Theoretical calculations for phenomenology at the LHC

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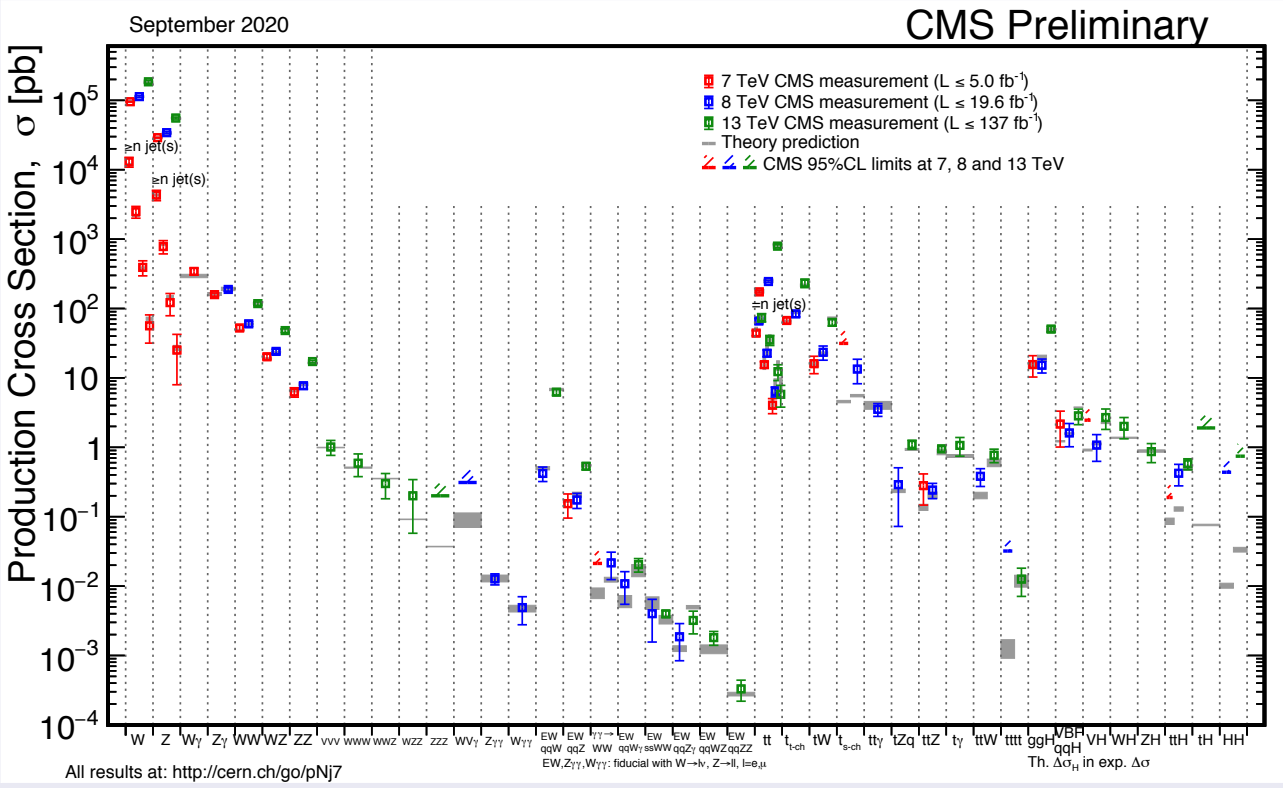
26th of January 2021

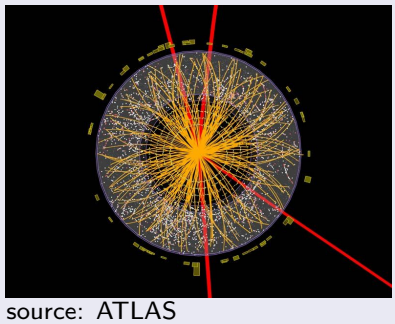
Legacy of the LHC:



Outline:

→ Selection of ...

