Pinning down the Standard Model
- Precision phenomenology at the LHC -

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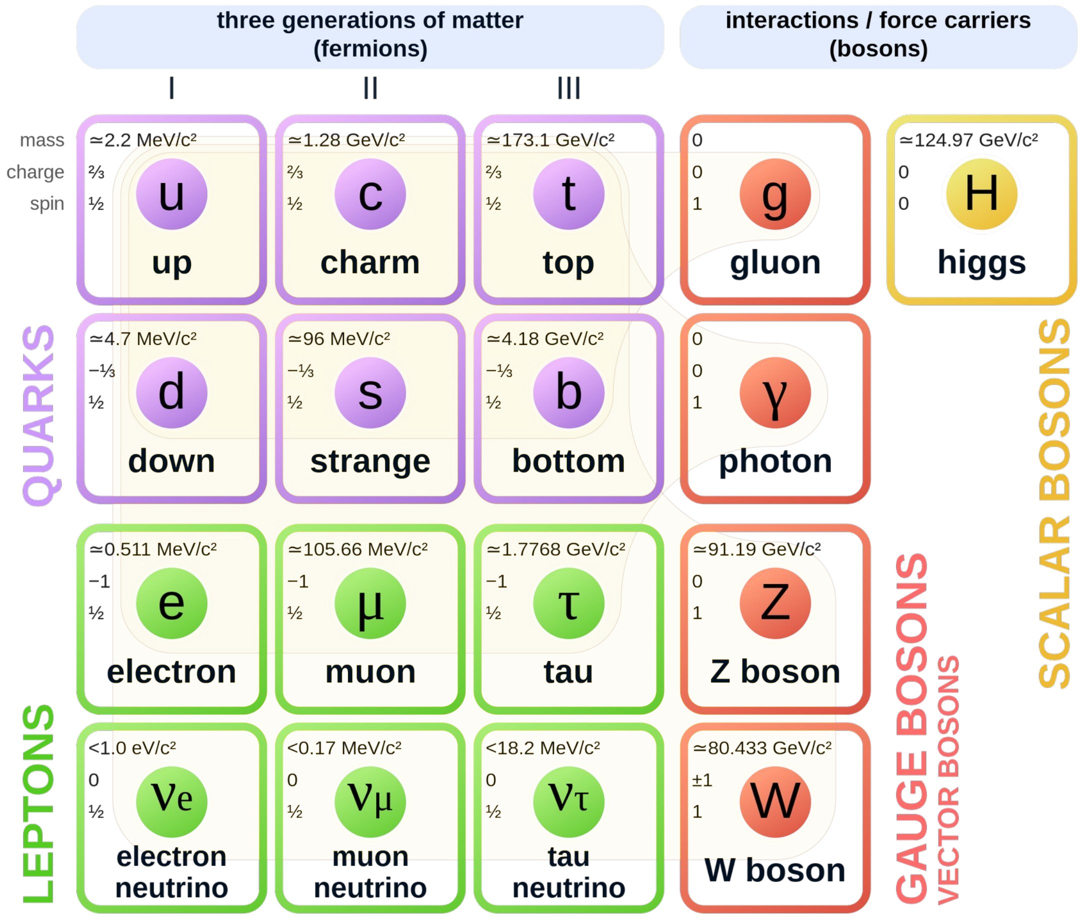
COMETA

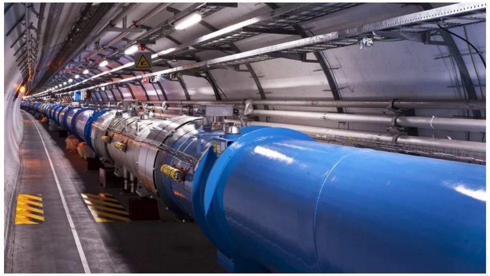
Standard Model of Elementary Particles



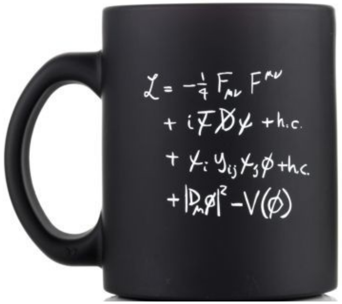
What are the fundamental building blocks of matter?

Scattering experiments

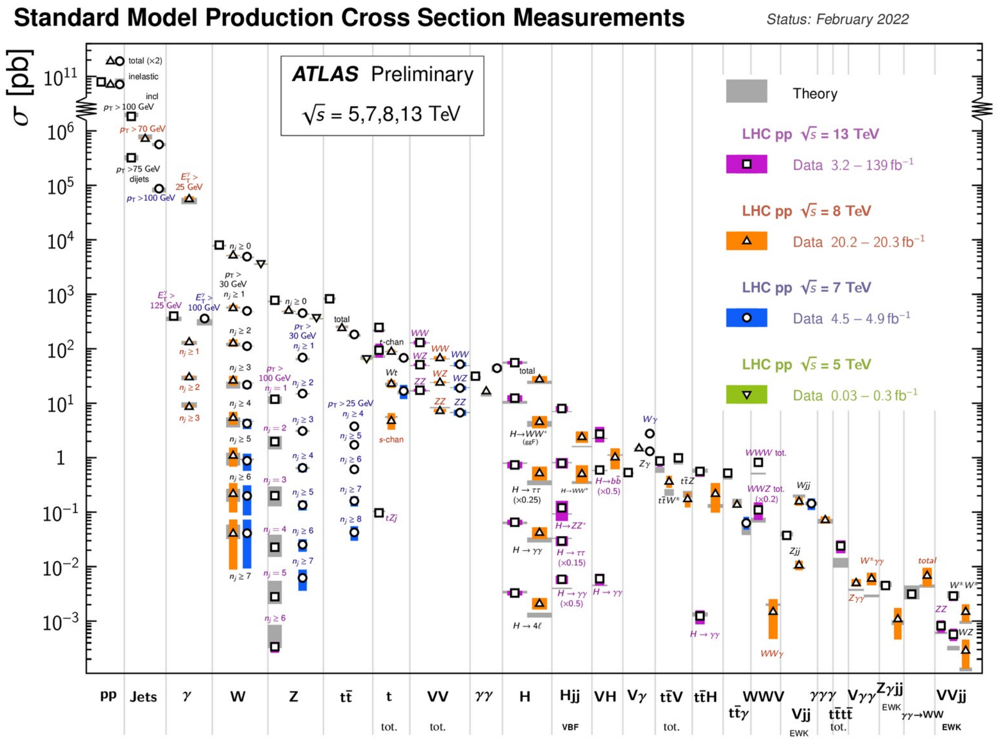
Large Hadron Collider (LHC)



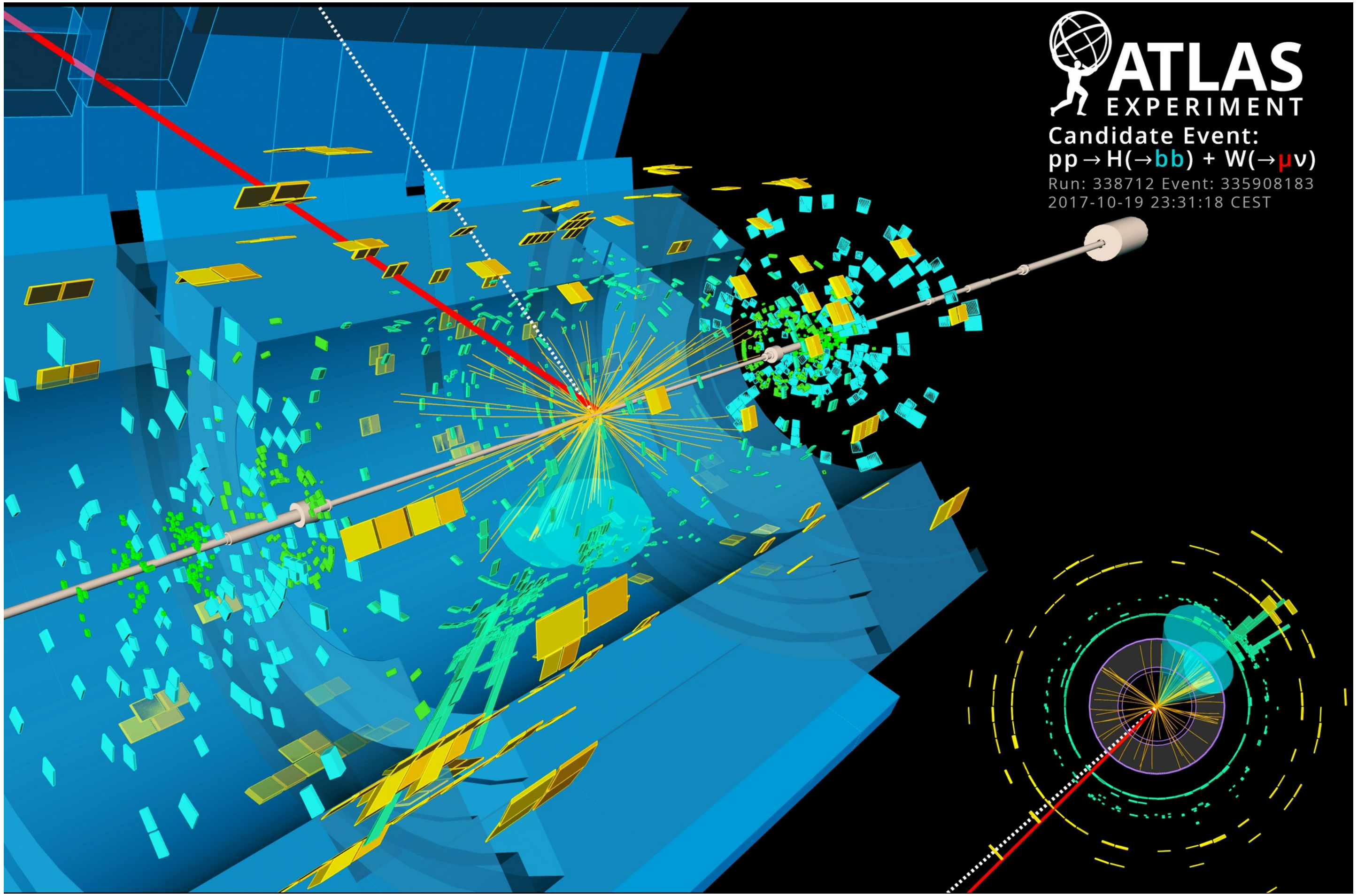
Credit: CERN



Theory/ Standard Model



Collision events



Theory picture of hadron collision events

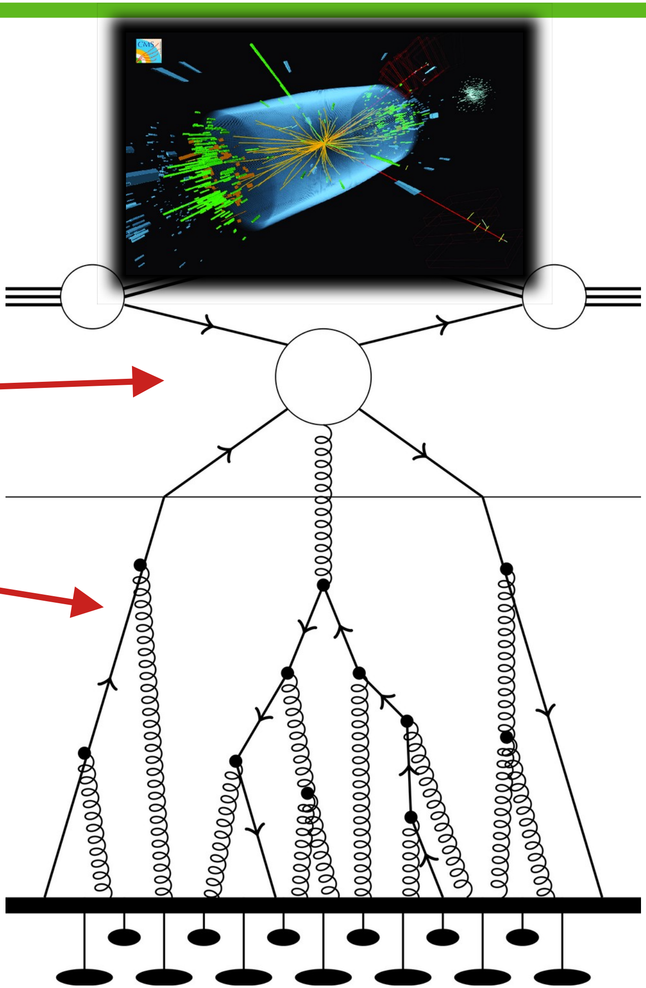
Guiding principle: factorization
"What you see depends on the energy scale"

In Quantum Chromodynamics (QCD):

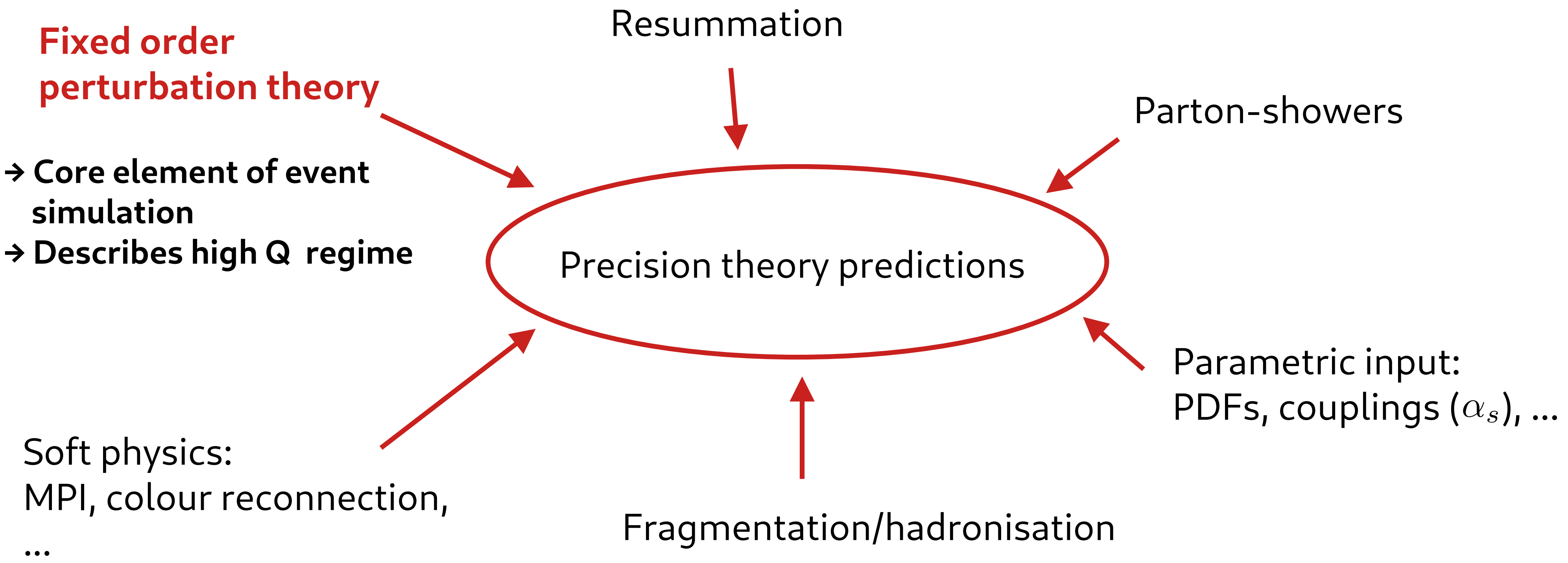
$Q \gg \Lambda_{\mathrm{QCD}}$ **Fixed-order perturbation theory**
scattering of individual partons

$Q \gtrsim \Lambda_{\mathrm{QCD}}$ **Parton-shower/Resummation**
all-order bridge between perturbative and non-perturbative physics

$Q \sim \Lambda_{\mathrm{QCD}}$ **"Hadronization"/MPI/...**
non-perturbative physics



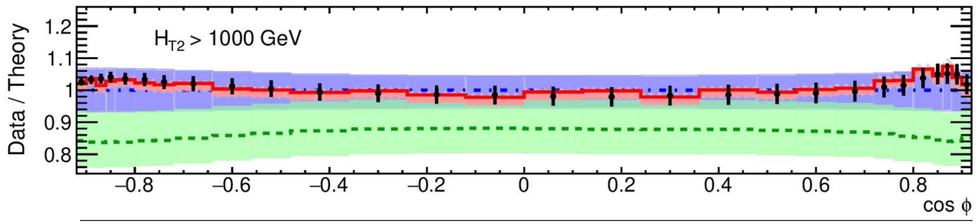
Precision predictions

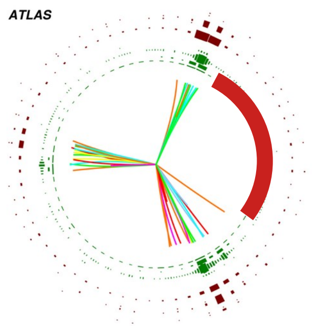


Precision through higher-order perturbation theory

Example: ATLAS multi-jet measurements

[ATLAS 2301.09351]





$\cos\phi$

Cross section = **LO** + **NLO** + **NNLO** + **O(α_s^3)**

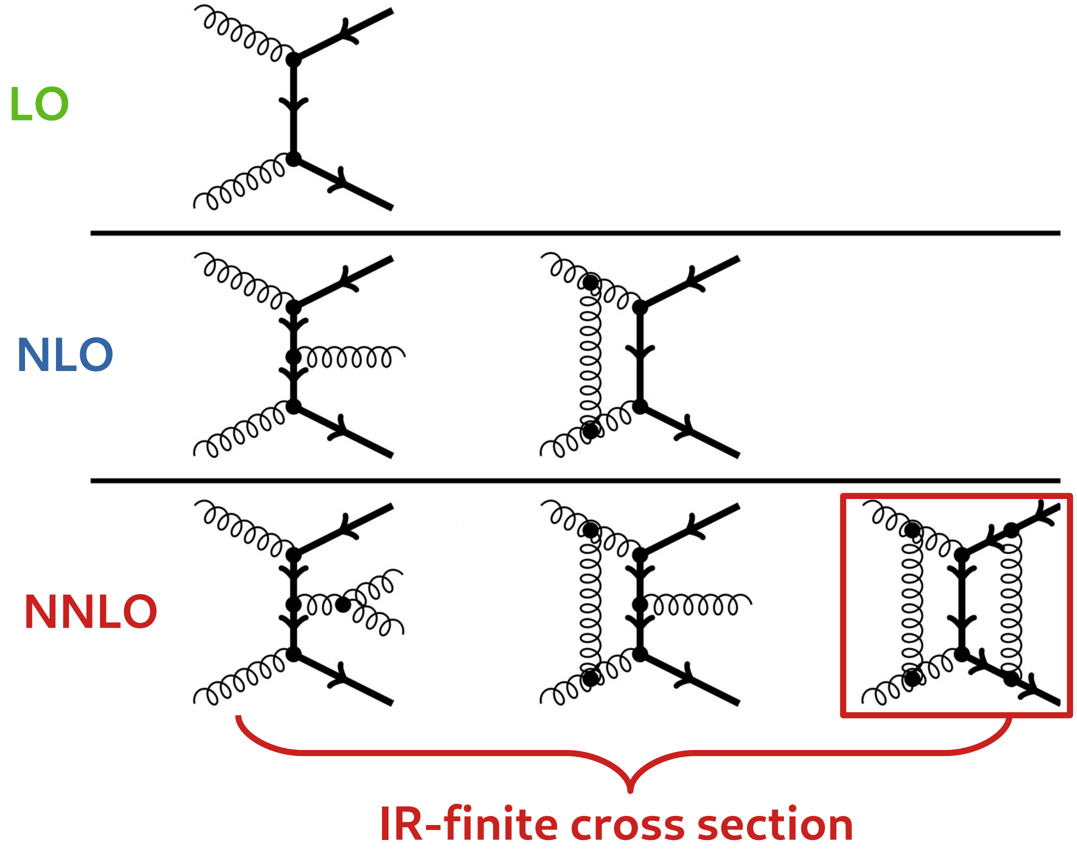
$\sim (\alpha_s)^1$ $\sim (\alpha_s)^2$

Theory uncertainty: **Order of magnitude** **O(10%)** **O(1%)**

Fixed-order expansion in the strong coupling $\alpha_s(m_Z) \approx 0.118$

Experimental precision reaches percent-level already at LHC
next-to-next-to-leading order QCD needed on theory side!

