Precision phenomenology

with the sector-improved residue subtraction scheme

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Outline

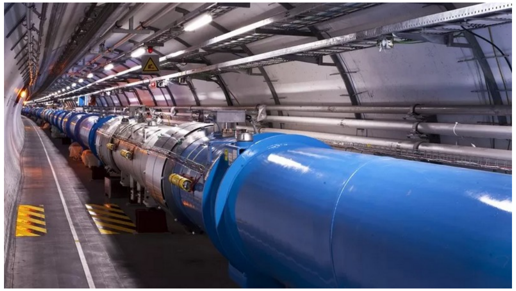
- Introduction
- Two examples:
  - Polarized EW bosons
  - Heavy-flavour jets
- HighTEA
- Summary

What are the fundamental building blocks of matter?

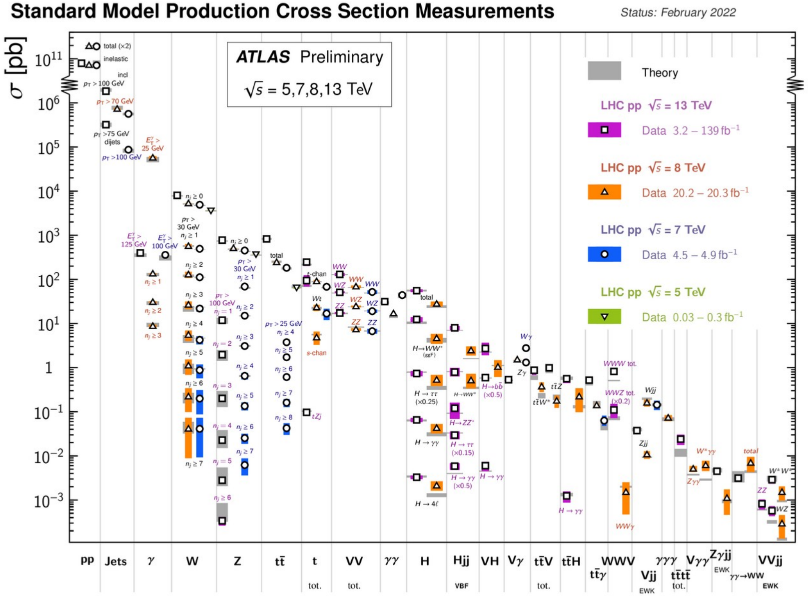
Collider phenomenology

Theory/Model

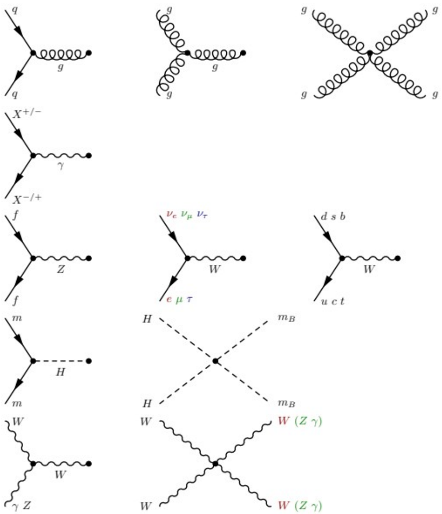
Scattering experiments



[Credit: CERN]



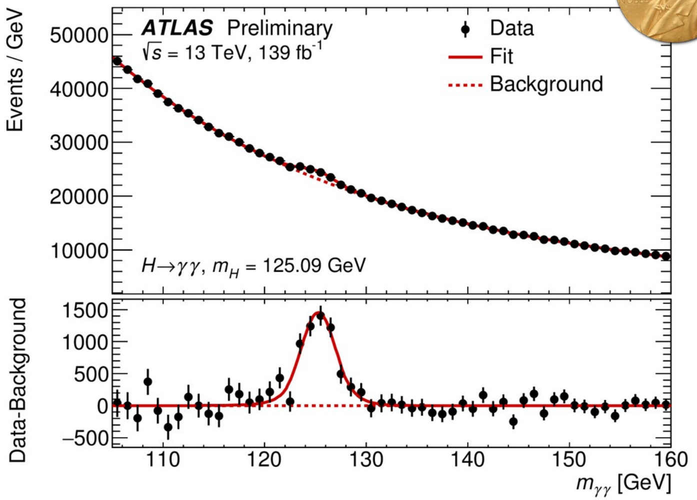
[Credit: ATLAS]



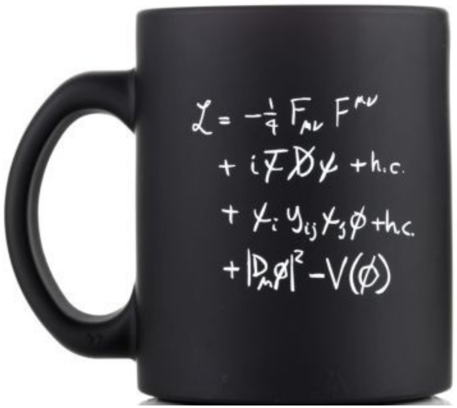
[Credit: Jack Lindon, CERN]

Standard Model of Particle Physics and beyond

Higgs discovery 2012



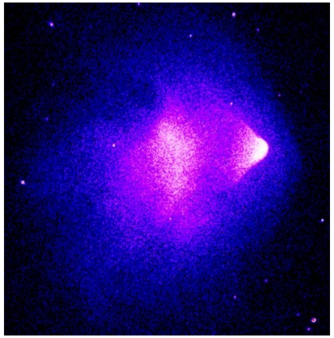
[Credit: ATLAS]



[Credit: CERN]

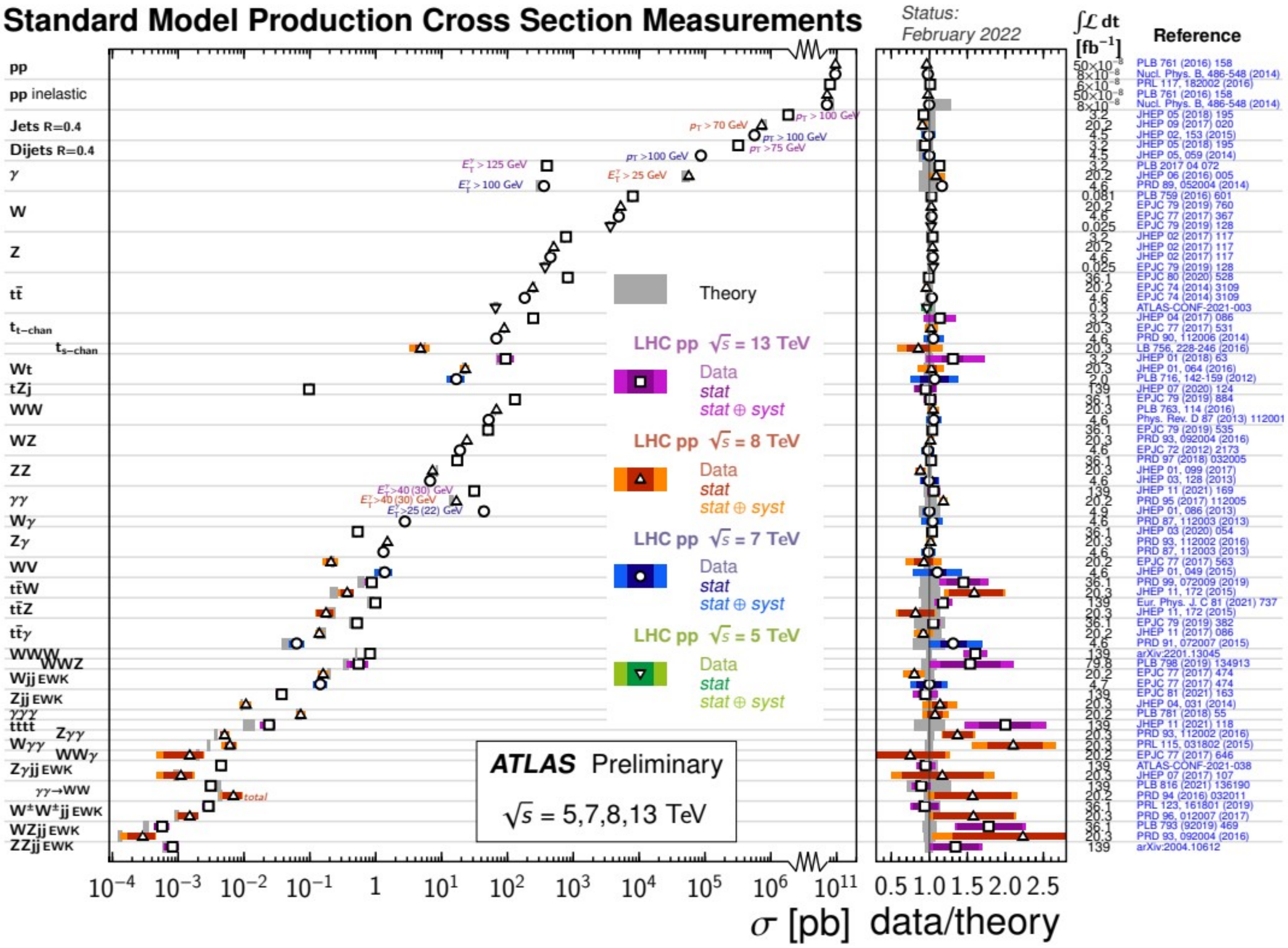
BUT:

- Is the Higgs a fundamental scalar?
- What is dark matter?
- Why is there a matter-anti-matter asymmetry?
- Reason behind flavour structure?
- …



[Credit: NASA]

SM measurements at the LHC



How could answers look like?