- **Physics results**



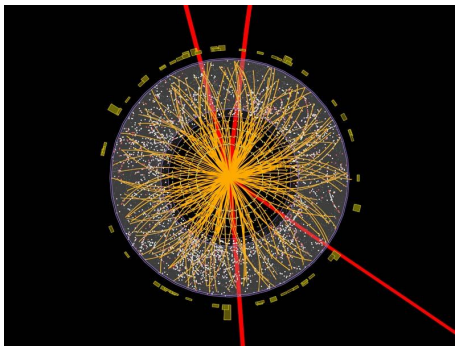
source: ATLAS

- **Tools to obtain these results**

source: www.nist.gov

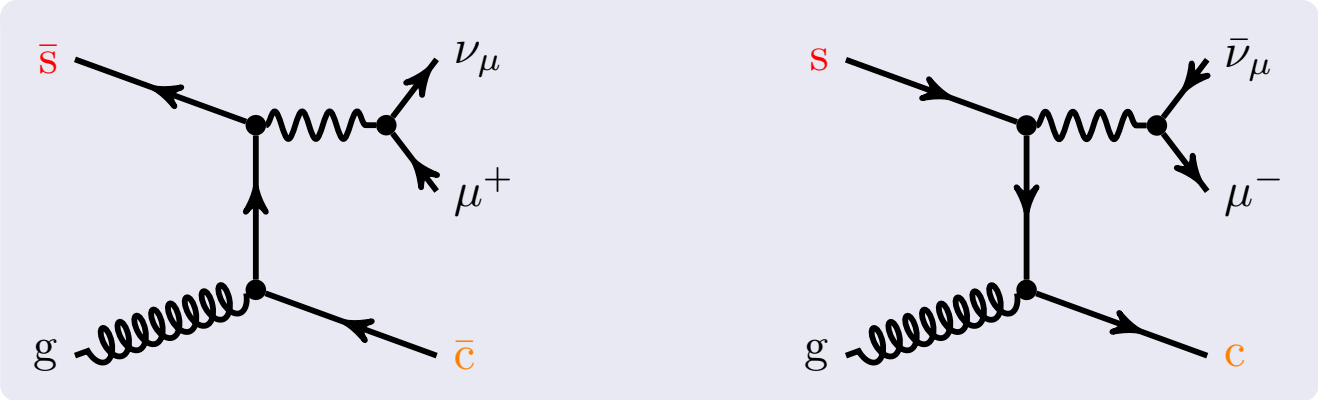
→ ... at the LHC

Exploring the Electroweak sector of the Standard Model



- $pp \to W^{\pm} + j_c$ @ NNLO QCD
- $pp \to W^{+}W^{-}j$ @ NLO QCD+EW with parton shower
- $pp \to W^{\pm}W^{\pm}jj$ @ full NLO

1) pp $\to$ W$^{\pm}$ + j$_c$ @ NNLO QCD



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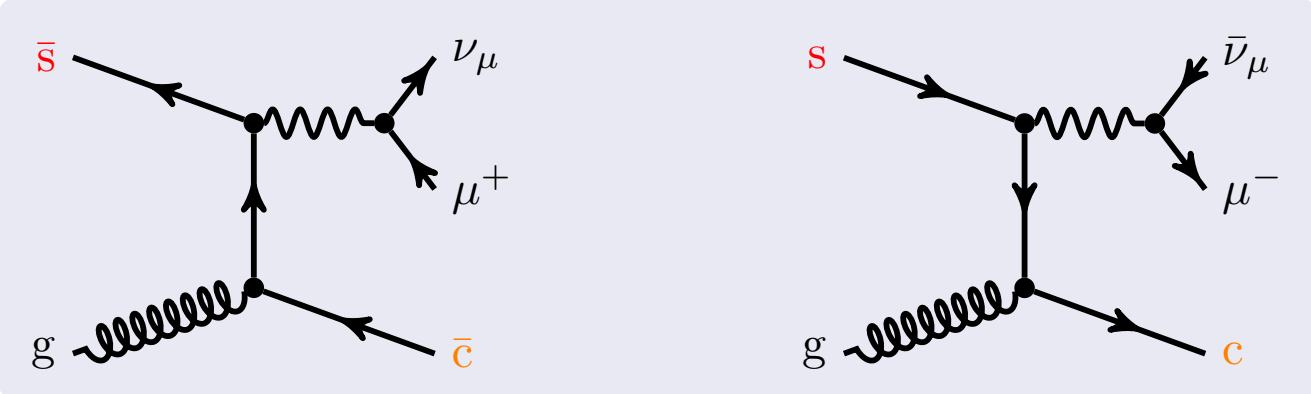
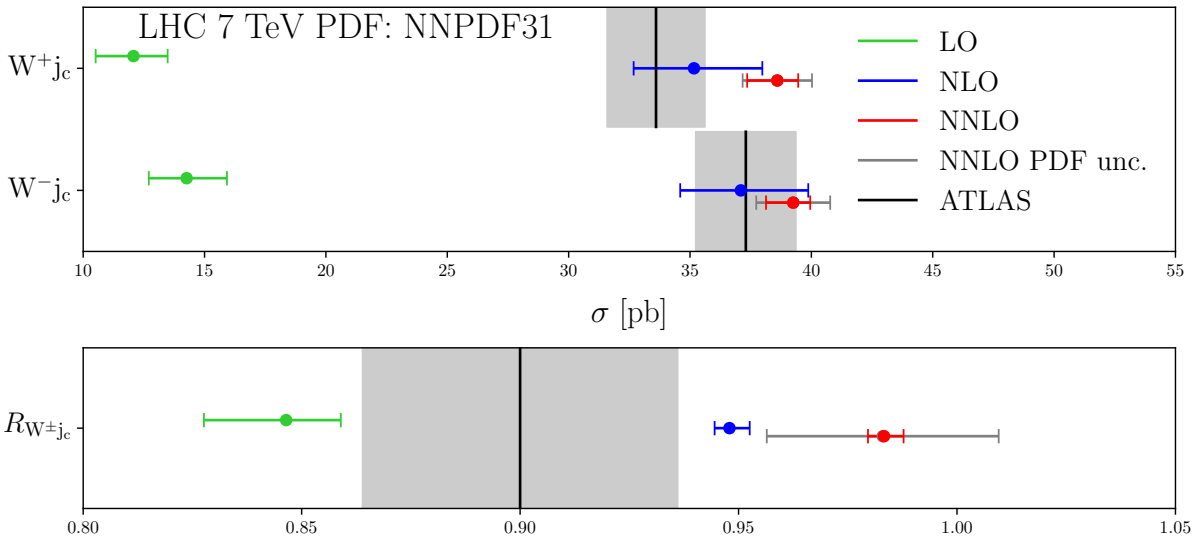