NNLO QCD challenges

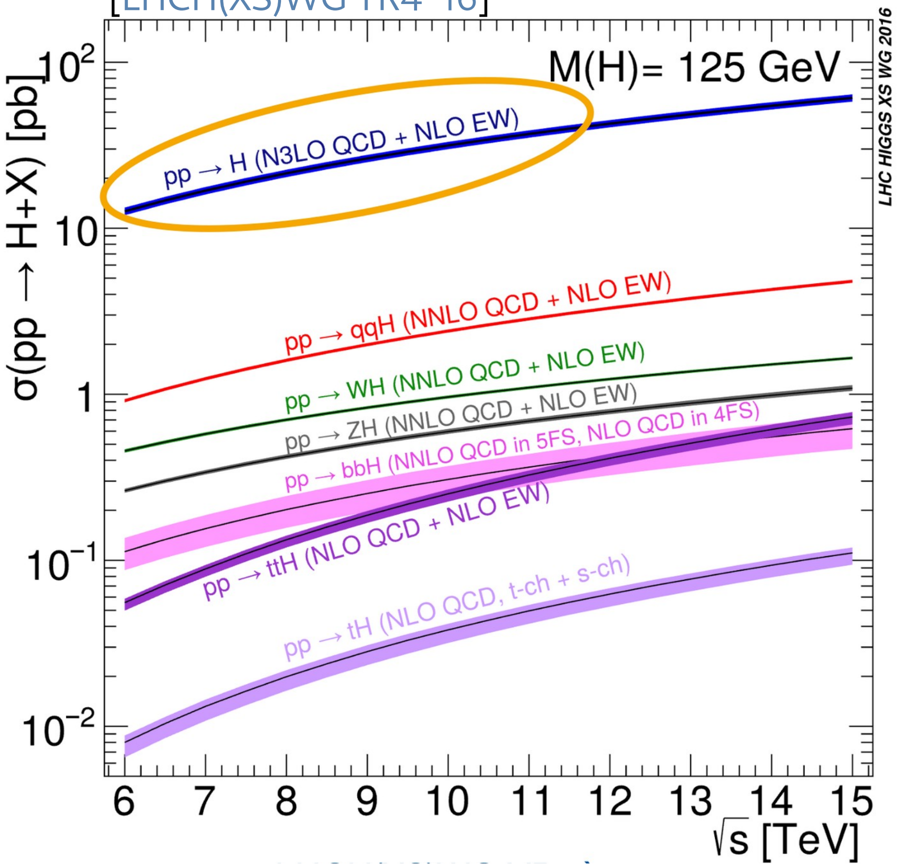


1) How to compute **multi-scale two-loop amplitudes**?
   → **fast growing complexity: rational** and **transcendental**
   → deeper understanding of the analytical properties
   → refinement of computational tools

2) How to achieve **infrared finite differential** cross sections at NNLO QCD?
   ~20 years to solve this problem
   → highly non-trivial IR structure
   → plethora of subtraction schemes

Higgs-production at hadron colliders

[LHCH(XS)WG YR4' 16]



- Higgs production is dominated through gluon-fusion
- Experimental measurement

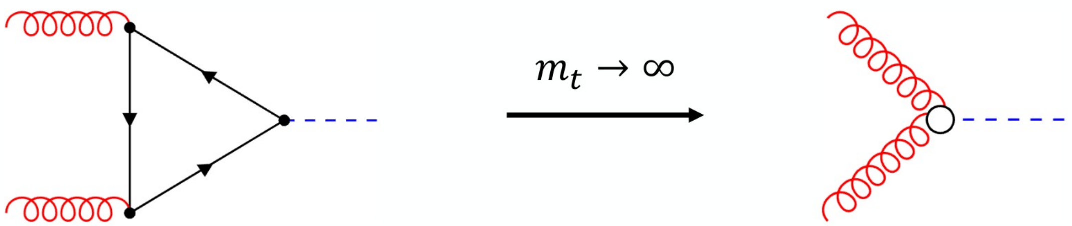
$$\sigma^{\text{exp.}}_{gg\to H} = 47.1 \pm 3.8 \text{ pb}$$

[CMS'22]

- HL LHC expects 2 % uncertainty
- Theory predictions need to keep up → Higher-order predictions crucial!

HTL and HEFT

Heavy Top Limit (HTL or EFT):



$$\sigma_{gg\to H} = \sigma^{\mathrm{HTL}}_{gg\to H} + \mathcal{O}\left(\frac{m_H^2}{m_t^2}\right) \quad \text{for} \quad m_t \to \infty$$

Higgs Effective Field Theory (HEFT or rEFT): $\sigma^{\mathrm{N}^n\mathrm{LO}}_{\mathrm{HEFT}} = \frac{\sigma^{\mathrm{LO}}}{\sigma^{\mathrm{LO}}_{\mathrm{HTL}}}\sigma^{\mathrm{N}^n\mathrm{LO}}_{\mathrm{HTL}} \approx 1.064 \times \sigma^{\mathrm{N}^n\mathrm{LO}}_{\mathrm{HTL}}$

captures some of the top-quark mass effects for inclusive observables.
At higher loop-order questionable → needs full computation.
How to deal with other quark mass effects?

Precision predictions for Higgs production in gluon-fusion

[LHCH(XS)WG YR4' 16]

Immense community effort to achieve precise theory predictions

$$\sigma = 48.58\,\mathrm{pb}^{+2.22\,\mathrm{pb}\,(+4.56\%)}_{-3.27\,\mathrm{pb}\,(-6.72\%)}\ (\text{theory}) \pm 1.56\,\mathrm{pb}\,(3.20\%)\ (\text{PDF}+\alpha_s)\,.$$

$48.58\,\mathrm{pb} =$	$16.00\,\mathrm{pb}$	$(+32.9\%)$	(LO, rEFT)	[Georgi, Glashow, Machacek, Nanopoulos'78]
	$+\,20.84\,\mathrm{pb}$	$(+42.9\%)$	(NLO, rEFT)	[Dawson '91][Djouadi, Spira Zerwas '91]
	$-\ 2.05\,\mathrm{pb}$	(-4.2%)	$((t,b,c)$, exact NLO)	[Graudenz, Spira, Zerwas '93]
	$+\ 9.56\,\mathrm{pb}$	$(+19.7\%)$	(NNLO, rEFT)	[Ravindran, Smith, Van Neerven '02] [Harlander, Kilgore '02][Anastasiou, Melnikov '02]
	$+\ 0.34\,\mathrm{pb}$	$(+0.7\%)$	(NNLO, $1/m_t$)	[Harlander, Ozeren'09][Pak, Rogal, Steinhauser'10] [Harlander, Mantler, Marzani, Ozeren '10]
	$+\ 2.40\,\mathrm{pb}$	$(+4.9\%)$	(EW, QCD-EW)	[Aglietti, Bonciani, Degrassi,Vicini'04] [Actis, Passarino, Sturm, Uccirati'08] [Anastasiou, Boughezal, Petriello'09]
	$+\ 1.49\,\mathrm{pb}$	$(+3.1\%)$	($\mathrm{N^3LO}$, rEFT)	[Anastasiou, Duhr, Dulat, Herzog, Mistlberger'15]

Remaining theory uncertainties

[LHCH(XS)WG YR4' 16]

N4LO approximation
[Das, Moch, Vogt '20]

aN3LO PDFs
[MSHT'22,NNPDF'24]

Exact top-mass dependence through NNLO QCD
[Czakon, Harlander, Klappert, Niggetiedt'21]

Input parameters

$\sqrt{S}$	13 TeV
m_h	125 GeV
PDF	PDF4LHC15_nnlo_100
$\alpha_s(m_Z)$	0.118
$m_t(m_t)$	162.7 GeV ($\overline{\text{MS}}$)
$m_b(m_b)$	4.18 GeV ($\overline{\text{MS}}$)
$m_c(3GeV)$	0.986 GeV ($\overline{\text{MS}}$)
$\mu = \mu_R = \mu_F$	62.5 GeV ($= m_H/2$)

δ(scale)	δ(trunc)	δ(PDF-TH)	δ(EW)	$\delta(t,b,c)$	$\delta(1/m_t)$
$+0.10$ pb -1.15 pb	±0.18 pb	±0.56 pb	±0.49 pb	±0.40 pb	±0.49 pb
$+0.21\%$ -2.37%	$\pm0.37\%$	$\pm1.16\%$	$\pm1\%$	$\pm0.83\%$	$\pm1\%$

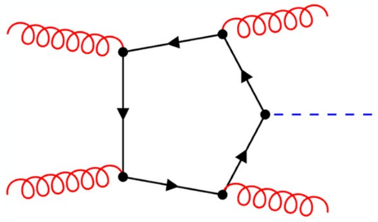
N3LO HEFT
[Mistlberger'18]

Improved QCD-EW predictions
[Bonetti, Melnikov, Trancredi'18] [Anastasiou et al '19]
[Bonetti et al. '20][Bechetti et al. '21] [Bonetti, Panzer, Trancredi '22]

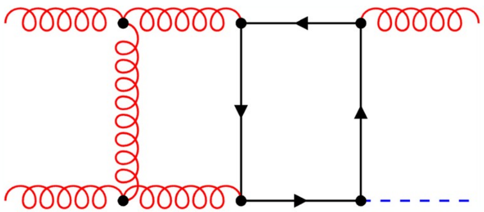
Bottom-top-interference
[Czakon, Eschment, Niggetiedt, Poncelet, Schellenberger, Phys.Rev.Lett. 132 (2024) 21, 211902, JHEP 10 (2024) 210, EurekAlert]

Bottom-top interference effects through NNLO QCD

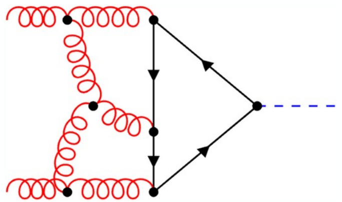
Double real (one-loop)



Real virtual (two-loop)



Double virtual (three-loop)



Renorm. scheme	$\overline{\text{MS}}$	on-shell
$\mathcal{O}(\alpha_s^2)$	-1.11	-1.98
LO	$-1.11^{+0.28}_{-0.43}$	$-1.98^{+0.38}_{-0.53}$
$\mathcal{O}(\alpha_s^3)$	-0.65	-0.44
NLO	$-1.76^{+0.27}_{-0.28}$	$-2.42^{+0.19}_{-0.12}$
$\mathcal{O}(\alpha_s^4)$	$+0.02$	$+0.43$
NNLO	$-1.74(2)^{+0.13}_{-0.03}$	$-1.99(2)^{+0.29}_{-0.15}$

Renormalisation scheme independence at NNLO

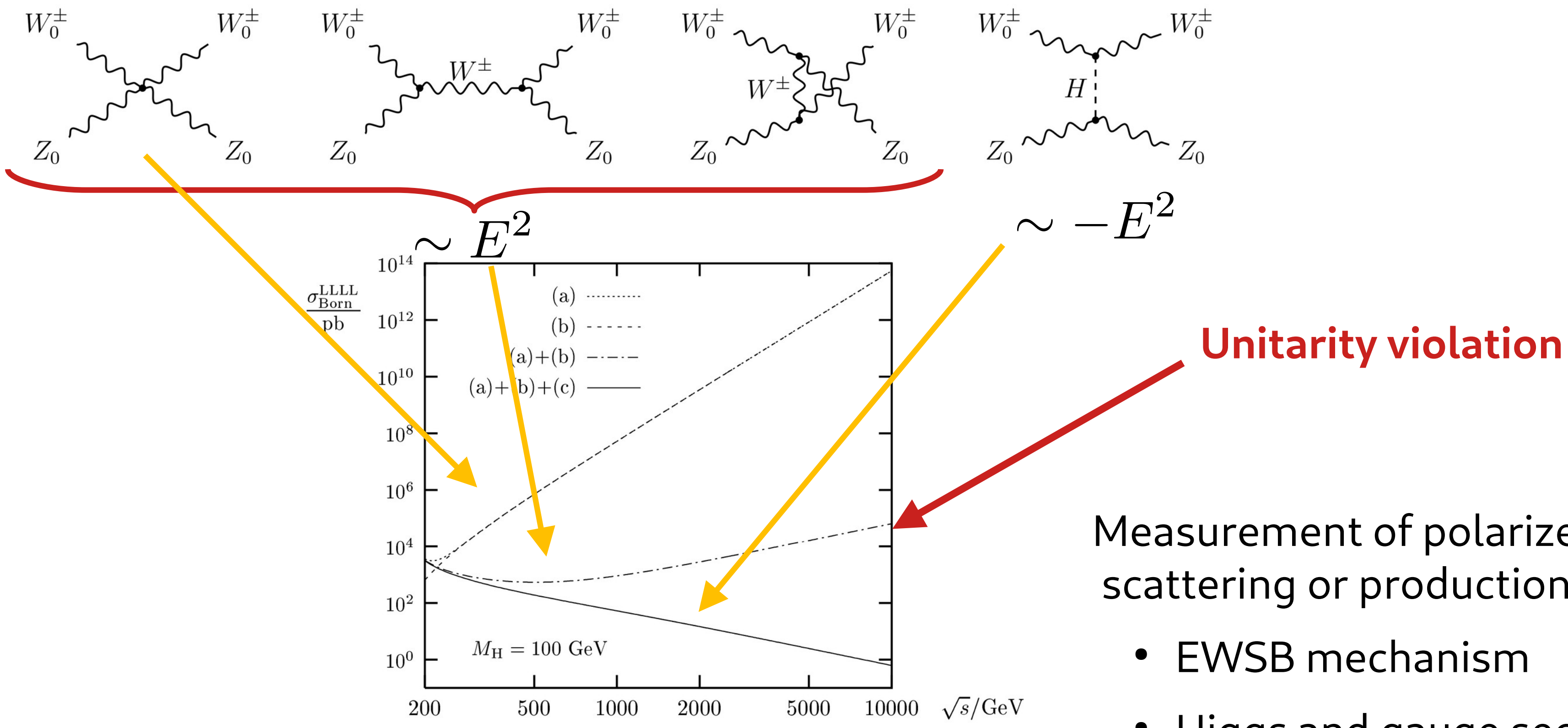
Pure top-quark mass effects

Order	σ_{HEFT} [pb]	$(\sigma_t - \sigma_{\text{HEFT}})$ [pb]
$\mathcal{O}(\alpha_s^2)$	$+16.30$	–
LO	$16.30^{+4.36}_{-3.10}$	–
$\mathcal{O}(\alpha_s^3)$	$+21.14$	-0.303
NLO	$37.44^{+8.42}_{-6.29}$	$-0.303^{+0.10}_{-0.17}$
$\mathcal{O}(\alpha_s^4)$	$+9.72$	$+0.147(1)$
NNLO	$47.16^{+4.21}_{-4.77}$	$-0.156(1)^{+0.13}_{-0.03}$

Bottom-top interference larger than top mass effect

Other ways to probe the Higgs? → Polarised bosons!

Longitudinal Vector-Boson-Scattering (VBS)



Radiative corrections to W+ W- → W+ W- in the electroweak standard model
A. Denner, T. Hahn hep-ph/9711302

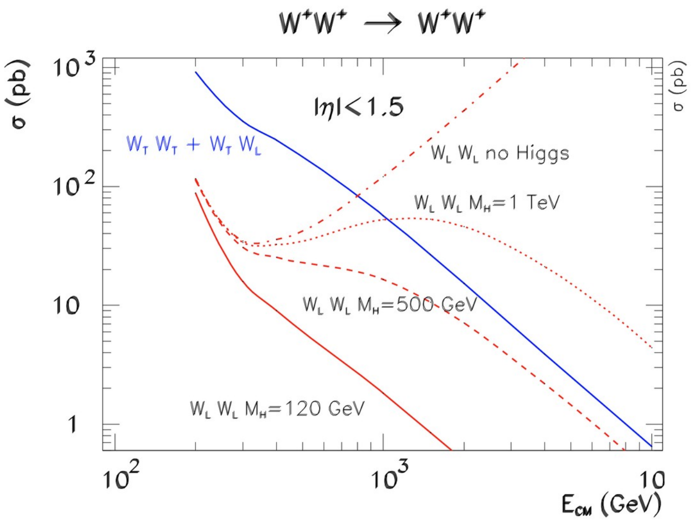
Measurement of polarized boson scattering or production probes:

- EWSB mechanism
- Higgs and gauge sector
- New physics models

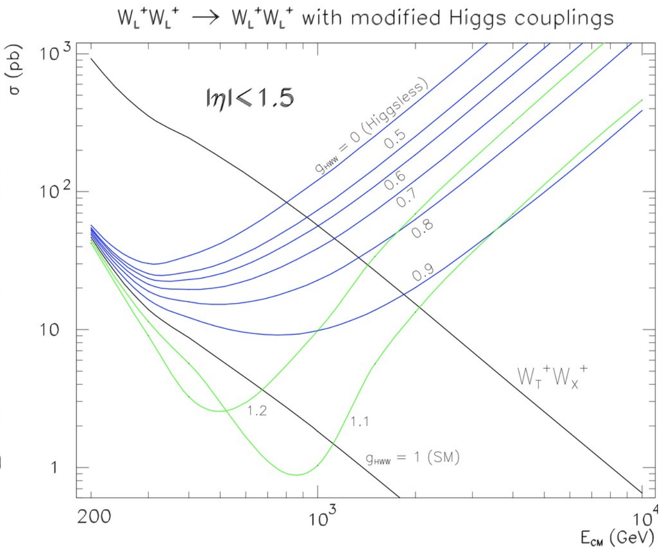
Longitudinal Vector-Boson-Scattering (VBS)

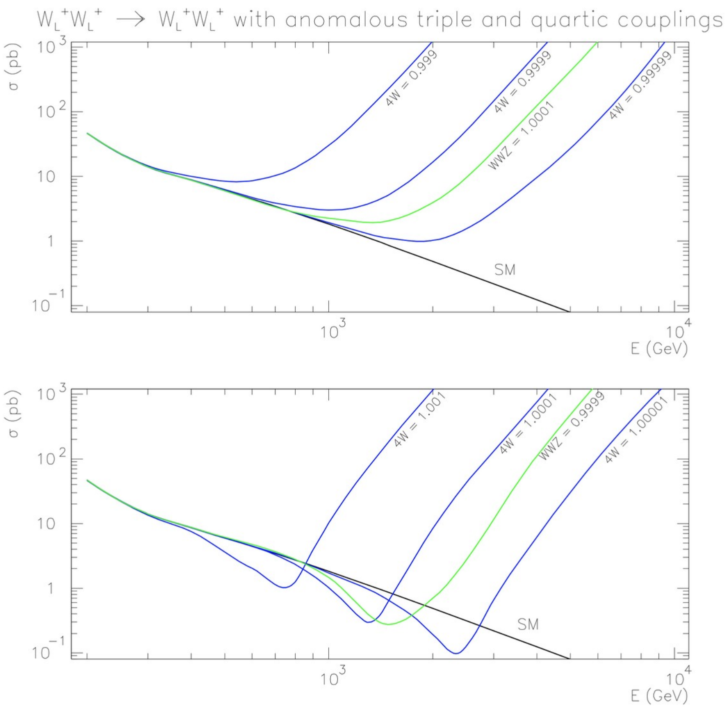
The Higgs boson and the physics of WW scattering before and after Higgs discovery
M. Szleper 1412.8367

Sensitivity to the Higgs mass



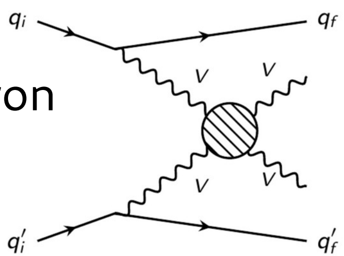
Modified HVV, VVV, VVVV couplings



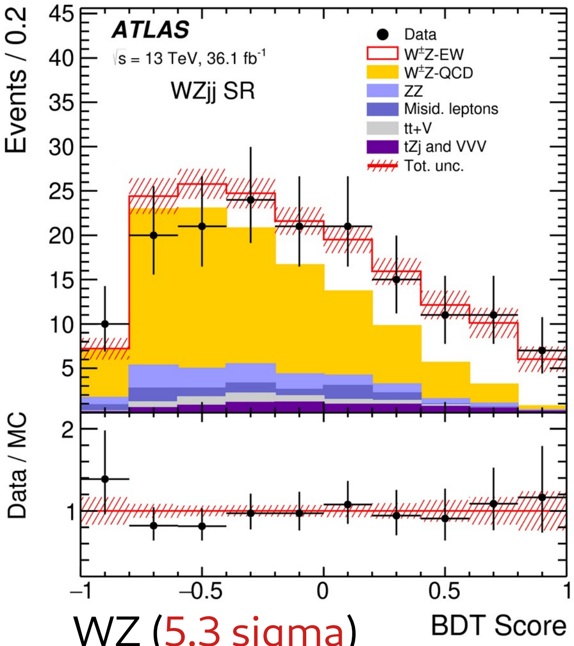


VBS at hadron colliders

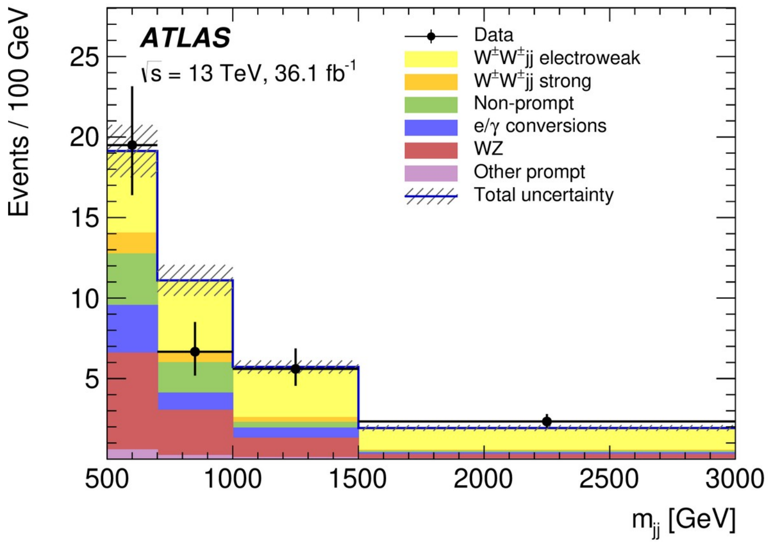
VBS at hadron colliders



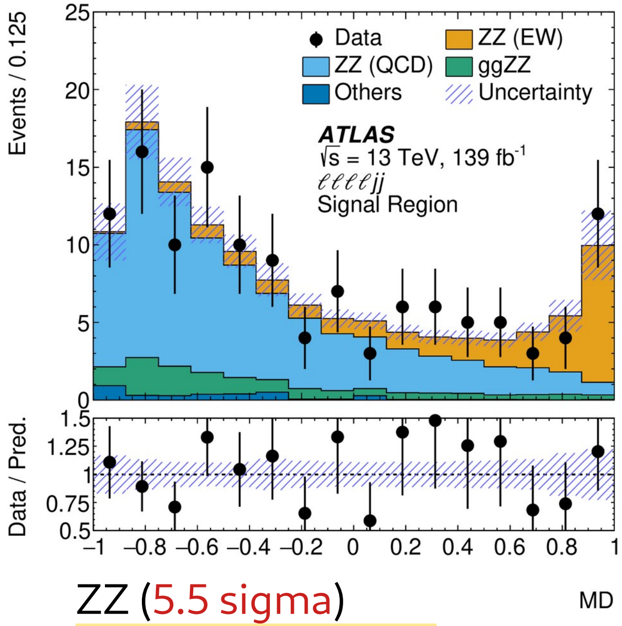
Separate from background processes through VBS topology
→ a rare process, but observed.



