.283617     0.019256     5.283613
ePDF (x = 0.999, S/GAM/NS) =    53.973578     0.016663    53.973578

Check singlet-nonsinglet linear combination

ePDF (x = 0.950, e- - [S + NS]/2) =     0.000000
ePDF (x = 0.950, e+ - [S - NS]/2) =     0.000000
```

ePDFs for polarized leptons !?

QED ISR [+FSR], exclusive part

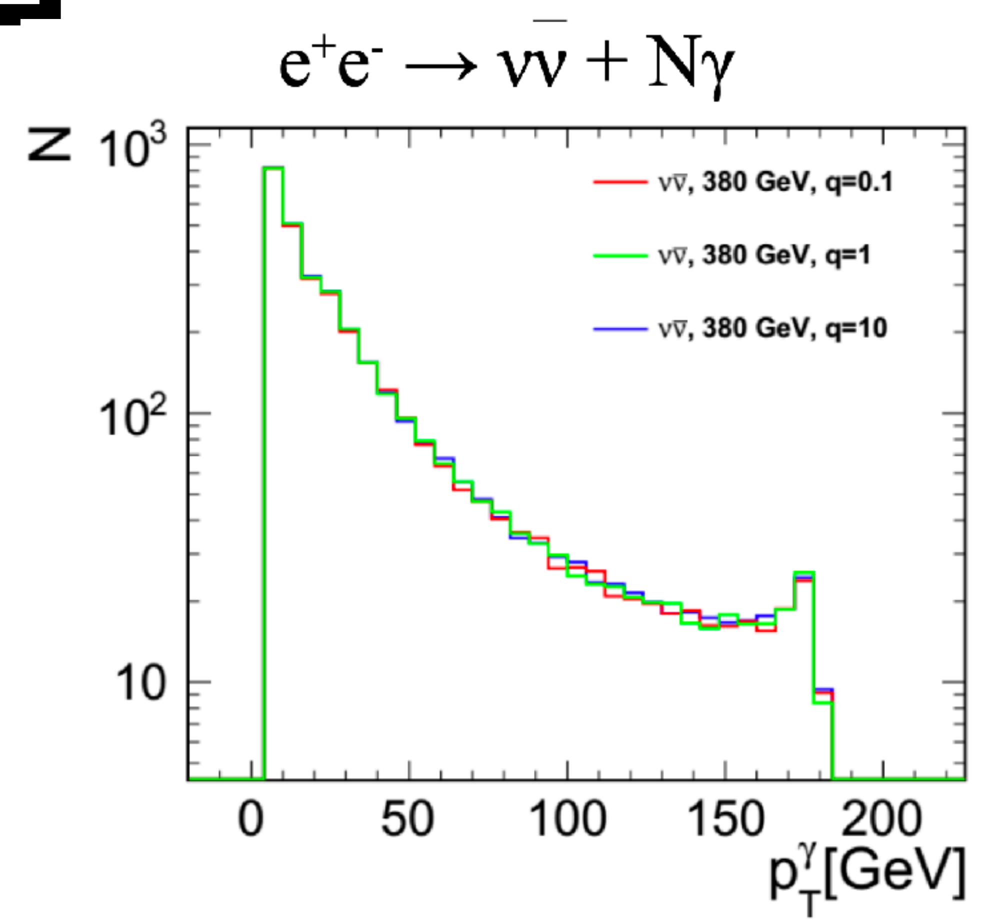
↪ Talk by Alan Price

- Soft resummation + exclusive photons: Yennie/Frautschi/Suura, 1961; Jadach/Ward/Yost, hep-ph/0006359/0103163+0104049+0211132+0602197+1409.4171, Piccinini ea.; Krauss/Price/Schönherr, 2203.10948
- Infrastructure in WHIZARD has started — W. Kilian, K. Mękała, M. Löschner, JRR, T. Striegl

QED showers + matching: EW PDFs + EW shower

QED ISR [+FSR], matching