- Direct link between W+c measurements and strange PDF
- Study of flavour jets [Banfi, Salam, **Zanderighi**; hep-ph/0601139]

⚠ **First NNLO QCD computation of W+c-jet**

[Czakon, Mitov, **MP**, Poncelet; 2011.01011]

1) pp $\to$ $W^{\pm} + j_c$ @ NNLO QCD

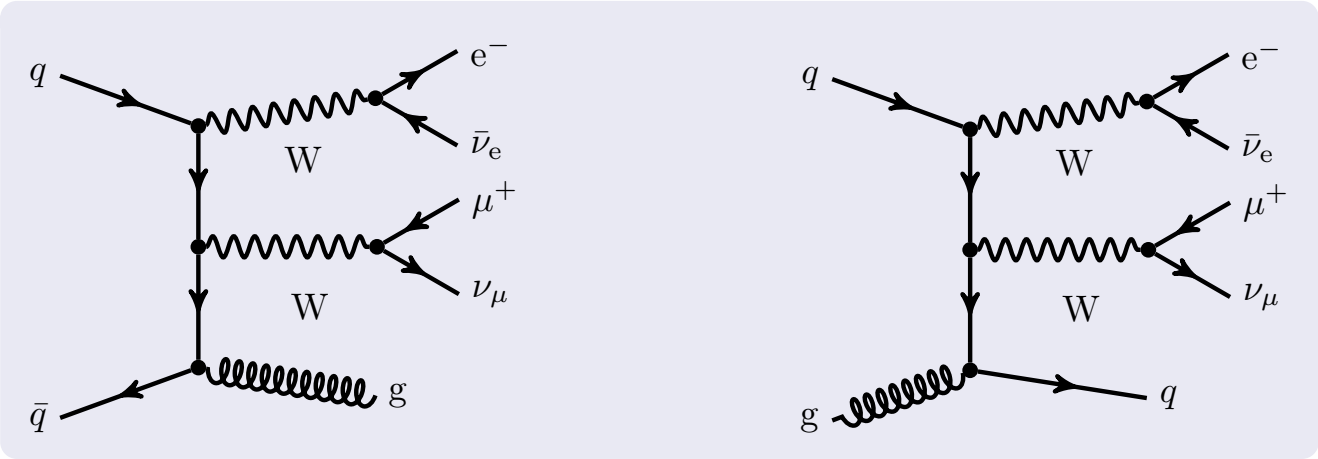


[Czakon, Mitov, **MP**, Poncelet; 2011.01011]

Comparison against ATLAS data

- Good overall agreement
  ⚠ PDF uncertainty dominant
- Potential to improve understanding of strange within proton:
  $\to$ Strange asymmetry / Global PDF fit