WZ (5.3 sigma)
ATLAS 1812.09740



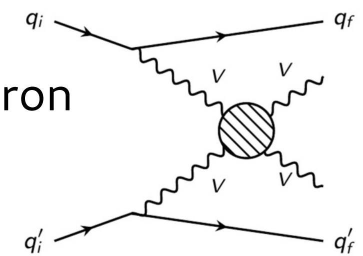
W+W+/W-W- (6.5 sigma)
ATLAS 1906.03203



ZZ (5.5 sigma)
ATLAS 2004.10612

VBS at hadron colliders

VBS at hadron colliders



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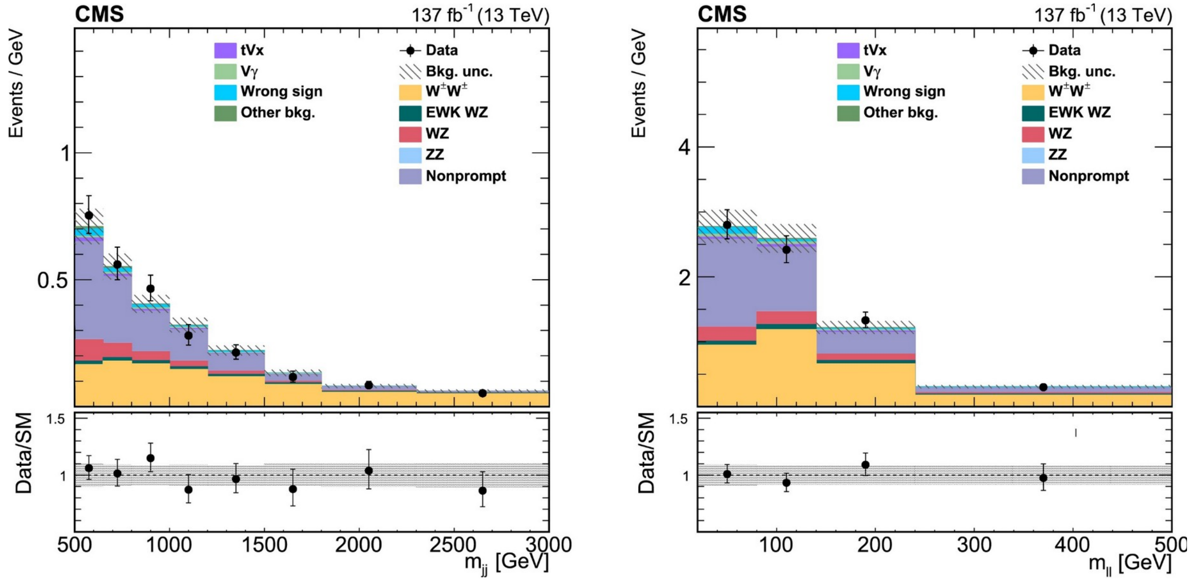
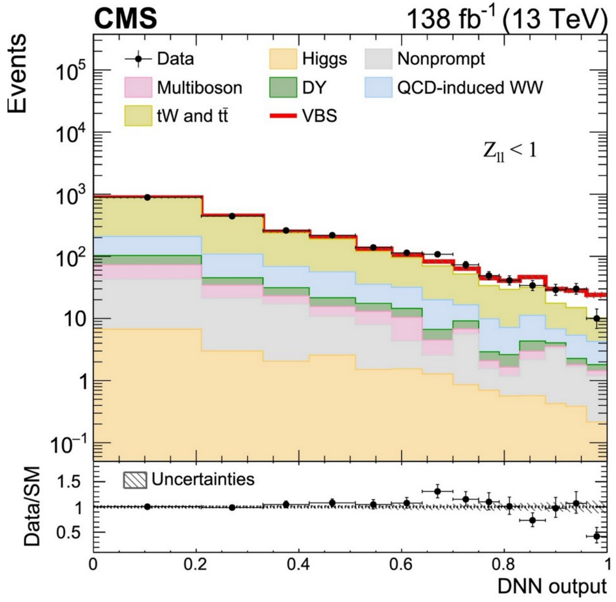
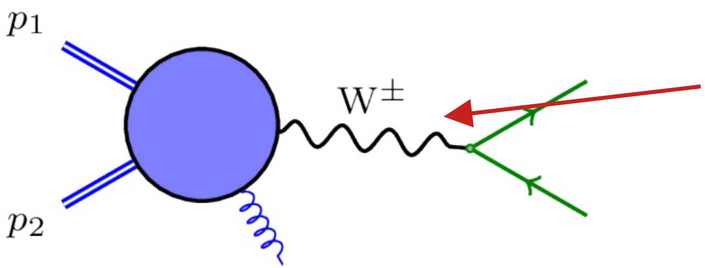


WZ (6.8 sigma) + W+W+/W-W- (diff. xsec)
CMS 2005.01173



W+W- (5.6 sigma)
CMS 2205.05711

Polarised boson production



$$\left(-g^{\mu\nu} + \frac{k^\mu k^\nu}{k^2}\right) \to \sum_\lambda \epsilon_\lambda^{*\mu} \epsilon_\lambda^\nu$$

λ = +/-/L

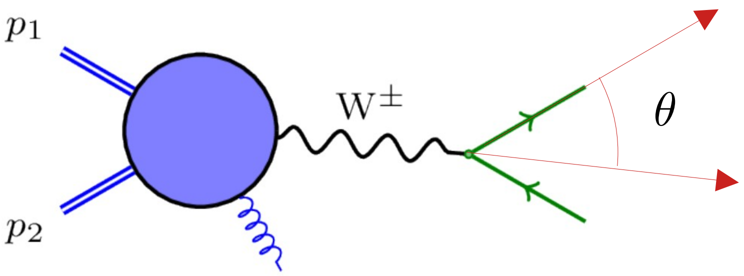
Can we extract the longitudinal component?

Measurements of longitudinal polarisation fractions:

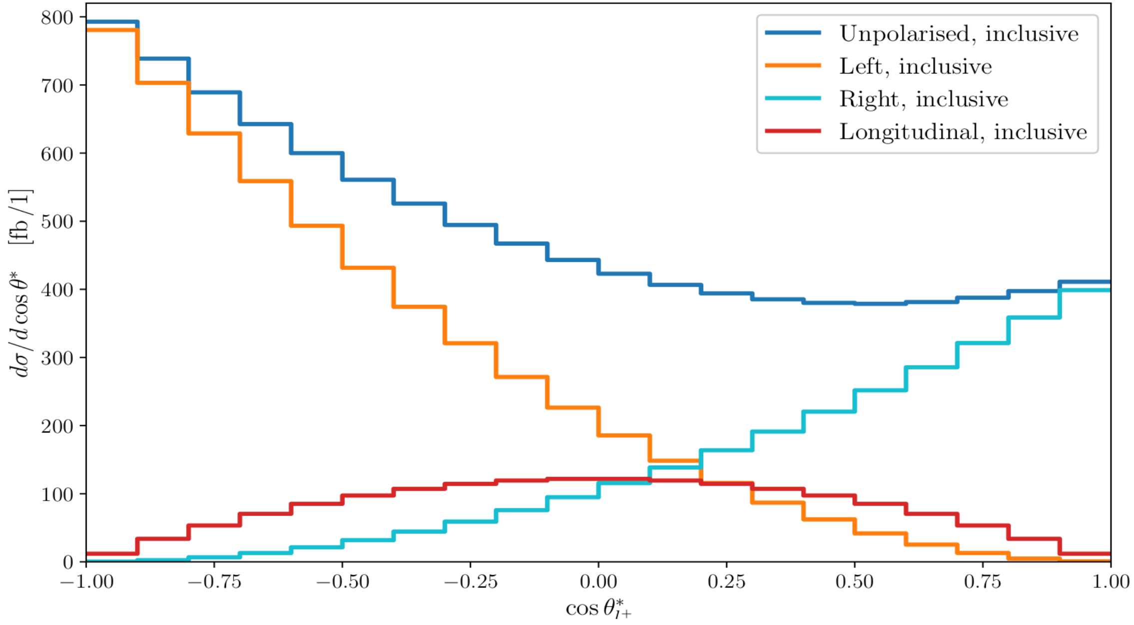
Measurement of the Polarization of W Bosons with Large Transverse Momenta in W+Jets Events at the LHC,
CMS 1104.3829
Measurement of the polarisation of W bosons produced with large transverse momentum in pp collisions at \sqrt{s}=7 TeV with the ATLAS experiment,
ATLAS 1203.2165
Measurement of WZ production cross sections and gauge boson polarisation in pp collisions at sqrt(s) = 13 TeV with the ATLAS detector,
ATLAS 1902.05759
Measurement of the inclusive and differential WZ production cross sections, polarization angles, and triple gauge couplings in pp collisions at sqrt(s) = 13 TeV,
CMS 2110.11231
Observation of gauge boson joint-polarisation states in WZ production from pp collisions at sqrt(s) = 13 TeV with the ATLAS detector
ATLAS 2211.09435
Evidence of pair production of longitudinally polarised vector bosons and study of CP properties in ZZ → 4ℓ events with the ATLAS detector at sqrt(s) = 13 TeV
ATLAS 2310.04350
Studies of the Energy Dependence of Diboson Polarization Fractions and the Radiation-Amplitude-Zero Effect in WZ Production with the ATLAS Detector
ATLAS 2402.16365

How to measure polarized bosons?

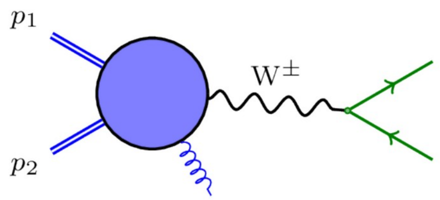
- We can't measure boson polarization directly.
- Luckily decay products can be used as a "polarimeter":



W+ decay (W- mirrored around 0)



Polarized cross sections



$$M = \mathbf{P}_\mu \cdot \frac{-g_{\mu\nu} + \frac{k^\mu k^\nu}{k^2}}{k^2 - M_V^2 + iM_V\Gamma_V} \cdot \mathbf{D}_\nu$$

On-shell bosons:
(DPA or NWA)

$$\left(-g^{\mu\nu} + \frac{k^\mu k^\nu}{k^2}\right) \to \sum_\lambda \epsilon_\lambda^{*\mu} \epsilon_\lambda^\nu$$

$$|M|^2 = \underbrace{\sum_\lambda |M_\lambda|^2}_{} + \underbrace{\sum_{\lambda \neq \lambda'} M_\lambda^* M_{\lambda'}}_{}$$

→ polarised x-sections Interferences

Create samples of fixed polarisation:

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

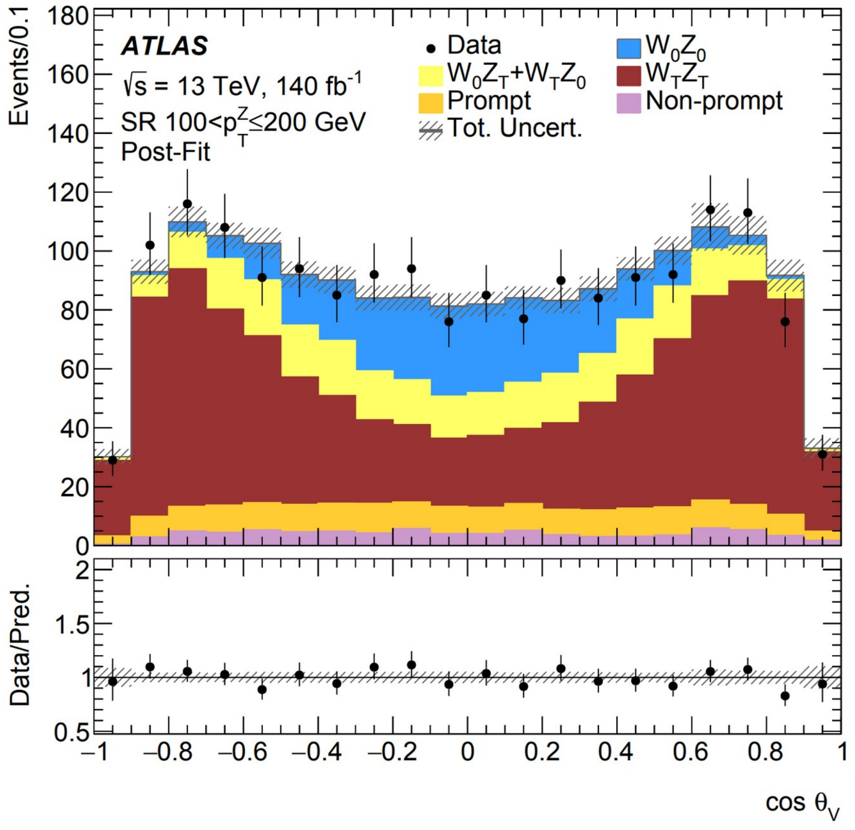
and fit f_L, f_R, f_0 to measured $\frac{d\sigma^{exp.}}{dX}$

Polarized cross sections

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

- Interferences can be handled
- Does not rely on extrapolations to the full phase space
  X can be any observable → lab frame observables
- $\frac{\mathrm{d}\sigma_i}{\mathrm{d}X}$ can be systematically improved

Example polarisation measurement in ATLAS



Studies of the Energy Dependence of Diboson Polarization Fractions and the Radiation-Amplitude-Zero Effect in WZ Production with the ATLAS Detector, ATLAS 2402.16365

	Measurement	
	$100 < p_T^Z \leq 200$ GeV	$p_T^Z > 200$ GeV
f_{00}	$0.19 \pm^{0.03}_{0.03}$ (stat) $\pm^{0.02}_{0.02}$ (syst)	$0.13 \pm^{0.09}_{0.08}$ (stat) $\pm^{0.02}_{0.02}$ (syst)
f_{0T+T0}	$0.18 \pm^{0.07}_{0.08}$ (stat) $\pm^{0.05}_{0.06}$ (syst)	$0.23 \pm^{0.17}_{0.18}$ (stat) $\pm^{0.06}_{0.10}$ (syst)
f_{TT}	$0.63 \pm^{0.05}_{0.05}$ (stat) $\pm^{0.04}_{0.04}$ (syst)	$0.64 \pm^{0.12}_{0.12}$ (stat) $\pm^{0.06}_{0.06}$ (syst)
f_{00} obs (exp) sig.	5.2 (4.3) σ	1.6 (2.5) σ

	Prediction	
	$100 < p_T^Z \leq 200$ GeV	$p_T^Z > 200$ GeV
f_{00}	0.152 ± 0.006	0.234 ± 0.007
f_{0T}	0.120 ± 0.002	0.062 ± 0.002
f_{T0}	0.109 ± 0.001	0.058 ± 0.001
f_{TT}	0.619 ± 0.007	0.646 ± 0.008

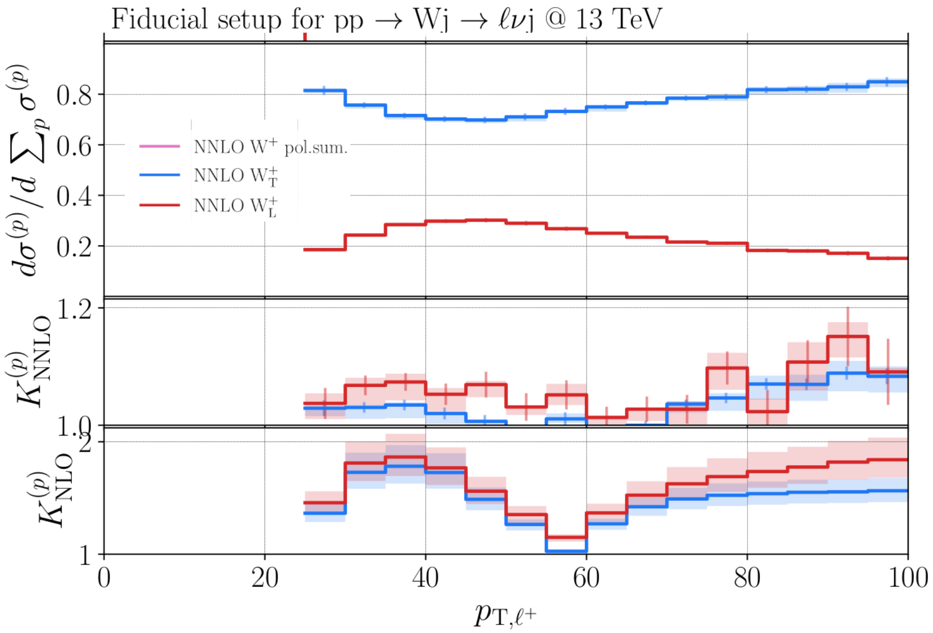
Polarized cross sections

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

- Interferences can be handled
- Does not rely on extrapolations to the full phase space
  X can be any observable → lab frame observables
- $\frac{\mathrm{d}\sigma_i}{\mathrm{d}X}$ can be systematically improved

Higher-order QCD/EW corrections + PS
to minimize uncertainties from missing higher orders (scale uncertainties)

Why do we need higher-order corrections?



