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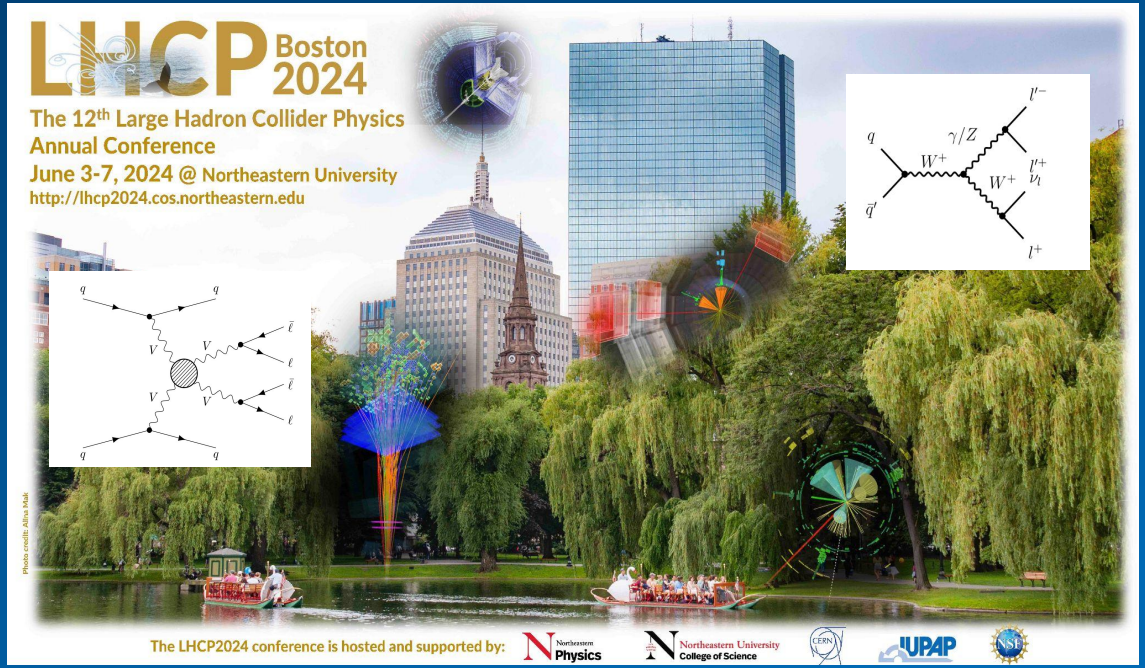
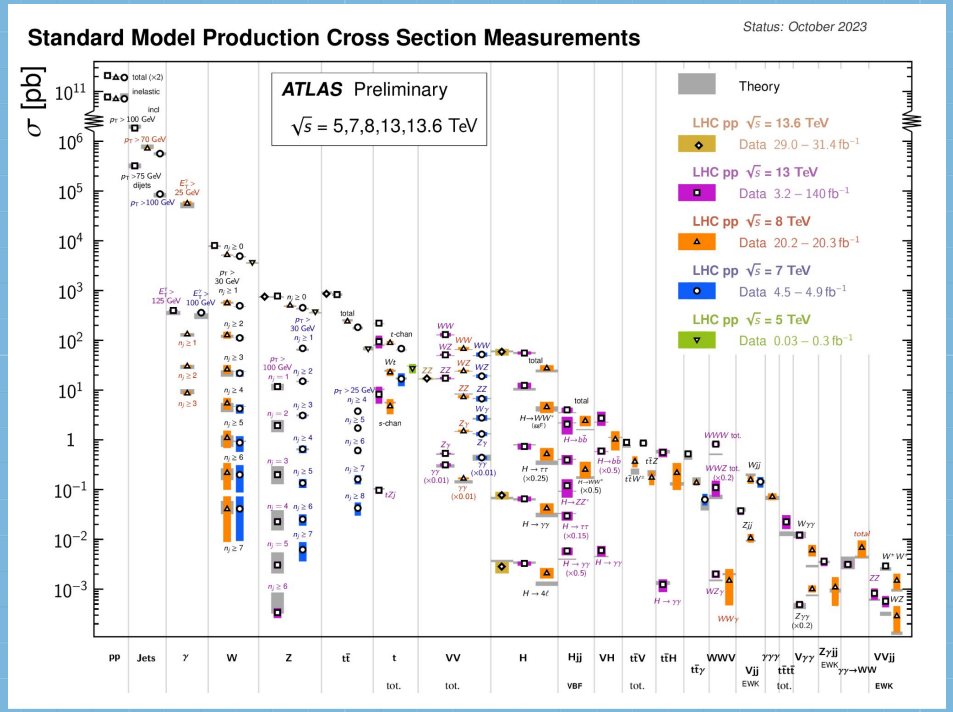
Theory of Diboson production -

Polarized & Unpolarized



Why Diboson production?



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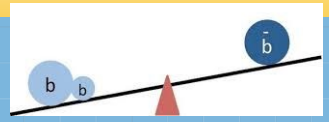

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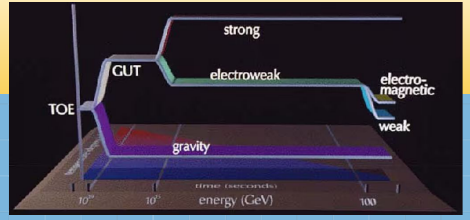

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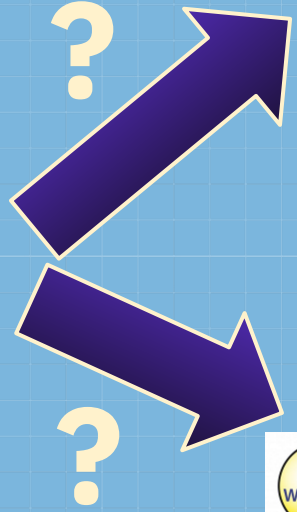

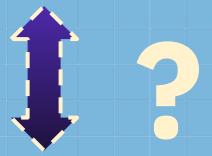

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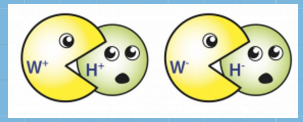

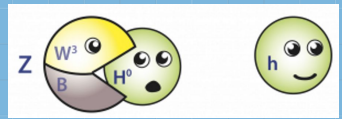

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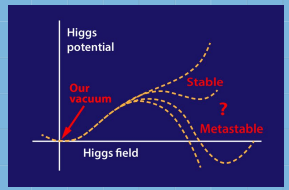

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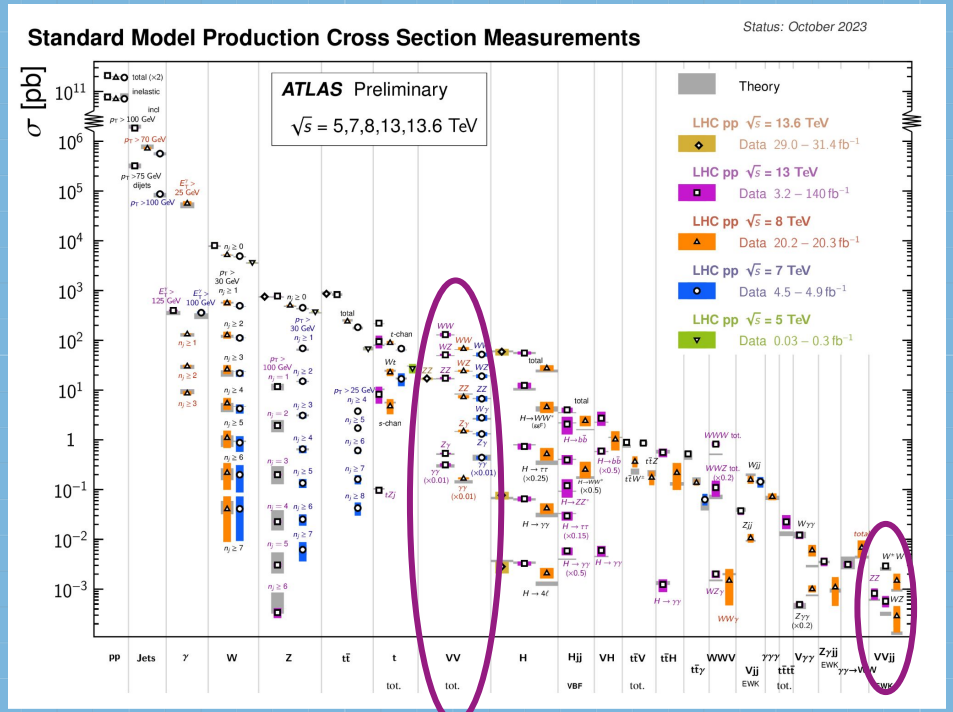
Why Diboson production?