- "Shower-recoil approach": generate $p_\perp$ according to $\frac{\alpha}{\pi} \cdot \log \frac{p_\perp^2}{m_e^2}$
- Boost according to the generated $p_\perp$ (avail. for for ISR, EPA or ISR+EPA)
- Algorithm applied recursively (similar to massive NLO EWISR PS construction)
- Recursive algorithm resembles a photon shower with *n* exclusive photons
- Implementation is starting W. Kilian/JRR/T. Striegl



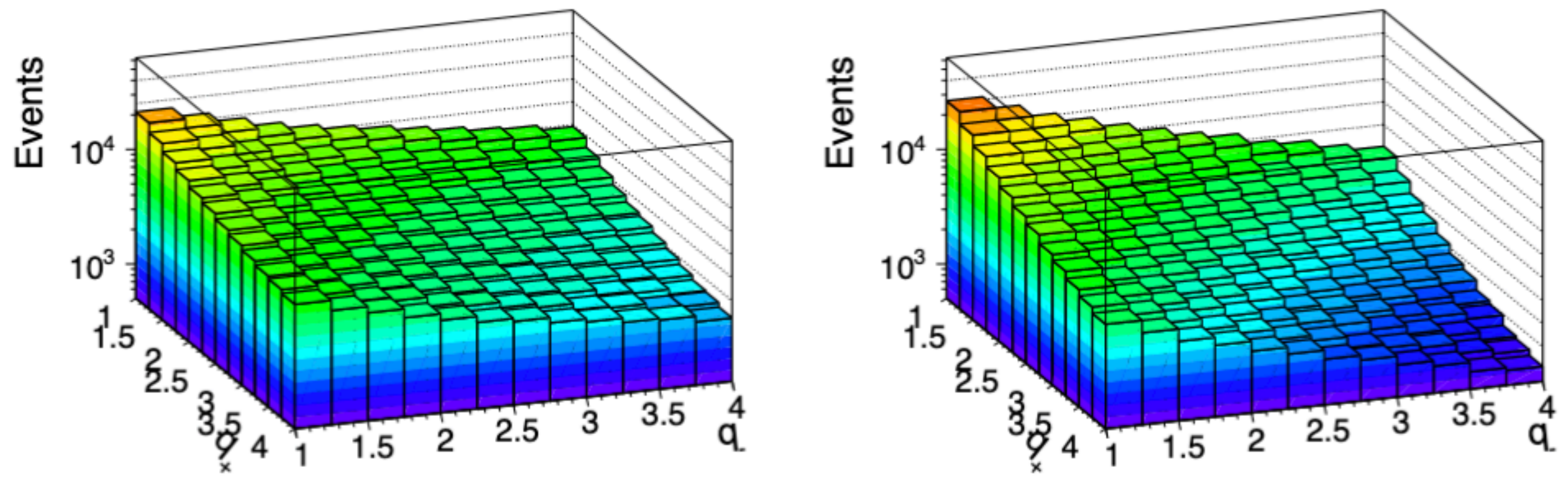
Full QED shower

- Based either on dipoles or antennae
- Can then be combined with POWHEG-type matching
- Implementation is starting [building on code infrastructure of `WHIZARD` QCD (virt.) shower]

Kalinowski/Kotlarski/Mękała/Sopicki/Żarnecki, 2020

Matching between EPA+beam γ