Important observation:

Inclusive K-factors are not enough

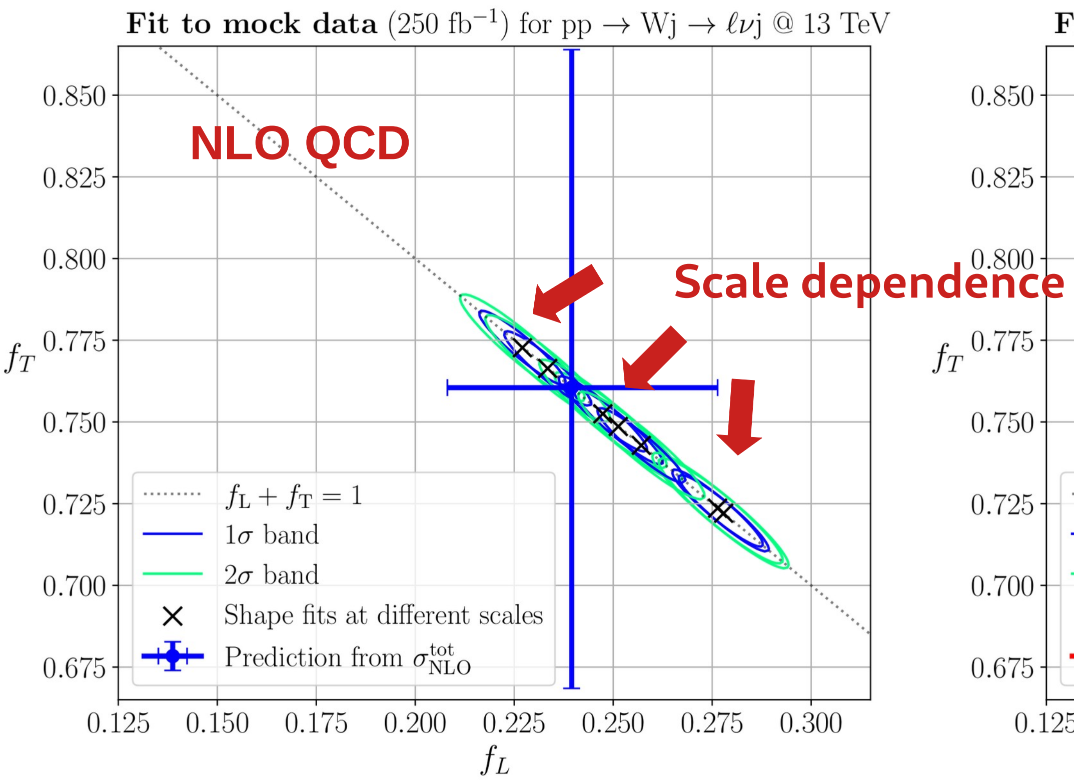
1) Differential polarization fraction have shapes
2) Higher-order corrections dependent on polarization! Just using unpolarized K-factor would lead to distortion of spectrum.
3) NNLO QCD needed to reach percent-level scale-dependence → MHOU

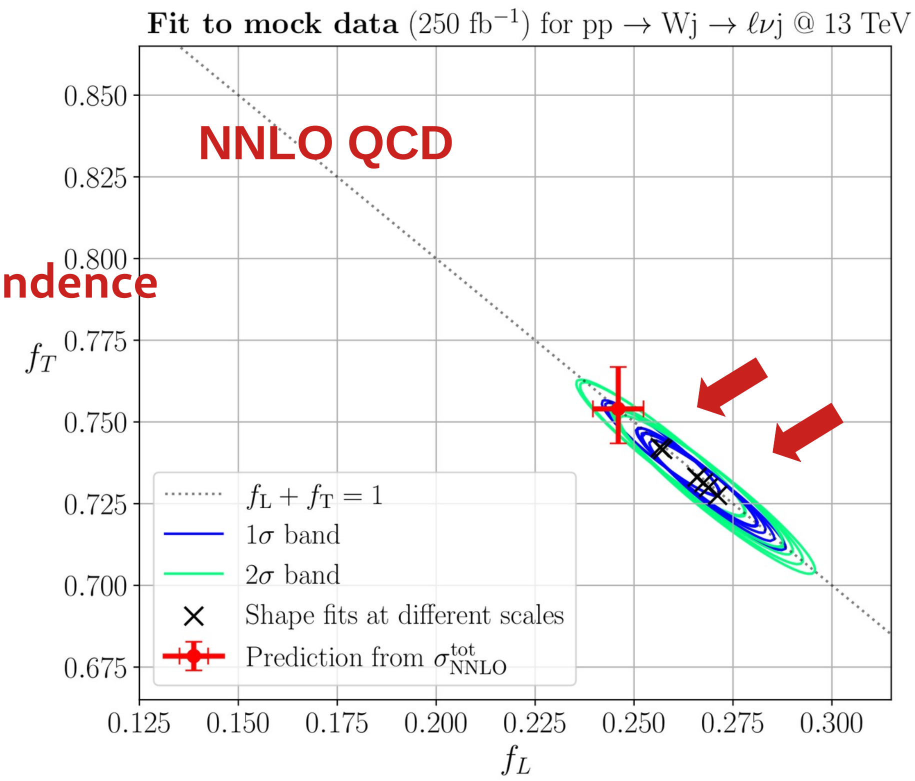
Polarised W+j production at the LHC: a study at NNLO QCD accuracy, Pellen, Poncelet, Popescu 2109.14336

W+jet: mock-data fit

Fit to mock-data (based on NNLO QCD and 250 fb^{-1} stats):
→ extreme case to see effect of scale dependence reduction

Observable: $\cos(\ell, j_1)$





COMETA polarisation study

Precise Standard-Model predictions for polarised Z-boson pair production and decay at the LHC

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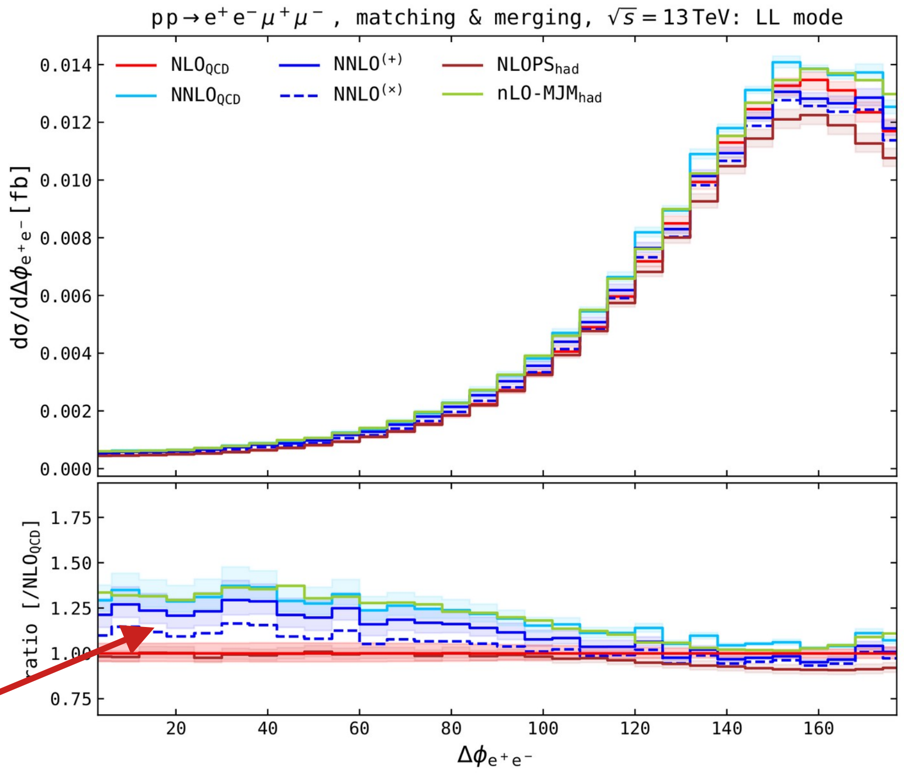
Validation/comparisons of MC codes

Fixed order:
BBMC, Mocanlo, MulBos, Stripper
Event generators:
MadGraph, Sherpa, Powheg+Pythia

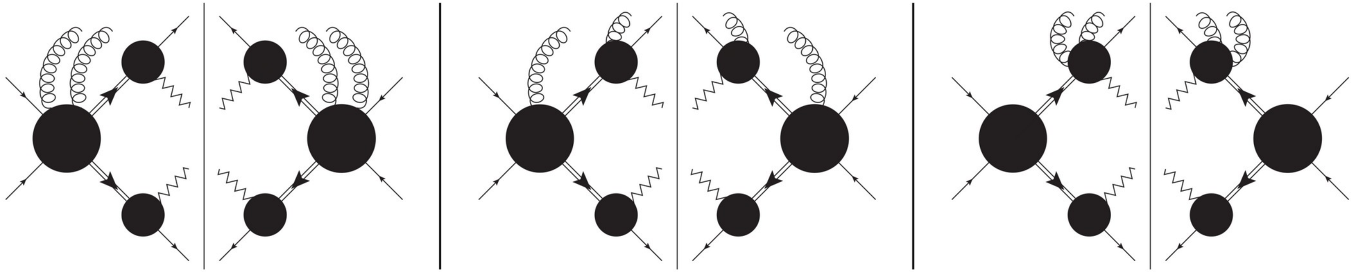


Largest QCD corrections come from the modelling of hard radiation (recoil) → not captured by PS

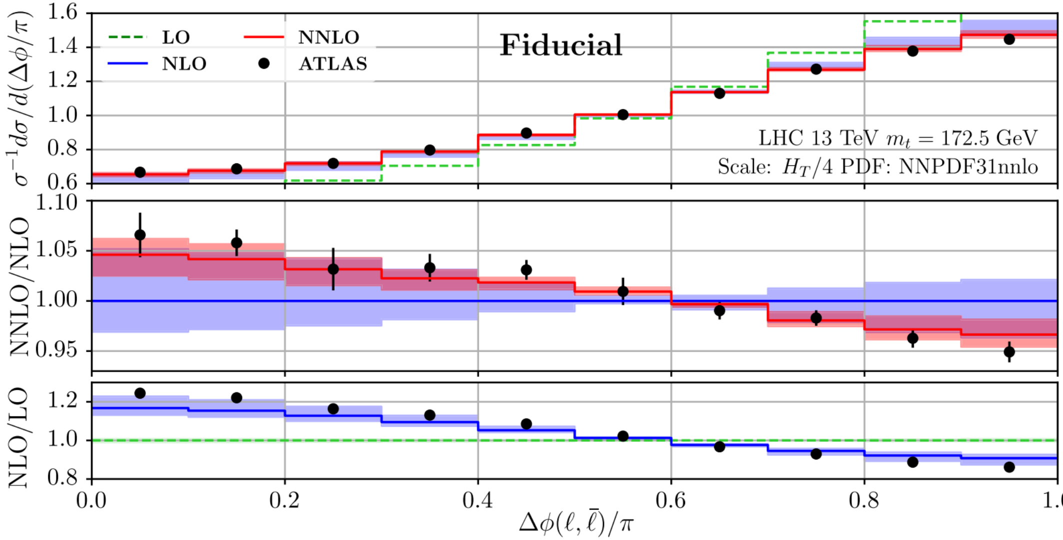
Spin-correlations in top-quark pair production

[Behring, Czakon, Mitov, Papanastasiou,Poncelet PRL 123 (2019) 8 082001]

This is not really a surprise…



Hard recoil in top-quark pair production and decay causes significant shape effects!



P3EWSB

[High **P**recision **P**redictions to **P**robe the **E**lectro**W**eak-**S**ymmetry **B**reaking]

Funded under SONATA 20 UMO-2024/55/D/ST2/00934

NARODOWE CENTRUM NAUKI

More holistic analysis of NNLO QCD corrections to spin-observables

→ more **polarised LHC processes**: top-quark production, Higgs-strahlung, ...

→ impact on **quantum information observables**

which are typically based of angular correlations

→ implementation in **HighTEA** for easy access

high tea — for your freshly brewed analysis [2304.05993]

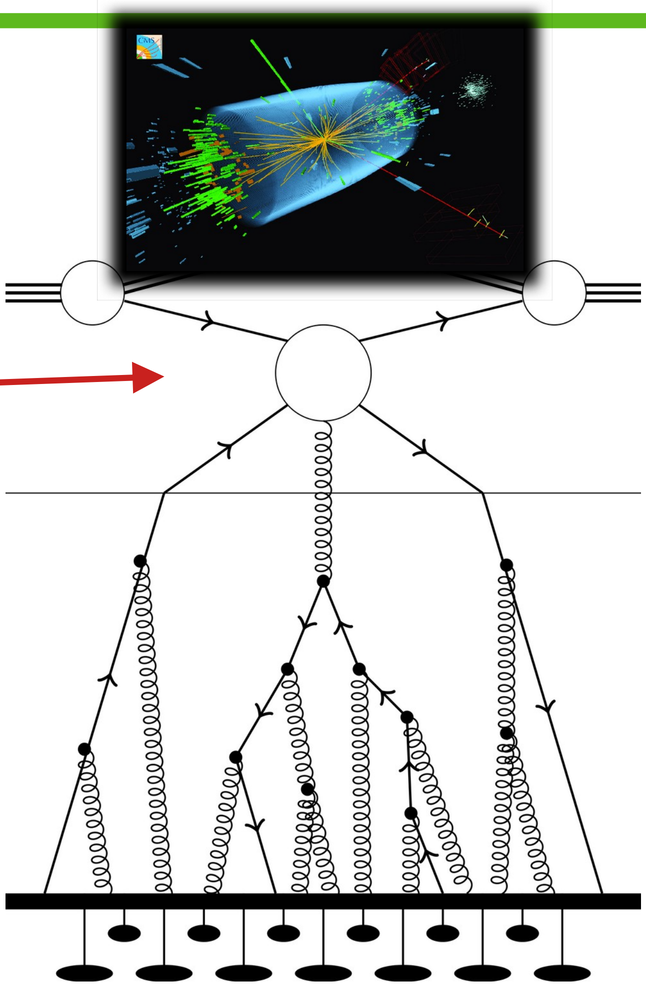
https://www.precision.hep.phy.cam.ac.uk/hightea

Beyond fixed-order perturbation theory

Guiding principle: factorization
"What you see depends on the energy scale"

In Quantum Chromodynamics (QCD):

$Q \gg \Lambda_{\mathrm{QCD}}$ **Fixed-order perturbation theory**
scattering of individual partons



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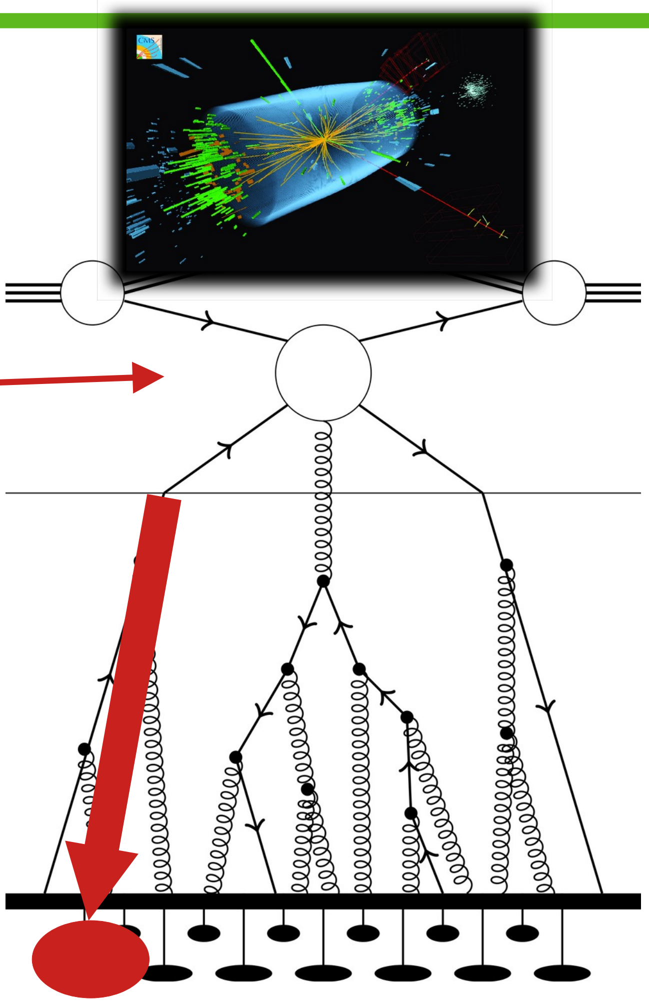


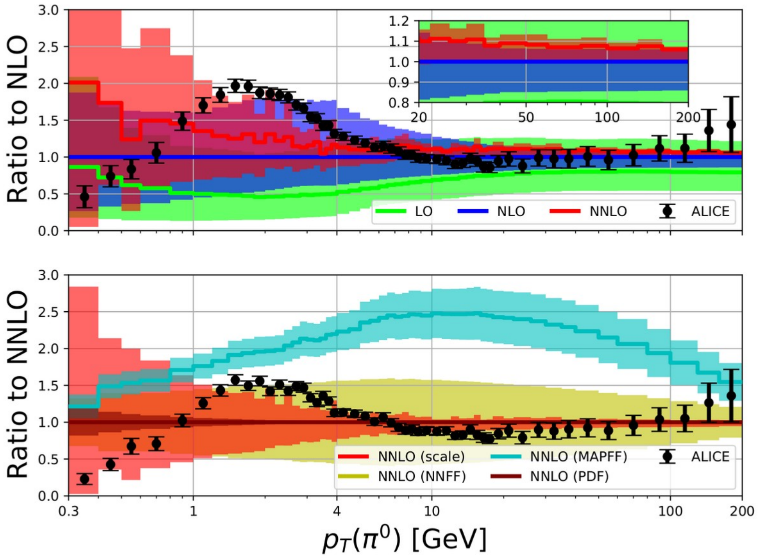
Parton to identified object transition “**Fragmentation**”
→ Resummation of collinear logs through ‘DGLAP’
→ Non perturbative fragmentation functions
Example: B-hadrons in e+e-

$$\frac{d\sigma_B(m_b,z)}{dz} = \sum_i \left\{ \frac{d\sigma_i(\mu_{Fr},z)}{dz} \otimes D_{i\to B}(\mu_{Fr},m_b,z) \right\}(z) + \mathcal{O}(m_b^2)$$

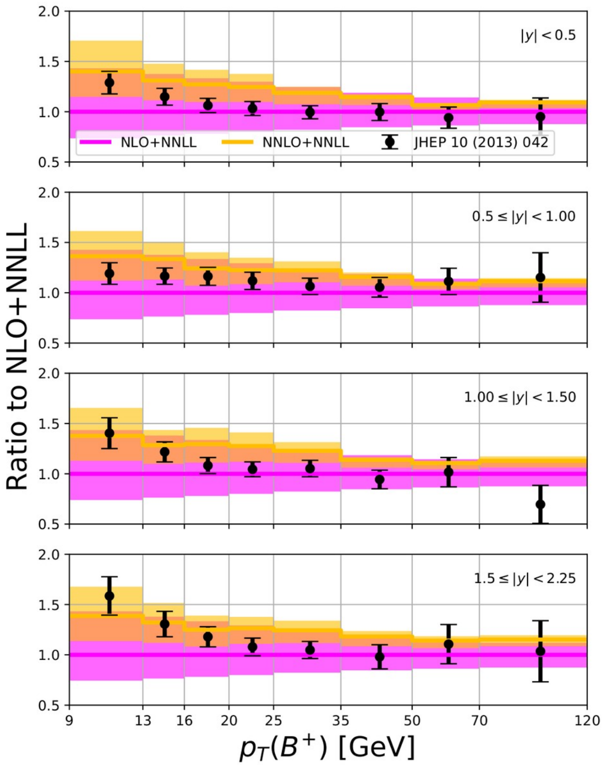
Identified hadrons

Inclusion of fragmentation through NNLO QCD:
[Czakon, Generet, Mitov, Poncelet]
- B-hadrons in top-decays [2210.06078,2102.08267]
- Open-bottom [2411.09684] → accepted in PRL
- Identified hadrons [2503.11489] → accepted in PRL

$$d\sigma_{pp\to h}(p) = \sum_i \int dz\ d\hat{\sigma}_{pp\to i}\left(\frac{p}{z}\right) D_{i\to h}(z)$$



Pion production

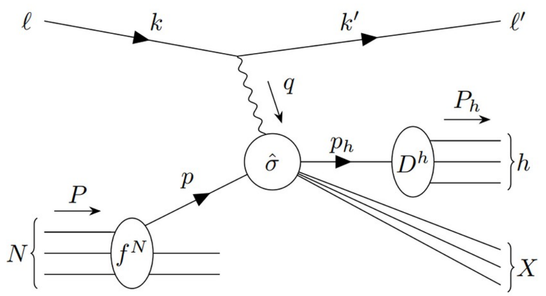


Open-bottom @FONNLL:

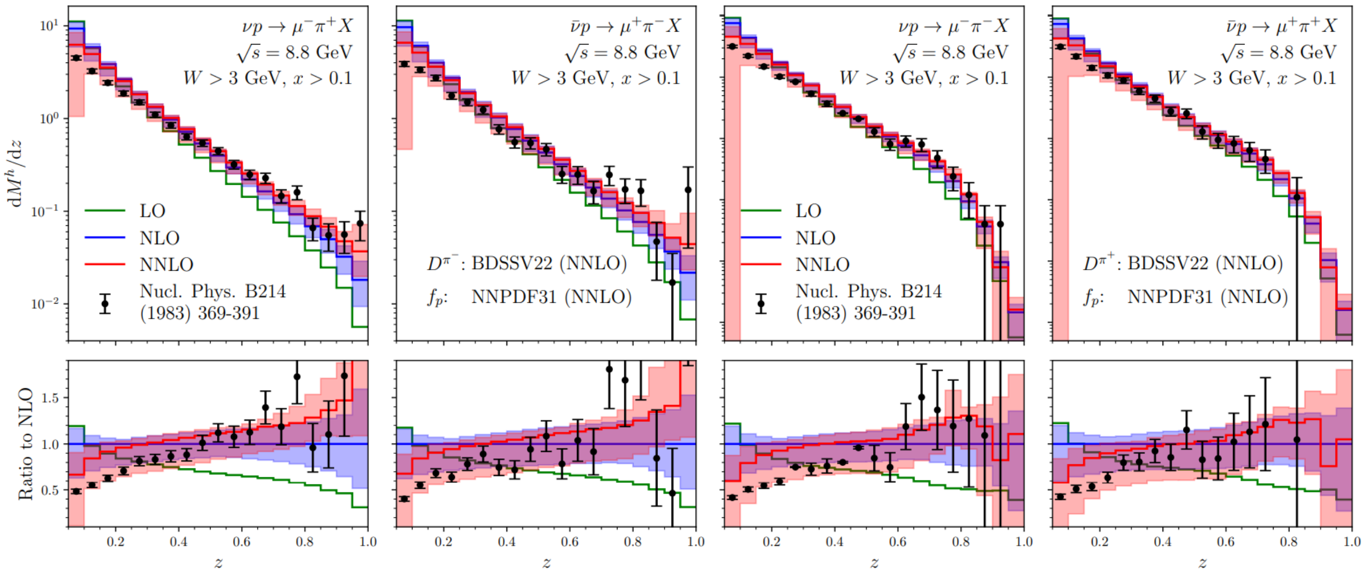
$$\sigma(p_T) = \sigma(m, p_T) + G(p_T)(\sigma(0, p_T) - \sigma(0, p_T)|_{\mathrm{FO}})$$

Semi-inclusive Deep Inelastic Scattering

Series of works on SIDIS through NNLO QCD:
[Bonino, Gehrmann, Loechner, Schoenwald, Stagnitto]



- Polarised initial states [2404.08597]
- Neutrino-Nucleon Scattering [2504.05376]
- CC and NC [2506.19926]



[2504.05376]

Jet substructure

Semi-inclusive jet function [1606.06732, 2410.01902]

$$\frac{d\sigma_{\mathrm{LP}}}{dp_T d\eta} = \sum_{i,j,k} \int_{x_{i,\min}}^{1} \frac{dx_i}{x_i} f_{i/P}(x_i,\mu) \int_{x_{j,\min}}^{1} \frac{dx_j}{x_j} f_{j/P}(x_j,\mu) \int_{z_{\min}}^{1} \frac{dz}{z} \mathcal{H}_{ij}^{k}(x_i, x_j, p_T/z, \eta, \mu)$$
$$\times J_k\left(z, \ln\frac{p_T^2 R^2}{z^2\mu^2}, \mu\right),$$

The same hard function as for identified hadrons!