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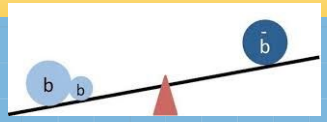

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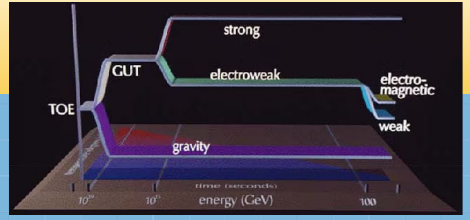

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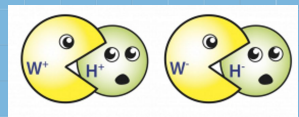
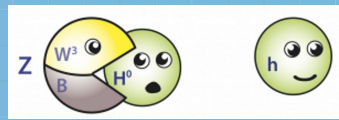


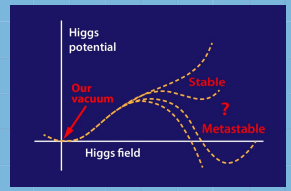


[7]

Inclusive Diboson production

Vector boson scattering

[6]

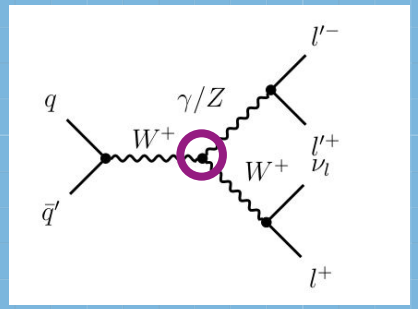


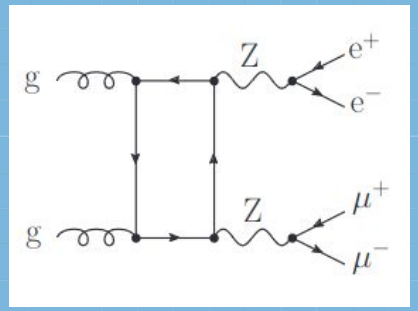
[5]

Diboson production?

Inclusive Diboson production

- ★ production of two VBs **without** any FS jets @LO
- ★ electroweak LO production + decay: $O(\alpha^4)$

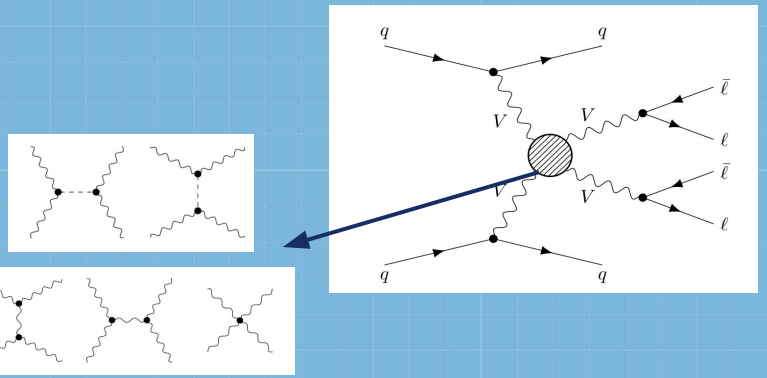




- ➢ **probes of triple gauge coupling**
- ➢ **important background for many analyses e.g. Higgs production**

Vector boson scattering

- ★ production of two VBs with **two** FS jets @LO
- ★ electroweak LO production + decay: $O(\alpha^6)$

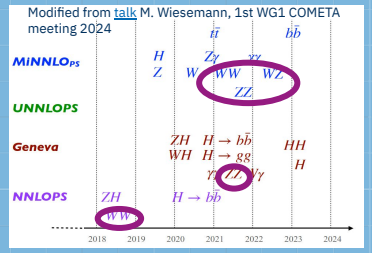


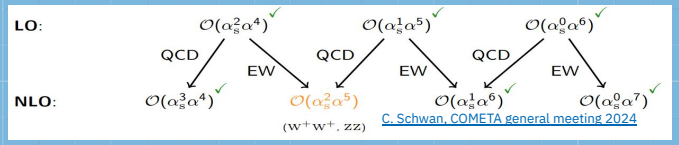
- ➢ **probes of triple & quartic gauge coupling**
- ➢ **probes of HVV coupling**
- ➢ **test of EW symmetry breaking**

Talk outline

Unpolarized Diboson production

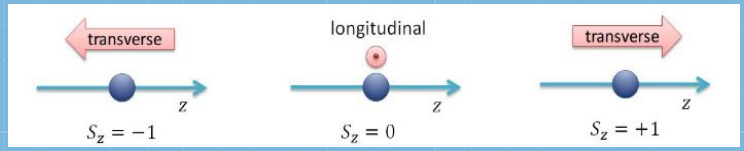
- state of the art in precision calculations
- new recent fixed-order & PS matched calculations





Polarized Diboson production

- state of the art in fixed order precision calculations
- new recent fixed-order calculations
- new tools for simulation of polarization templates with higher order QCD effects matched to PS

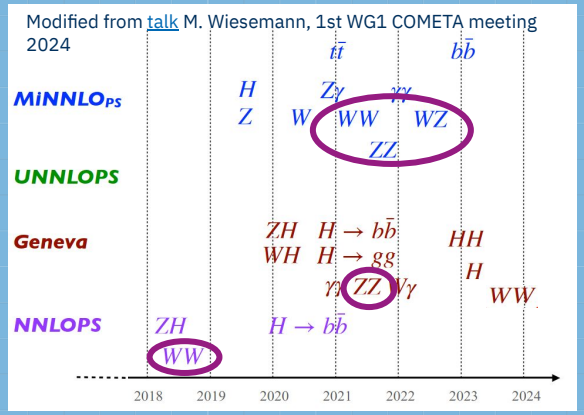


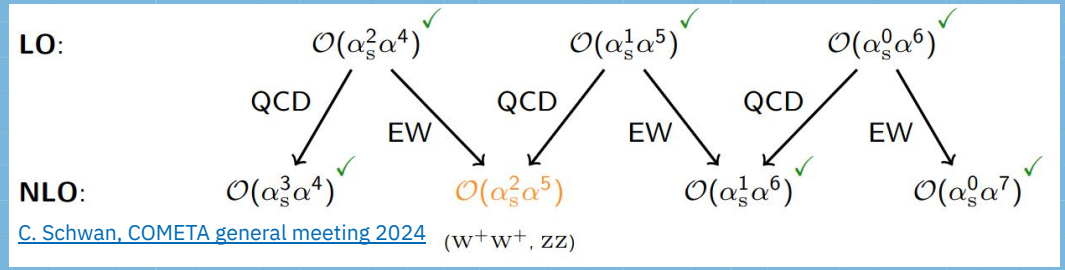
Dr. Z. Zinonos: Tests of the Standard Model of Particles. https://www.mpp.mpg.de/~zinonos/material/lecture10.pdf

Not covered:

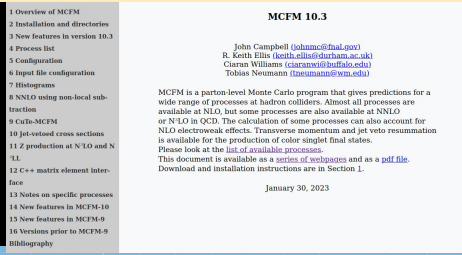
- massless VBs: Vh, Vy, yy, hh studies
- semi-/fully hadronic decays only partly covered
- BSM studies
- quantum entanglement studies in diboson production
- resummation in inclusive diboson production
- interference with off-shell Higgs contribution in gg -> VV at NLO QCD ...

Unpolarized cross sections for diboson production





State-of-the-art - Fixed order



Les Houches wish list 2021 : fully leptonic decays

Process	State-of-the-art
$pp \to VV'$	$\mathrm{NNLO_{QCD}} + \mathrm{NLO_{EW}}$ $+ \mathrm{NLO_{QCD}}$ (gg channel)
$pp \to VV' + 2j$	$\mathrm{NLO_{QCD}}$ (QCD component) $\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$ (EW component)
$pp \to W^+W^+ + 2j$	Full $\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$
$pp \to W^+W^- + 2j$	$\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$ (EW component)
$pp \to W^+Z + 2j$	$\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$ (EW component)
$pp \to ZZ + 2j$	Full $\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$

public available tools:

- MATRIX
- MCFM: QCD calculations

NNLO QCD: [T.Gehrmann et al. 2014; F. Cascioli et al. 2014; M. Grazzini et al. 2015, 2016, 2016, 2017; S. Kallweit & M. Wiesemann 2018; G. Heinrich et al. 2017]

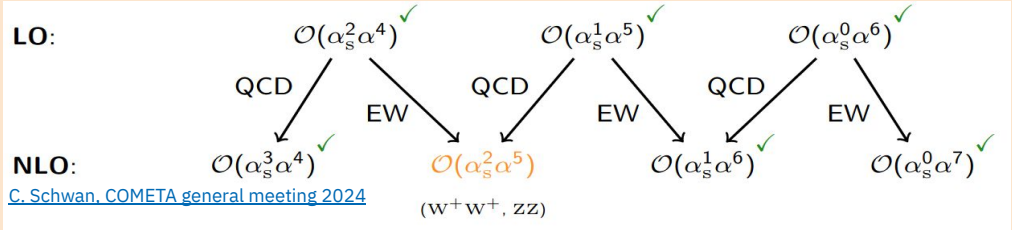
NLO EW: [B. Biedermann et al. 2016, 2016, 2016, 2017; S. Kallweit et al. 2017; M. Chiesa, A. Denner, J.-N. Lang 2018]