2) pp $\to$ W^+W^-j @ NLO QCD+EW with parton shower



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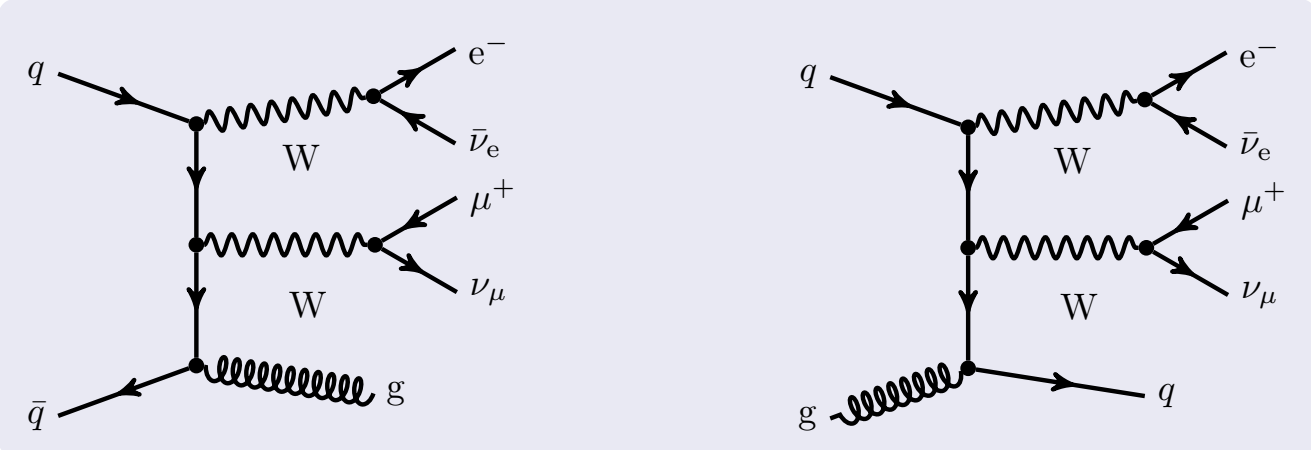
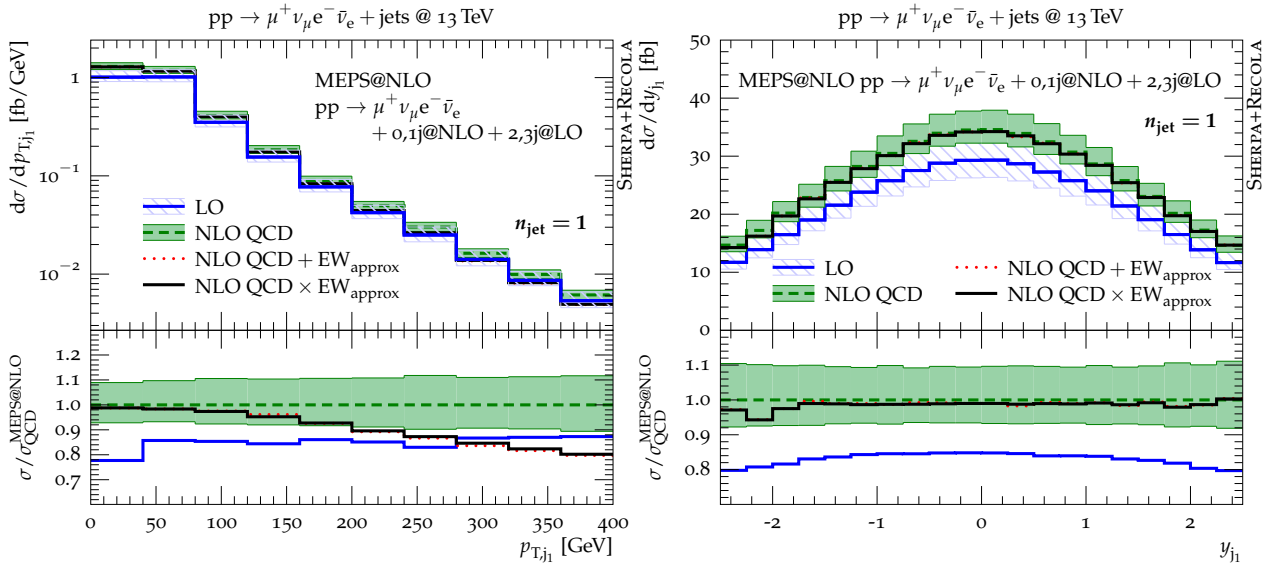


- Motivated by **ATLAS** measurement [1608.03086]
- Search for anomalous triple gauge-boson couplings
- Complementary to di-boson measurements
  $\to$ Similar effect with different kinematic