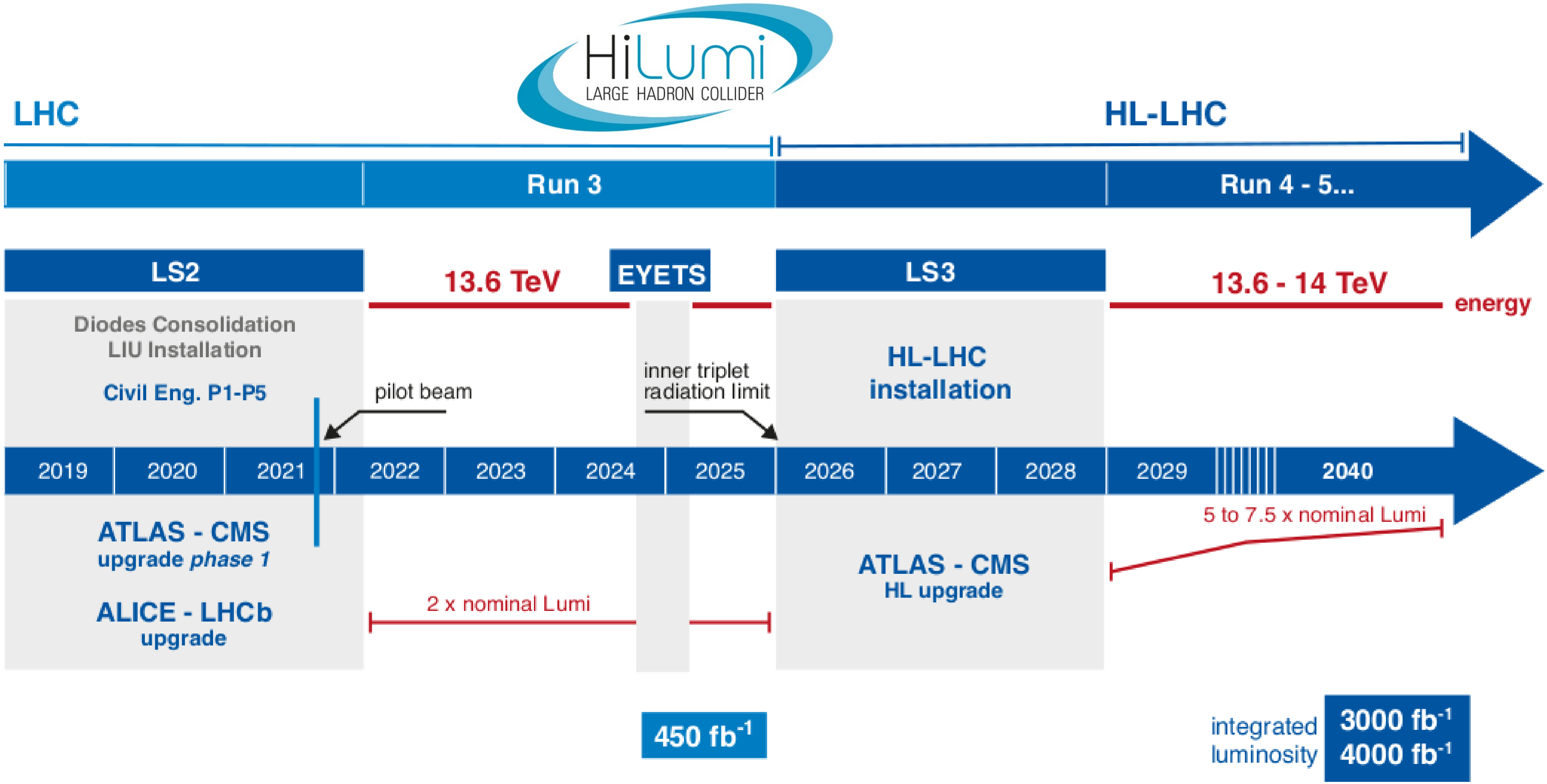
Likely:

- Weakly coupled
- Heavy particles (> accessible energies)

→ Need to look for small deviations

→ Requires precision experimentally and theoretically

LHC Precision era and future experiments



[Credit: CERN]

Theory picture of hadron collision events

Factorization
"What you see depends on the energy scale"

In Quantum Chromodynamics (QCD):

$Q \sim \Lambda_{\mathrm{QCD}}$

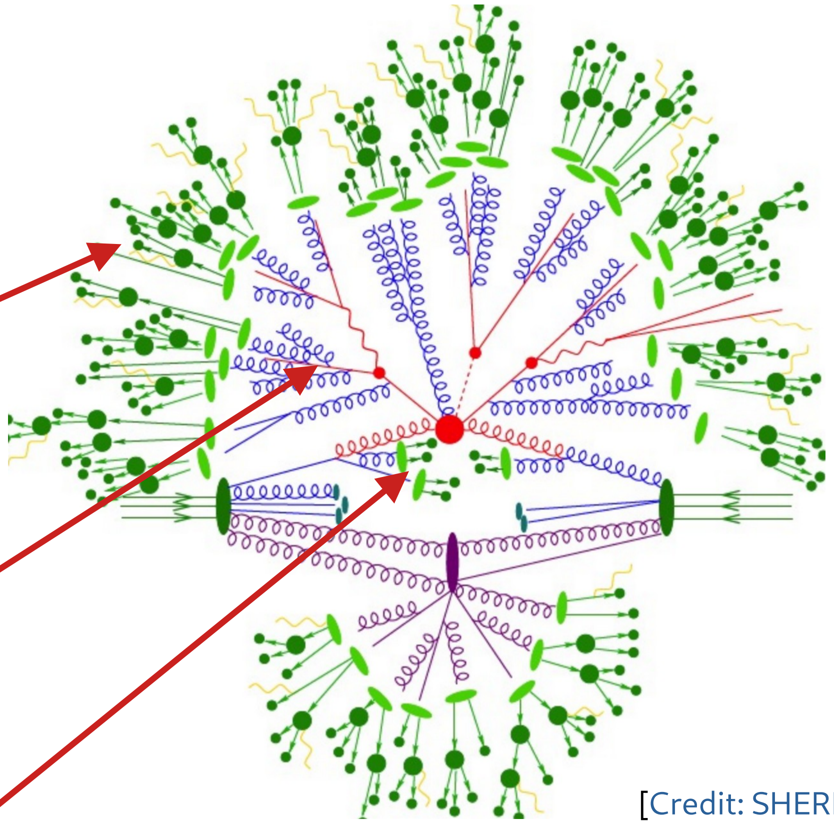
Strong coupling
- Realm of confined states
- non-perturbative physics