NLO QCD (gg channel): [F. Caola et al. 2015, 2015; M. Grazzini et al. 2018, 2020]

NNLO QCD & NLO EW combination: [M. Grazzini et al. 2020]

First NLO VBS offshell calculations:

- **W^+W^+:** [T. Melia et al., 2017], [B. Biedermann, A. Denner, M. Pellen, 2016, 2017]
- **W^+Z:** [F. Campanario et al. 2013 , A. Denner et al. 2019]
- **ZZ:** [F. Campanario et al. 2014, A. Denner et al. 2020, 2021]
- **W^+W^-:** [T. Melia et al. 2011, A. Denner et al. 2022]



C. Schwan, COMETA general meeting 2024

State-of-the-art - FO matched to parton shower

Les Houches wish list 2021 :

Process	State-of-the-art
$pp \to VV'$	NNLO QCD + PS NLO QCD + NLO EW + PS
$pp \to VV' + 2j$ $pp \to W^+W^+ + 2j$ $pp \to W^+W^- + 2j$ $pp \to W^+Z + 2j$ $pp \to ZZ + 2j$	NLO QCD + PS (EW, QCD component), mostly in VBS approximation

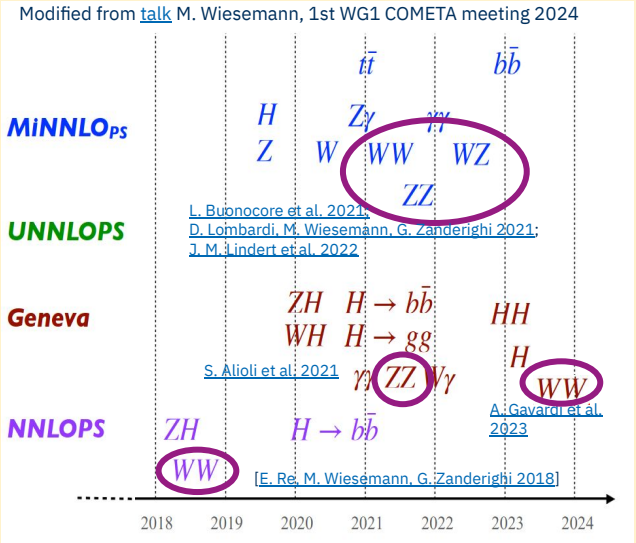
NLO QCD + NLO EW + PS :
Recola2-Collier+POWHEG-BOX-RES+PYTHIA8
[M. Chiesa, C. Oleari, E. Re 2020]

NLO QCD + PS (gg channel):
POWHEG+Pythia8
ZZ: [S. Alioli et al. 2021, L. Buonocore et al. 2021]

NLO QCD + PS + 1,2,3j + approximate NLO EW:
Sherpa+OpenLoops/Recola
WW: [S. Bräuer et al. 2020];
ZZ: [E. Bothmann et al. 2021]

NNLO QCD+PS:

Modified from talk M. Wiesemann, 1st WG1 COMETA meeting 2024



W⁺W⁺ NLO EW (+NLO QCD) (EW component): *POWHEG+Recola+Pythia8* : [M. Chiesa et al. 2019]

NLO QCD (EW, QCD component): mostly with approximations
(VBFNLO, POWHEG, MadGraph5)+Pythia8/Herwig, Sherpa+Recola
[A. Ballestrero et al. 2018], [B. Jäger et al. 2011, 2013, 2013, 2018], [J. Baglio et al. 2014], [M. Rauch & S. Plätzer 2016] ...

Special color flow in PS!
Recent effort to get it right:
[B. Cabouat & T. Sjöstrand 2017]
[A. Ballestrero et al. 2018]
[ATL-PHYS-PUB-2019-004]

Recent progress

Les Houches wish list 2021 : fully leptonic decays

Process	State-of-the-art	Desired
$pp \to VV'$	$\mathrm{NNLO_{QCD}} + \mathrm{NLO_{EW}}$ $+ \mathrm{NLO_{QCD}}$ (gg channel)	$\mathrm{NLO_{QCD}}$ +PS (gg channel, w/ massive loops) $\mathrm{N^{(1,1)}LO_{QCD\otimes EW}}$ +PS
$pp \to VV' + 2j$	$\mathrm{NLO_{QCD}}$ (QCD component) $\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$ (EW component)	Full $\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$ +PS
$pp \to W^+W^+ + 2j$	Full $\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$	
$pp \to W^+W^- + 2j$	$\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$ (EW component)	
$pp \to W^+Z + 2j$	$\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$ (EW component)	
$pp \to ZZ + 2j$	Full $\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$	

Complete NLO QCD in gg->ZZ: B. Agarwall et al. 2024

Virtual QCD corrections to gg->ZZ: top-quark loops from a transverse-momentum expansion: G. Degrassi, R. Gröber, M. Vitti 2024

First WW NNLO+PS result with GENEVA method: A. Gavardi 2023

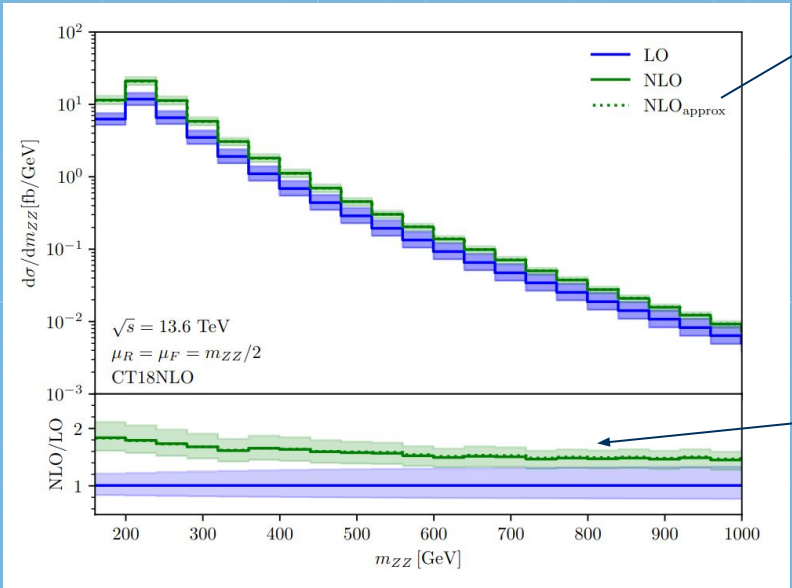
no new results since 07/22
more focus on:

(Semi-) hadronic decays: **NLO QCD for semi- & fully hadronic decays in WZ+2j in POWHEG** B. Jäger, A. Karlberg, S. Reinhardt, 2024

Independent recalculation: **Full NLO tower for WW+ with Bonsay+OpenLoops & study of various approximations** S. Dittmaier et al. 2023

Complete NLO QCD in gluon-induced ZZ production

B. Agarwall et al. 2024



exact for all but massive two-loop virtual amplitude → replaced by rescaled top only Born

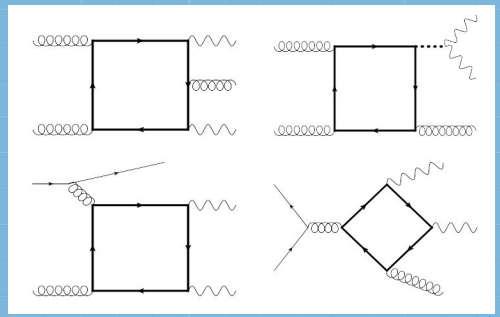
very good agreement between calc with approximate massive effects & full calc even in high mass tails → maybe different for other observables

$$\sigma_{\text{LO}} = 1316^{+23.0\%}_{-18.0\%}\,\text{fb}\,,$$
$$\sigma_{\text{NLO}} = 2275(12)^{+14.0\%}_{-12.0\%}\,\text{fb}\,.$$

huge NLO contribution, but mostly covered by massless calculation (~ -2% diff total XS)

Gluon-induced ZZ production

- **~60%** of NNLO QCD contribution [F. Cascioli et al. 2014]
- NLO corrections = no Z boson couples to external quark lines → well defined
- NLO QCD with massless quarks / approximate massive contribution: **5-8%** increase in total XS [M. Grazzini et al. 2018, F. Caola et al. 2015]



Complete NLO tower for W^+W^+ + 2j with Bonsay+OpenLoops

S. Dittmaier et al. 2023

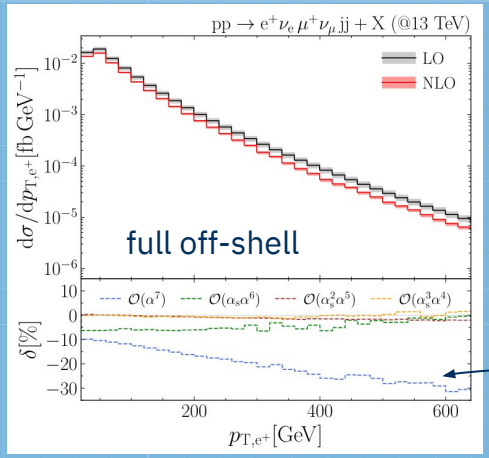
	Order	MOCANLO +RECOLA		BONSAY+OpenLoops
LO	$\mathcal{O}(\alpha^6)$	1.4178(2)	EW	1.41773(5)
	$\mathcal{O}(\alpha^5\alpha_s)$	0.04815(2)	Int	0.048138(3)
	$\mathcal{O}(\alpha^4\alpha_s^2)$	0.17229(5)	QCD	0.17233(2)
NLO	$\mathcal{O}(\alpha^7)$	−0.1732(3)		−0.1728(6)
	$\mathcal{O}(\alpha^6\alpha_s)$	−0.0568(5)		−0.0560(8)
	$\mathcal{O}(\alpha^5\alpha_s^2)$	−0.00032(13)		0.0047(2)
	$\mathcal{O}(\alpha^4\alpha_s^3)$	−0.0063(4)		−0.0073(2)