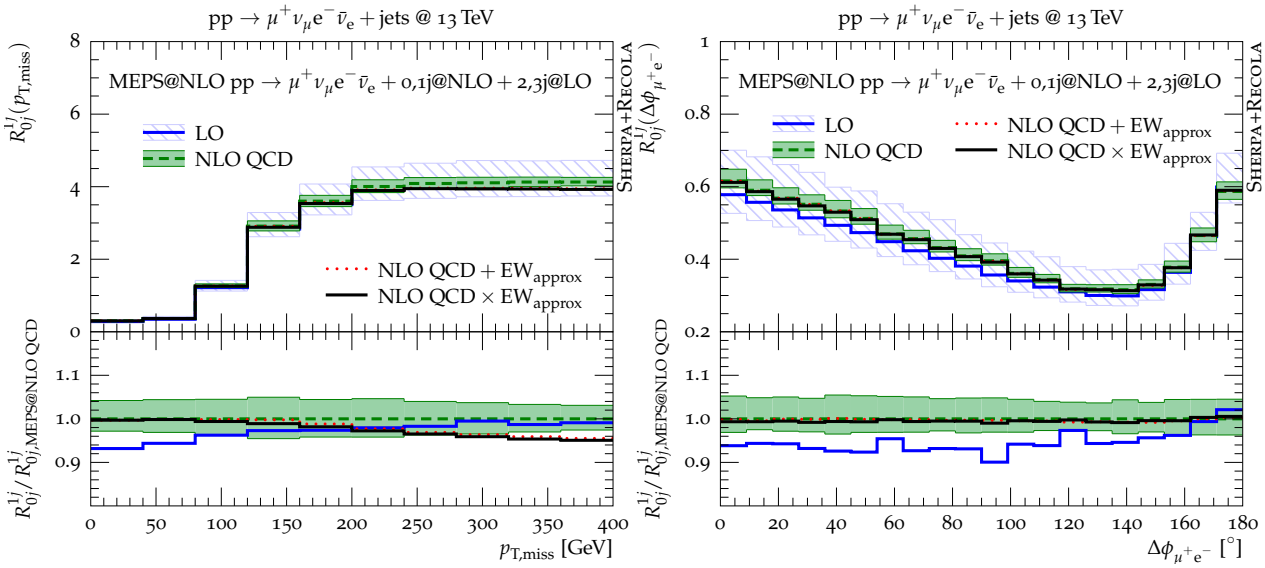
2) pp → W^+W^-j @ NLO QCD+EW with parton shower



[Bräuer, Denner, **MP**, Schönherr, Schumann; 2011.01011]

- Inclusion of EW effects in NLO+Parton Shower simulation
- Typical EW Sudakov logarithms

2) pp → W^+W^-j @ NLO QCD+EW with parton shower

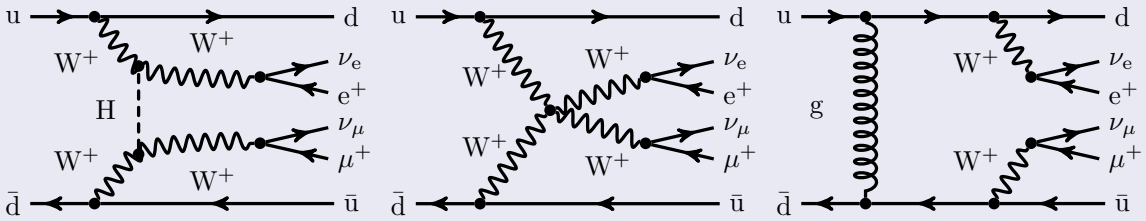


[Bräuer, Denner, **MP**, Schönherr, Schumann; 2011.01011]

- Use of ratios WWj/WW
  - → WW known up to NNLO + PS [Re, **Wiesemann**, **Zanderighi**; 1805.09857]
  - → Cancellation of uncertainties
  - → Sensitive probe of the Standard Model

3) pp $\to$ $W^{\pm}W^{\pm}$jj @ full NLO

Vector-boson scattering and its background



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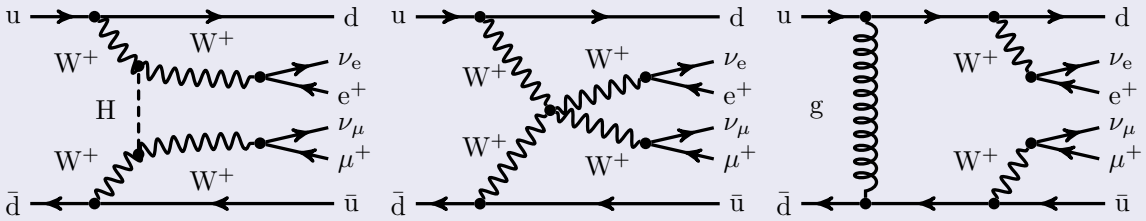