$Q \gtrsim \Lambda_{\mathrm{QCD}}$

Transition region
- Parton-shower
- Resummation
- DGLAP / PDF evolution

$Q \gg \Lambda_{\mathrm{QCD}}$

Small coupling → perturbative regime
- Scattering of individual partons

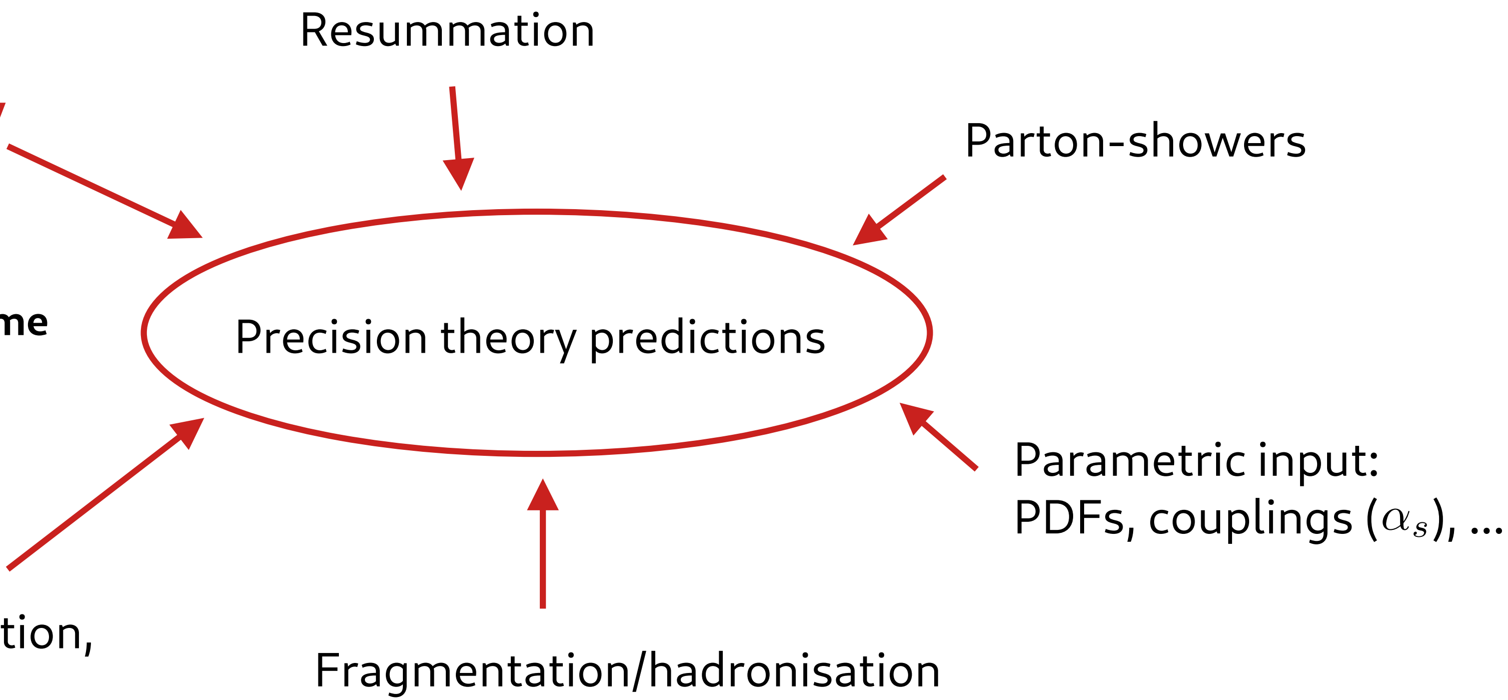


[Credit: SHERPA]

Precision predictions

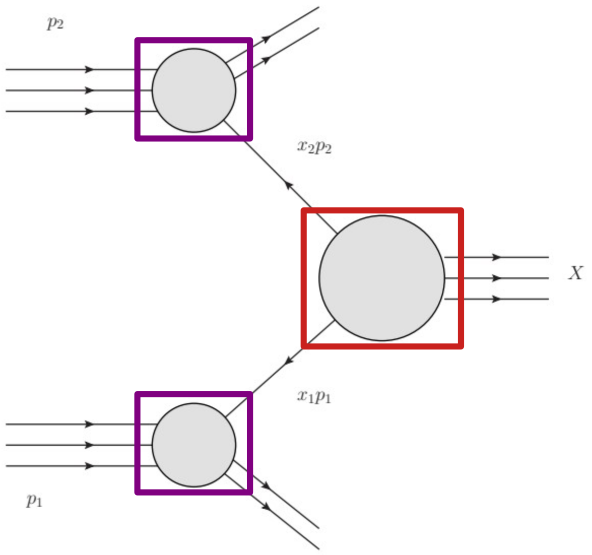
Fixed order perturbation theory

→ **Core element of event simulation**
→ **Describes high Q regime**



Soft physics:
MPI, colour reconnection, ...

Perturbative QCD



Hadronic cross section in collinear factorization:

$$\sigma_{h_1 h_2 \to X} = \sum_{ij} \int_0^1 \int_0^1 \mathrm{d}x_1 \mathrm{d}x_2 \phi_{i,h_1}(x_1, \mu_F^2) \phi_{j/h_2}(x_2, \mu_F^2) \hat{\sigma}_{ij \to X}(\alpha_s(\mu_R^2), \mu_R^2, \mu_F^2)$$

Perturbative expansion of partonic cross section:

$$\hat{\sigma}_{ab \to X} = \hat{\sigma}^{(0)}_{ab \to X} + \hat{\sigma}^{(1)}_{ab \to X} + \hat{\sigma}^{(2)}_{ab \to X} + \mathcal{O}(\alpha_s^3)$$

Typical uncertainties from scale variations: δLO O(~100%), δNLO O(~10%), δNNLO (~1%)

(estimate for corrections from missing higher orders based on renormalisation scale invariance $\frac{\mathrm{d}\sigma_{h_1 h_2 \to X}}{\mathrm{d}\mu} = 0$)