Matching real photons (beam spectra) and virtual photons (EPA) M. Berggren/W. Kilian/K. Mękała/JRR



(a) Double EPA (b) Full matrix elements

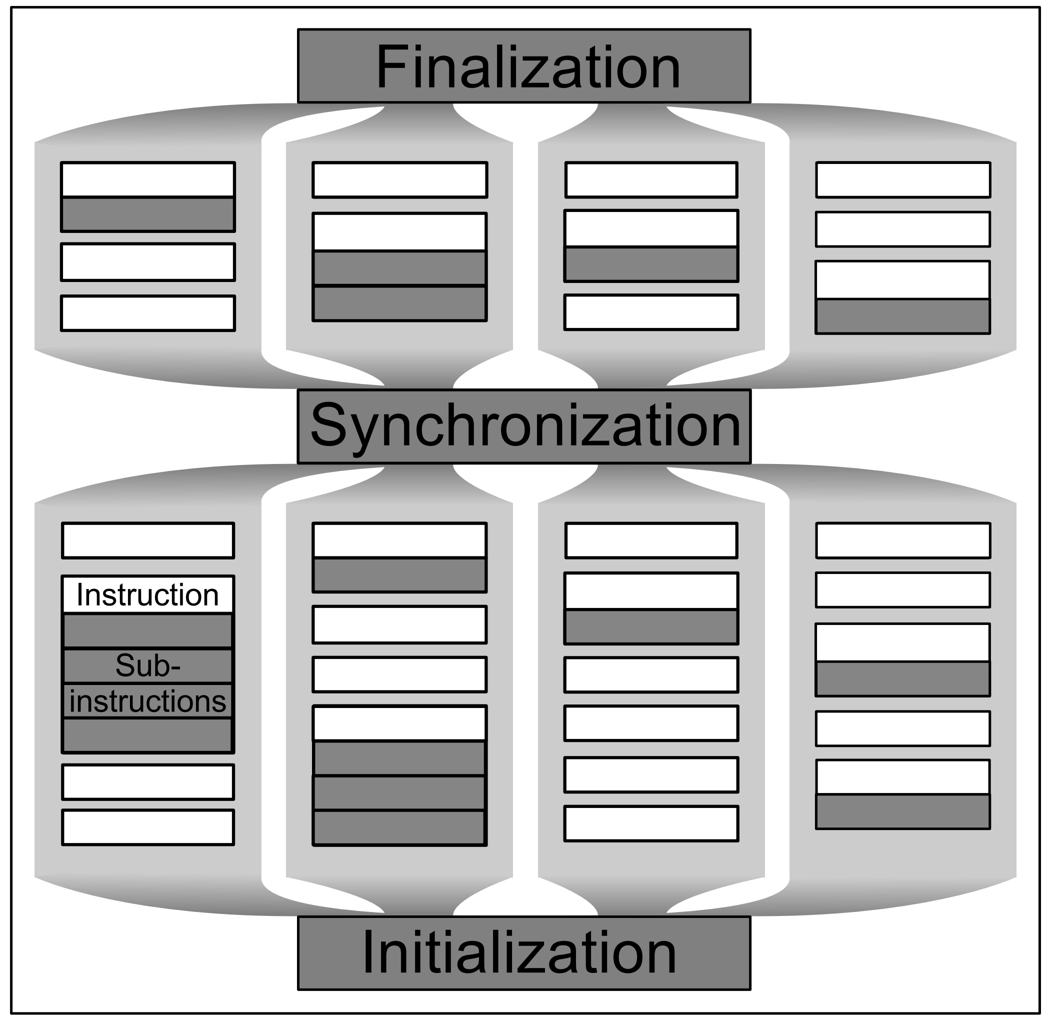
EW PDFs

- At very high energies ($ee/\mu\mu$) [cf. Talk M. Peskin] EW PDFs are needed: *w.i.p.* T. Han/K. Mękała/JRR/K. Xie

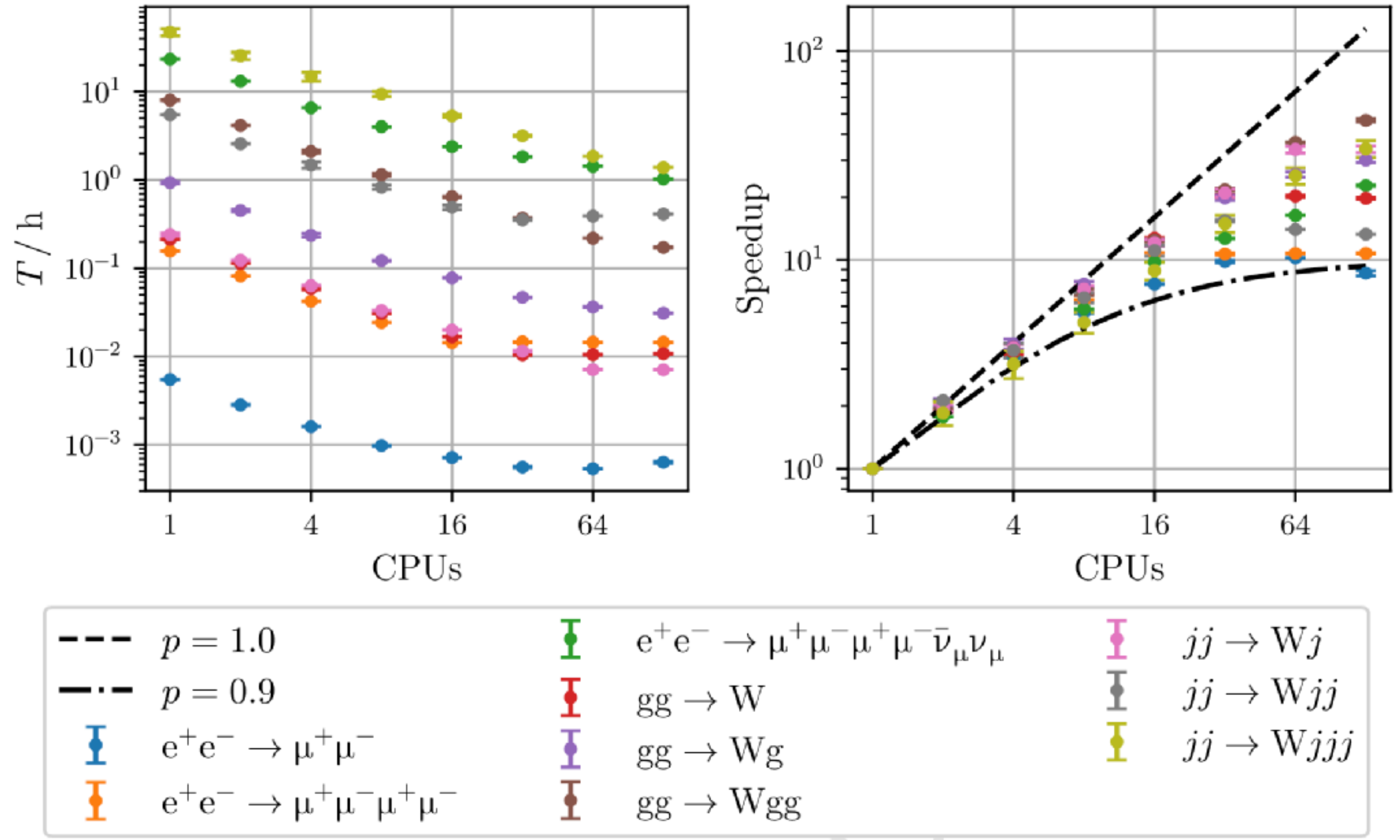
WHIZARD in parallel

WHIZARD MC Integrators:

- VAMP: adaptive multi-channel Monte Carlo integrator
- VAMP2: fully MPI-parallelized version, using RNG stream generator
- [VXInt: new adaptive generator + integrator based on normalizing flows]
  - (w.i.p first as a stand-alone tool)

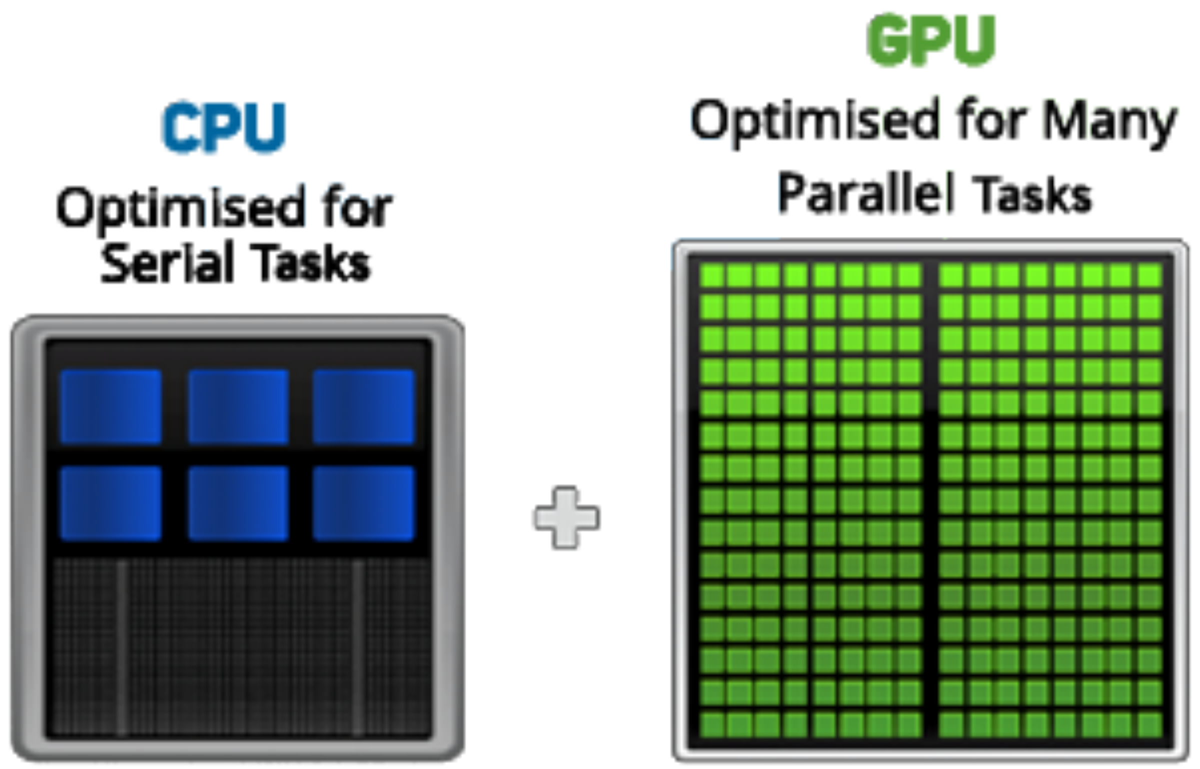


Braß/Kilian/JRR, arXiv:1811.09711