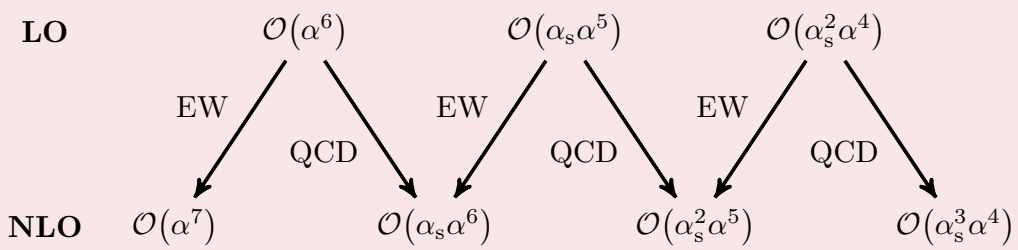

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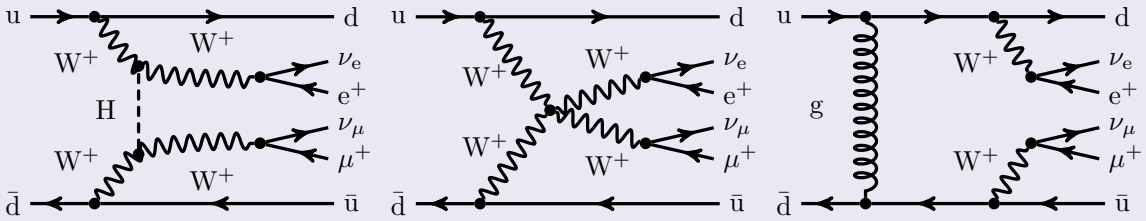
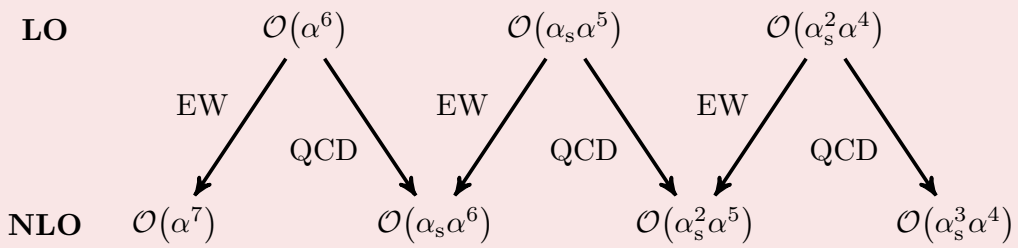




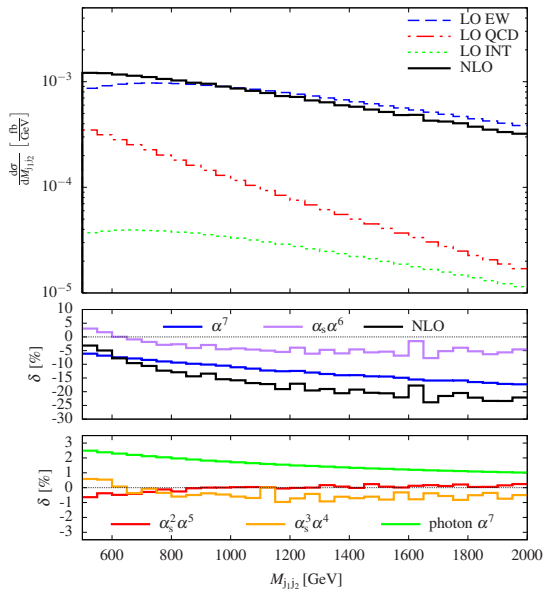
- **First full NLO computation for same-sign WW**

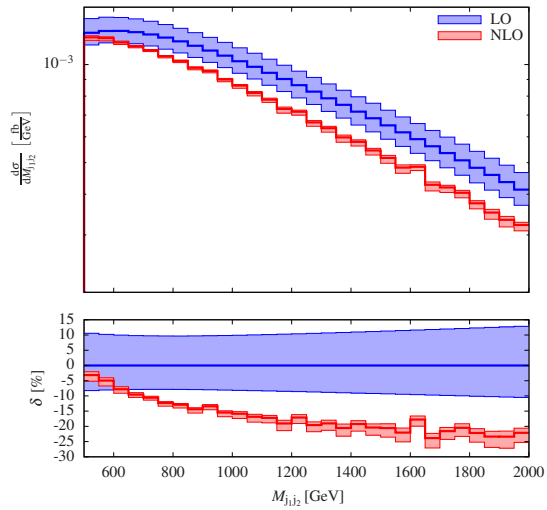
⚠ Already known:

→ approx. $\mathcal{O}(\alpha_s\alpha^6)$ [Jäger, Oleari, Zeppenfeld; 0907.0580], [Denner, Hošeková, Kallweit; 1209.2389]

→ $\mathcal{O}(\alpha_s^3\alpha^4)$ [Melia, Melnikov, Röntsch, **Zanderighi**], [Campanario, Kerner, Ninh, Zeppenfeld; 1311.6738]

3) pp → $W^{\pm}W^{\pm}$jj @ full NLO





[Biedermann, Denner, **MP**; 1708.00268]