Example: Production of three isolated photons

$$pp \to \gamma\gamma\gamma$$

Theory to data comparison

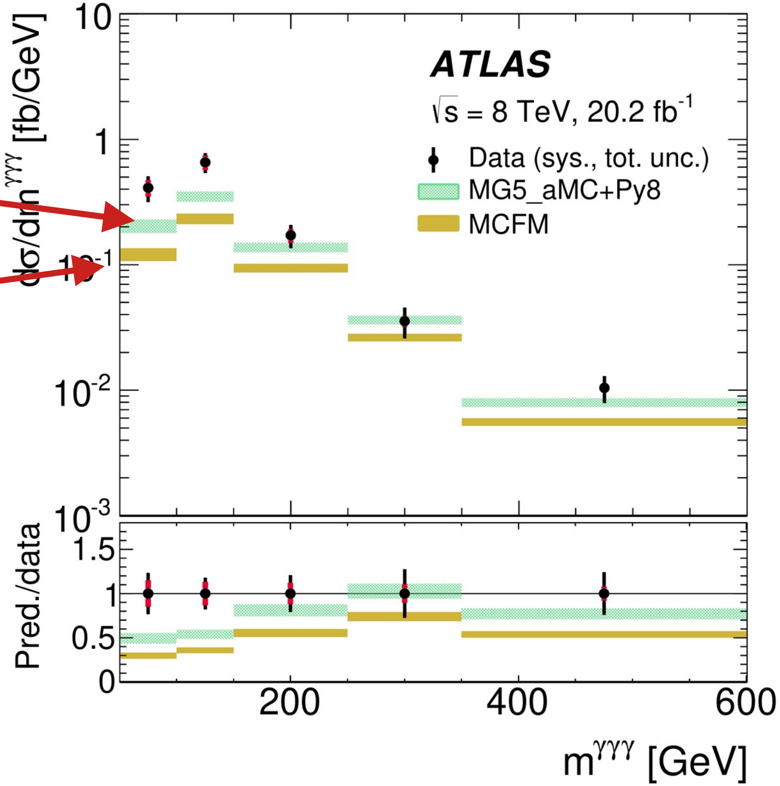
NLO QCD
+ Parton-shower simulation

Fixed-order NLO QCD

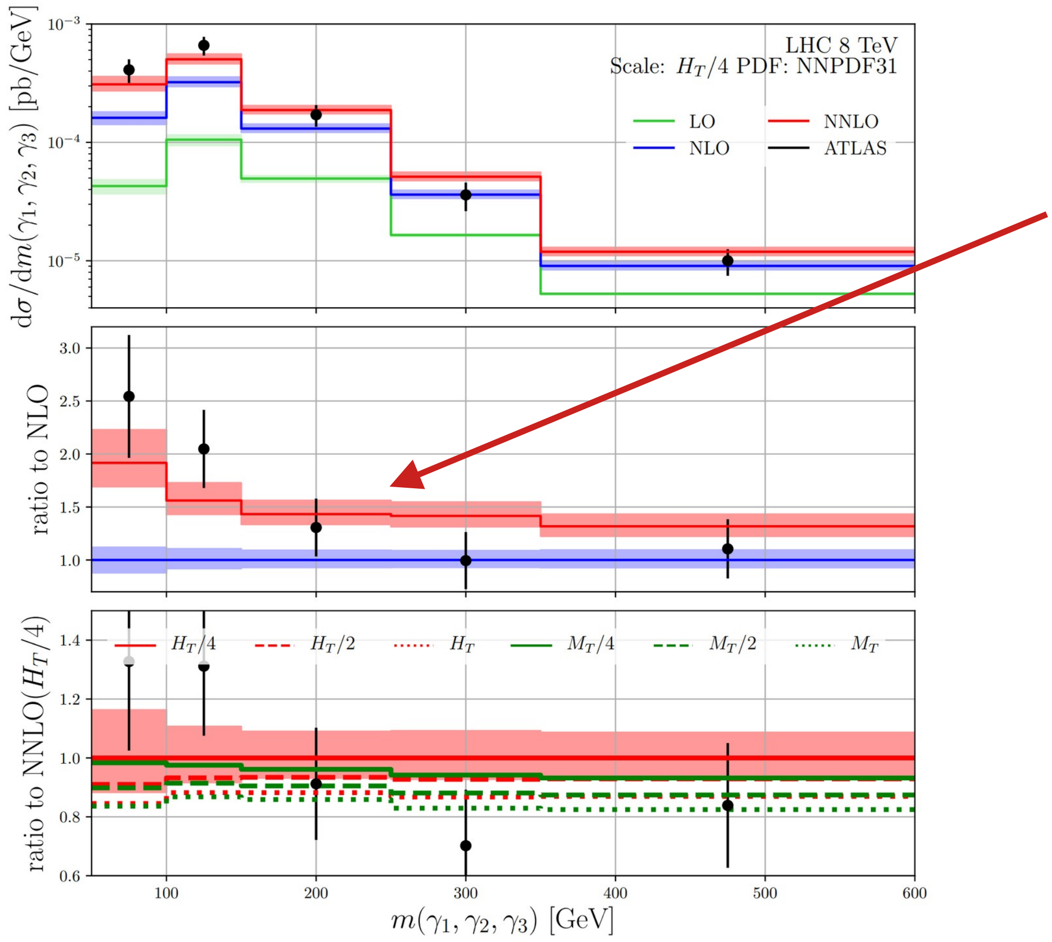
Both fail to describe data (normalization and shape)

Why?
→ NNLO QCD effects!

Measurement of the production cross section of three isolated photons in pp collisions at √s = 8 TeV using the ATLAS detector, ATLAS [1712.07291]



NNLO QCD in three photon production



NNLO QCD corrections to three-photon production at the LHC, Chawdhry, Czakon, Mitov, **Poncelet** [JHEP 02 (2020) 057]

Corrections to **normalization** and **shape**

→ (Much) improved description of data

Without NNLO QCD corrections the data

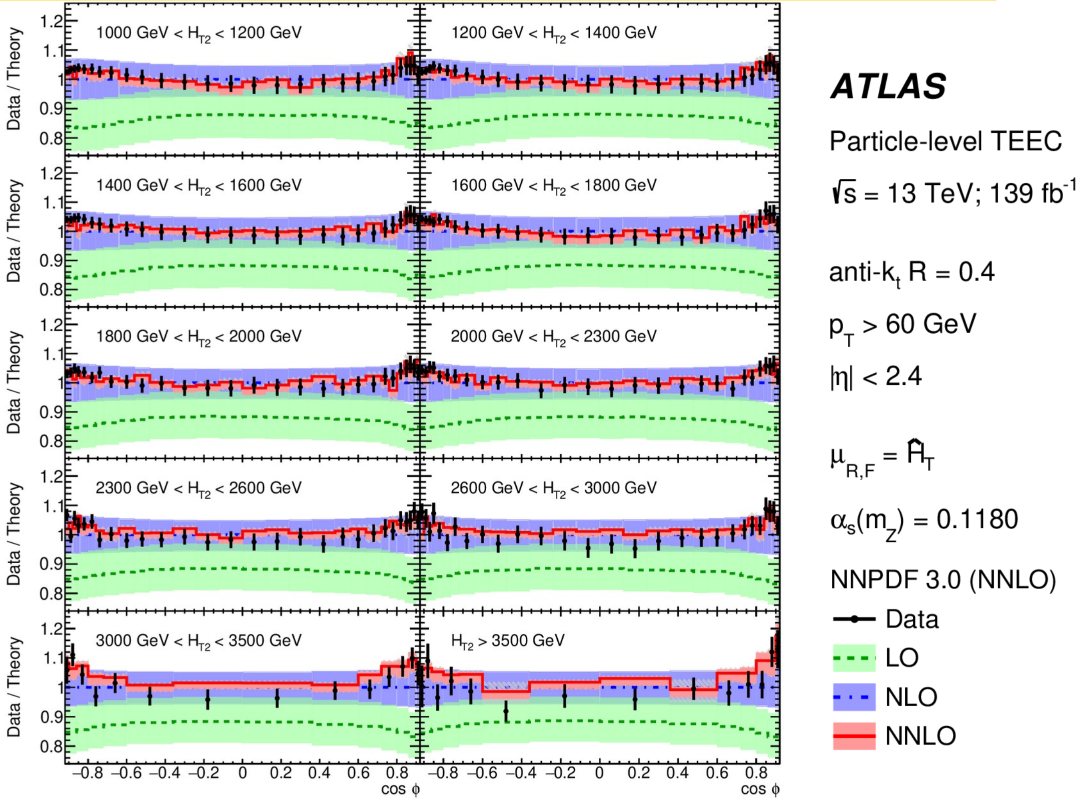
- is not interpretable
  → loss of information

or

- is misleading
  → looks like "New Physics" = data - SM

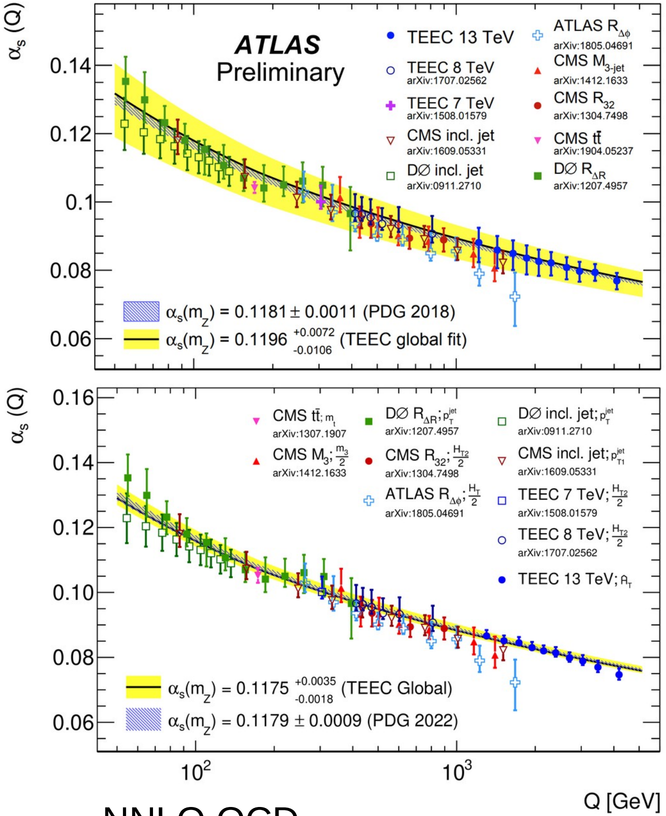
Strong coupling from Transverse-Energy-Energy-Correlators

NNLO QCD corrections to event shapes at the LHC
Alvarez, Cantero, Czakon, Llorente, Mitov, **Poncelet** JHEP 03 (2023) 129



