The polarisation of weak bosons: precision and new ideas for the LHC

Mathieu PELLEN

University of Freiburg

CERN, Geneva, Switzerland

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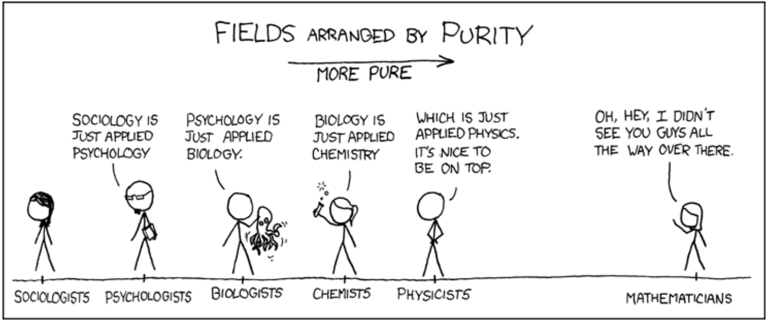
Outline:

→ Introduction:

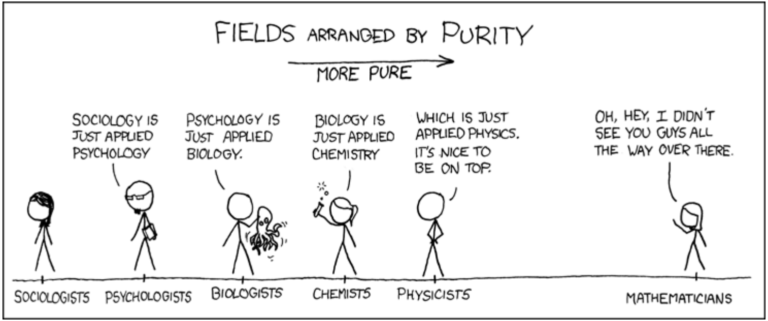
Why the polarisation of weak boson is interesting

- QCD corrections in polarised $pp \to W^{\pm} + j$
  → Why precision matters

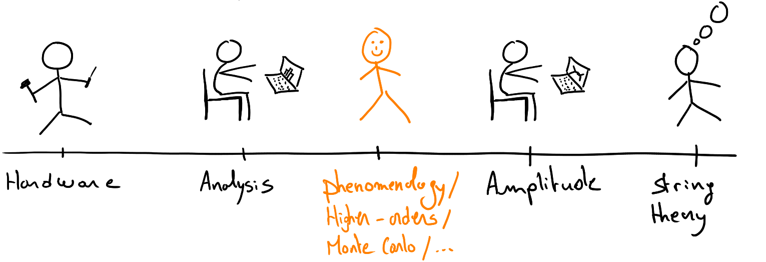
- Extracting polarisation using amplitudes and machine learning
  → New idea



FIELDS ARRANGED BY PURITY
MORE PURE
SOCIOLOGY IS JUST APPLIED PSYCHOLOGY
PSYCHOLOGY IS JUST APPLIED BIOLOGY.
BIOLOGY IS JUST APPLIED CHEMISTRY
WHICH IS JUST APPLIED PHYSICS. IT'S NICE TO BE ON TOP.
OH, HEY, I DIDN'T SEE YOU GUYS ALL THE WAY OVER THERE.
SOCIOLOGISTS
PSYCHOLOGISTS
BIOLOGISTS
CHEMISTS
PHYSICISTS
MATHEMATICIANS



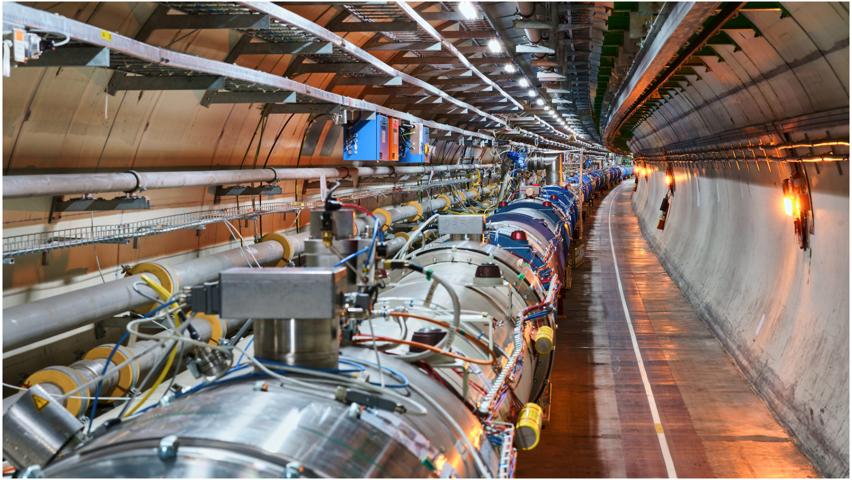
High-energy physics purity (adapted from xkcd)



[source: MatiasEnElMundo/Getty Images]

Large Hadron Collider (LHC) @ CERN, Geneva (Switzerland)

→ 27km-long tunnel where protons are collided at high-energy (13.6 TeV currently)



→ Cross talk between **experiment** and **theory**

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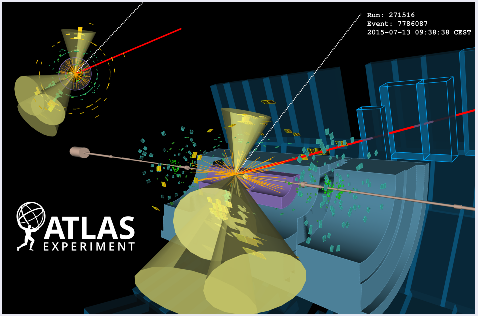
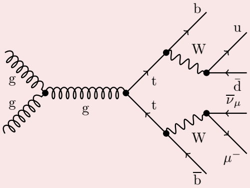