Modified RGE:

[2402.05170,2410.01902]

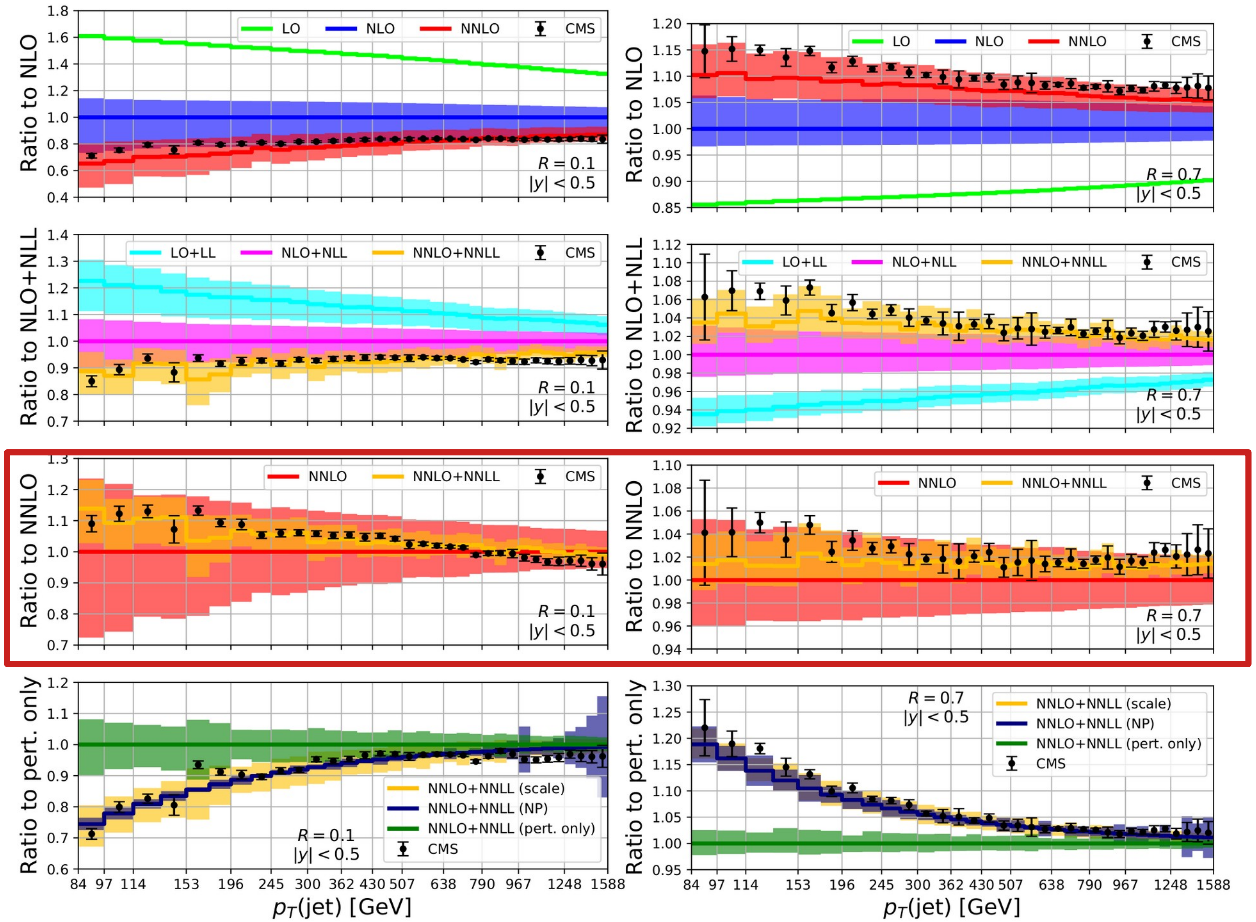
$$\frac{d\vec{J}\left(z, \ln\frac{p_T^2 R^2}{z^2\mu^2}, \mu\right)}{d\ln\mu^2} = \int_z^1 \frac{dy}{y} \vec{J}\left(\frac{z}{y}, \ln\frac{y^2 p_T^2 R^2}{z^2\mu^2}, \mu\right) \cdot \widehat{P}_T(y)$$

Energy-Energy correlators obey similar factorization!

Small-R jets

Application to small-R jets
[Generet, Lee, Moult, Poncelet, Zhang]
[2503.21866]

'Triple' differential measurement by CMS:
Y, pT, R [2005.05159]



Theory picture of hadron collision events

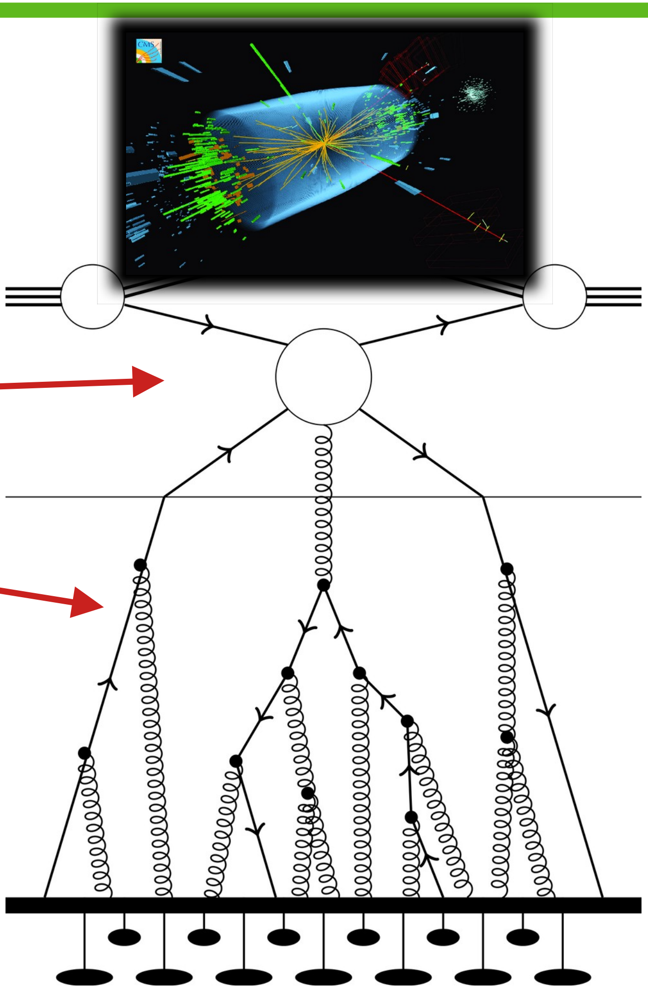
Guiding principle: factorization
"What you see depends on the energy scale"

In Quantum Chromodynamics (QCD):

$Q \gg \Lambda_{\text{QCD}}$ **Fixed-order perturbation theory**
scattering of individual partons

$Q \gtrsim \Lambda_{\text{QCD}}$ **Parton-shower/Resummation**
all-order bridge between perturbative and non-perturbative physics

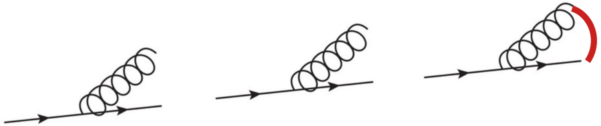
$Q \sim \Lambda_{\text{QCD}}$ **"Hadronization"/MPI/...**
non-perturbative physics



Fixed-order matching to parton-showers

The challenge

Combine fixed-order with parton shower evolution while **preserving** the precision/accuracy of both!

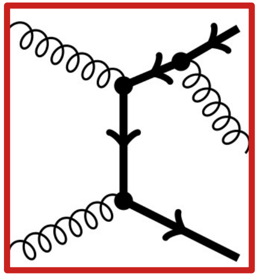


v ← shower scale

parton shower approximation: $\alpha_S^i(v)\ln^j(v)$
but to all orders!

accuracy: LL, NLL, NNLL, ...

"Hard" scattering scale Q



Fixed-order: expansion in $\alpha_S(Q)$

→ cross section ~ $e^{\sum_{ij}\alpha_S^i(v)\ln^j(v)} \times$ (LO + NLO + NNLO + …)

A matching scheme needs to avoid double counting of the logarithmic contributions!

Matching parton showers

At NLO QCD a solved problem → a breakthrough for LHC phenomenology

Local matching NLO+PS: MC@NLO, Powheg, Nagy-Soper, …

(core of event generators Madgraph_aMC@NLO, Sherpa, Powheg+Pythia, Herwig)

>80% of all exp. LHC papers cite at least one these!

Core idea: using subtractions schemes to construct showers & matching

(subtraction terms ⟷ parton shower kernels)

This is the **big challenge at NNLO QCD** for the theory community!

Some NNLO+PS matching approaches appeared recently but are either

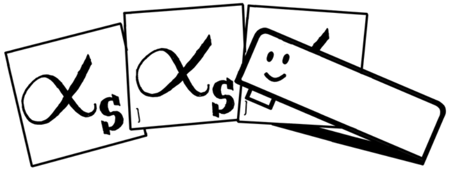
- non-local → resummation/slicing based (for example: MiNNLOPS, Geneva)
  → limited generality
- or work only for simple cases like e+e- → jets (for example: Vincia)
  → work only where NNLO is known analytically

No scheme so far is based on a general local subtraction.

A general matching scheme at NNLO would be the next big breakthrough for precision collider physics!

This is what I want to achieve with

STAPLE!



Funded by the European Union

European Research Council
Established by the European Commission

Two core aspects:

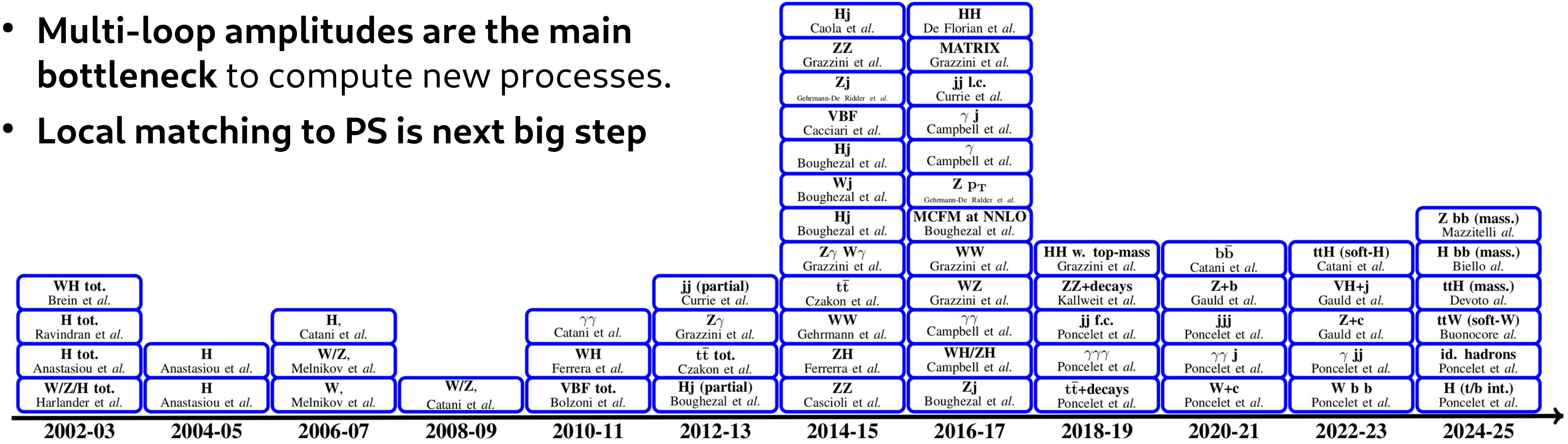
1) **preserving the precision/accuracy** of the fixed-order & parton shower

2) achieving a parton shower with **high logarithmic accuracy**

Summary/Outlook

Higher-order (NNLO) QCD corrections are an important corner stone of LHC phenomenology

- Many phenomenological applications
  - **Precision tests of the SM**
  - PDF + SM parameter extractions: masses + couplings
  - Fragmentation processes start to appear → fits of fragmentation functions
- **Multi-loop amplitudes are the main bottleneck** to compute new processes.
- **Local matching to PS is next big step**



Backup

COMETA

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

- WG1 - Theoretical framework, precision calculations and simulation
- WG2 - Technological innovation in data analysis
- WG3 - Experimental Measurements
- WG4 - Management and Event Organization
- WG5 - Inclusiveness and Outreach

Further information:
https://www.cost.eu/actions/CA22130/ and https://cometa.web.cern.ch/

Polarised nLO+PS: SHERPA

Polarised cross sections for vector boson production with SHERPA
Hoppe, Schönherr, Siegert 2310.14803

- New bookkeeping of boson polarizations in SHERPA for LO MEs
- Approximate NLO corrections: nLO+PS
  → Reals+matching are treated exact
  → loop matrix elements unpolarised
- Comparison with multi-jet merged calculations

Comparison with literature
- nLO+PS approximation in fair agreement with full NLO
  → good for polarization fractions

W^+Z	σ^{NLO} [fb]	Fraction [%]	K-factor	$\sigma^{\text{nLO+PS}}_{\text{SHERPA}}$ [fb]	Fraction [%]	K-factor
full	35.27(1)		1.81	33.80(4)		
unpol	34.63(1)	100	1.81	33.457(26)	100	1.79
Laboratory frame						
L-U	8.160(2)	23.563(9)	1.93	7.962(5)	23.796(25)	1.91
T-U	26.394(9)	76.217(34)	1.78	25.432(21)	76.01(9)	1.75
int	0.066(10) (diff)	0.191(29)	2.00	0.064(7)	0.191(22)	2.40(40)
U-L	9.550(4)	27.577(14)	1.73	9.275(16)	27.72(5)	1.72
U-T	25.052(8)	72.342(31)	1.83	24.156(18)	72.20(8)	1.81
int	0.028(10) (diff)	0.081(29)	-0.49	0.026(7)	0.079(22)	-0.471(34)

Polarized VV @ (N)NLO QCD / NLO EW

Fiducial polarization observables in hadronic WZ production: A next-to-leading order QCD+EW study,
Baglio, Le Duc 1810.11034
Anomalous triple gauge boson couplings in ZZ production at the LHC and the role of Z boson polarizations,
Rahama, Singh 1810.11657
Polarization observables in WZ production at the 13 TeV LHC: Inclusive case,
Baglio, Le Duc 1910.13746
Unravelling the anomalous gauge boson couplings in ZW+- production at the LHC and the role of spin-1 polarizations,
Rahama, Singh 1911.03111
Polarized electroweak bosons in W+W- production at the LHC including NLO QCD effects,
Denner, Pellicciol 2006.14867
NLO QCD predictions for doubly-polarized WZ production at the LHC,
Denner, Pellicciol 2010.07149
NNLO QCD study of polarised W+W- production at the LHC,
Poncelet, Popescu 2102.13583
NLO EW and QCD corrections to polarized ZZ production in the four-charged-lepton channel at the LHC,
Denner, Pellicciol 2107.06579
Breaking down the entire spectrum of spin correlations of a pair of particles involving fermions and gauge bosons,
Rahama, Singh 2109.09345
Doubly-polarized WZ hadronic cross sections at NLO QCD+EW accuracy,
Duc Ninh Le, Baglio 2203.01470
Doubly-polarized WZ hadronic production at NLO QCD+EW: Calculation method and further results
Duc Ninh Le, Baglio, Dao 2208.09232
NLO QCD corrections to polarised di-boson production in semi-leptonic final states
Denner, Haitz, Pellicciol 2211.09040
Polarised cross sections for vector boson production with SHERPA
Hoppe, Schönherr, Siegert 2310.14803
Polarised-boson pairs at the LHC with NLOPS accuracy
Pellicciol, Zanderighi 2311.05220
NLO EW corrections to polarised W+W- production and decay at the LHC
Denner, Haitz, Pellicciol 2311.16031
NLO electroweak corrections to doubly-polarized W+W- production at the LHC
Thi Nhung Dao, Duc Ninh 2311.17027
Polarized ZZ pairs in gluon fusion and vector boson fusion at the LHC
Javurkova, Ruiz, Coelho, Sandesara 2401.17365

Other polarized cross section calculations

- Polarised VBS (so far LO):
  W boson polarization in vector boson scattering at the LHC,
  Ballestrero, Maina, Pellicciol 1710.09339
  Polarized vector boson scattering in the fully leptonic WZ and ZZ channels at the LHC,
  Ballestrero, Maina, Pellicciol 1907.04722
  Automated predictions from polarized matrix elements
  Buarque Franzosi, Mattelaer, Ruiz, Shil 1912.01725
  Different polarization definitions in same-sign WW scattering at the LHC,
  Ballestrero,Maina, Pellicciol 2007.07133

- Single boson production
  Left-Handed W Bosons at the LHC,
  Z. Bern et. al. 1103.5445
  Electroweak gauge boson polarisation at the LHC,
  Stirling, Vryonidou 1204.6427
  What Does the CMS Measurement of W-polarization Tell Us about the Underlying Theory of the Coupling of W-Bosons to Matter?,
  Belyaev, Ross 1303.3297
  Polarised W+j production at the LHC: a study at NNLO QCD accuracy,
  Pellen, Poncelet, Popescu 2109.14336

EWSB

The reason is the EWSB in the SM:

$$\mathcal{L}_{\text{EW}} = -\frac{1}{4}(W^i_{\mu\nu})^2 - \frac{1}{4}(B^i_{\mu\nu})^2 + (D_\mu\phi)^2 - V(\phi^\dagger\phi)$$

- Higgs potential and minimum:

$$V(\phi^\dagger\phi) = -\mu^2(\phi^\dagger\phi)^2 + \lambda(\phi^\dagger\phi)^4 \qquad \phi = U(\pi^i)\begin{pmatrix} 0 \\ \frac{v+H}{\sqrt{2}} \end{pmatrix}$$

VEV: $\phi^\dagger\phi = \frac{\mu^2}{2\lambda} \equiv \frac{v^2}{2}$

- Goldstone bosons can be absorbed via gauge transformation (unitary gauge).
  This gives rise to massive gauge bosons:

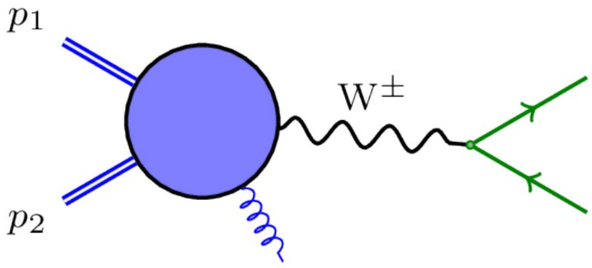
$$\phi = U^{-1}(\pi^i)\phi, \qquad W_\mu = U^{-1}W_\mu U - \frac{i}{g_W}U^{-1}\partial_\mu U$$

$$|D_\mu\phi|^2 \ni \frac{v^2}{8}\left[2g_W^2 W^+_\mu W^{-\mu} + (g_W W^3_\mu - g'_W B_\mu)^2\right] \Rightarrow M_W = \frac{1}{2}v g_W\,, \quad M_Z = \frac{M_W}{\cos\theta_W}$$

- Restores renormalizability and unitarity

Polarised W+j production

Polarised W+jet cross sections



Why looking at polarised W+jet with leptonic decays?

- The EW part is simple:
  - no non-resonant backgrounds
  - neutrino momentum approx. accessible (missing ET)
- Large cross section → precise measurements

Goals:

- Use W+j data to **extract the longitudinal polarisation fraction** (done before by exp.)
  → understand impact of NNLO QCD corrections (reduced scale dependence)
- Study **inclusive** (in terms of W decay products) and **fiducial** phase spaces
  → How does the sensitivity to longitudinal Ws depend on this?
  Which observables have **small interference/off-shell** effects?
- Are there any differences between W+ and W-?
  From PDFs and the fact that we cut on the charged lepton?