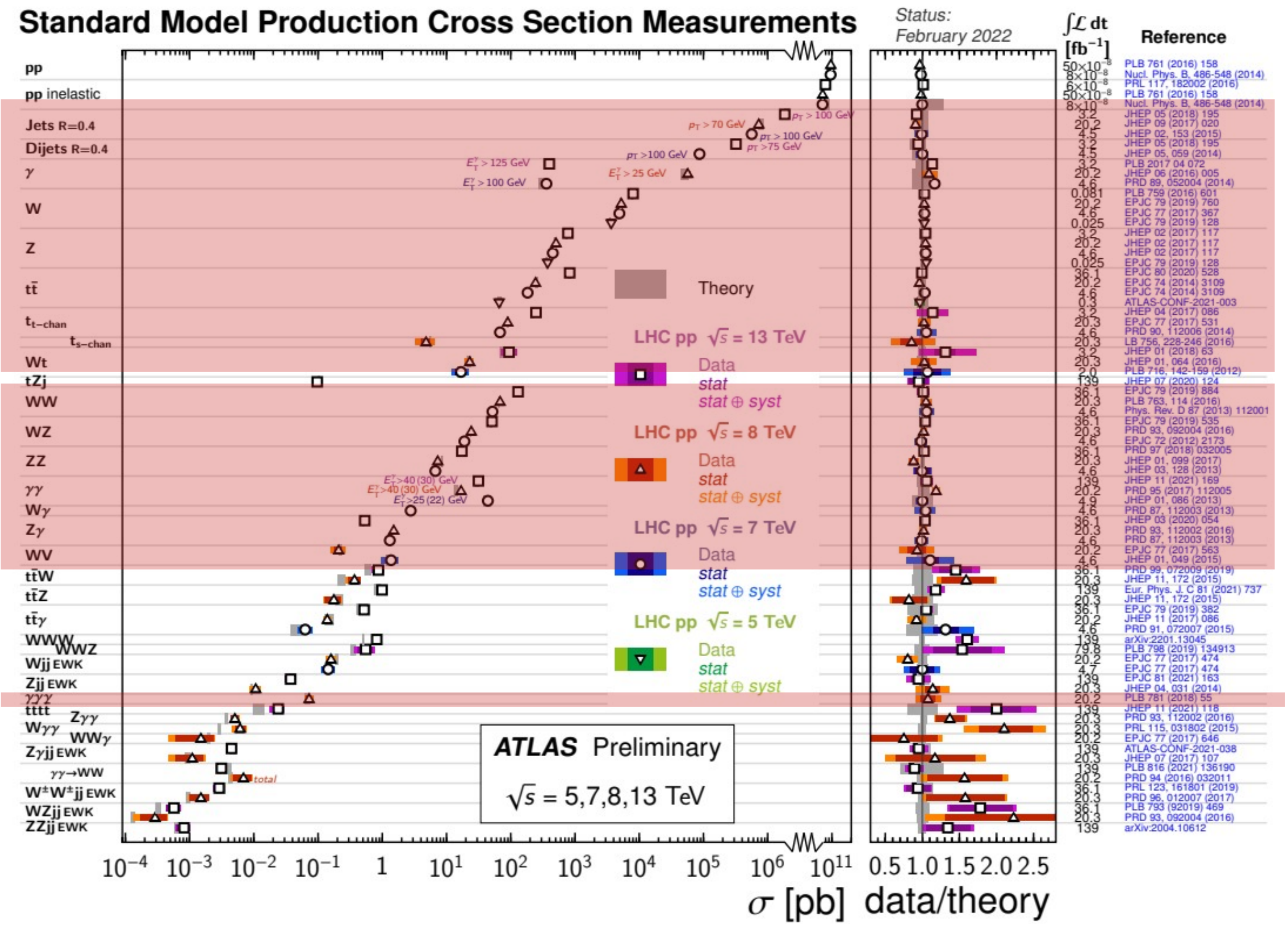
[ATLAS 2301.09351]

NLO QCD



NNLO QCD

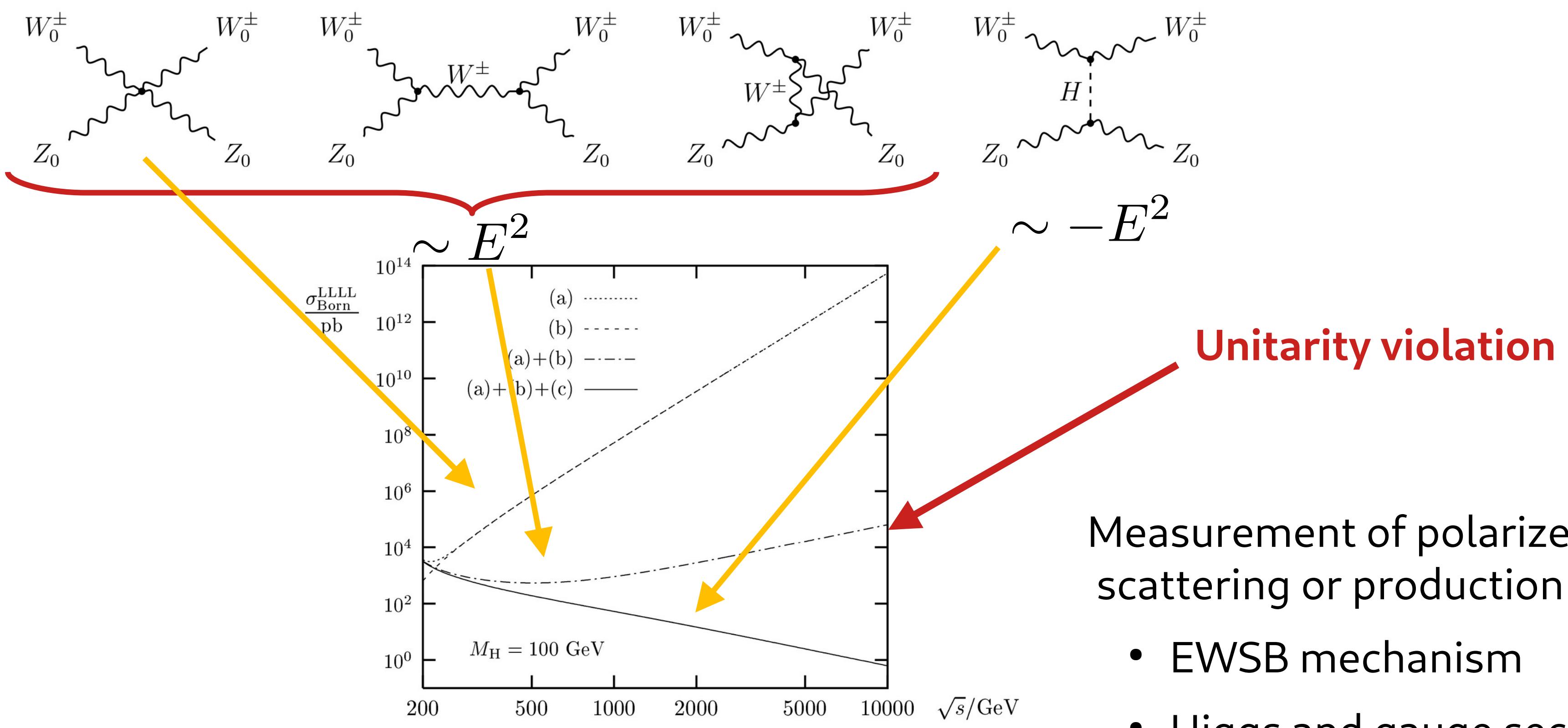
NNLO QCD coverage



Processes with second-order theory

Polarized EW bosons

Longitudinal Vector-Boson-Scattering (VBS)



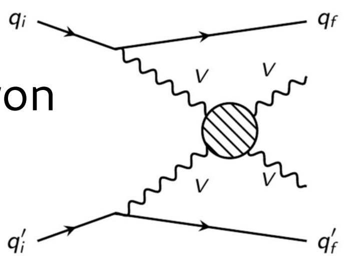
Radiative corrections to W+ W- → W+ W- in the electroweak standard model
A. Denner, T. Hahn hep-ph/9711302

Measurement of polarized boson scattering or production probes:

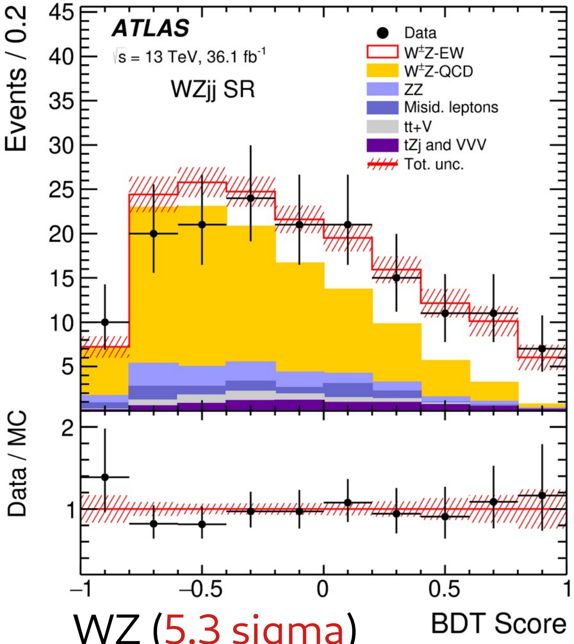
- EWSB mechanism
- Higgs and gauge sector
- New physics models

VBS at hadron colliders

VBS at hadron colliders

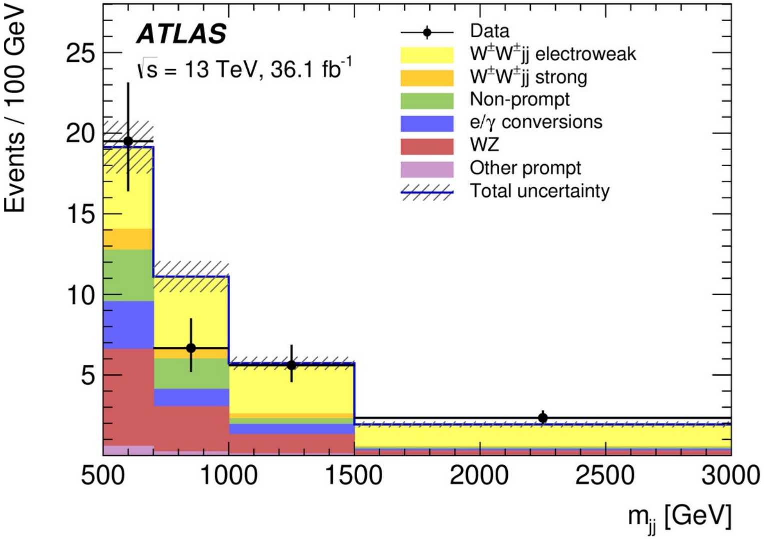


Separate from background processes through VBS topology
→ a rare process, but observed.