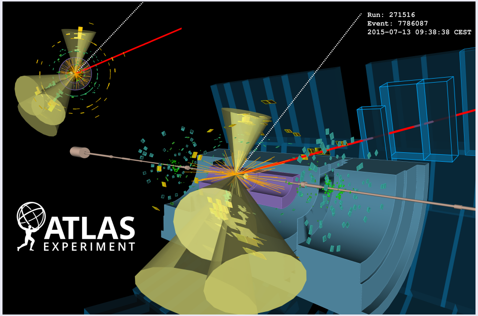
- Final state objects measured
- Kinematic selection

$$\mathrm{pp} \to \mathrm{t}^{\star}\bar{\mathrm{t}}^{\star} \to \left(\mathrm{W}^{\star} \to \nu_\mu \mu^-\right)\left(\mathrm{W}^{\star} \to \mathrm{jj}\right)\mathrm{b}\bar{\mathrm{b}}$$



- First-principle predictions (QFT)
  → Standard Model

$\longrightarrow$ Cross talk between **experiment** and **theory**



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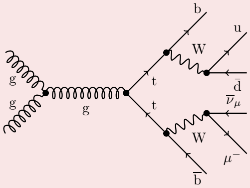
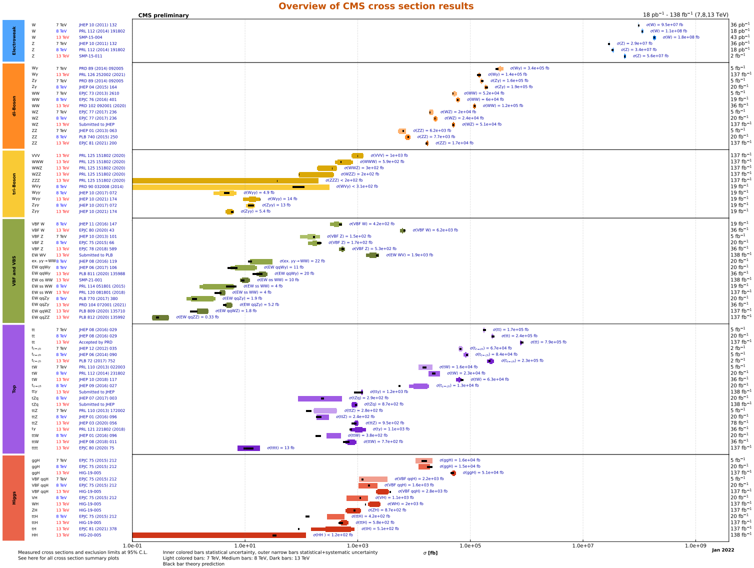


- First-principle predictions (QFT)
  $\longrightarrow$ Standard Model

By comparing cross sections / differential distributions
$\longrightarrow$ learn about fundamental aspects of particle physics



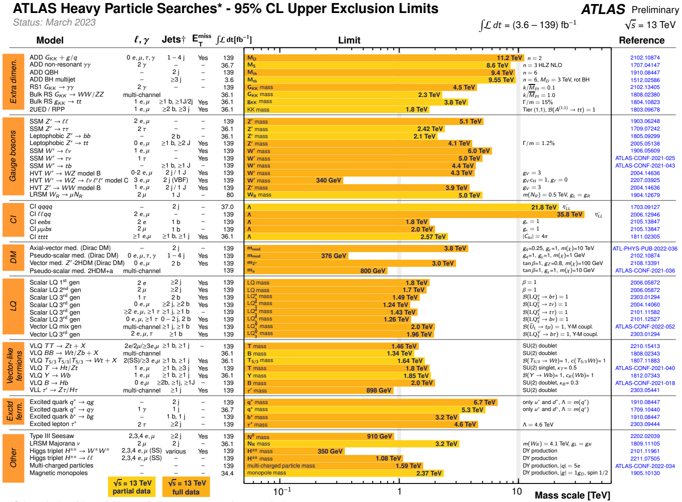
- Triumph of the Standard Model ...

- ... which culminated with:

Discovery of the Higgs boson

→ Great interest in measuring properties of the Higgs boson ...

... but we learnt about other things



*Only a selection of the available mass limits on new states or phenomena is shown.

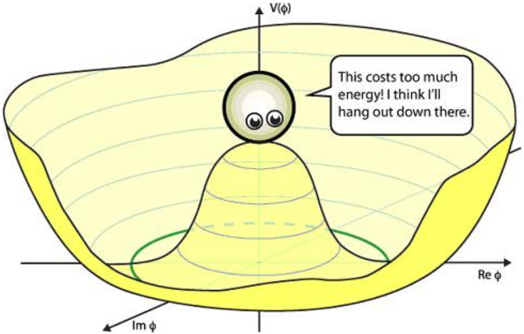
†Small-radius (large-radius) jets are denoted by the letter j (J).

- New physics only at high energy or very subtle effects (if at all)

  $\rightarrow$ Precision (First part) and new ideas (Second part)

Motivation for polarisation studies

- Polarisation of gauge bosons (W and Z) related to Electroweak symmetry breaking
  → longitudinal polarisation
  "'"the Higgs mechanism implies the conversion of Goldstone modes into the longitudinal polarisation mode of massive weak bosons" [Pelliccioli]
  → probe of new physics/extended Higgs sector



Definition

Master formula

$$\left|\mathcal{M}^{\mathrm{NWA}}(\mathrm{Wj})\right|^2 = \frac{\pi}{M_W\Gamma_W}\left|\sum_{h\in\Lambda}\mathcal{M}_h(\mathrm{pp}\to\mathrm{Wj})\cdot\mathcal{M}_h\left(\mathrm{W}\to\ell\nu_\ell\right)\right|^2$$

with $\Lambda = \{+1,-1\}\,(\mathrm{Transverse}), 0\,(\mathrm{Longitudinal})$

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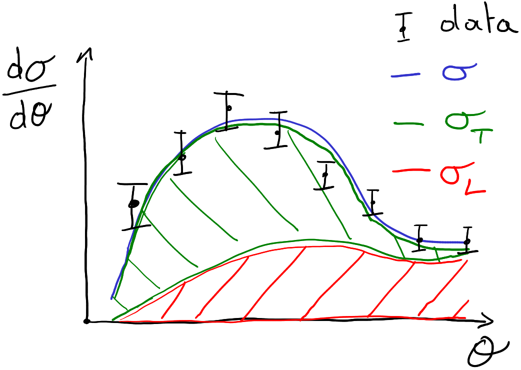
- Unpolarised cross section $\sigma_{\rm unp.} \sim |\mathcal{M}^{\rm NWA}|^2$ **(experimentally measured)**
- Polarised cross section: $\sigma_{\rm L} \sim |\mathcal{M}_0|^2 \cdot |\Gamma_0|^2$
- Polarisation fraction: $\boxed{f_{\rm L} = \sigma_{\rm L}/\sigma_{\rm unp.}}$