Setup: LHC @ 13 TeV

Polarised W+j production at the LHC: a study at NNLO QCD accuracy, Pellen, Poncelet, Popescu 2109.14336

Inclusive phase space:

- At least one jet with $|y(j)| \leq 2.4$ and $p_T(j) \geq 30$ GeV

Fiducial phase space:

Measurement of the differential cross sections for the associated production of a W boson and jets in proton-proton collisions at \sqrt{s}=13 TeV, CMS 1707.05979

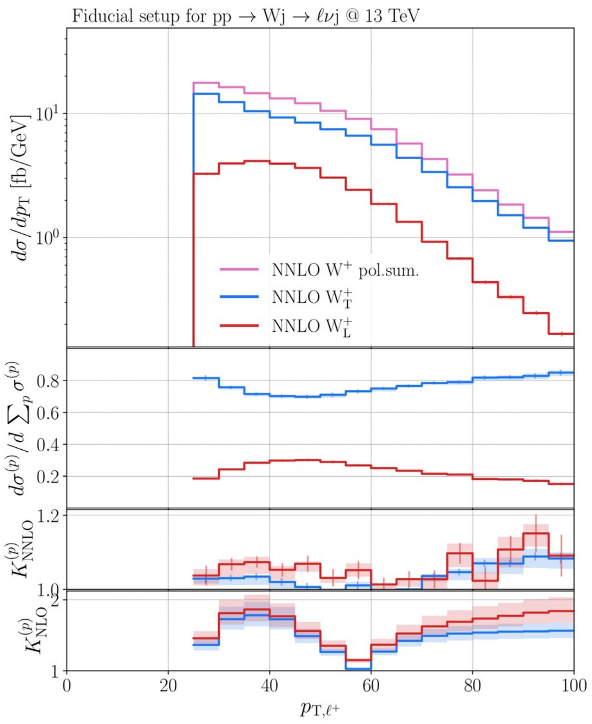
- Lepton cuts: $p_T(\ell) \geq 25$ GeV, $|\eta(\ell)| \leq 2.5$ and $\Delta R(\ell, j) > 0.4$
- Transverse mass of the W: $M_T(W) = \sqrt{m_W^2 + p_T^2(W)} \geq 50$ GeV

Technical aspects:

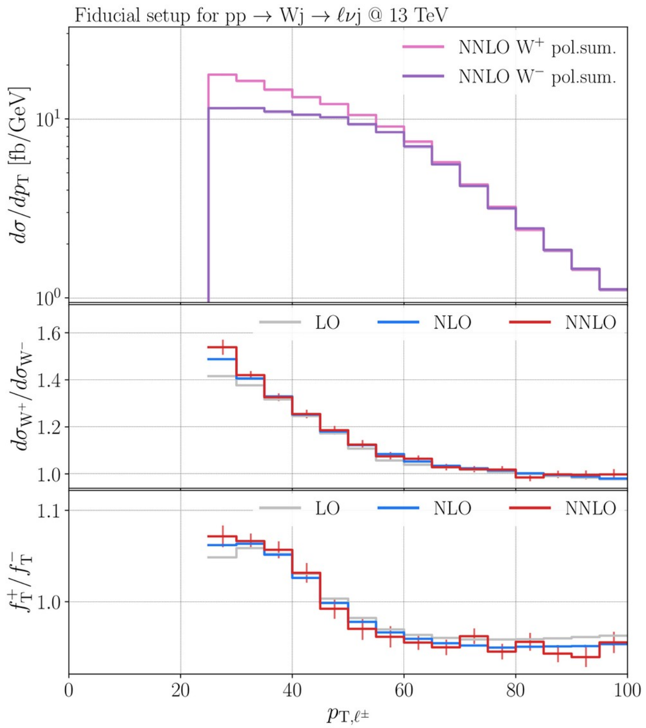
- NNPDF31 and dynamical scale choice: $\mu_R = \mu_F = \frac{1}{2}\left(m_T(W) + \sum p_T(j)\right)$
- Implementation in STRIPPER framework (NNLO QCD subtractions) [1408.2500]
    - Narrow-Width-Approximation and OSP/Pole-Approximation
    - Matrix elements from: AvH[1503.08612], OpenLoops2 [1907.13071](cross checks with Recola [1605.01090]) and VVamp [1503.04812]

Example: lepton transverse momentum

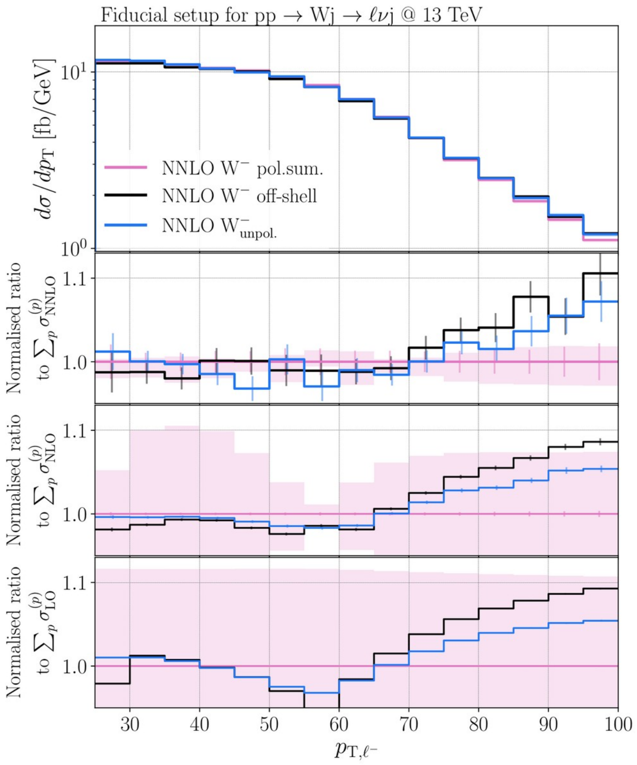
Perturbative corrections



Charge differences



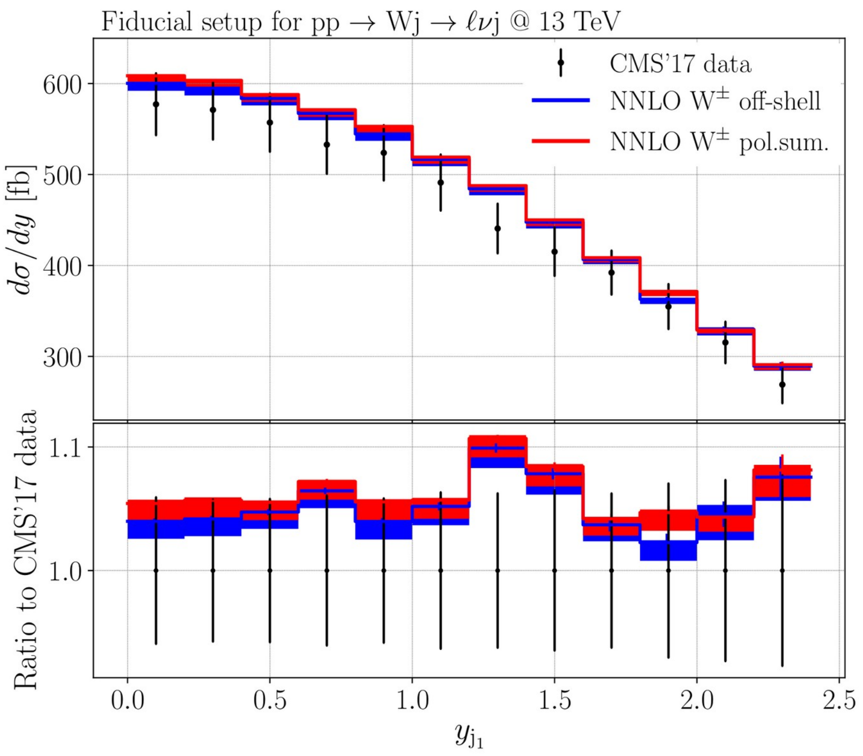
Off-shell/Interference effects



Extraction of polarisation fractions

Identified 4 observables (ranges) with
→ Small interference effects (<2%)
→ Small off-shell effects (<2%)
→ Shape differences between L and T

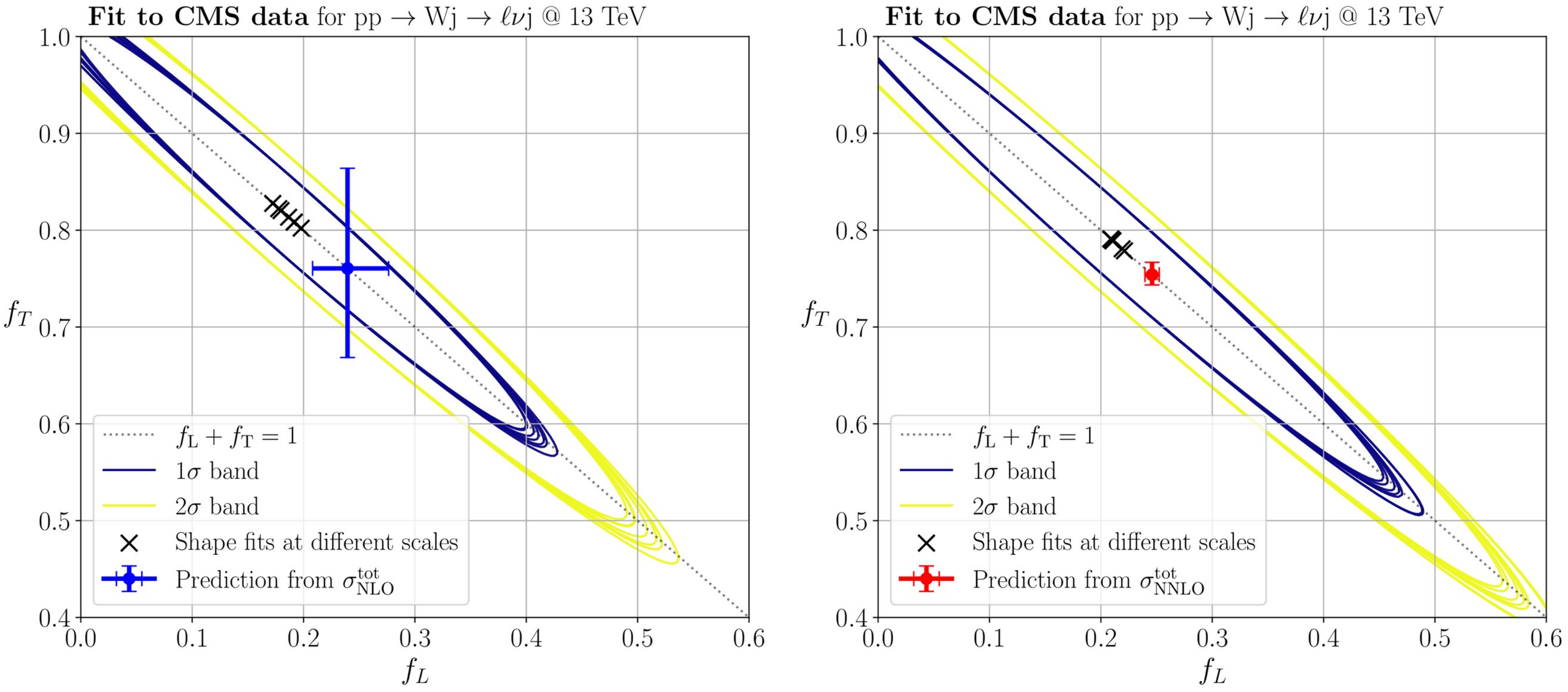
- $\Delta\phi(\ell, j_1) \geq 0.3$
- $25 \text{ GeV} \leq p_T(\ell) < 70 \text{ GeV}$
- $\cos(\theta^*_\ell) \geq -0.75$
- $|y(j_1)| \leq 2$



W+jet : fit to CMS data

Fit to actual data, here $|y(j_1)|$

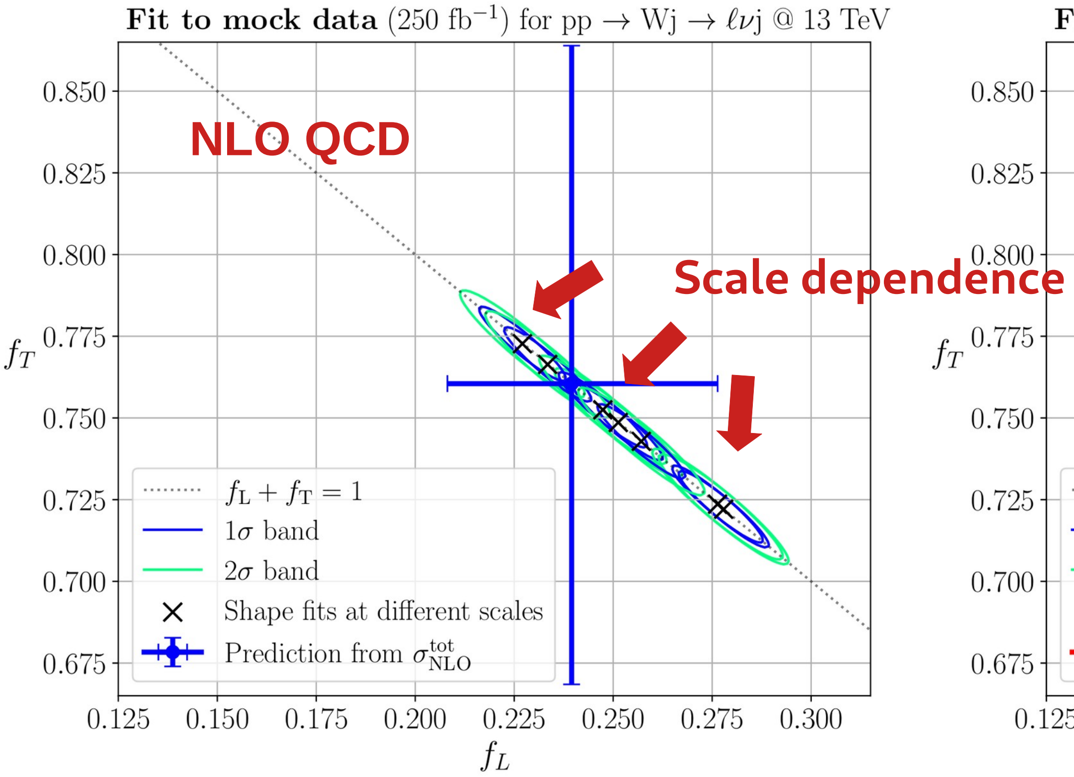
→ dominated by experimental uncertainties (no correlations available)

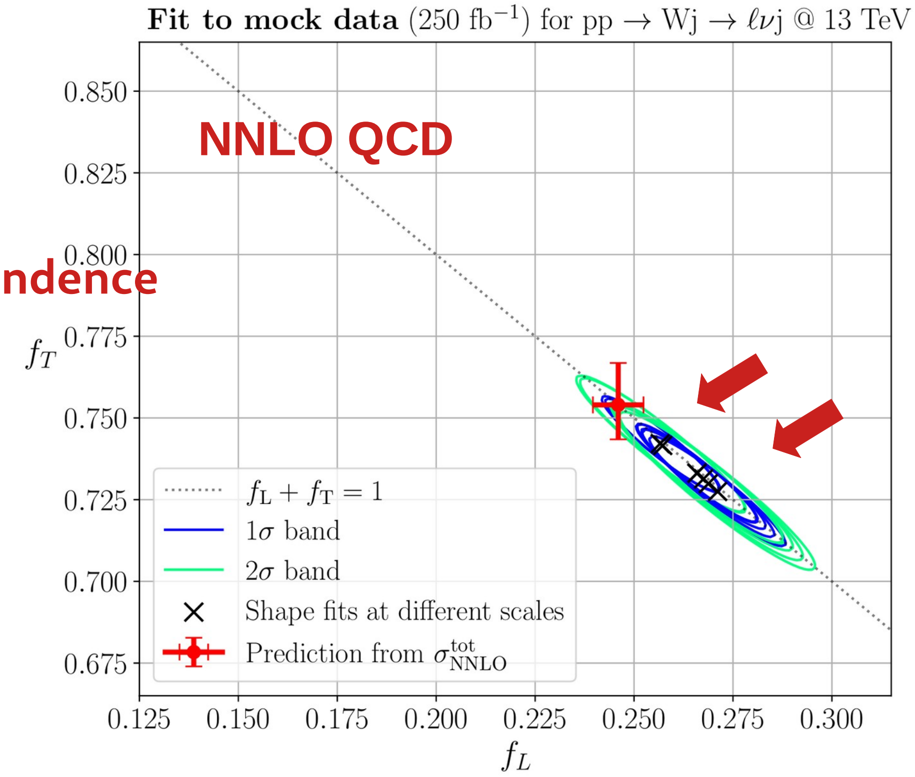


W+jet: mock-data fit

Fit to mock-data (based on NNLO QCD and 250 fb^{-1} stats):
→ extreme case to see effect of scale dependence reduction

$\cos(\ell, j_1)$





Polarised W+W-

NNLO QCD polarized WW production

NNLO QCD study of polarised W+W- production at the LHC,
Poncelet, Popescu 2102.13583

Technical aspects:

- Implementation of NNLO QCD in c++ sector-improved residue subtraction framework [1408.2500,1907.12911]
- Massive b-quarks → get rid of top production ($pp \to b\bar{b}W^+W^-$ enters at NNLO)
- NNPDF31 and a fixed renormalisation scale: $\mu_R = \mu_F = m_W$

Measurement of fiducial and differential W+W- production cross-sections at sqrt(s) = 13 TeV with the ATLAS detector
ATLAS 1905.04242

Fiducial phase space

- Leptons: $p_T(\ell) \geq 27$ GeV $\quad |y(\ell)| < 2.5 \quad m(\ell\bar{\ell}) > 55$ GeV
- Missing transverse momentum: $p_{T,\mathrm{miss}} = p_T(\nu_e + \bar{\nu}_\mu) \geq 20$ GeV
- Jet-veto: $p_T(j) > 35$ GeV $\quad |y(j)| < 4.5$

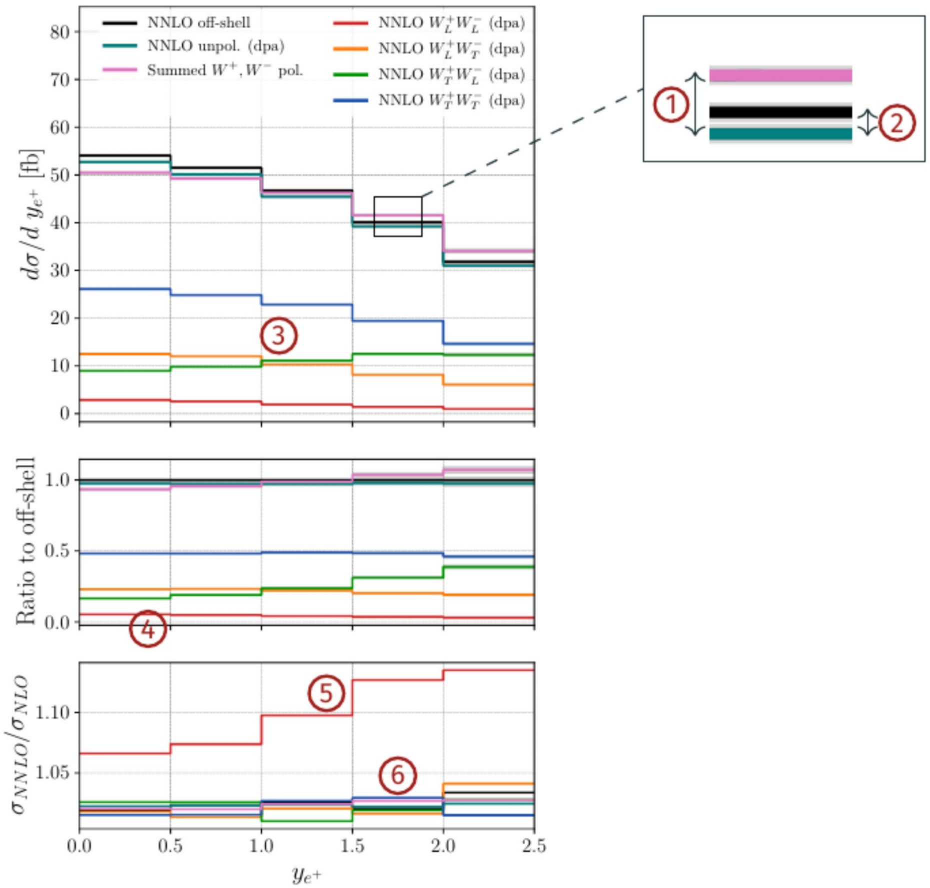
Doubly polarised cross sections

	NLO	NNLO	K_{NNLO}	LI	NNLO+LI
off-shell	$220.06(5)^{+1.8\%}_{-2.3\%}$	$225.4(4)^{+0.6\%}_{-0.6\%}$	1.024	$13.8(2)^{+25.5\%}_{-18.7\%}$	$239.1(4)^{+1.5\%}_{-1.2\%}$
unpol. (nwa)	$221.85(8)^{+1.8\%}_{-2.3\%}$	$227.3(6)^{+0.6\%}_{-0.6\%}$	1.025	$13.68(3)^{+25.5\%}_{-18.7\%}$	$241.0(6)^{+1.5\%}_{-1.1\%}$
unpol. (dpa)	$214.55(7)^{+1.8\%}_{-2.3\%}$	$219.4(4)^{+0.6\%}_{-0.6\%}$	1.023	$13.28(3)^{+25.5\%}_{-18.7\%}$	$232.7(4)^{+1.4\%}_{-1.1\%}$
W^+_L (dpa)	$57.48(3)^{+1.9\%}_{-2.6\%}$	$59.3(2)^{+0.7\%}_{-0.7\%}$	1.032	$2.478(6)^{+25.5\%}_{-18.3\%}$	$61.8(2)^{+1.0\%}_{-0.8\%}$
W^-_L (dpa)	$63.69(5)^{+1.9\%}_{-2.6\%}$	$65.4(3)^{+0.8\%}_{-0.8\%}$	1.026	$2.488(6)^{+25.5\%}_{-18.3\%}$	$67.9(3)^{+0.9\%}_{-0.8\%}$
W^+_T (dpa)	$152.58(9)^{+1.7\%}_{-2.1\%}$	$155.7(6)^{+0.7\%}_{-0.6\%}$	1.020	$11.19(2)^{+25.5\%}_{-18.8\%}$	$166.9(6)^{+1.6\%}_{-1.3\%}$
W^-_T (dpa)	$156.41(7)^{+1.7\%}_{-2.1\%}$	$159.7(6)^{+0.5\%}_{-0.6\%}$	1.021	$11.19(2)^{+25.5\%}_{-18.8\%}$	$170.9(6)^{+1.7\%}_{-1.3\%}$
$W^+_L W^-_L$ (dpa)	$9.064(6)^{+3.0\%}_{-3.0\%}$	$9.88(3)^{+1.3\%}_{-1.3\%}$	1.090	$0.695(2)^{+25.5\%}_{-18.8\%}$	$10.57(3)^{+2.9\%}_{-2.4\%}$
$W^+_L W^-_T$ (dpa)	$48.34(3)^{+1.9\%}_{-2.5\%}$	$49.4(2)^{+0.9\%}_{-0.7\%}$	1.021	$1.790(5)^{+25.5\%}_{-18.3\%}$	$51.2(2)^{+0.6\%}_{-0.8\%}$
$W^+_T W^-_L$ (dpa)	$54.11(5)^{+1.9\%}_{-2.5\%}$	$55.5(4)^{+0.6\%}_{-0.7\%}$	1.025	$1.774(5)^{+25.5\%}_{-18.3\%}$	$57.2(4)^{+0.7\%}_{-0.7\%}$
$W^+_T W^-_T$ (dpa)	$106.26(4)^{+1.6\%}_{-1.9\%}$	$108.3(3)^{+0.5\%}_{-0.5\%}$	1.019	$9.58(2)^{+25.5\%}_{-18.9\%}$	$117.9(3)^{+2.1\%}_{-1.6\%}$