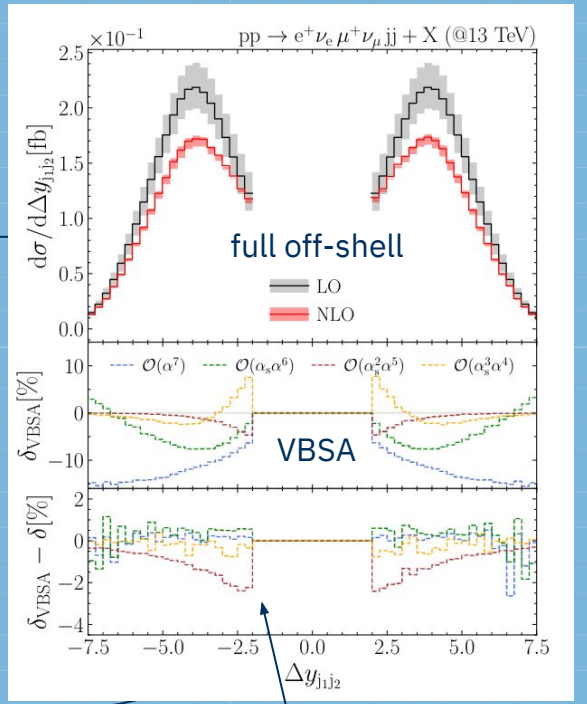
EW-induced contribution dominates in VBS phase space

large EW corrections (>-12%)

very good agreement for leading contributions

inconsistency with previous calculation





VBSA: VBS approximation + DPA for virtual corrections
→ ~10 times faster
EVA: effective VB approximation not suitable for LHC precision

diff ≤1.5% dominant phase space regions, even better with only DPA

Electroweak Sudakov approximation

- NLO EW corrections more & more important to reach precision targets
- complete NLO EW calculation possible, but not always feasible
- possible approximation: **EW Sudakov logarithms**

  [A. Denner & S. Pozzorini 2001, 2001]

  ➢ NLO EW logarithmically enhanced for energies above EW scale

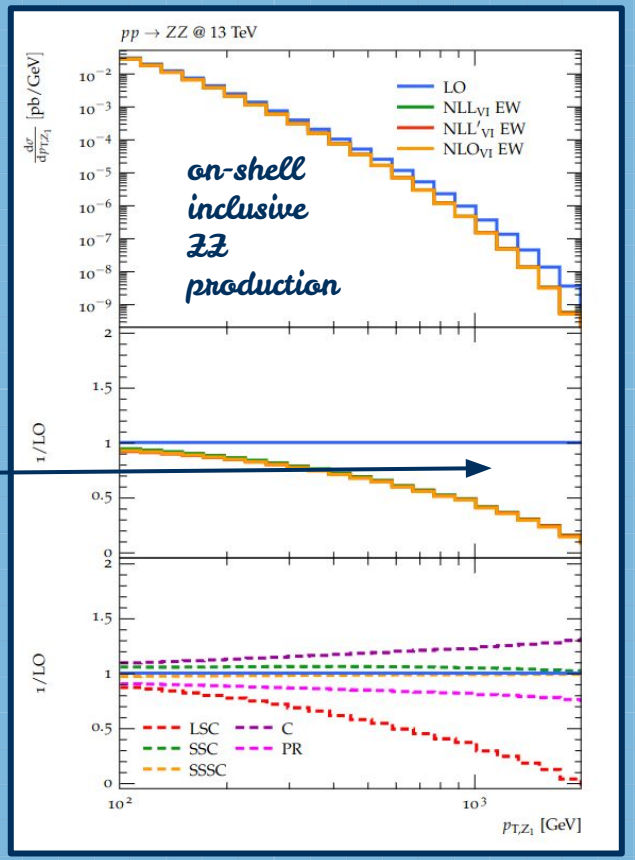
  ➢ large contributions in tails of kinematic distributions

- automated in SHERPA & MadGraph

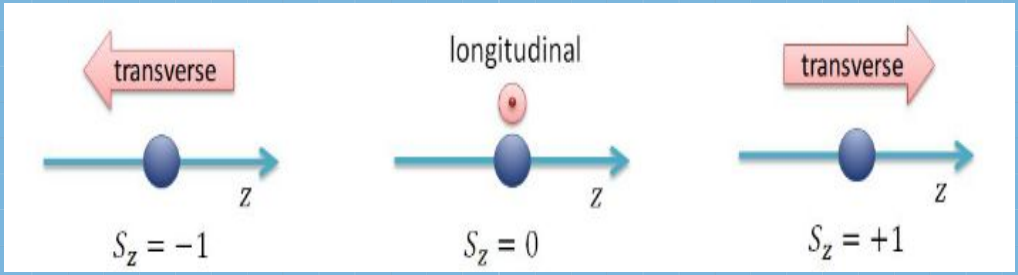
  [E. Bothmann & D. Napoletano 2020]
  [D. Pagani & M. Zaro 2021, D. Pagani, T. Vitos & M. Zaro 2023]

- **recently enabled in OpenLoops** [J. M. Lindert & L. Mai 2023]
  - extensive validation incl. inclusive diboson production
  - comparison with NLO_{VI}EW approximation

    [S. Kallweit et al. 2015]



Polarized cross sections for diboson production



Dr. Z. Zinonos: Tests of the Standard Model of Particles. https://www.mpp.mpg.de/~zinonos/material/lecture10.pdf

How to measure vector boson polarization …

Traditional idea / LHC Run 1 strategy

- at tree-level, polarization in helicity basis, no cuts on decay products, massless leptonic decays
  [Z. Bern et al. 2011, A. Ballestrero et al. 2018]

$$\frac{1}{\frac{d\sigma(X)}{dX}}\frac{d\sigma(\theta^*,X)}{d\cos\theta^* dX} = \frac{3}{8}f_L(X)\left(1+\cos^2\theta^* \mp \frac{2(c_L^2-c_R^2)}{(c_L^2+c_R^2)}\cos\theta^*\right) + \frac{3}{8}f_R(X)\left(1+\cos^2\theta^* \pm \frac{2(c_L^2-c_R^2)}{(c_L^2+c_R^2)}\cos\theta^*\right) + \frac{3}{4}f_0(X)\sin^2\theta^*$$

with lepton decay angle θ^*: angle between lepton momentum in VB rest frame and VB momentum in some Lorentz frame

- **idea:** extract $\{f_i\}$ from unpolarized distribution with projections on Legendre polynomials or via fits

Problems:

- *lepton selection criteria* spoil factorization of angular dependence of decay angle and other variables X
- decomposition breaks up for *higher order corrections to decay*
- *W rest frame* difficult to reconstruct

Solution / LHC Run 2 strategy

- fit with polarized templates from MC simulation

Separate templates!

$$\frac{\mathrm{d}\sigma}{\mathrm{d}X} = f_L\frac{\mathrm{d}\sigma_L}{\mathrm{d}X} + f_R\frac{\mathrm{d}\sigma_R}{\mathrm{d}X} + f_0\frac{\mathrm{d}\sigma_0}{\mathrm{d}X}\left(+f_{int.}\frac{\mathrm{d}\sigma_{int.}}{\mathrm{d}X}\right)$$

Fully exclusive events for polarized cross sections - Theoretical caveats

$$\frac{\mathrm{d}\sigma}{\mathrm{d}X} = f_L \frac{\mathrm{d}\sigma_L}{\mathrm{d}X} + f_R \frac{\mathrm{d}\sigma_R}{\mathrm{d}X} + f_0 \frac{\mathrm{d}\sigma_0}{\mathrm{d}X} \left(+ f_{int.} \frac{\mathrm{d}\sigma_{int.}}{\mathrm{d}X} \right)$$

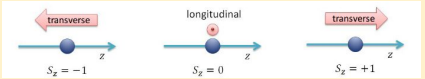
Polarization for intermediate particles

- completeness relation

$$\left(-g^{\mu\nu} + \frac{q^\mu q^\nu}{m_V^2}\right) = \sum_\lambda \quad \varepsilon^\mu(q,\lambda)\varepsilon^{*\nu}(q,\lambda)$$

- lead to interferences between different polarizations

Polarization basis



Dr. Z. Zinonos: Tests of the Standard Model of Particles. https://www.mpp.mpg.de/~zinonos/material/lecture10.pdf

- helicity basis

$$\varepsilon_\pm^\mu(q) = \frac{e^{\mp i\phi}}{\sqrt{2}}(0,\ -\cos\theta\cos\phi \pm i\sin\phi,\ -\cos\theta\sin\phi \mp i\cos\phi,\ \sin\theta)$$

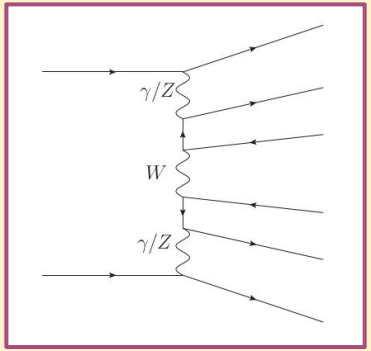
$$\varepsilon_0^\mu(q) = \frac{q^0}{m}\left(\frac{|\vec{q}|}{q^0}, \cos\phi\sin\theta, \sin\phi\sin\theta, \cos\theta\right)$$

- frame dependent!