“Measuring polarisation”

- No measurement of polarisation: *template method*
  → extraction of parameters based on theory input



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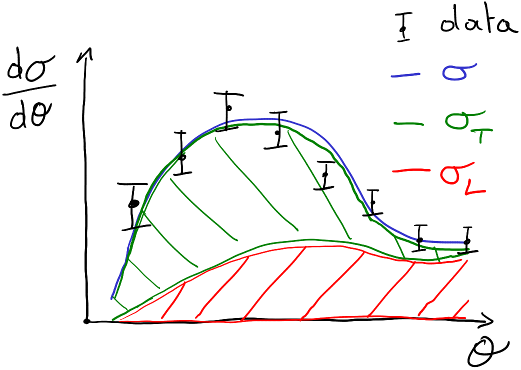
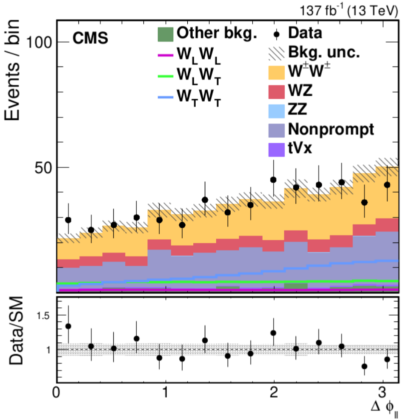


Shortcomings about polarisation extraction

⚠ Polarisation only defined for on-shell bosons

⚠ Only the unpolarised prediction is observed

- WZ: [ATLAS; 1902.05759, 2211.09435], [CMS; 2110.11231]
- Vector-boson scattering $W^{\pm}W^{\pm}$ [CMS; 2009.09429]



[CMS; 2009.09429]

Process	$\sigma\mathcal{B}$ (fb)	Theoretical prediction (fb)
$W^{\pm}_{L}W^{\pm}_{L}$	$0.32^{+0.42}_{-0.40}$	0.44 ± 0.05
$W^{\pm}_{X}W^{\pm}_{T}$	$3.06^{+0.51}_{-0.48}$	3.13 ± 0.35
$W^{\pm}_{L}W^{\pm}_{X}$	$1.20^{+0.56}_{-0.53}$	1.63 ± 0.18
$W^{\pm}_{T}W^{\pm}_{T}$	$2.11^{+0.49}_{-0.47}$	1.94 ± 0.21

- **Precision:**
  NNLO QCD for polarised $\mathrm{pp} \to \mathrm{W}^{\pm} + \mathrm{j}$

State of the art: W+j

- NLO QCD:

  [Giele et al.; hep-ph/9302225], [Arnold et al.; Nucl.Phys. B319 (1989) 37-71, Phys.Rev. D40 (1989) 912],
  [Campbell et al.; hep-ph/0202176, 0809.3003, 1107.3714]

- NNLO QCD:

  [Boughezal et al.; 1504.0213, 1602.06965], [Gehrmann-De Ridder et al.; 1901.11041]

- NLO EW:

  [Kühn et al.; hep-ph/0703283, 0708.0476], [Hollik et al.; 0707.2553], [Denner et al.; 0906.1656]

- Combinations of QCD and EW corrections:

  [Kallweit et al.; 1412.5157, 1511.08692], [Lindert et al.; 1511.08692],
  [MP, Popescu, Poncelet, Vitos; 2204.12394]

State of the art (polarised W+j)

- NLO QCD for polarised W-jet:

  [Bern et al.; 1103.5445], [Stirling, Vryonidou; 1204.6427]

- Interpretation of polarisation in terms of BSM / Phenomenology:

  [Belyaev, Ross; 1303.3297]

- Recent polarised predictions (diboson)
  - NLO QCD+EW: [Denner, Haitz, Pelliccioli; 2006.14867, 2010.07149, 2107.06579, 2211.09040, 2311.16031], [Baglio, Le Duc; 1810.11034, 1910.13746, 2203.01470, 2208.09232]
  - NNLO QCD: [Poncelet, Popescu; 2102.13583] + PS [Pelliccioli, Zanderighi; 2311.05220]
  - Automation: [Buarque Franzosi, Mattelaer, Ruiz, Shil; 1912.01725]
  - Pheno/BSM: [Dao Thi, Le Duc; 2302.03324, 2311.17027], [Javurkova et al.; 2401.17365]

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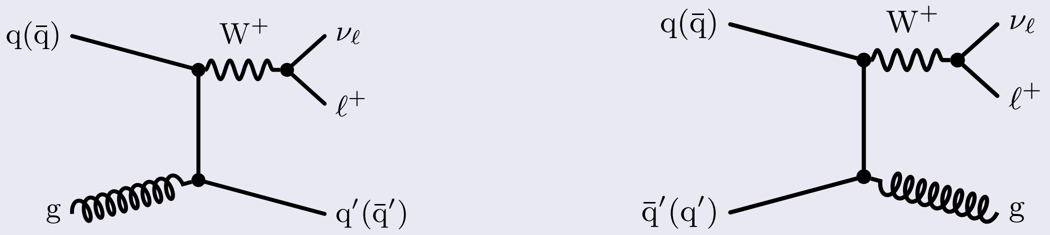
→ This work: [MP, Popescu, Poncelet; 2109.14336]

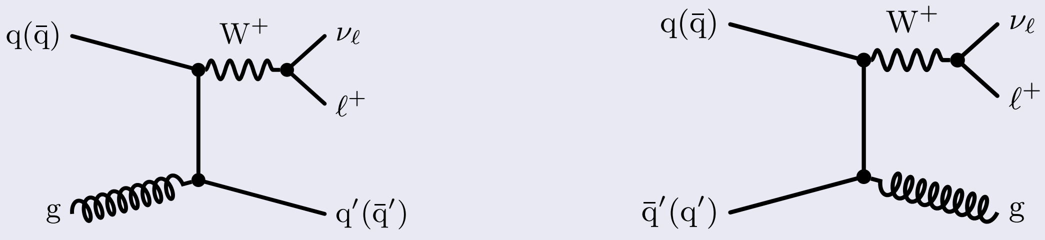
NNLO QCD computation for polarised W+jet production

LO process



- pp $\to \ell^\pm \overset{(-)}{\nu}_\ell$ j is the experimentally-observed process
  $\to$ Not pp $\to$ W$^\pm$ j !