Small LL contribution, with large corrections

Polarised di-boson production

Credit: Andrei Popescu



Features:

1. Polarisation interference
2. Non-resonant background
3. "Monte-Carlo true" polarisation distributions
4. $W^+_L W^-_L$ contribution is small, $W^+_T W^-_T$ dominates
5. Distinct and large K_{NNLO} for $W^+_L W^-_L$
6. small K-factor for other setups

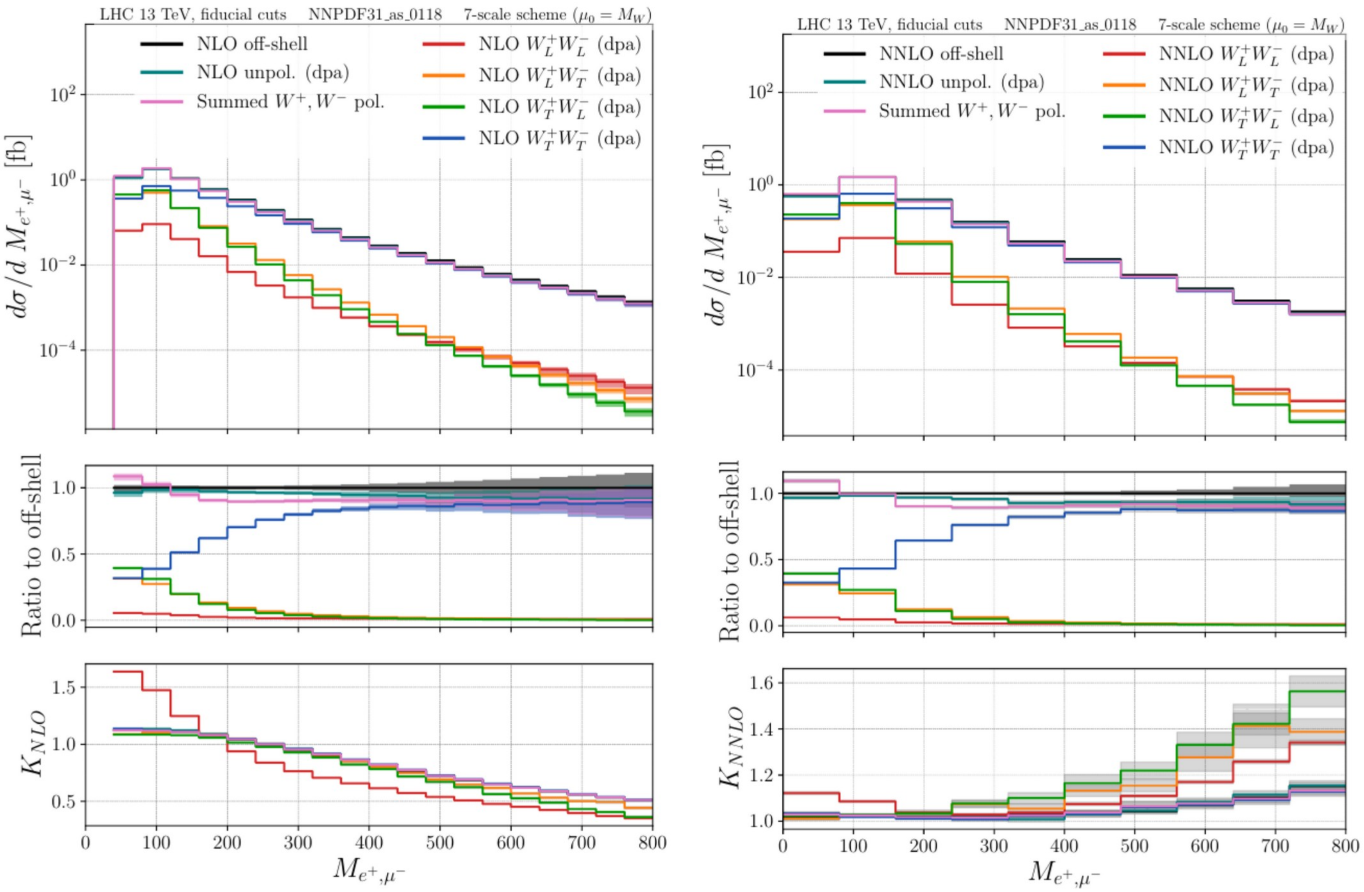
Summary:

→ NNLO effects are **2-3%** of σ_{tot} for all setups except $W^+_L W^-_L$ where it is **9%**.

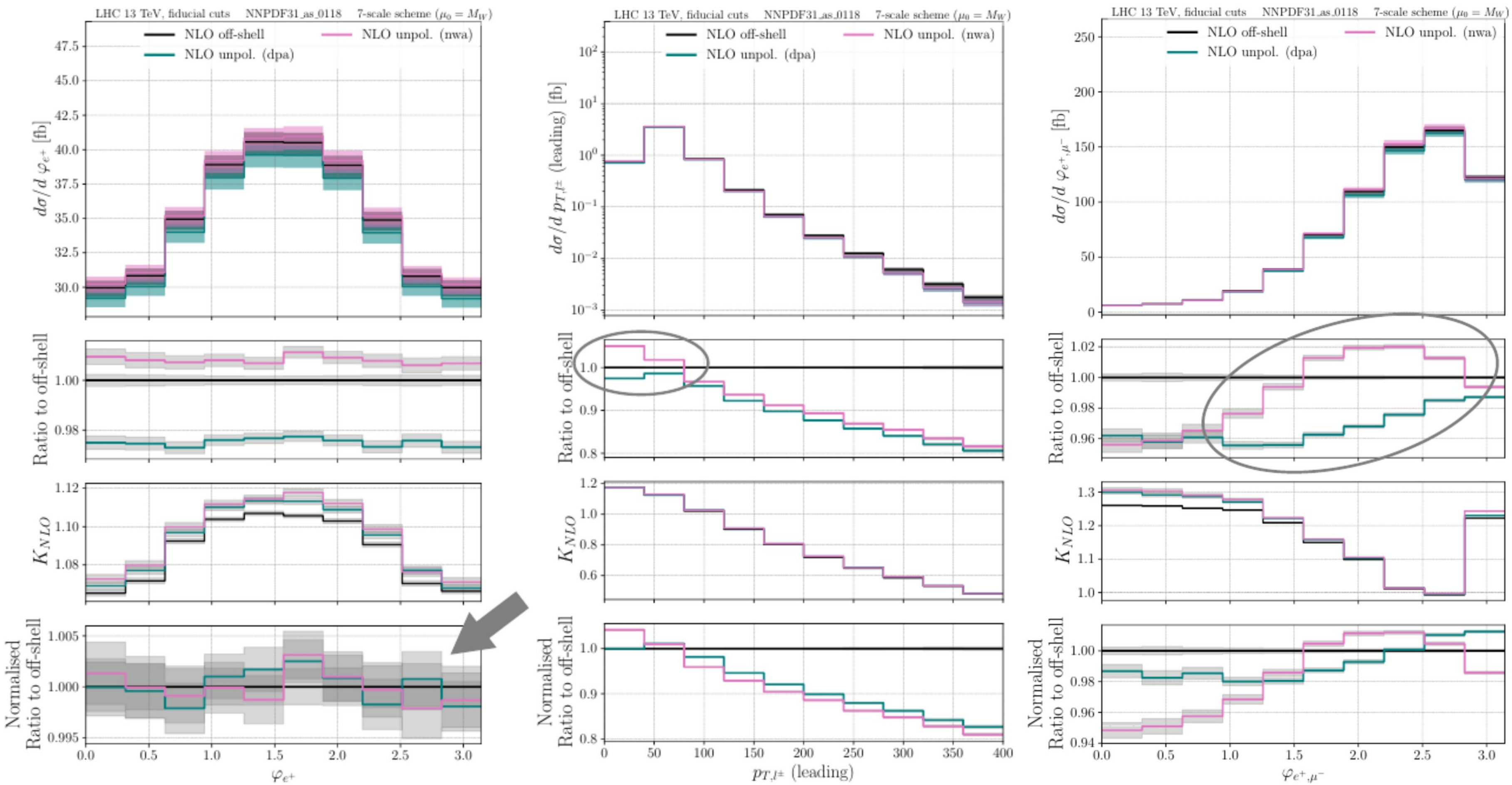
→ Scale uncertainty is reduced by a **factor of 3** w.r.t NLO.

Polarised di-boson production

- Longitudinal contribution largest around production threshold.
- At high energy W effectively massless → transverse polarised



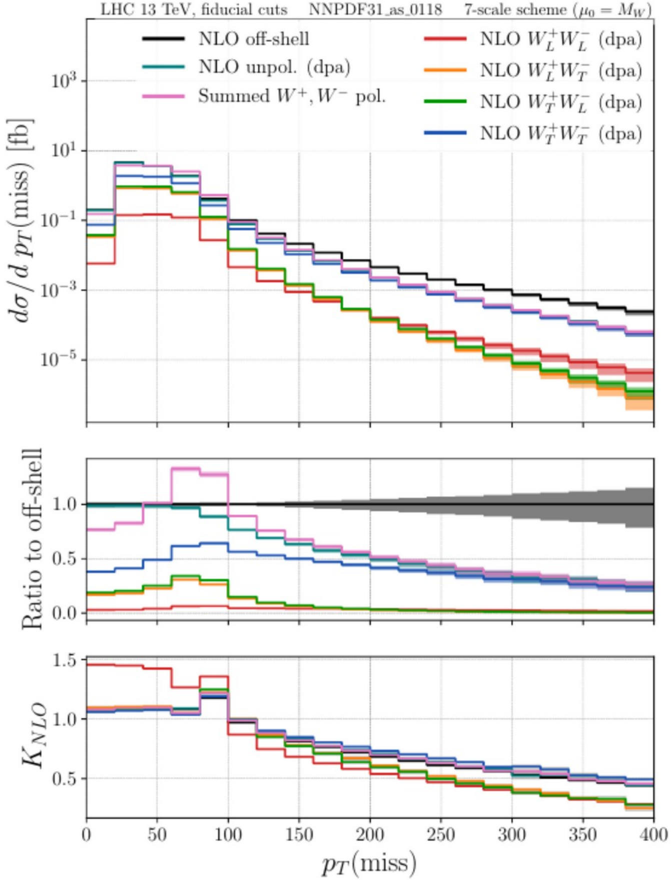
NWA vs. DPA

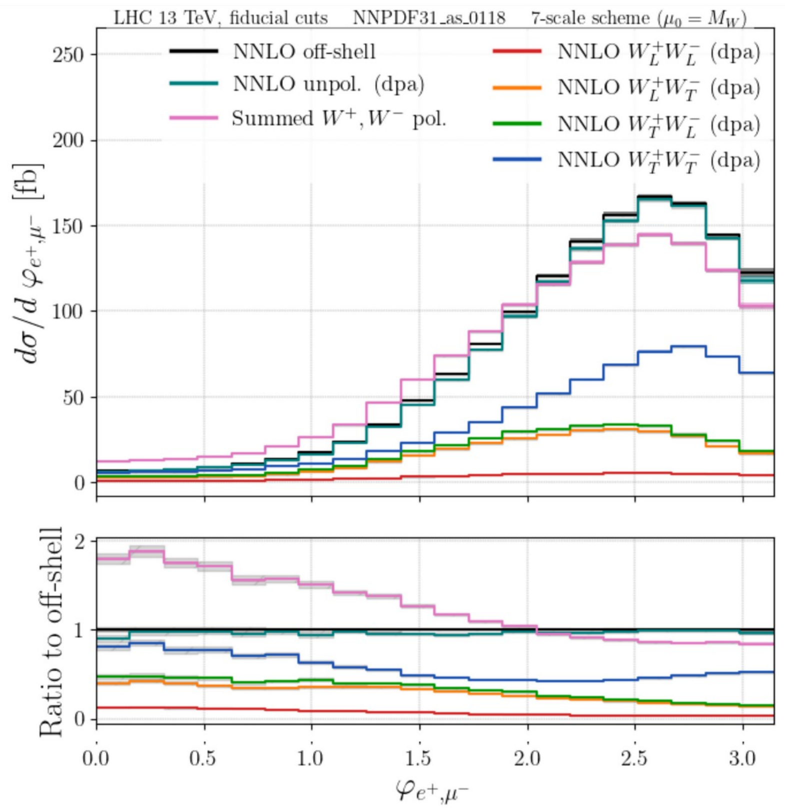


LHC 13 TeV, fiducial cuts NNPDF31_as_0118 7-scale scheme ($\mu_0 = M_W$)
NLO off-shell
NLO unpol. (nwa)
NLO unpol. (dpa)
$d\sigma/d\,\varphi_{e^+}$ [fb]
Ratio to off-shell
K_{NLO}
Normalised Ratio to off-shell
φ_{e^+}
$d\sigma/d\,p_{T,l^\pm}$ (leading) [fb]
$p_{T,l^\pm}$ (leading)
$d\sigma/d\,\varphi_{e^+,\mu^-}$ [fb]
φ_{e^+,μ^-}

Interference and off-shell effects

Large off-shell effect from single-resonant contributions

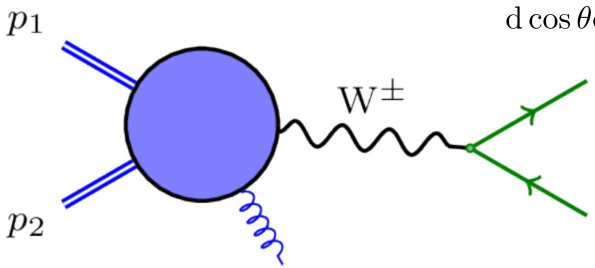




Large interference effects through phase space constraints

How to measure polarized bosons?

Angular decomposition of 2-body W decay:



$$\frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta\,\mathrm{d}\phi\,\mathrm{d}X} = \frac{\mathrm{d}\sigma}{\mathrm{d}X}\frac{3}{16\pi}\Big[(1+\cos^2\theta) + \frac{A_0}{2}(1-3\cos^2\theta) + A_1\sin 2\theta\cos\phi + \frac{A_2}{2}\sin^2\theta\cos 2\phi$$

$$+ A_3\sin\theta\cos\phi + A_4\cos\theta + A_5\sin^2\theta\sin 2\phi + A_6\sin 2\theta\sin\phi + A_7\sin\theta\sin\phi\Big]$$

After azimuthal integration:

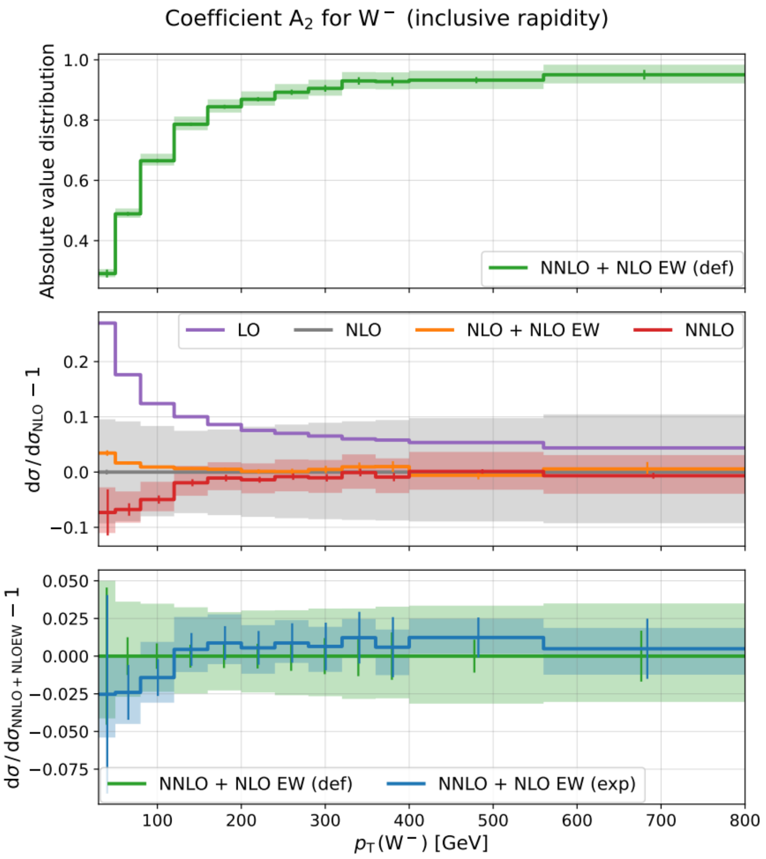
$$\frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\cos\theta} = \frac{3}{4}\sin\theta f_0 + \frac{3}{8}(1-\cos\theta)^2 f_L + \frac{3}{8}(1+\cos\theta)^2 f_R$$

Idea: Suitable projections (or fits) extract fractions of left, right and longitudinal components.

Angular coefficients as function of V kinematics

Keeping azimuthal dependence & boson kinematics:

$$\frac{d\sigma}{dp_{T,W}\, dy_W\, dm_{\ell\nu}\, d\Omega} = \frac{3}{16\pi} \frac{d\sigma^{U+L}}{dp_{T,W}\, dy_W\, dm_{\ell\nu}} \Bigg((1+\cos^2\theta) + A_0 \frac{1}{2}(1-3\cos^2\theta) + A_1 \sin 2\theta \cos\phi + A_2 \frac{1}{2} \sin^2\theta \cos 2\phi + A_3 \sin\theta\cos\phi + A_4 \cos\theta + A_5 \sin^2\theta \sin 2\phi + A_6 \sin 2\theta \sin\phi + A_7 \sin\theta \sin\phi \Bigg),$$

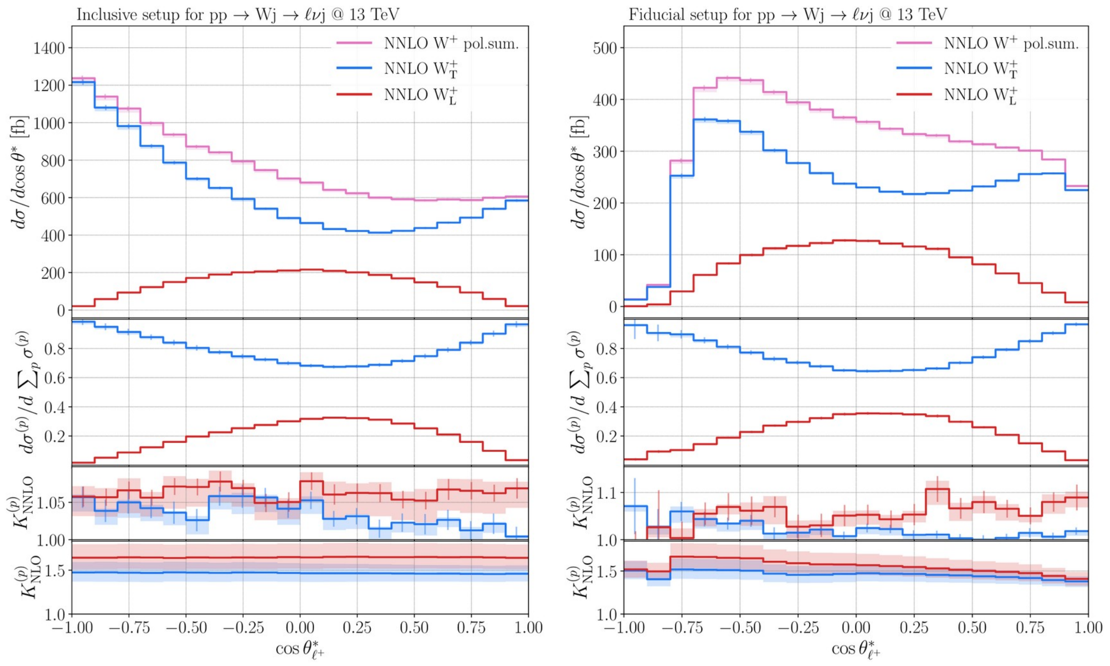


Angular coefficients in W+j production at the LHC with high precision
Pellen, Poncelet, Popescu, Vitos, 2204.12394

Practical considerations

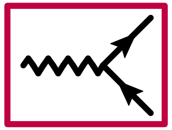
This simple idea suffers from:

- Fiducial phase space requirements
  → Interferences do not cancel
  → Correspondence between fractions (f_0, f_L, f_R) and distributions broken.
- Higher order corrections to decay (QED or QCD in hadronic decays)
  → Decomposition in $\{A_i\}$ does not hold any more
- Angles in boson rest frame
  → Z rest frame accessible, but W more difficult to reconstruct

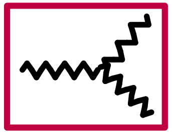


The more general solution is to generate polarized events!