Polarization only defined in production ⊗ propagator ⊗ decay factorizable amplitudes

- problem: non-resonant diagrams
  → no polarisation definition, but necessary for gauge invariance

- **solution:** appropriate approximations - gauge invariant options:
  - Pole Approximation ((D)PA)
  - Narrow-Width Approximation (NWA)



Fixed-order phenomenological landscape

Polarization frames: Lab, COM, Lab & COM

Inclusive Diboson production

Fully leptonic decays: NLO QCD + NLO EW

Large NLO QCD effects on pol due to RAZ @LO

WZ: [D.N. Le, J. Baglio 2022, D.N. Le, J. Baglio, T.N. Dao 2022], [A. Denner & G. Pellicioli 2020]

ZZ: [A. Denner & G. Pellicioli 2021]

W^+W^-: [A. Denner & G. Pellicioli 2020, A. Denner, C. Haitz, G. Pellicioli 2023, T.N. Dao & D.N. Le 2023], [R. Poncelet & A. Popescu 2021]

Semi-leptonic decays: increasing interest very recently

WZ: NLO QCD [A. Denner, C. Haitz, G. Pellicioli 2022]

new!

NNLO QCD

Vector boson scattering

Fully leptonic decays: LO

WW: [A. Ballestrero, E. Maina, G. Pelliccioli, 2017], [A. Ballestrero, E. Maina, G. Pelliccioli, 2020]

WZ: [A. Ballestrero, E. Maina, G. Pelliccioli, 2019]

ZZ: [A. Ballestrero, E. Maina, G. Pelliccioli, 2019]

Semi-leptonic decays: conceptually possible, but not well studied

all calculations in DPA

Generator landscape

- **several private fixed-order tools:**
  - RECOLA+MOCANLO/BBMC
  - AvH+OpenLoops+STRIPPER
  - ...

- **public codes & predictions matched to PS:**
  - ***PHANTOM***: 2->6 processes @ LO+PS [A. Ballestrero et al. 2008, 2017]
  - ***MG5_aMC@NLO***: arbitrary processes @ LO+ PS, multi-jet merging [D. Buarque Franzosi et al. 2020, M. Javurkova et al. 2024]

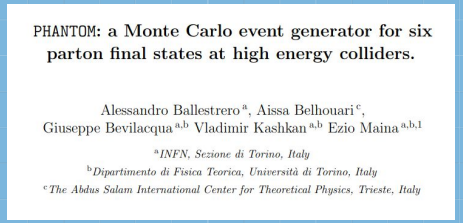
DPA

truncated propagator

NWA

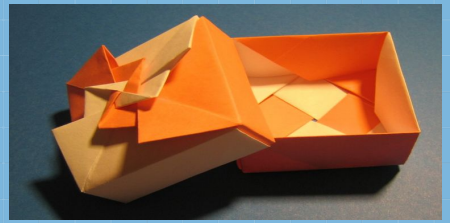
new

- ***SHERPA:*** arbitrary processes @nLO QCD+PS, multi-jet merging [MH, M. Schönherr, F. Siegert 2023]
- ***POWHEG-BOX-RES+PYTHIA:*** inclusive diboson processes @NLO QCD+PS [G. Pelliccioli, G. Zanderighi 2023]


PHANTOM: a Monte Carlo event generator for six parton final states at high energy colliders.

Alessandro Ballestrero[a], Aissa Belhouari[c], Giuseppe Bevilacqua[a,b] Vladimir Kashkan[a,b] Ezio Maina[a,b,1]

[a]INFN, Sezione di Torino, Italy
[b]Dipartimento di Fisica Teorica, Università di Torino, Italy
[c]The Abdus Salam International Center for Theoretical Physics, Trieste, Italy



New polarization frameworks beyond LO - SHERPA

[MH, M. Schönherr, F. Siegert, 2023]

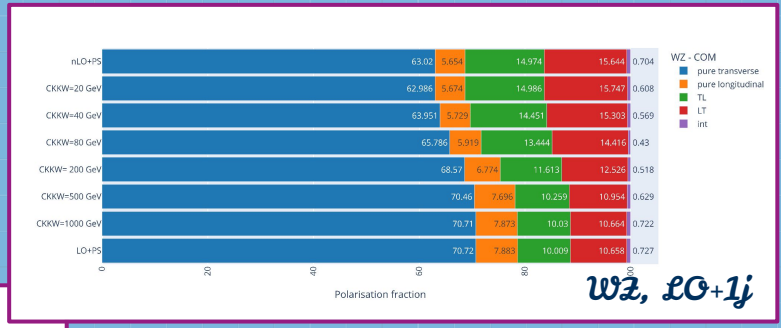
Methodology: unpolarized simulation run, polarized XS as event weights

➢ all polarization combinations, interferences, reference frames in one simulation run

Processes: arbitrary processes with intermediate vector bosons

Order: nLO QCD +PS for VB production, multi-leg merging

➢ nLO: approximation for calculation of polarization fractions:



Born amplitude tensor
no virtual
ultra-collinear/-soft
corrections

Amplitude tensor of
real correction

$$\langle O\rangle^{(\mathrm{NLOMC})} = \sum_{\{\vec{f}\}}\int \mathrm{d}\Phi_B(\{\vec{p}\})\,\bar{\mathrm{B}}^{(\mathrm{A})}(\{\vec{a}\})\left[\underbrace{\bar{\Delta}^{(\mathrm{A})}(t_0;\{\vec{a}\})}_{\text{unresolved}}\,O(\{\vec{p}\})\right.$$

$$+\sum_{\{\tilde{ij},\tilde{k}\}}\sum_{F_i=q,g}\int \mathrm{d}\Phi^{ij,k}_{R|B}\;\Theta(t(\Phi^{ij,k}_{R|B})-t_0)\;O(r_{\tilde{ij},\tilde{k}}(\{\vec{p}\}))$$

S-event

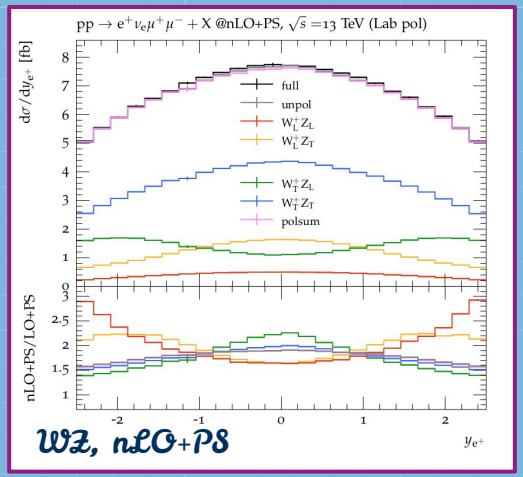
$$\left.\times\underbrace{\frac{1}{S_{ij}}\frac{S(r_{\tilde{ij},\tilde{k}}(F_i;\{\vec{f}\}))}{S(\{\vec{f}\})}\frac{\mathrm{D}^{(\mathrm{A})}_{ij,k}(r_{\tilde{ij},\tilde{k}}(F_i,\Phi^{ij,k}_{R|B};\{\vec{a}\}))}{\mathrm{B}(\{\vec{a}\})}\bar{\Delta}^{(\mathrm{A})}(t;\{\vec{a}\})}_{\text{resolved, singular}}\right]$$

H-event

$$+\sum_{\{\vec{F}\}}\int \mathrm{d}\Phi_R(\{\vec{F}\})\underbrace{\left[\mathrm{R}(\{\vec{A}\})-\sum_{ij,k}\mathrm{D}^{(\mathrm{A})}_{ij,k}(\{\vec{A}\})\right]}_{\text{resolved, non-singular}}O(\{\vec{F}\})\,.$$