LO process



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  $\rightarrow$ Not pp $\rightarrow$ W$^\pm$ j !

Shortcomings

⚠ Polarisation only defined for on-shell bosons
⚠ Only the unpolarised prediction is physical

Set-up

→ Set-up taken from CMS analysis 13 TeV analysis [1707.05979]

$$|y_{\rm j}| < 2.4 \quad \text{and} \quad p_{\rm T,j} > 30\,\text{GeV}$$

- Inclusive setup:
  Only jet requirement
- Fiducial setup:
  Jet requirement
  +

$$\Delta R(\ell, j) > 0.4$$

+

$$p_{\rm T,\ell} > 25\,\text{GeV}, \qquad |\eta_\ell| < 2.5, \qquad M_{\rm T}(\text{W}) > 50\,\text{GeV}$$

Tools

- Private Monte Carlo STRIPPER

  [Czakon, Heymes, Poncelet; 1005.0274, 1101.0642, 1408.2500]
- Tree level: AVH [Bury, van Hameren; 1503.08612]
- One-loop: OPENLOOP2 [Buccioni et al.; 1907.13071]

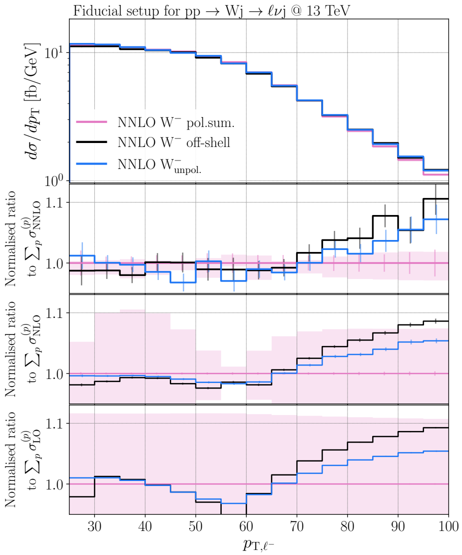
  (checked against RECOLA [Actis et al.; 1605.01090])
- Two-loop: [Gehrmann, Tancredi; 1112.1531]

  (adapted to obtain polarised amplitudes)

  $\rightarrow$ using GINAC [Bauer, Frink, Kreckel], [Vollinga, Weinzierl; hep-ph/0410259]
- PDF: LHAPDF [Buckley et al.; 1412.7420]

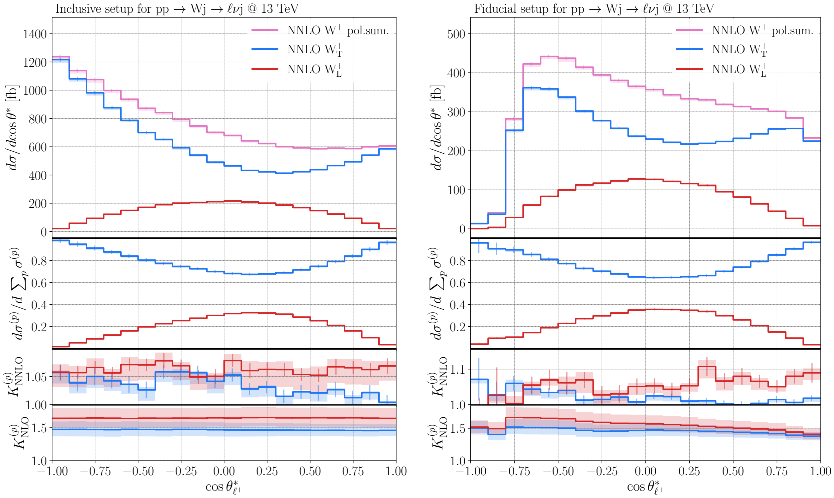
[source: bing image creator]

Addressing shortcomings



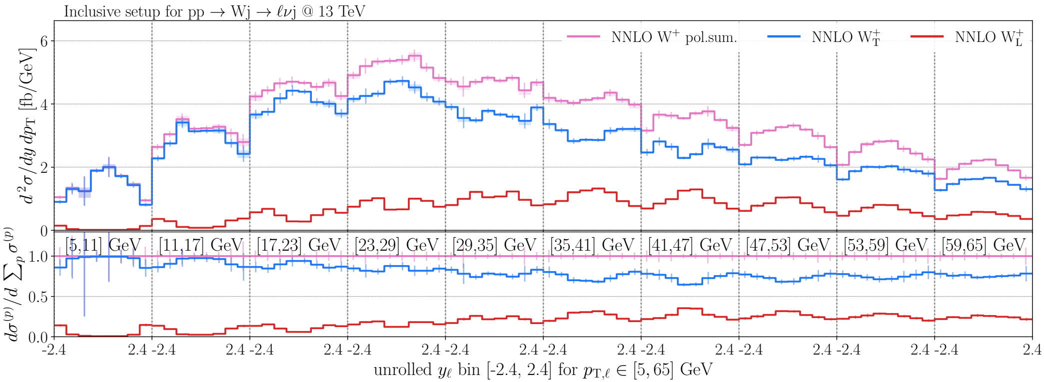
- Off-shell and interference effect up to 10%
  → dangerous regions for extraction of polarisation