- Different LO and NLO behaviours
  ⚠ Large EW corrections

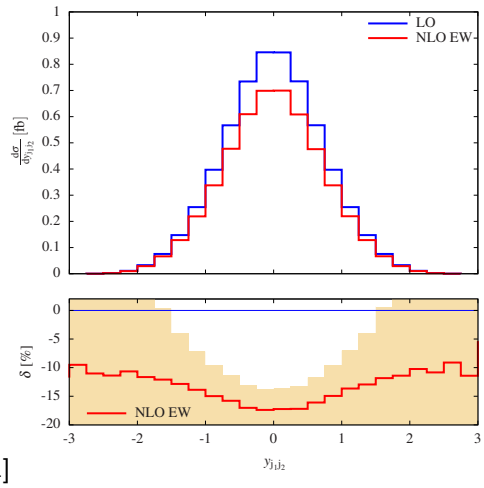
3) pp → $W^{\pm}W^{\pm}$jj @ full NLO

→ $\mathcal{O}(\alpha^7)$ reproduced by Leading-Log approximation

$$\sigma_{\rm LL} = \sigma_{\rm LO}\left[1 - \frac{\alpha}{4\pi}4C_{\rm W}^{\rm ew}\log^2\left(\frac{Q^2}{M_{\rm W}^2}\right) + \frac{\alpha}{4\pi}2b_{\rm W}^{\rm ew}\log\left(\frac{Q^2}{M_{\rm W}^2}\right)\right]$$

- $C^{\rm ew}$ larger for bosons than fermions
- $\langle m_{4\ell}\rangle$ larger for VBS (massive t-channel [Denner, **Hahn**; hep-ph/9711302])

→ Large EW corrections: intrinsic feature of VBS at the LHC



[Biedermann, Denner, **MP**; 1611.02951]

- Sensitive to EW corrections at High-Luminosity LHC

At the core of this work: Development of methods and tools

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- All LHC results are obtained with computer programs!
- All cutting edge computations requires huge CPU resources
- Automation necessary to cover all LHC physics
- Programs are a way to communicate results
  $\rightarrow$ Golden standard: automatised and public tools!

NLO QCD/EW corrections in **POWHEG**

→ Implementation process by process in POWHEG

[Alioli, Frixione, Ježo, Nason, Oleari, Re; hep-ph/0409146, 0709.2092, 1002.2581, 1509.09071]

1) Squark production and decay at NLO SUSY QCD

   [Gavin, Hangst, Krämer, Mühlleitner, **MP**, Popenda, Spira; 1305.4061, 1407.7971]

2) Same-sign W-boson scattering at NLO EW

   [Chiesa, Denner, Lang, **MP**; 1906.01863]

Work

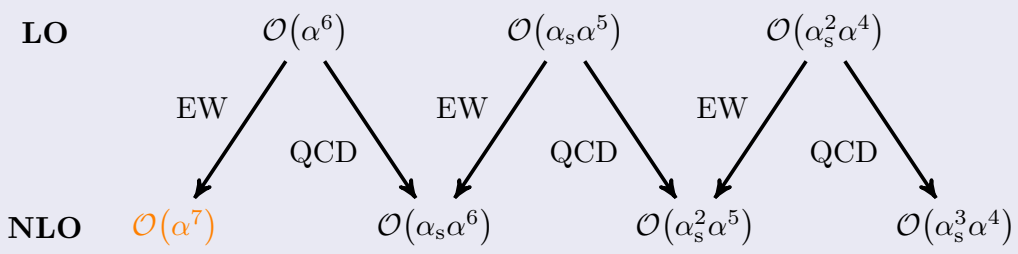
- Implementation of all partonic/decay channels
- Implementation of necessary pieces
  → Matrix elements, colour-correlated matrix elements, etc.
  → Either own subroutines or automatised code

NLO QCD/EW corrections in POWHEG

2) Same-sign W-boson scattering at NLO EW

[Chiesa, Denner, Lang, **MP**; 1906.01863]

- Interface with general matrix-element generator: RECOLA [Actis, Denner, Hofer, Lang, Scharf; 1605.01090]
  → Basis of general interface [Chiesa, Oleari, Re; 2005.12146]



→ To be used with other contributions available in POWHEG

[Melia, Nason, Rontsch, **Zanderighi**; 1102.4846] [Jäger, **Zanderighi**; 1108.0864]

NNLO QCD corrections in **Stripper**

STRIPPER:

Implementation of sector-improved residue subtraction scheme

[Czakon, Heymes, Poncelet; 1005.0274, 1101.0642, 1408.2500]

→ General framework for NNLO QCD computations

→ As POWHEG, implementation on a process-by-process basis

My work

- Implementation of integration channel
  → mapping of resonance
- Interface with OPENLOOPS2 [Buccioni, et al.; 1907.13071]
- Implementation of two-loop virtual [Gehrmann, Tancredi; 1112.1531]
  → Convention matching with complex expressions
  → Evaluation of harmonic polylogarithms with ...
  ... GINAC [Bauer, Frink, Kreckel], [Vollinga, Weinzierl; hep-ph/0410259]