Matching: MC@NLO

On-Shell approximation: Narrow-Width Approximation
+ Breit-Wigner Mass-Smearing



First higher order QCD effects for W^+W^+jj

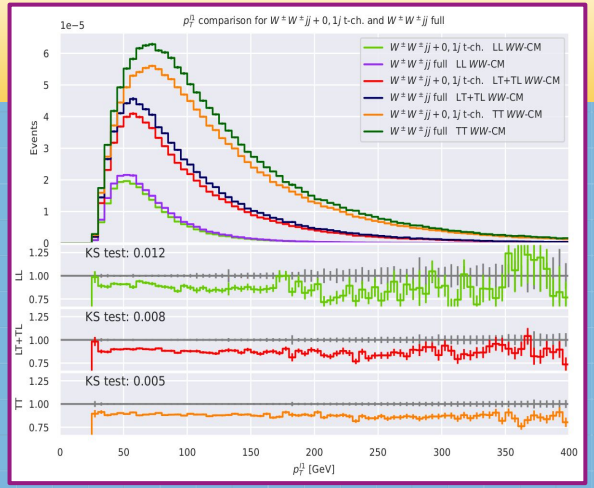
Preliminary results

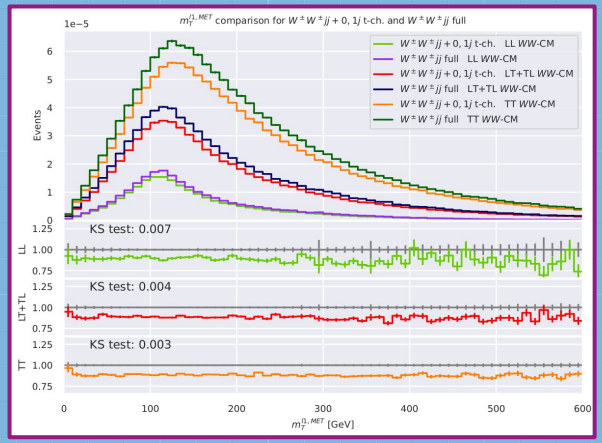
fully leptonic channel, LO+1j simulation in VBS approximation

[MH, M.Stange, to be published]

W^+W^+jj	unpol [fb]	LL [fb]	Fraction [%]	LT+TL [fb]	Fraction [%]	TT [fb]	Fraction [%]
LO+PS	2.459	0.237	9.63	0.765	31.12	1.497	60.88
LO+1j VBS approx.	2.302	0.224	9.73	0.716	31.10	1.399	60.77

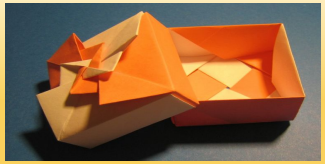
Only sub-percent level effects of QCD corrections on polarization fractions!





New polarization frameworks beyond LO - POWHEG + PYTHIA

[G. Pelliccioli, G. Zanderighi 2023]



Matrix elements: RECOLA 1

Processes: inclusive diboson production

Order: NLO QCD + PS

Matching: POWHEG approach

On-Shell-Approximation: Double-Pole-Approximation

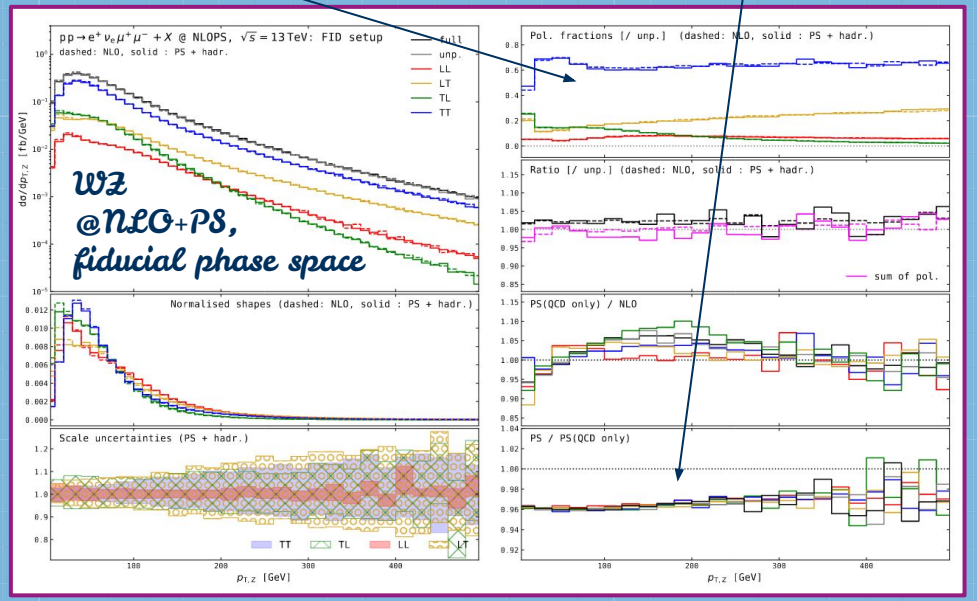
	POWHEG	SHERPA	
state	NLOPS	nLO+PS [37]	$\frac{\text{nLO+PS}}{\text{NLOPS}} - 1$
full off-shell	34.04(5)	33.80(4)	−0.7%
unpolarised	33.30(5)	33.46(3)	+0.5%
LL	1.892(3)	1.902(2)	+0.5%
LT	5.140(7)	5.241(4)	+1.9%
TL	4.888(6)	5.002(4)	+2.3%
TT	21.16(3)	21.10(2)	−0.3%
interference	0.217	0.215	−0.9%

main NLO QCD effect on pol fractions from real corrections

detailed phenomenological analysis of inclusive diboson-production @ NLO QCD incl. PS effects

pol fractions only sizable affected for boosted setups, jet-activity vetoes

largest overall PS effects from QED shower



Summary & future prospects

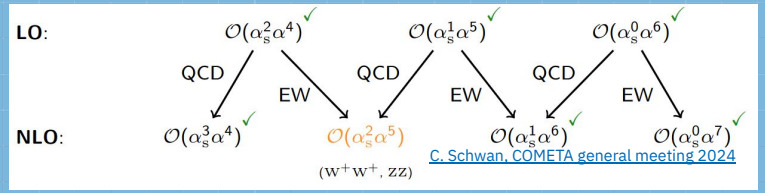
Unpolarized Diboson production

Inclusive Diboson production

- ✓ NNLO QCD + PS & NLO QCD + NLO EW + PS state of the art
- ✓ NLO QCD for loop-induced processes available
  - first calculations including top mass effects

Vector boson scattering

- ✓ full NLO tower available for W^+W^+ + 2j and ZZ + 2j, otherwise only $O(\alpha_s^2\alpha^5_{EW})$ missing



- ✓ matching to PS only partly available
- ✓ semi- & fully hadronic channels become interesting

both process groups interesting for quantum entanglement measurements

Polarized Diboson production

- ✓ first tools for fully realistic polarization templates with higher-order QCD effects

Inclusive Diboson production

- ✓ NLO QCD + NLO EW state of the art in fixed-order calculations for fully leptonic channels
- ✓ semi-leptonic channels become interesting

Vector boson scattering

- ✓ LO state of the art in fixed-order calculations for fully leptonic channels
- ✓ first higher order QCD effects simulated

Summary & future prospects

Lots of open tasks!

Unpolarized Diboson production

- matching to parton shower
- precision calculation in SMEFT / full BSM models

Inclusive Diboson production

- top mass effects for all loop-induced contributions
- inclusion of NLO EW contributions in NNLO QCD predictions

Vector boson scattering

- completion of NLO tower
- semi-leptonic predictions

Polarized Diboson production

- inclusion of NLO EW (& beyond) in particle-level simulations for inclusive diboson production
- NLO QCD & NLO EW predictions for VBS processes
- study of BSM effects
- tool comparison
- polarization tagger
- connections between quantum entanglement & polarization community
- more model independent approaches ...


https://www.zeppelinschule-speyer.de/aussblick-auf-die-zeit-nach-pfingsten/

Interested? Stay tuned!

COmprehensive **M**ultiboson **E**xperiment-**T**heory **A**ction

COST-Action Wiki

COMETA

Summary & future prospects

Lots of open tasks!

Unpolarized Diboson production

- matching to parton shower
- precision calculation in SMEFT / full BSM models

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- top mass effects for all loop-induced contributions
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https://www.zeppelinschule-speyer.de/aussblick-auf-die-zeit-nach-pfingsten/

Thank you for your attention! Questions?

Interested? Stay tuned!