W_T^+ vs. W_L^+



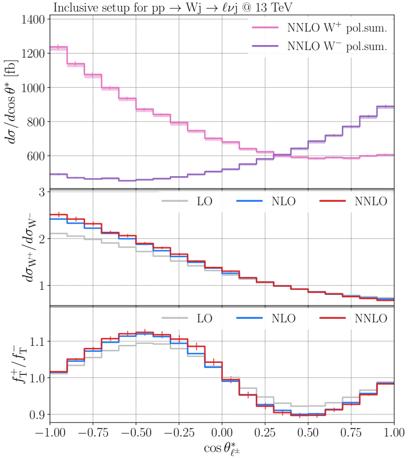
- W_T^+ and W_L^+ different
- Corrections observable dependent
- Large effect of event selection

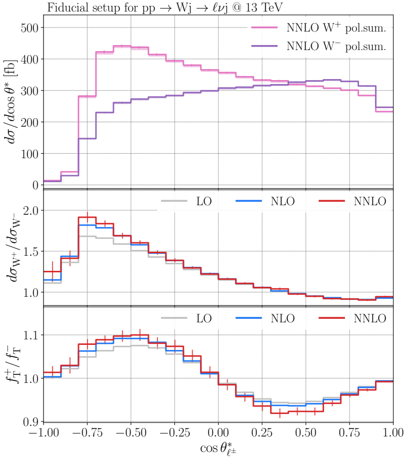
W^+_T vs. W^+_L (II)



- 2D-information
- Usable in experimental analysis
  → CMS Drell-Yan at 13 TeV [2008.04174]

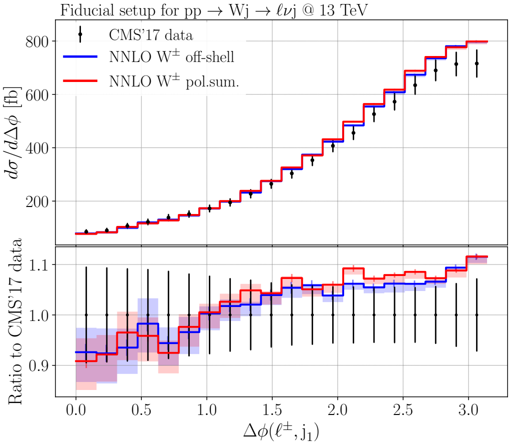
W^+ vs. W^-

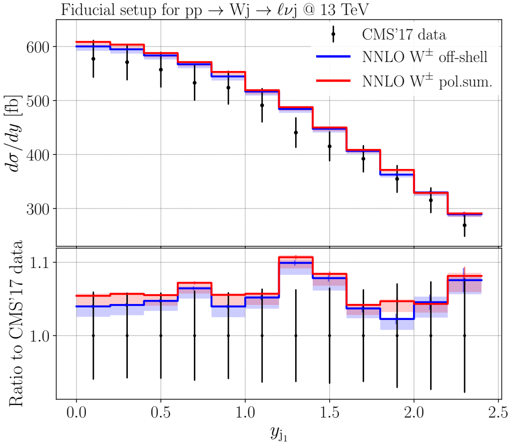




- W^+ and W^- different
- Ratios stable
- Interesting feature for $\cos\theta^*_{\ell\pm}$

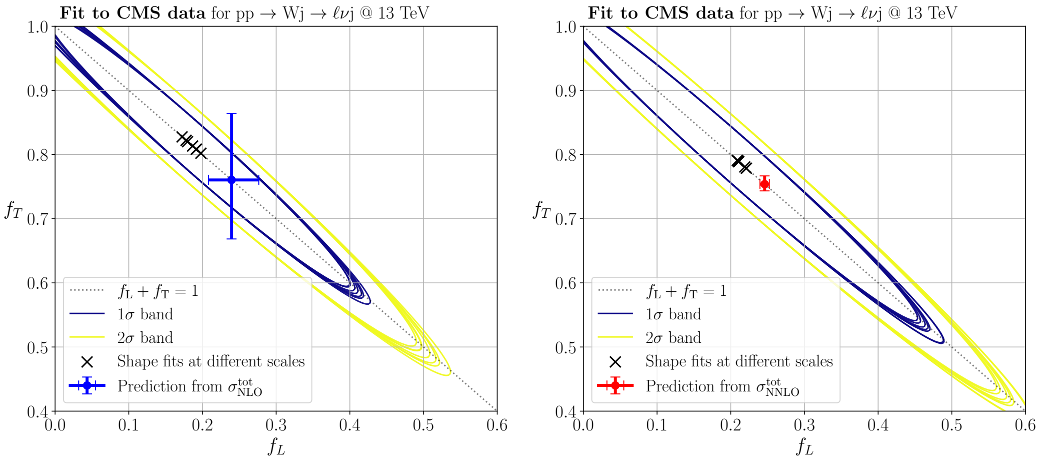
Comparison against data





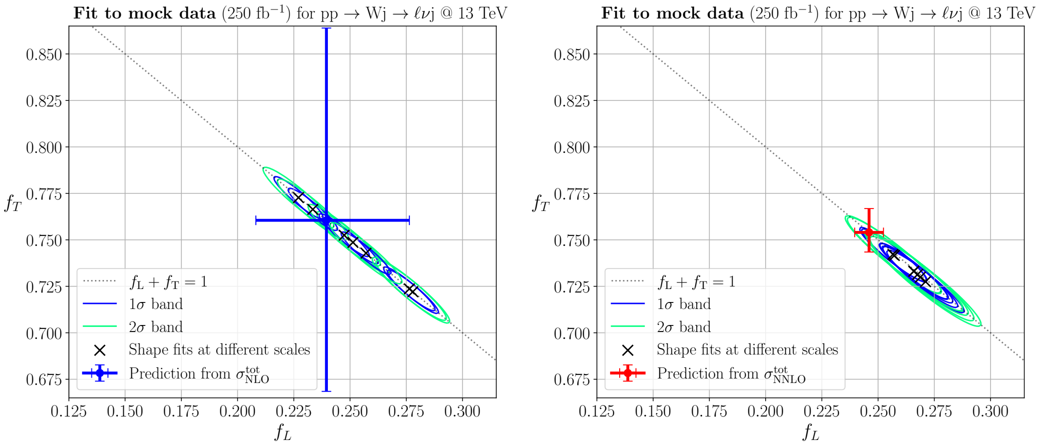
- Good agreement between theory and data
- Off-shell and interference effects negligible