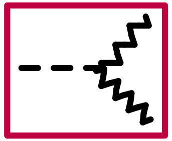
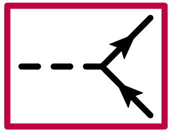
Interactions of the electroweak sector



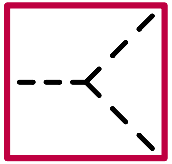
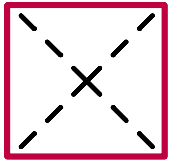
Vff : Drell-Yan processes and decays



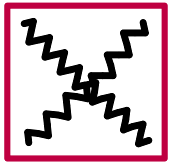
VVV: LEP and VV production at hadron colliders

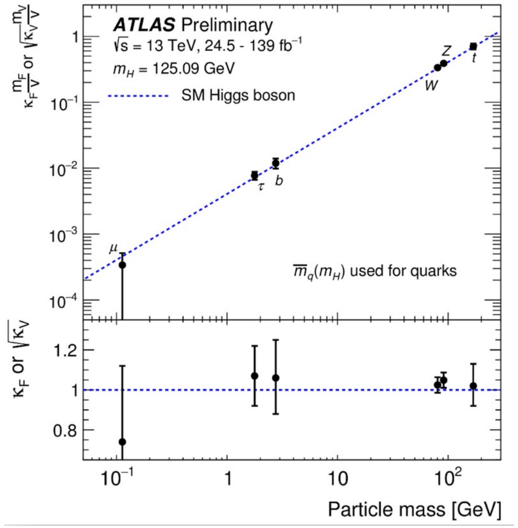
HVV/Hff: Higgs-production and decays

Higgs self-interactions: not yet measured

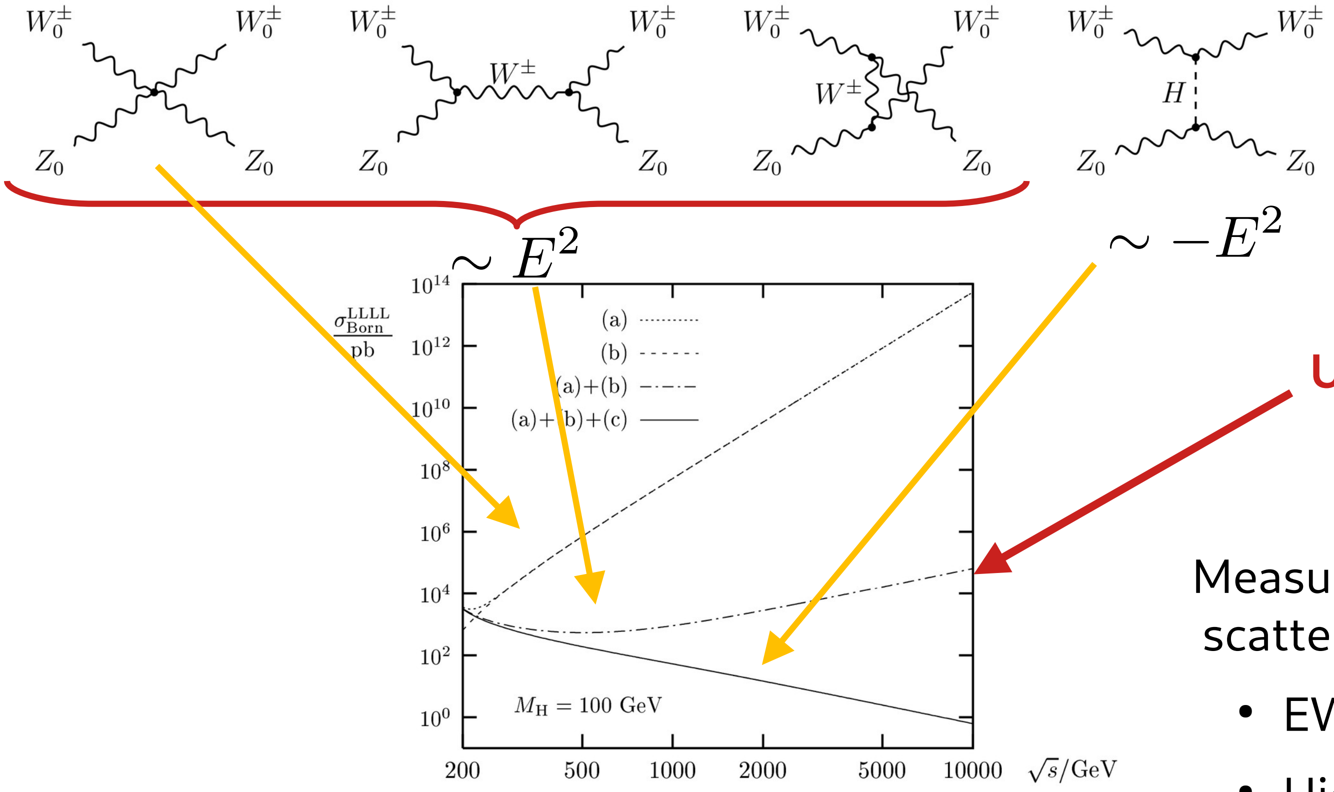


Quartic V-couplings: constraints limited by data



EWSB mechanism?

Longitudinal Vector-Boson-Scattering (VBS)



Unitarity violation

Radiative corrections to W+ W- → W+ W- in the electroweak standard model
A. Denner, T. Hahn hep-ph/9711302

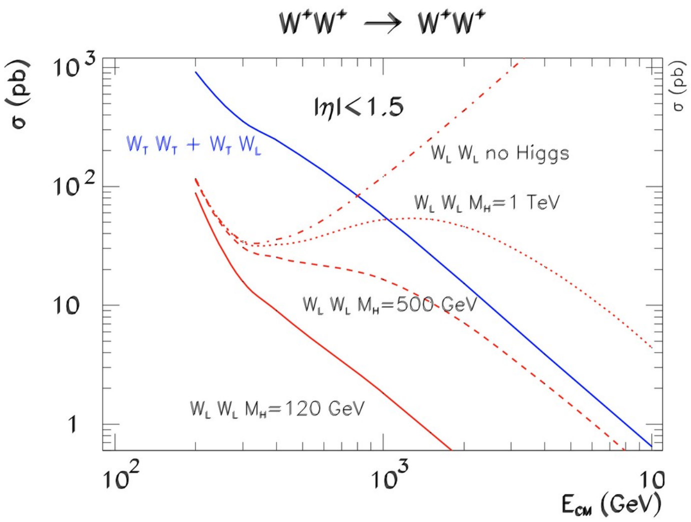
Measurement of polarized boson scattering or production probes:

- EWSB mechanism
- Higgs and gauge sector
- New physics models

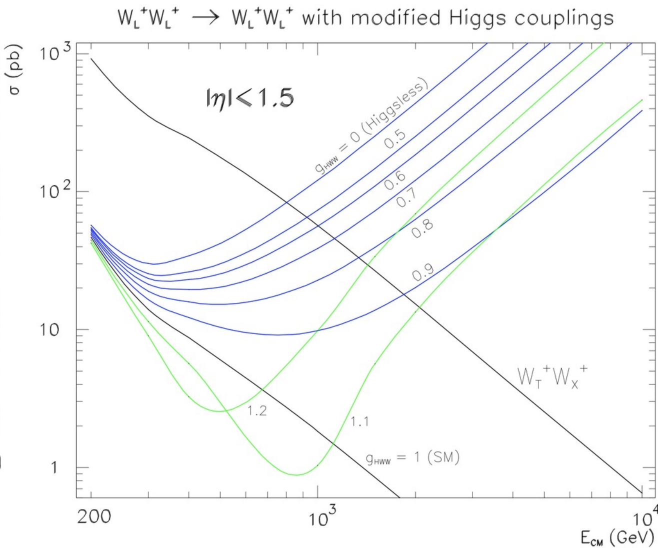
Longitudinal Vector-Boson-Scattering (VBS)

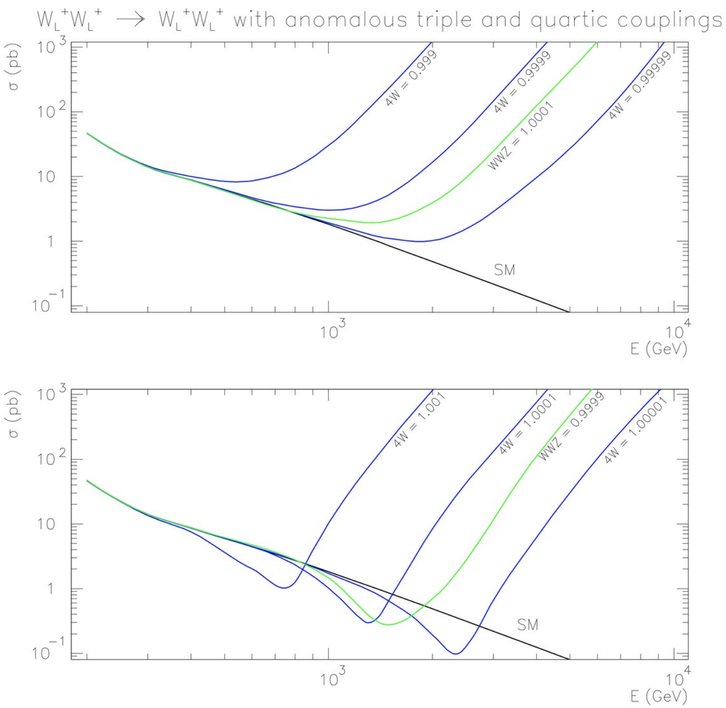
The Higgs boson and the physics of WW scattering before and after Higgs discovery
M. Szleper 1412.8367

Sensitivity to the Higgs mass



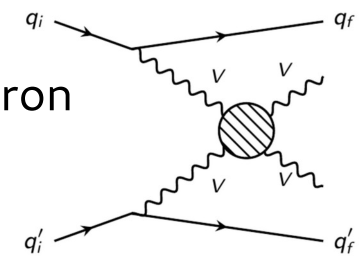
Modified HVV, VVV, VVVV couplings



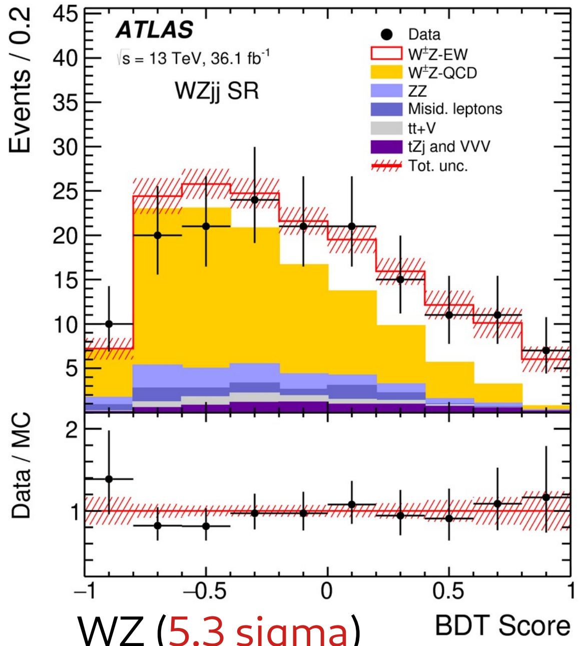


VBS at hadron colliders

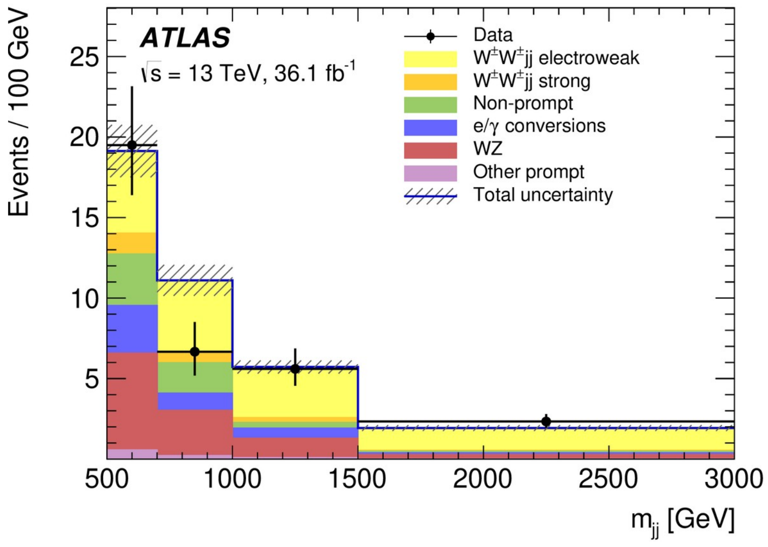
VBS at hadron colliders



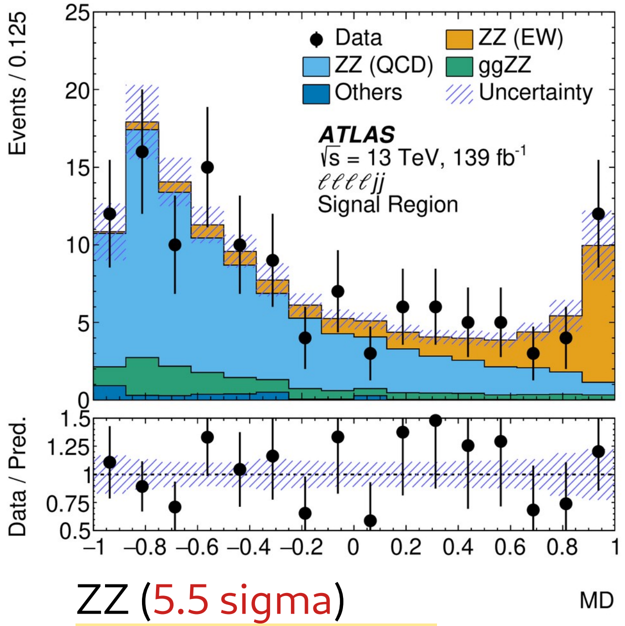
Separate from background processes through VBS topology
→ a rare process, but observed.



WZ (5.3 sigma)
ATLAS 1812.09740



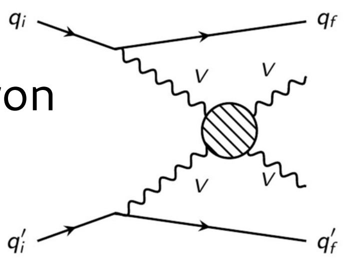
W+W+/W-W- (6.5 sigma)
ATLAS 1906.03203



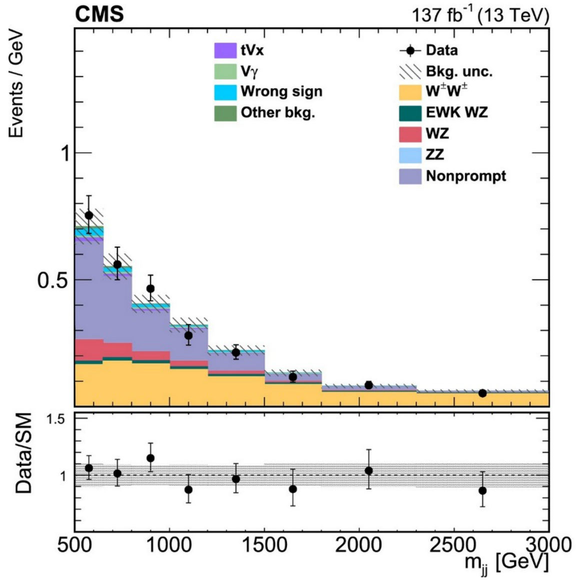
ZZ (5.5 sigma)
ATLAS 2004.10612

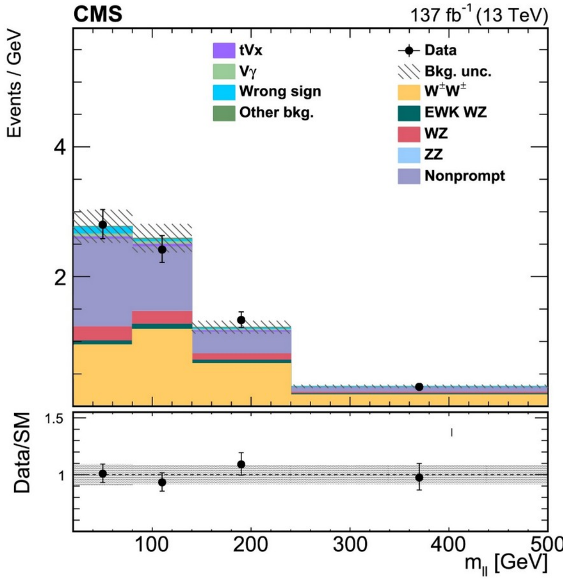
VBS at hadron colliders

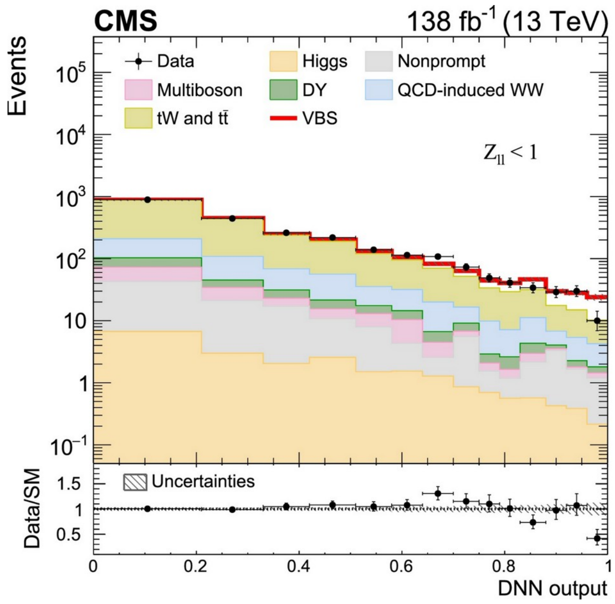
VBS at hadron colliders



Separate from background processes through VBS topology
→ a rare process, but observed.







WZ (6.8 sigma) + W+W+/W-W- (diff. xsec)
CMS 2005.01173

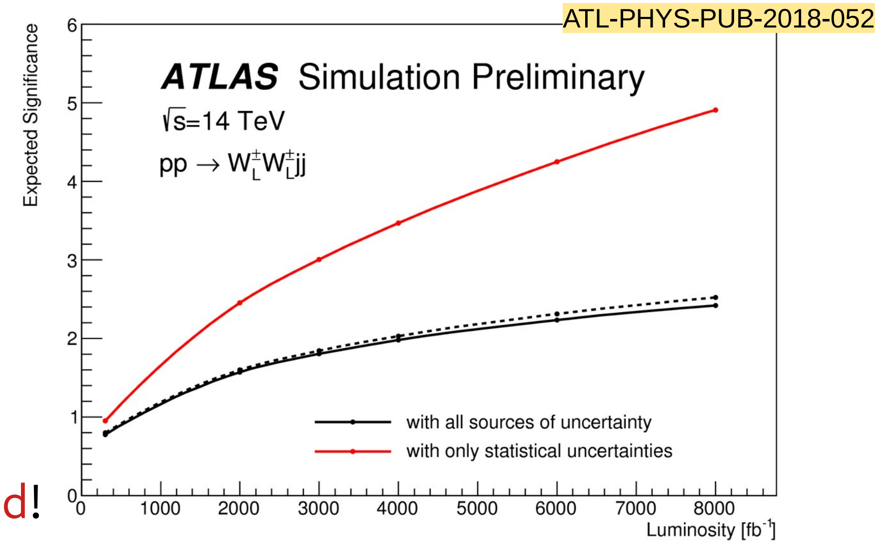
W+W- (5.6 sigma)
CMS 2205.05711

Polarised VBS at HL-LHC

If we want to study unitarisation/EWSB we need to **extract the longitudinal component**

- only 5-10 % of the total rate
  → very challenging
  (remember: 130fb^{-1} → ~5-7 sigma
  → naive improvement by factor 10 necessary for observation)
- Requires CMS/ATLAS combination and/or new techniques at HL-LHC
  → improvement of systematic uncertainties needed!

ATLAS HL-LHC projection



How to improve on the (theory) systematics?
→ Improved signal and background (i.e. transverse part)
→ Effective separation of boson polarisation