COmprehensive **M**ultiboson **E**xperiment-**T**heory **A**ction

COST-Action Wiki

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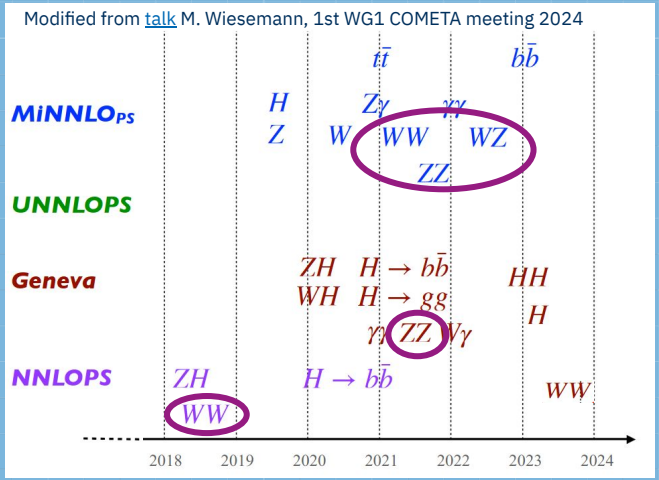
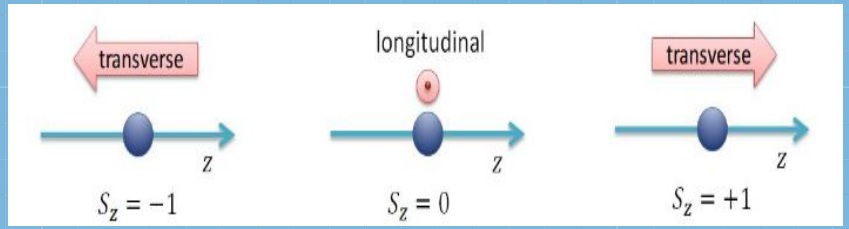
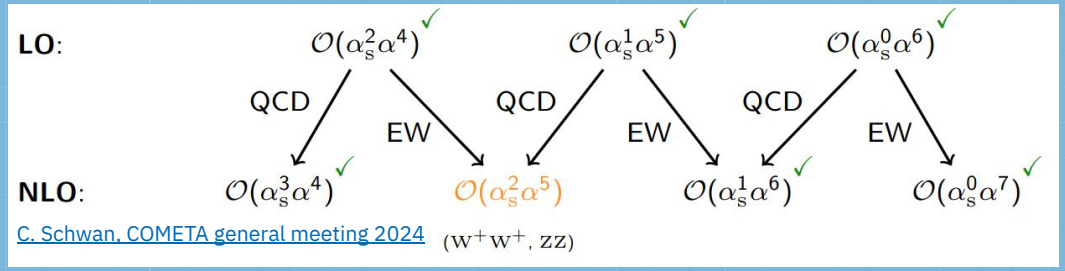
Backup





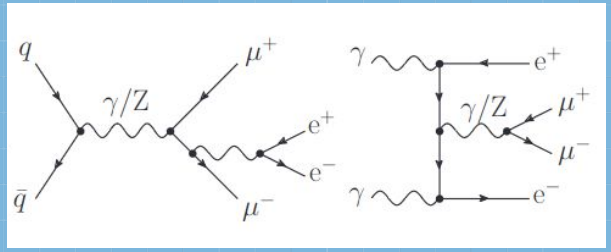
Dr. Z. Zinonos: Tests of the Standard Model of Particles. https://www.mpp.mpg.de/~zinonos/material/lecture10.pdf



C. Schwan, COMETA general meeting 2024

Inclusive Diboson production

- ★ production of two (massive) vector bosons
- ★ without any jets @LO
- ★ electroweak LO production + decay: $O(\alpha^4)$

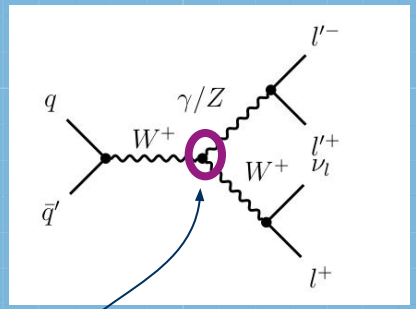


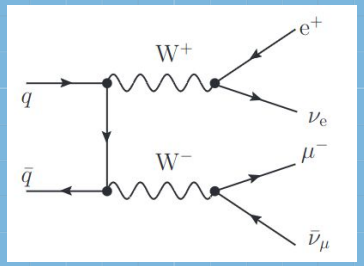
Three channels
(fully leptonic decays):

pp -> W^+W^-

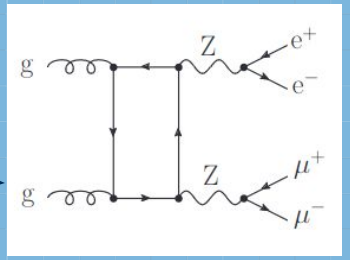
pp -> $W^{\pm}Z$

pp -> ZZ





loop-induced production



- ➢ **probes of triple gauge coupling**
- ➢ **important background for many analyses e.g. Higgs production**

Vector boson scattering

- ★ production of two (massive) vector bosons
- ★ in association with two jets @LO
- ★ electroweak LO production + decay: $O(\alpha^6)$

Four channels (fully leptonic decays):

pp -> $W^{\pm}W^{\pm}jj$: same-sign WW scattering

pp -> $W^{+}W^{-}jj$: opposite-sign WW scattering

pp -> $W^{\pm}Zjj$: WZ scattering

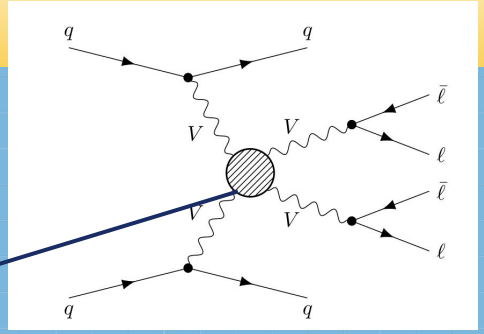
pp -> $ZZjj$: ZZ scattering

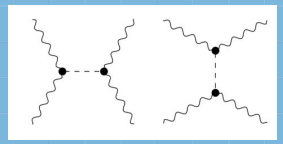
Important irreducible backgrounds @LO:

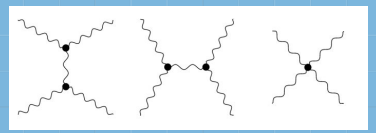
QCD-induced process: $O(\alpha_s^2\alpha^4)$

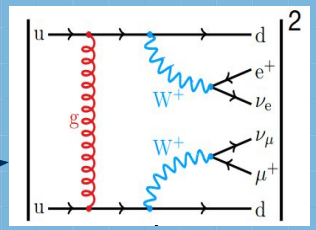
EW-QCD interference: $O(\alpha_s\alpha^5)$

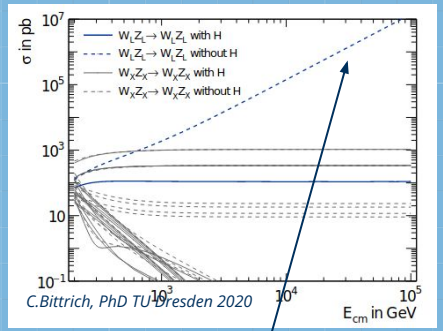
- ➢ **probes of triple & quartic gauge coupling**
- ➢ **probes of HVV coupling, Higgs usually off-shell**
- ➢ **test of EW symmetry breaking**