Fit to data



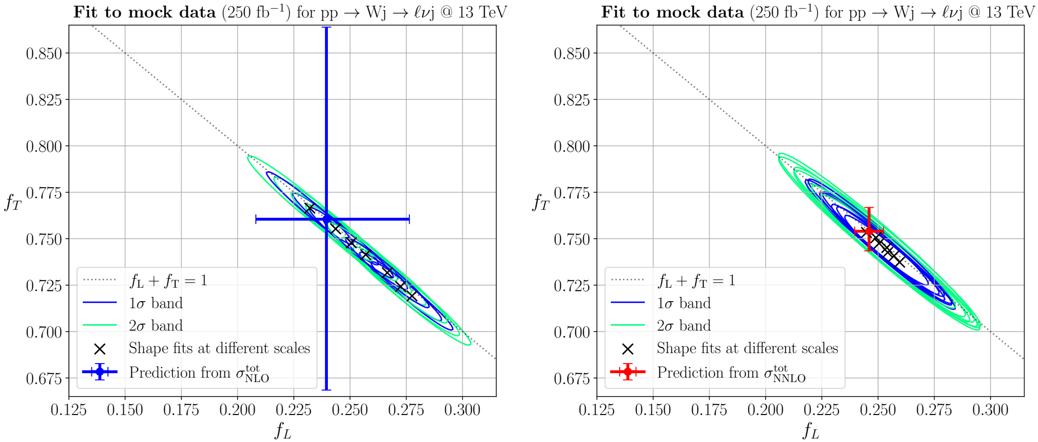
- Fits of y_j identical at NLO and NNLO
  → large experimental uncertainty

Fit to mock data



- Assume 250 fb^{-1} and the off-shell computation
- 1D fit → polar angle between the charged lepton and the hardest jet

Fit to mock data (II)



- 2D fit → rapidity and transverse momentum of charged lepton
- Missing correlation between two observables

Discussion

All theoretical ingredients provided ...
... but not enough

Open questions

- Should the two signatures be fitted separately or together?
- How should theoretical uncertainties be taken into account in the fit?
- How should one define the overall uncertainty on the fit of the polarisation fractions?

→ Answers in collaboration with experimental collaborations

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Drawbacks of the *template method*

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- Interpretation at the integrated level

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Typical in experiment:

→ NN/BDT on samples of longitudinally polarised vs. background samples

Drawbacks:

- Difficult learning
  → large samples needed
- Ill-defined discrimination between signal and background
  → Indirect link to polarisation definition
- Unclear what to feed (empirical and high-level variables)
  → possibly not optimal

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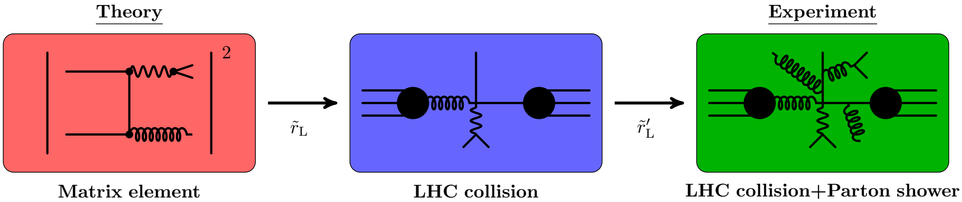

General idea

Use amplitude to extract theory parameters / pseudo observables from data
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- ~~Restricted to given observables~~ → No observable
- ~~Unclear what are the *optimal* observables~~ → optimal by definition
- ~~Interpretation at the integrated level~~
  → event-by-event interpretation (fully differential) → *Tagger*

⚠ General method usable for other problems

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⚠ General method usable for other problems
→ Alternative approaches:

- *matrix-element method* [Kondo; J. Phys. Soc. Jap. 57 (1988) 4126-4140 / 60 (1991) 836–844.]
- *optimal-observable method* [Diehl, Nachtmann; Z. Phys. C 62 (1994) 397-412, hep-ph/9603207], [Janot; 1503.01325]
- *MELA* *(Matrix Element Likelihood Approach)* [Gao, Gritsan, Melnikov, Schulze, et al.; 1001.3396, 1208.4018,1309.4819, 1606.03107]

Simple observation

$$f_{\mathrm{L}}(\mathcal{O}) = \frac{\mathrm{d}\sigma_{\mathrm{L}}}{\mathrm{d}\mathcal{O}} \Big/ \frac{\mathrm{d}\sigma_{\mathrm{unp}}}{\mathrm{d}\mathcal{O}} \quad \text{with} \quad \sigma \propto \int \mathrm{d}\Phi |\mathcal{M}|^2$$

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→ At the event-by-event/phase-space–point level, at leading order (LO), equivalent to

$$r_{\mathrm{L}} = \frac{|\mathcal{M}_{\mathrm{L}}|^2}{|\mathcal{M}|^2}$$

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NB:

- All information about longitudinal polarisation contained in r_{L}
- **If r_{L} was a physical observable,**
  only its measurement would be required to extract polarisation
  or
  Polarised predictions obtainable by reweighting unpolarised ones with r_{L}

Application

- Z+j production at the LHC at $\sqrt{s} = 13.6\,\text{TeV}$
- MadGraph5_aMC@NLO for checks

  [Alwall, et al.; 1405.0301], [Buarque Franzosi, Mattelaer, Ruiz, Shil; 1912.01725]
- Recola [Actis et al.; 1605.01090] for r_L computation
- Pythia [Sjöstrand et al.; 1410.3012] for Parton Shower (PS)

[source: bing image creator]

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[source: bing image creator]

→ *Generation* set-up

$$p_{\mathrm{T,j}} > 10\,\mathrm{GeV}\,, \qquad |y_{\mathrm{j}}| < 5, \qquad \text{and} \qquad 76\,\mathrm{GeV} < M_{\mu^+\mu^-} < 106\,\mathrm{GeV}$$