- Parallelization of integration: OMP multi-threading for different helicities
- MPI parallelization (using OpenMPI or MPICH)
- Distributes workers over multiple cores, grid adaption needs non-trivial communication
- Speedups of 10 to 30, saturation at O(100) tasks [can do also parallel event generation]
- Load balancer / non-blocking communication [v3.0.0]

WHIZARD on GPUs



- Joint project with former Phd student; now works for NEC supercomputers
- Main core serial (or MPI-parallel) on CPU, matrix elements as libraries off-loaded to GPU
- (Semi-) automatized ME generator exists for amplitudes on GPU
- First tests very simplistic: no fine-tuning, no sophisticated optimization of communication
- Moderate speed-ups can be seen for more complicated processes

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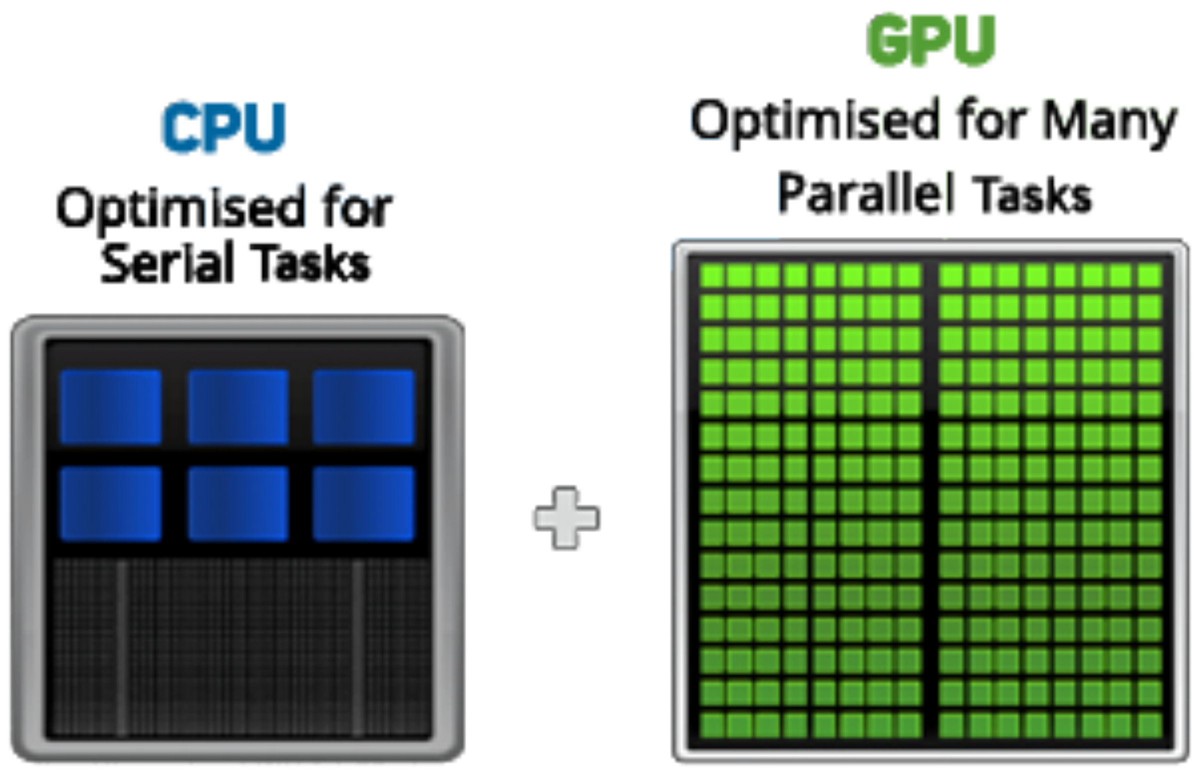

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Very preliminary:

Process	$t^{CPU}[s]$	$t^{GPU}[s]$
$e^+e^- \to t\bar{t}$	0.98	4.28
$e^+e^- \to bW^+\bar{b}W^-$	28.8	23.1
$e^+e^- \to bW^+\bar{b}W^-H$	57.5	37.8
$e^+e^- \to b\bar{b}\bar{\nu}_e e^-\bar{\nu}_\mu\mu^+$	154	124
$e^+e^- \to 2j$	1.9	5.4
$e^+e^- \to 3j$	45	65
$e^+e^- \to 4j$	870	608
$e^+e^- \to 5j$	4106	978
$pp \to jj$	42	86
$pp \to W^+W^-W^+W^-$	670	192

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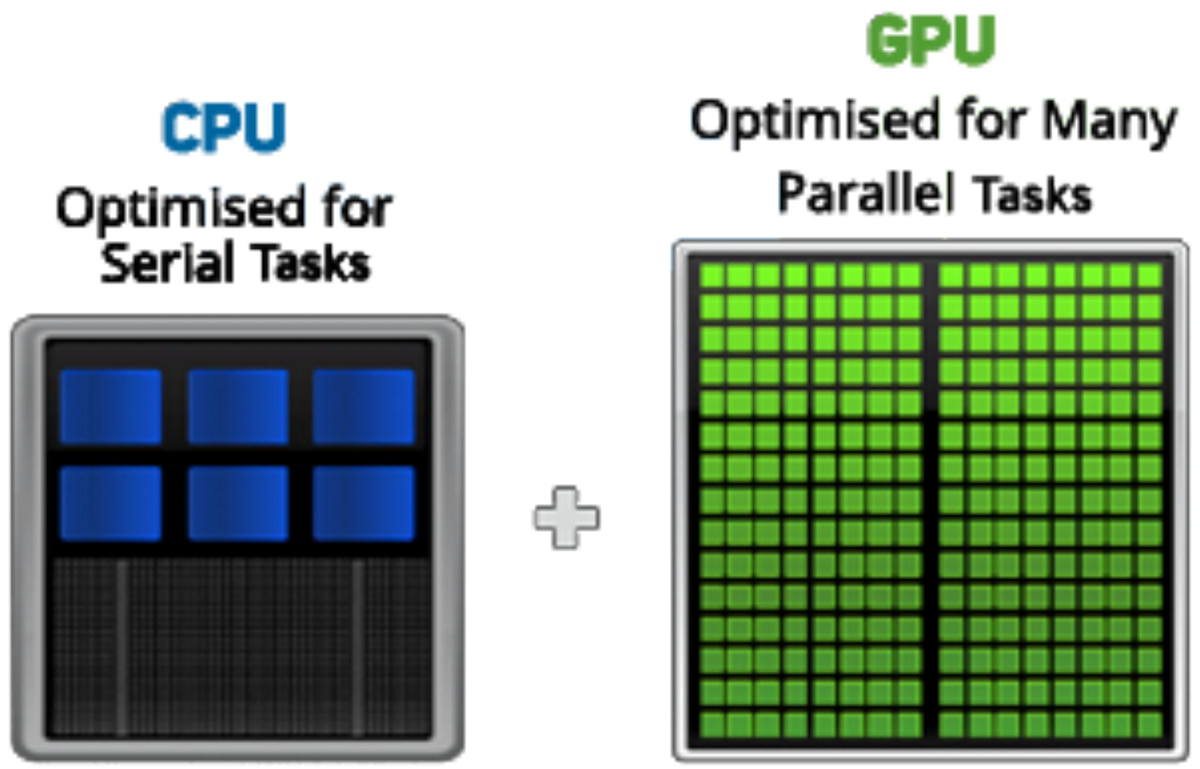

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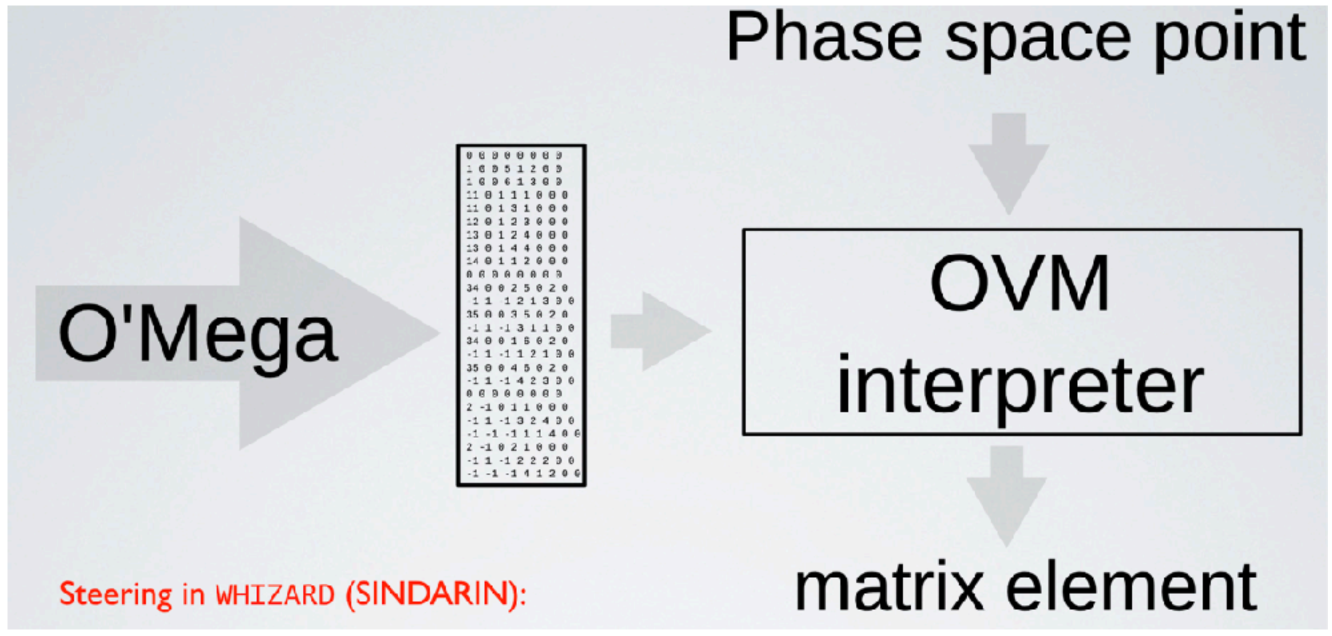

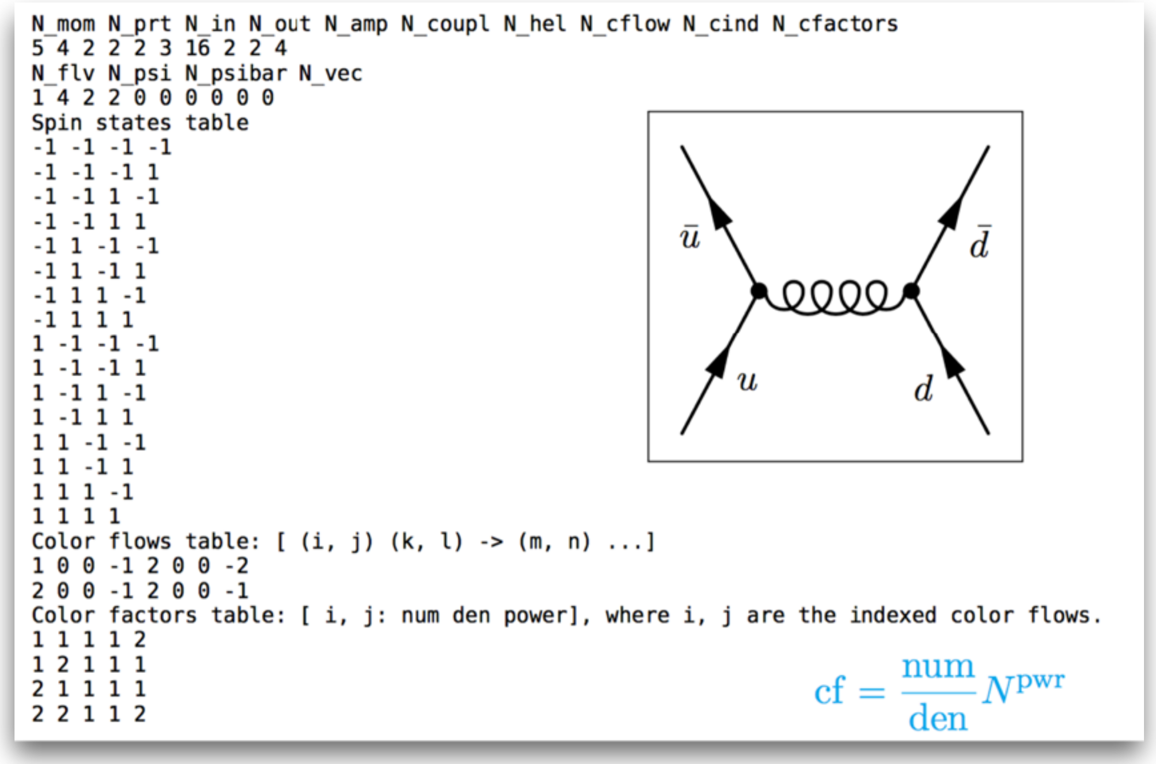