→ Outcome: **NNLO QCD corrections for W+c-jet**

[Czakon, Mitov, **MP**, Poncelet; 2011.01011]

Automation of NLO QCD and EW in **Sherpa**

SHERPA: General multi-purpose Monte Carlo

[Gleisberg, Höche, Krauss, Schönherr, Schälicke, Schumann, Siegert, Winter; hep-ph/0311263, 0811.4622]

[Biedermann, Bräuer, Denner, **MP**, Schumann, Thompson; 1704.05783]

- General implementation of any NLO corrections
  $\rightarrow$ also mixed corrections
- Design of interface between SHERPA and RECOLA
  $\rightarrow$ C++ $\leftrightarrow$ FORTRAN

Output

- NLO corrections for **any process**
- Use all functionalities of SHERPA along with NLO corrections
- Applications:
  $\rightarrow$ $t\bar{t}$, ZZ, $V + \text{jets}$ [Biedermann, Bräuer, Denner, **MP**, Schumann, Thompson; 1704.05783] 3-jets [Reyer, Schönherr, Schumann; 1902.01763], tri-bosons [Reyer, Schönherr, Schumann; 1806.00307], WW/WWj [Bräuer, Denner, **MP**, Schönherr, Schumann; 2011.01011]

NLO QCD corrections in MadGraph5_aMC@NLO

→ Automation NLO QCD for Dark-Matter simplified models

[Backovic, Krämer, Maltoni, Martini, Mawatari, **MP**; 1508.05327]

Tool chain

- FeynRules [Alloul et al.; 1310.1921]
- NLOCT [Degrande; 1406.3030]
- FeynArts [**Hahn**; hep-ph/0012260]

→ NLO QCD UFO files [Degrande et al.; 1108.2040]: DMSIMP

→ Can be used for **any process** in MG5_aMC [Alwall et al.; 1405.0301]

→ Used extensively by both communities:

- Experiment: for all Dark-Matter searches in **ATLAS** and CMS
- Theory: [**Haisch**, Kahlhoefer, Tait; 1603.01267], [Asadi et al.; 1603.01267], ...

Development of MoCaNLO - past

MoCaNLO: Monte Carlo event generator for NLO calculations of hadron-collider processes

→ Multi-channel Monte Carlo written by Robert Feger

My work

Make it more general

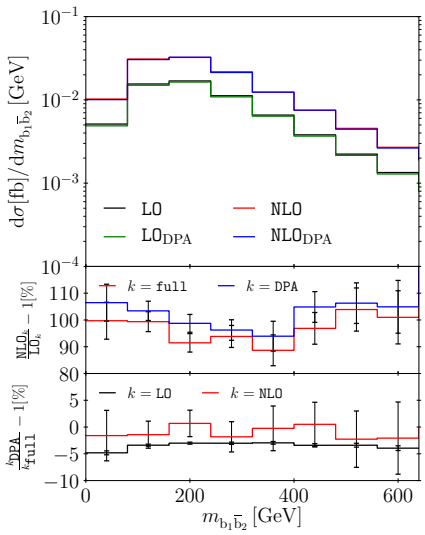
- NLO EW corrections
  → Treatment of mixed QCD-EW corrections
- Pole approximation at NLO QCD/EW
  → non-factorisable corrections
- Performance improvements
- Further automation of the code

→ Efficient for high-multiplicity processes ($2 \to 6$ and beyond)

Development of MoCaNLO - future

→ Frontier of the code:
pp → $\mu^- \bar{\nu}_\mu e^+ \nu_e \bar{b} b \bar{b} b$ at NLO QCD
(2 → 8 scattering with ...
... 6 external QCD particles)

[Denner, Lang, **MP**; 2008.00918]



Plan: Make it better and even more general

- Implementation of FKS subtraction [Frixione, Kunszt, Signer; hep-ph/9512328]
- Matching to parton shower
  → mixed QCD-EW corrections
- Usable for new physics models
- Making it public!

Partial summary

Focus

- Implementation of higher-order corrections
- Development of Monte Carlo programs

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Skills

- Knowledge of several programming languages
- Experience in using HEP tools
- Intensive use of High-performance computing
- Experience in maintaining codes

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→ Research mainly focused on LHC physics but ...

... tools can be used in other fields *e.g.* Astroparticle physics

[Ali Cavasonza, Krämer, **MP**; 1409.8226], [Ali Cavasonza, Gast, Krämer, **MP**, Schael; 1612.06634]

... also interest in numerical general relativity

[Di Menza, Nicolas, **MP**; 1903.02941]

General summary

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- Exploring the Electroweak sector of the Standard Model
  $\rightarrow$ several examples of recent computations

- Development of methods and tools for LHC phenomenology
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Back-up slides

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