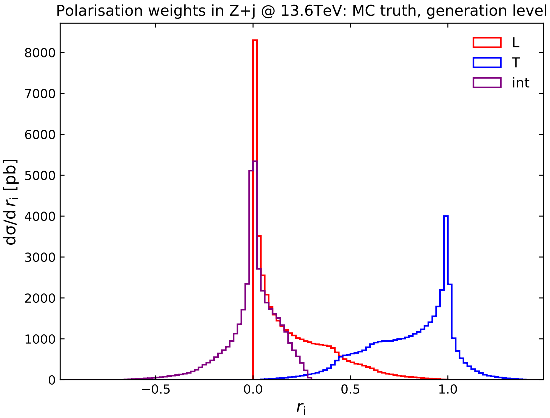
→ *Inclusive* set-up

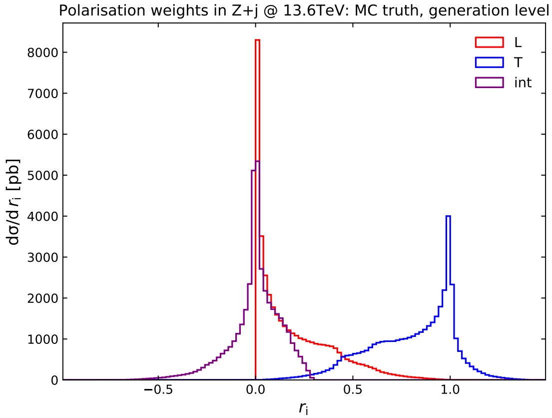
$$p_{\mathrm{T,j}} > 20\,\mathrm{GeV}\,, \qquad |y_{\mathrm{j}}| < 4, \qquad \text{and} \qquad 81\,\mathrm{GeV} < M_{\mu^+\mu^-} < 101\,\mathrm{GeV}$$

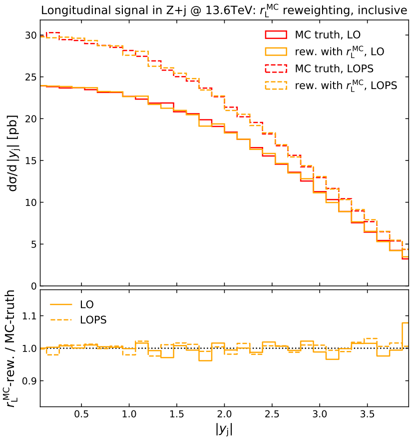
⚠ No cuts on Z-boson decay products

→ *Fiducial* set-up = *Inclusive* set-up +

$$p_{\mathrm{T},\mu^\pm} > 20\,\mathrm{GeV} \qquad \text{and} \qquad |y_{\mu^\pm}| < 2.7$$

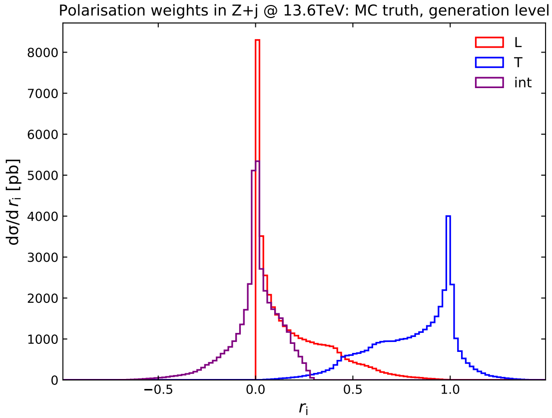

Polarisation weights in Z+j @ 13.6TeV: MC truth, generation level
L
T
int
dσ/d r_i [pb]
r_i
0
1000
2000
3000
4000
5000
6000
7000
8000
−0.5
0.0
0.5
1.0

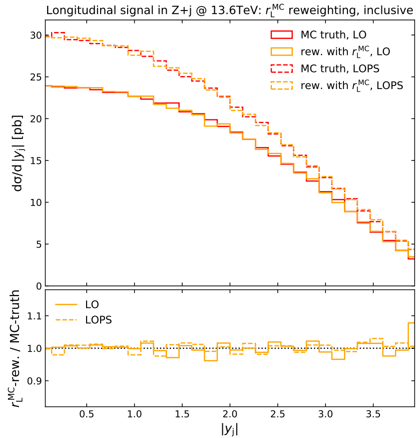




NB: For LO+PS, reweighting done on events before PS

→ assumption: polarisation is not influenced by PS





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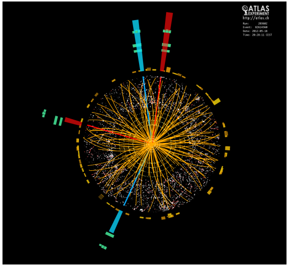
⚠ r_L requires knowledge of all momenta (initial and final)

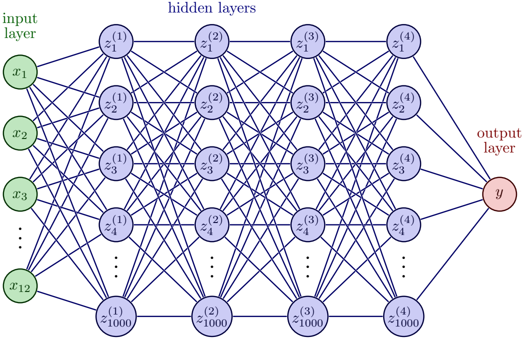
⚠ r_L requires knowledge of the partonic process and the PDF: ($qg \to q$, $q\bar{q} \to g$, ...)

Solution → Wide neural networks

IN:

- Training with Monte Carlo events
  → Truth
- Parameter to learn: r_{L}
- Input: all accessible information (leptons, jets, ...)