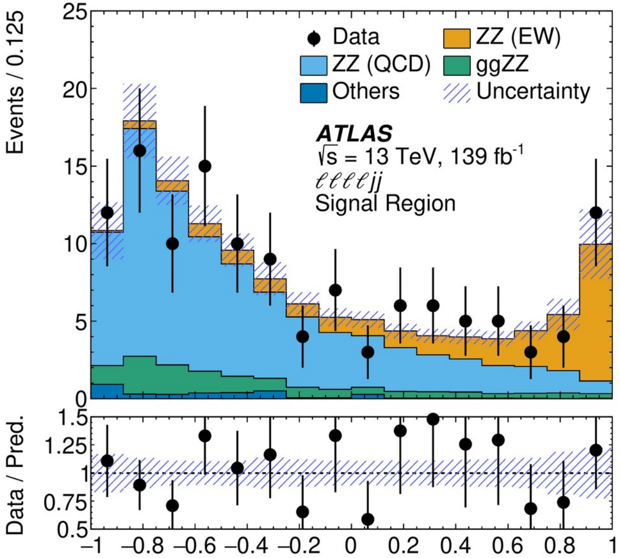
WZ (5.3 sigma)

ATLAS 1812.09740



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

ATLAS 1906.03203



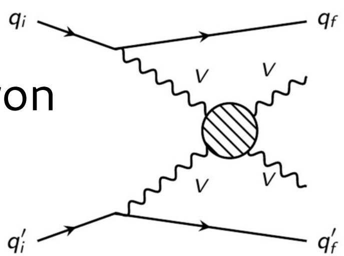
ZZ (5.5 sigma)

MD

ATLAS 2004.10612

VBS at hadron colliders

VBS at hadron colliders



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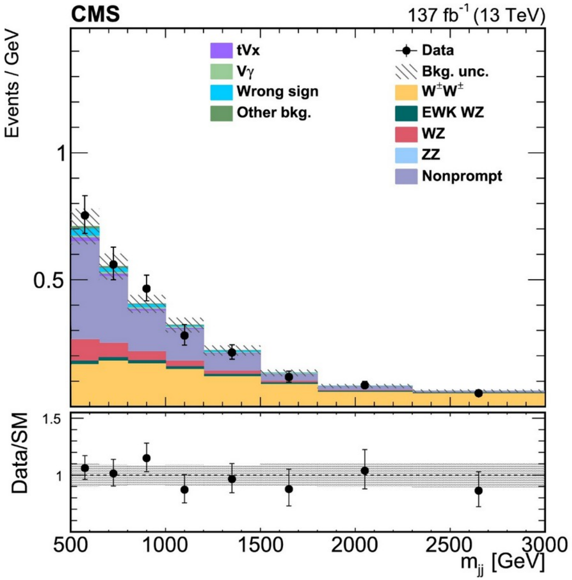
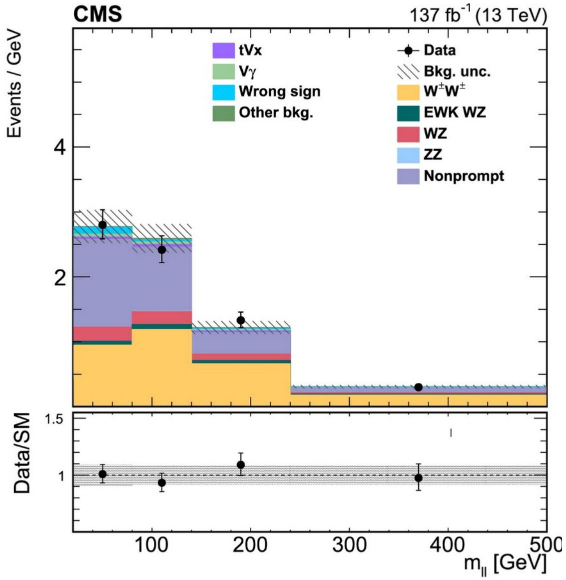
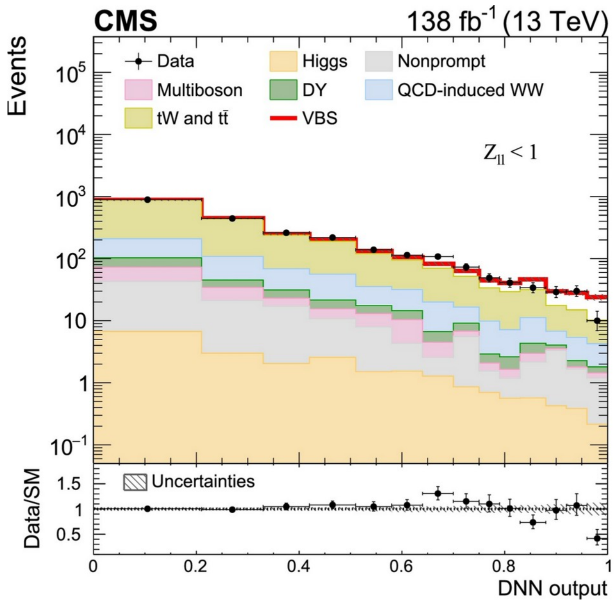






WZ (6.8 sigma) + W+W+/W-W- (diff. xsec)
CMS 2005.01173

W+W- (5.6 sigma)
CMS 2205.05711

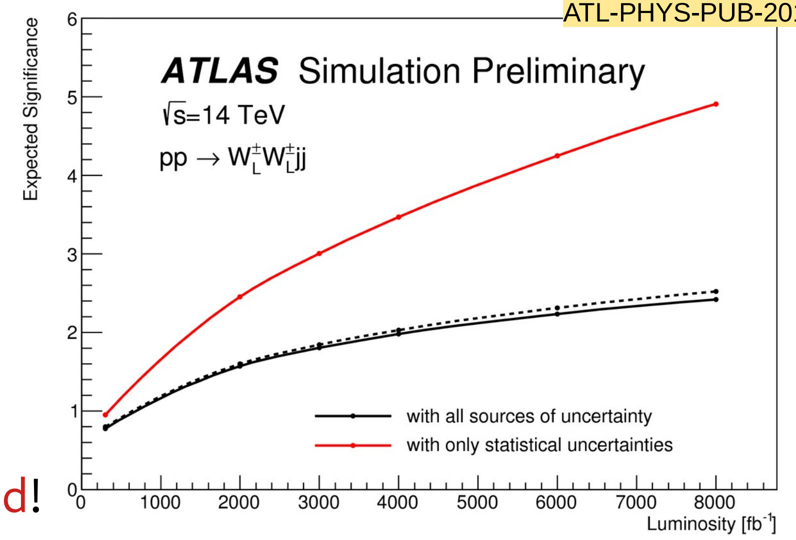
Polarised VBS at HL-LHC

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!