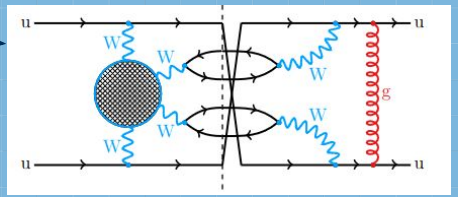






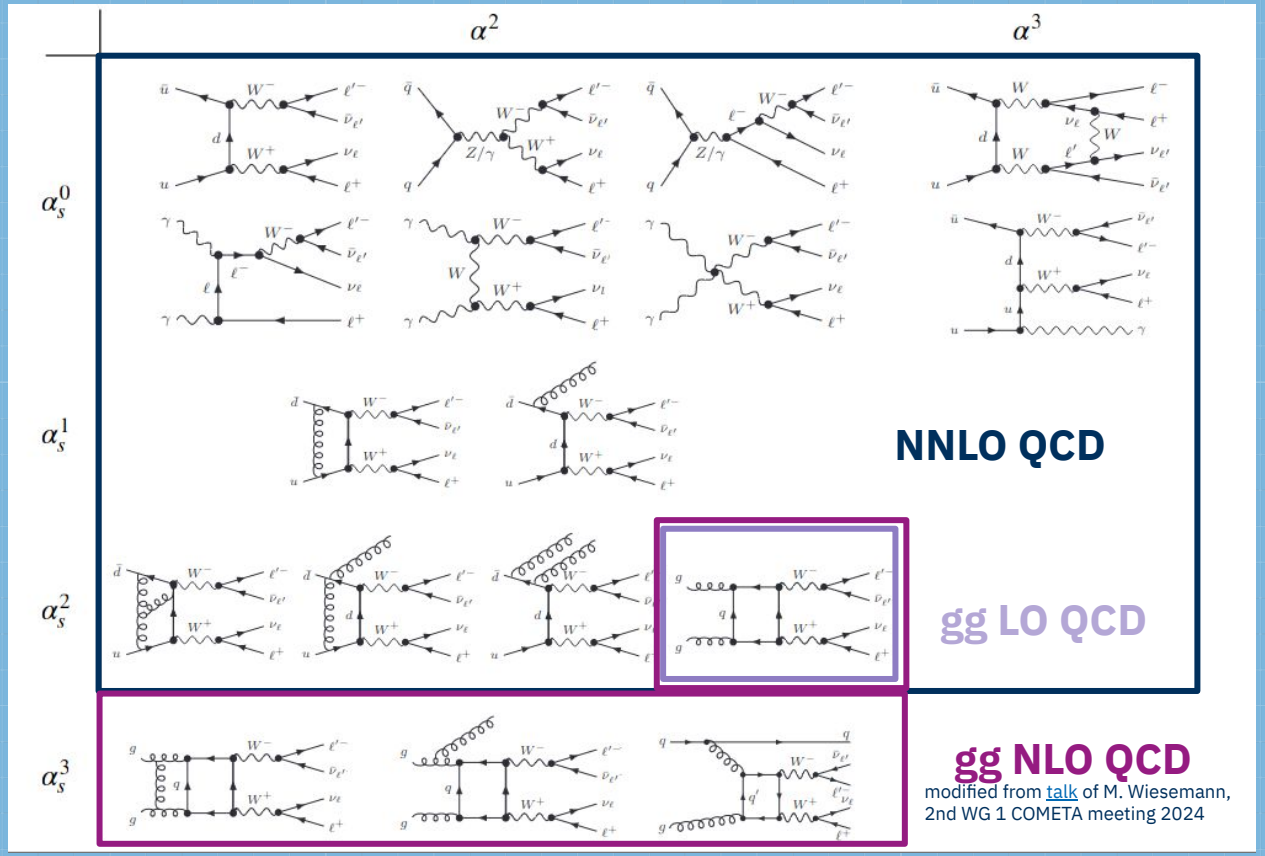






unitarity violation

Complete NLO QCD in gluon-induced ZZ production



modified from talk of M. Wiesemann, 2nd WG 1 COMETA meeting 2024

Gluon-induced ZZ production

- **~60%** of NNLO QCD contribution [F. Cascioli et al. 2014]
- NLO corrections = no Z boson couples to external quark lines -> well defined
- NLO QCD with massless quarks / approximate massive contribution: **5-8%** increase in total XS [M. Grazzini et al. 2018, F. Caola et al. 2015]
- top contributions **important**
  - -> high invariant mass region for production of Z_L (Goldstone equivalence theorem)
  - -> interplay with Higgs mediated production

Polarization tagging

- **ML methods for extracting polarization information from data**
  - standard in Run 2 analysis: [CMS 2020, ATLAS 2021, 2023, 2024]
  - topic of phenomenological studies: [J.Searcy et al. 2015, M.Grossi et al. 2020, T. Kim & A. Martin, 2021, J. Lee et al. 2018, J. Li et al. 2021, K. Ozdemir 2023 ...]

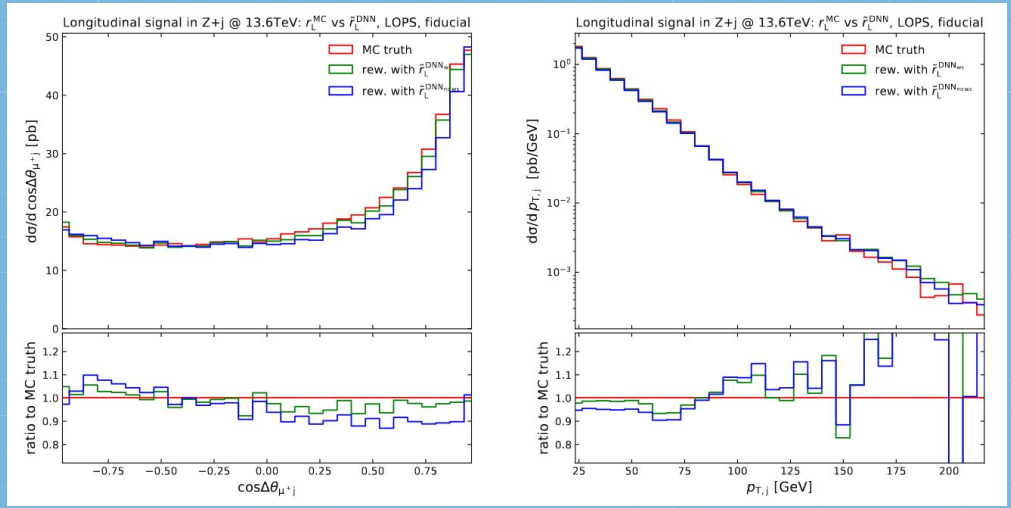
-> in common:

New approach: predict polarization fractions on event-by-event-basis via ML methods

-> training on MC polarization templates
-> use full differential information, no fitting procedure required

Proof of concept: [M. Grossi et al. 2023]

- using wide deep neural networks
- application on Z+j @LO, LO+PS

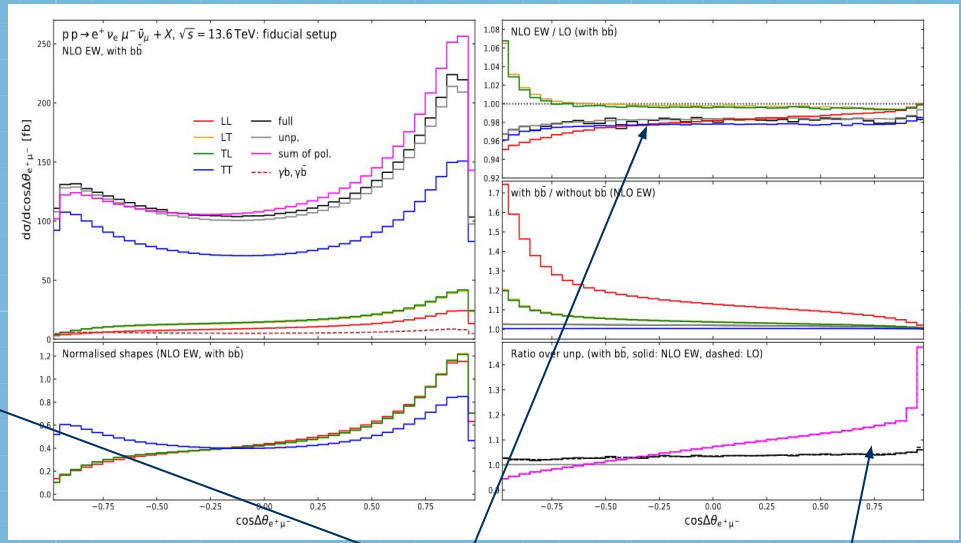


Most recent results - NLO EW for W^+W^- production

MOCANLO+RECOLA, fully leptonic, W^+W^- center of mass frame

[A. Denner, C. Haitz, G. Pelliccioli 2023]

state	σ_{LO} [fb]	$\sigma_{\text{NLO EW}}$ [fb]	δ_{EW}[%]	$f_{\text{NLO EW}}$[%]
$b\bar{b}$, γb, $\gamma\bar{b}$ excluded				
full	254.79(2)	249.88(9)	−1.93	103.5
unp.	245.79(2)	241.48(2)	−1.75	100
LL	18.752(2)	18.510(2)	−1.30	7.7
LT	32.084(3)	32.043(3)	−0.13	13.3
TL	33.244(5)	33.155(5)	−0.27	13.7
TT	182.17(2)	177.83(2)	−2.38	73.6
int.	−20.46(3)	−20.1(1)	−1.96	−8.3
$b\bar{b}$ included, γb, $\gamma\bar{b}$ excluded				
full	259.02(2)	253.95(9)	−1.96	103.4
unp.	249.97(2)	245.49(2)	−1.79	100.0
LL	21.007(2)	20.663(2)	−1.64	8.4
LT	33.190(3)	33.115(3)	−0.23	13.5
TL	34.352(5)	34.230(5)	−0.35	13.9
TT	182.56(2)	178.21(3)	−2.38	72.6
int.	−21.14(5)	−20.6(2)	−2.45	−8.4



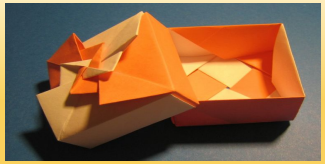
bbar channel -> + 12% LL (different helicity structure from t-channel top)

moderate negative EW corrections -> differ between different polarizations

huge interference (interplay between left-chiral couplings & pT(ll) selection)

New polarization frameworks beyond LO - POWHEG + PYTHIA

[G. Pelliccioli, G. Zanderighi 2023]



Matrix elements: RECOLA 1

Processes: Diboson production

Order: NLO QCD + PS

Matching: POWHEG approach

On-Shell-Approximation: Double-Pole-Approximation

Details: FKS mapping + specific DPA mapping guaranteeing cancellation of real phase space singularities

$$\langle \mathcal{O} \rangle = \int \mathrm{d}\Phi_{4\ell}\, \tilde{\mathrm{B}}(\tilde{\Phi}_{4\ell}) \left[\mathcal{O}(\tilde{\Phi}_{4\ell})\Delta(t_0) + \int_{t>t_0} \mathrm{d}\Phi_{\mathrm{rad}} \mathcal{O}(\tilde{\tilde{\Phi}}_{4\ell}, \Phi_{\mathrm{rad}}) \frac{\mathrm{R}(\tilde{\tilde{\Phi}}_{4\ell}, \Phi_{\mathrm{rad}})}{\mathrm{B}(\tilde{\Phi}_{4\ell})} \Delta(t) \right]$$

for fully-leptonic diboson production @ NLO QCD matching as in off-shell case (up to technical subtleties)

<u>kinematics:</u>
ME numerators: DPA-mapped
ME denominators, phase space weights: off-shell

detailed phenomenological analysis of diboson-production @ NLO QCD incl. PS effects

pol fractions only sizable affected for boosted setups, jet-activity vetoes

largest overall PS effects from QED shower