- Potential to combine with `O'Mega virtual machine (OVM)`
- Much smaller code size, no compilation time, ideally suited for GPU

process	BC size	Fortran size	t_{compile}
$gg \to gggggg$	428 MB	4.0 GB	-
$gg \to ggggg$	9.4 MB	85 MB	483(18) s
$gg \to q\bar{q}q'\bar{q}'q''\bar{q}''g$	3.2 MB	27 MB	166(15) s
$e^+e^- \to e^+e^-e^+e^-e^+e^-e^+e^-e^+e^-$	0.7 MB	1.9 MB	32.46(13) s

Simulation framework / bug fixes / new features

News on technicalities, work in progress, started projects:

- Interface to PYTHIA8: Simon Braß, 2019 Event record exchanged to WHIZARD , (piping via LHE of course always works!) seems to work, bug fixes for shower history and decay vertices; some information missing (resonance history lost in translation) ↪ Talk by Zhijie Zhao
- Bug fix (in `v3.0.0`) for PDFs with asymmetric beams; LHeC/FCC-eh: special PYTHIA6 interface setup
- HALHF: 500 GeV plasma e^- on 31 GeV e^+: some asymmetric quirks in PYTHIA6, interface to PYTHIA8 appears to work pending some technical issues M. Berggren/K. Mękała / JRR / Z. Zhao [↪ Talk by Brian Foster]
- Issue resolved for Z pole running: numerical failure + technical bug fixed (led to artificial shift/jump in cross section)
- Simulation of LLP (long-lived particles) / displaced vertices, also with oscillations of particles (just started)
- Technically allow for muon collider beam spectra (not yet produced for WHIZARD/CIRCE2)
- Bugfix: full ILC MC mass production files can be recasted (since `WHIZARD v3.0.1`)
- `WHIZARD v3.0.2`: SINDARIN now has `sum` and `prod` – `let scale = sum sqrt[Pt^2 + M^2] [t:T:j]`

Conclusions & Outlook

- Take-home message: `WHIZARD` is a full-fledged NLO Monte Carlo generator
- Highlights: NLO EW / NLO QCD for lepton colliders, NLO EW/QCD mixed corrections at LHC
- Loop-induced processes
- Generic POWHEG-type matching for NLO QCD ready, for NLO QED/EW starting
- Recently lot of improvement on UFO interface: color structures, fermion-number violating models, SMEFT
- New upcoming feature: displaced vertices / LLP
- Many ongoing projects at different frontiers:
  finalizing NLO+NLL ePDFs, w.i.p. Soft resummation, QED showers, EW PDFs, preparing for HALHF
- Caveat: only few plots yet due to severe person-power issues