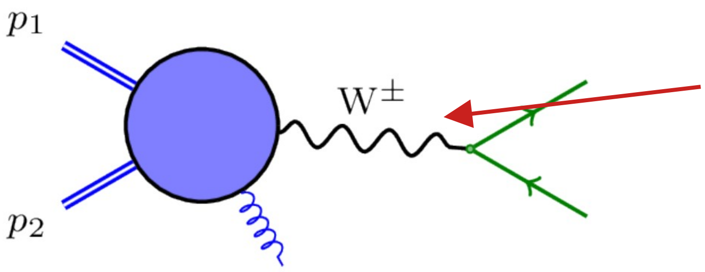
ATLAS HL-LHC projection

ATL-PHYS-PUB-2018-052



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

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

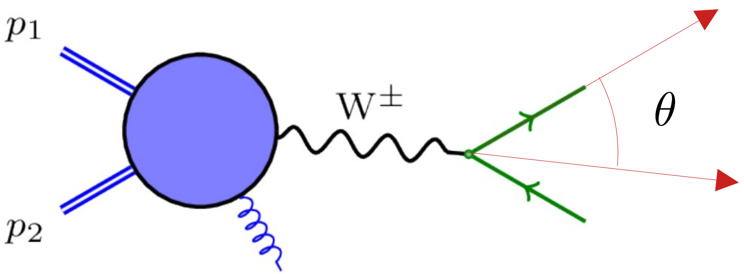
Can we extract the longitudinal component?

Measurements of longitudinal polarisation fractions:

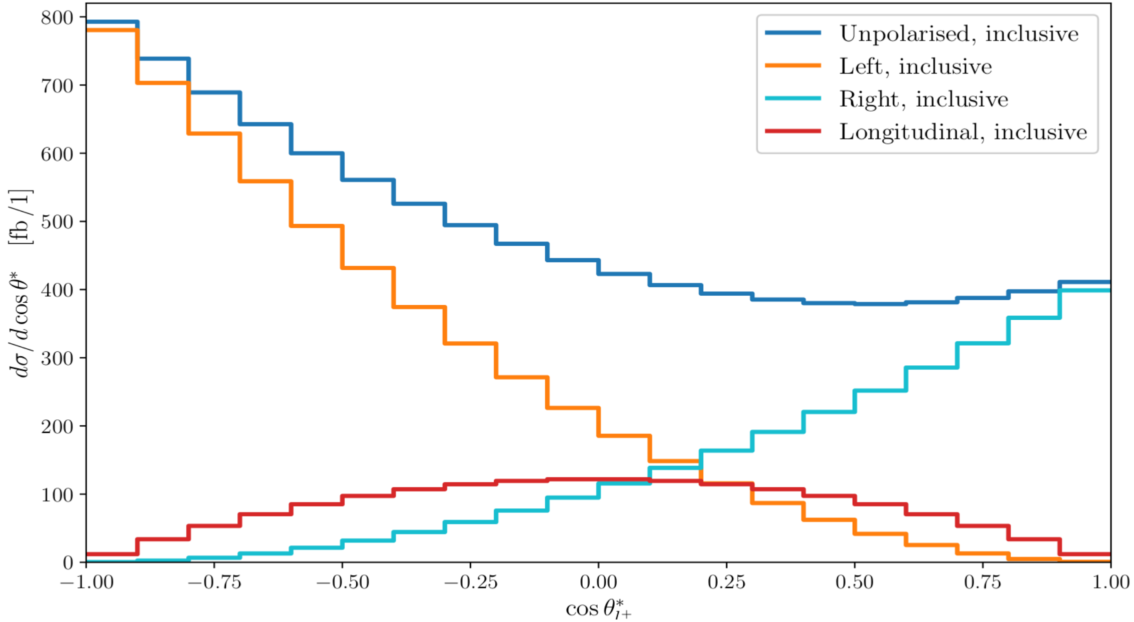
Measurement of the Polarization of W Bosons with Large Transverse Momenta in W+Jets Events at the LHC,
CMS 1104.3829
Measurement of the polarisation of W bosons produced with large transverse momentum in pp collisions at \sqrt{s}=7 TeV with the ATLAS experiment,
ATLAS 1203.2165
Measurement of WZ production 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

How to measure polarized bosons?

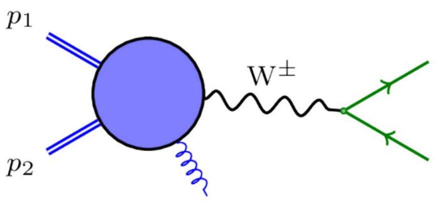
- We can’t measure boson polarization directly.
- Luckily decay products can be used as a “polarimeter”:



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:

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

Template fit f_L, f_R, f_0 to measured $\frac{\mathrm{d}\sigma^{exp.}}{\mathrm{d}X}$

Polarized cross sections

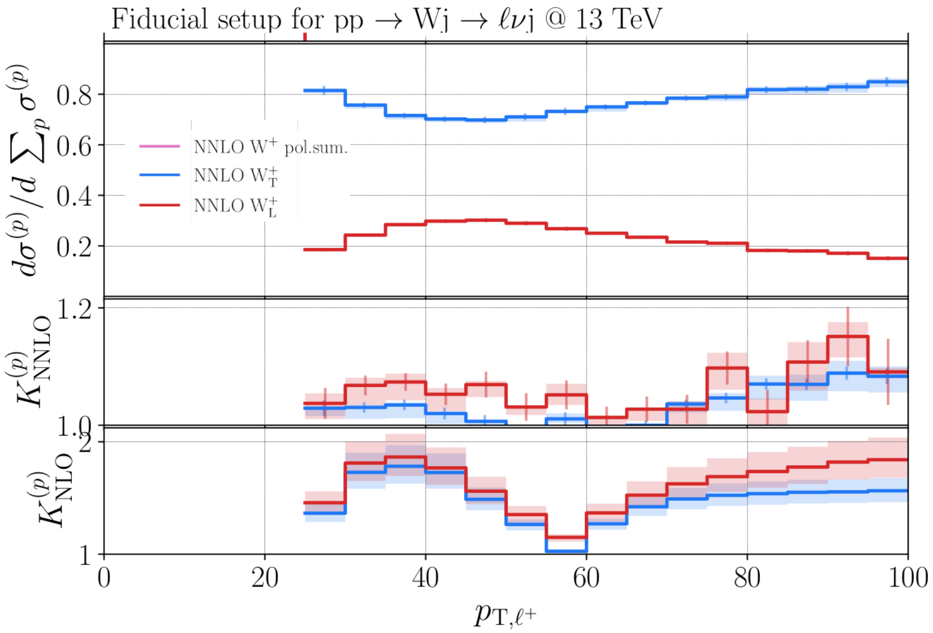
$$\frac{\mathrm{d}\sigma}{\mathrm{d}X} = f_L \frac{\mathrm{d}\sigma_L}{\mathrm{d}X} + f_R \frac{\mathrm{d}\sigma_R}{\mathrm{d}X} + f_0 \frac{\mathrm{d}\sigma_0}{\mathrm{d}X} \left(+ f_{int.} \frac{\mathrm{d}\sigma_{int.}}{\mathrm{d}X} \right)$$

- 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 MHO (scale uncertainties)

Why do we need higher-order corrections?