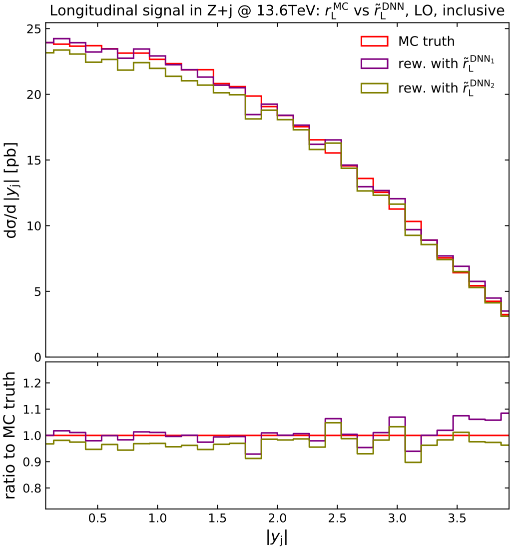




OUT:

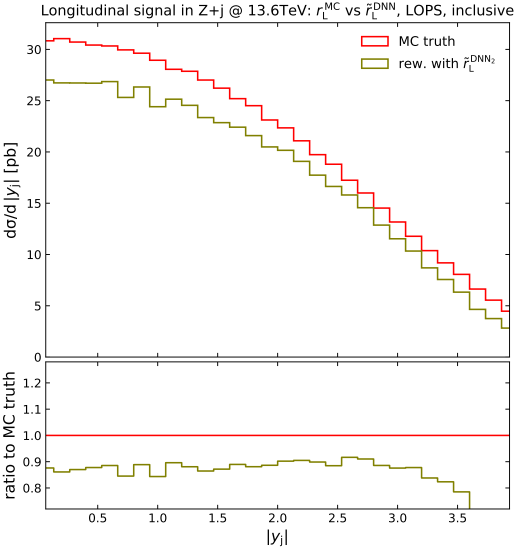
- Result: $\tilde{r}_{\mathrm{L}}$
  → Proxy of r_{L}
  → Relies only on accessible information

LO



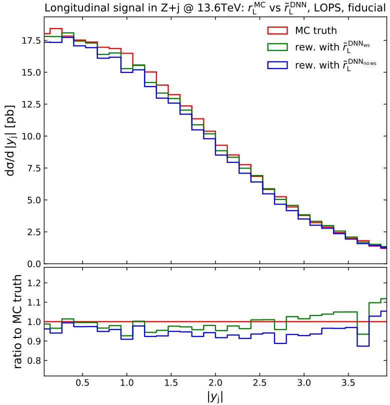
→ Method is working at LO at per-cent level

LO+PS using LO training



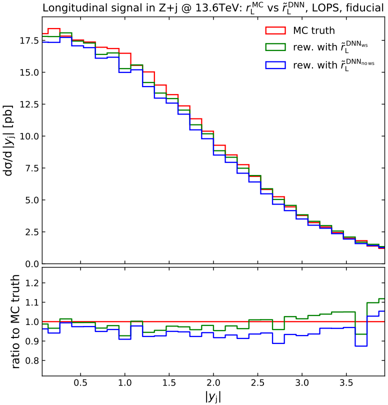
⚠ Failing!
(describing PS corrections instead of polarisation)
→ Retraining …
… with r_L computed before PS
… with PS events

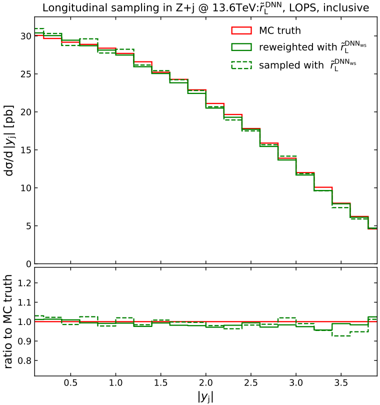
LO+PS with *warm start*



→ Warm start training gives better results
Initial conditions of the LO+PS learning is set by LO learning

LO+PS with *warm start*





→ Warm start training gives better results
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NB: LO+PS is better reproduced than LO (less $\tilde{r}_L < 0$) → mitigation effect?

Experiment / Theory

- $\tilde{r}_{\rm L}$ is an approximation of $r_{\rm L}$ relying only on physical inputs
  $\rightarrow$ Use wide neural network
- Given a set of data/unpolarised sample
  $\rightarrow$ $\tilde{r}_{\rm L}$ allows to tag/reweight longitudinally-polarised events
- Can be used in experimental analysis/theoretical calculations
  $\rightarrow$ f_L extracted to be compared to theory predictions

Discussion

- Validity of the method
  - Training inclusive, to be used within phase-space
    $\rightarrow$ out-of-support extrapolation possible?
  - One training per process at a given energy
    $\rightarrow$ Applicable at different energy?

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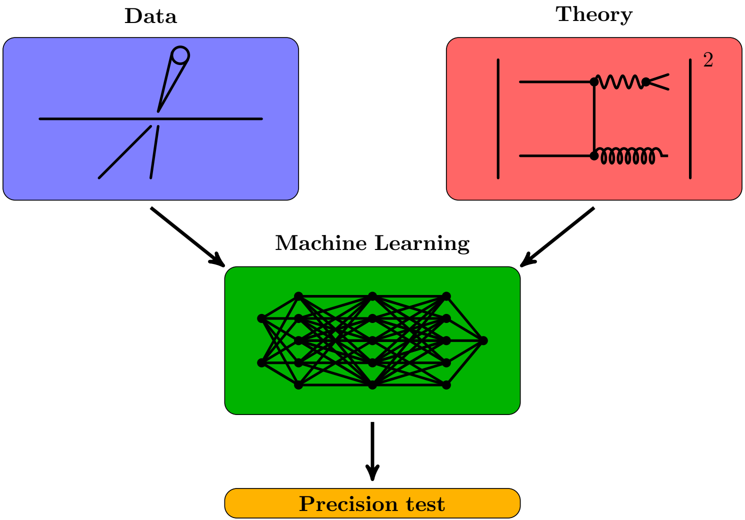
- Model independence
  $\rightarrow$ Any model can be used *e.g.* EFT or simplified models

Outlook

Natural extensions

- Extension of the method beyond LO
  → NLO QCD first
- Test on multi-boson processes
  → di-boson, tri-boson, vector-boson scattering
- Application to other problems (castable into ratios)
  → irreducible backgrounds: ttbb, vector-boson scattering, ...


Data
Theory
2
Machine Learning
Precision test

Summary

New computation and idea for boson polarisation:

- W+j @ NNLO QCD [MP, Poncelet, Popescu; 2109.14336]
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Thank you

BACK-UP