Example: $pp \to W^{\pm}(\to l\nu)j$



Important

Just using single NNLO K-factors is not enough

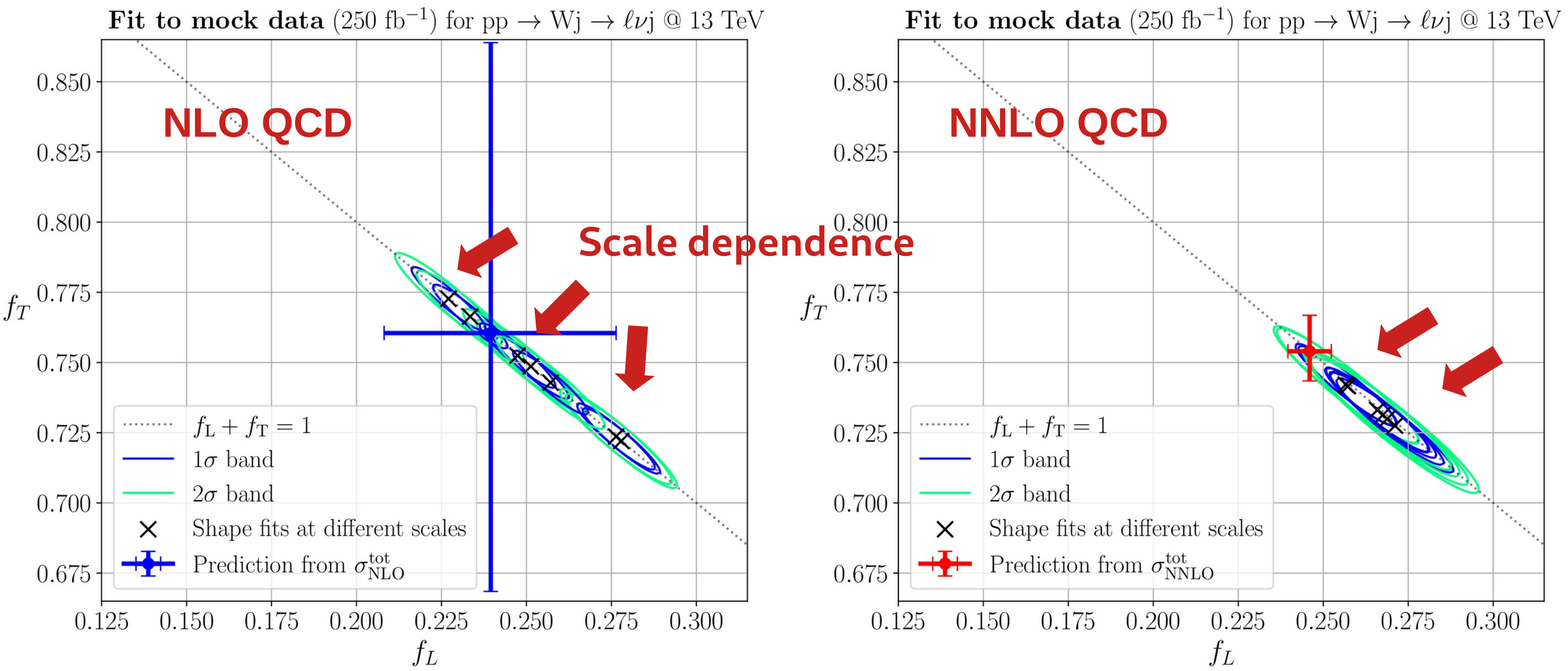
1) Differential polarization fraction have shapes (not just one number!)
2) Higher-order corrections dependent on polarization! Just using unpolarized K-factor would lead to distortion of spectrum.
3) NNLO QCD needed to reach percent-level scale-dependence → MHO

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

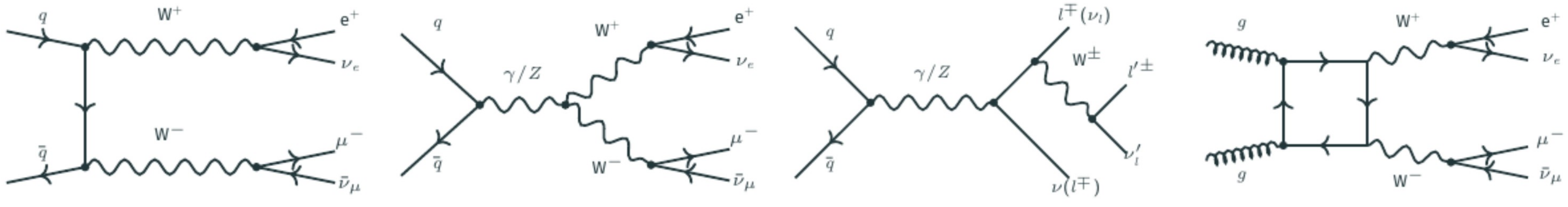
W+jet: mock-data fit

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

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

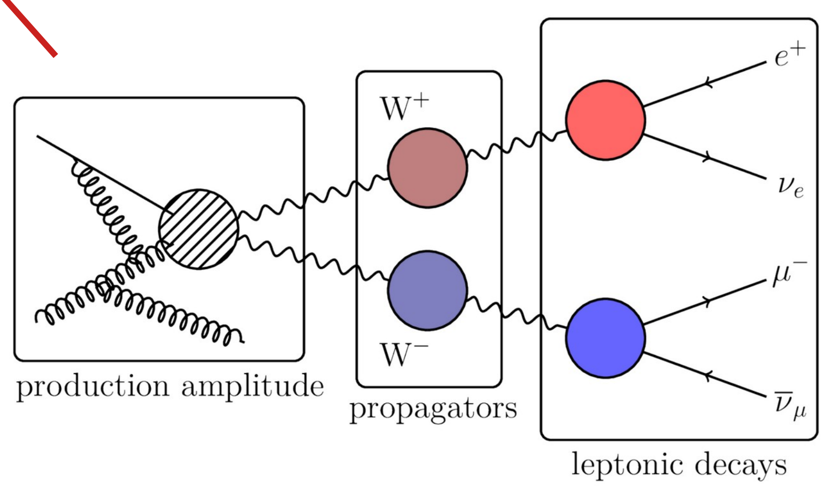


W-boson pair production

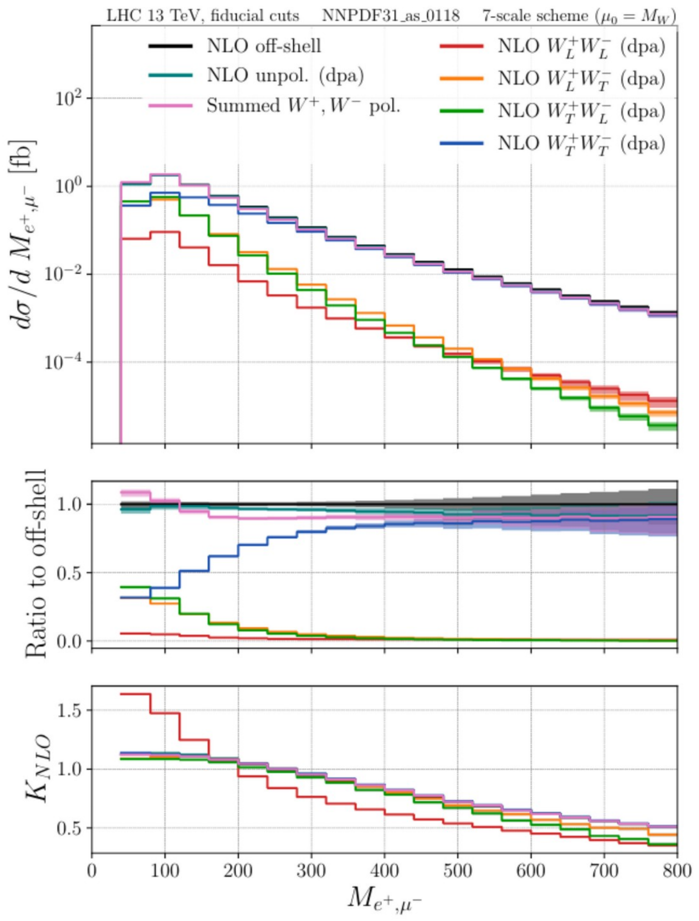


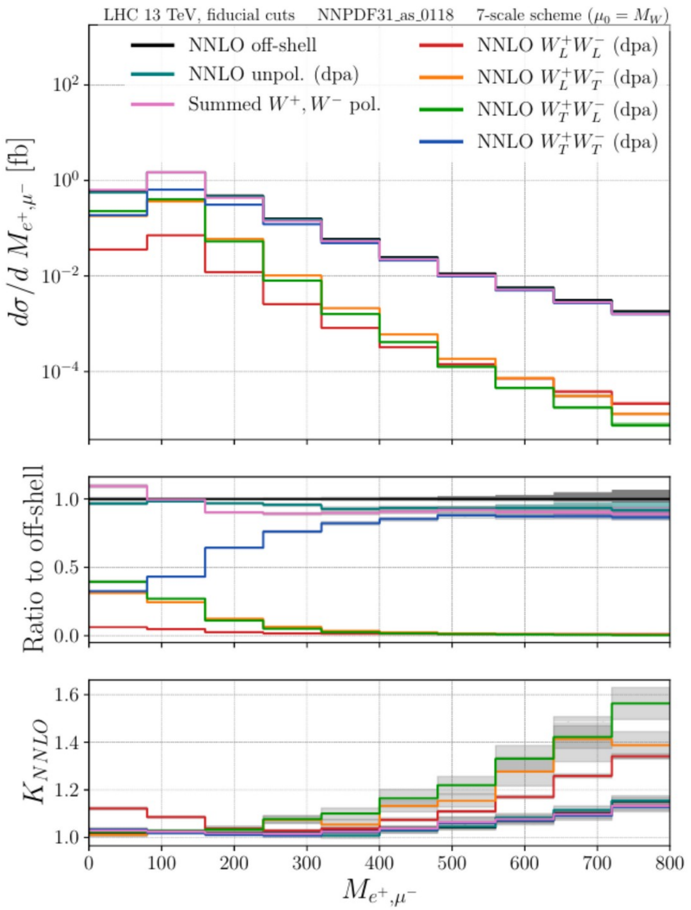
Double resonant (DR) | Double resonant (DR) | Single resonant (SR) | Loop-induced (LI)

formally NNLO



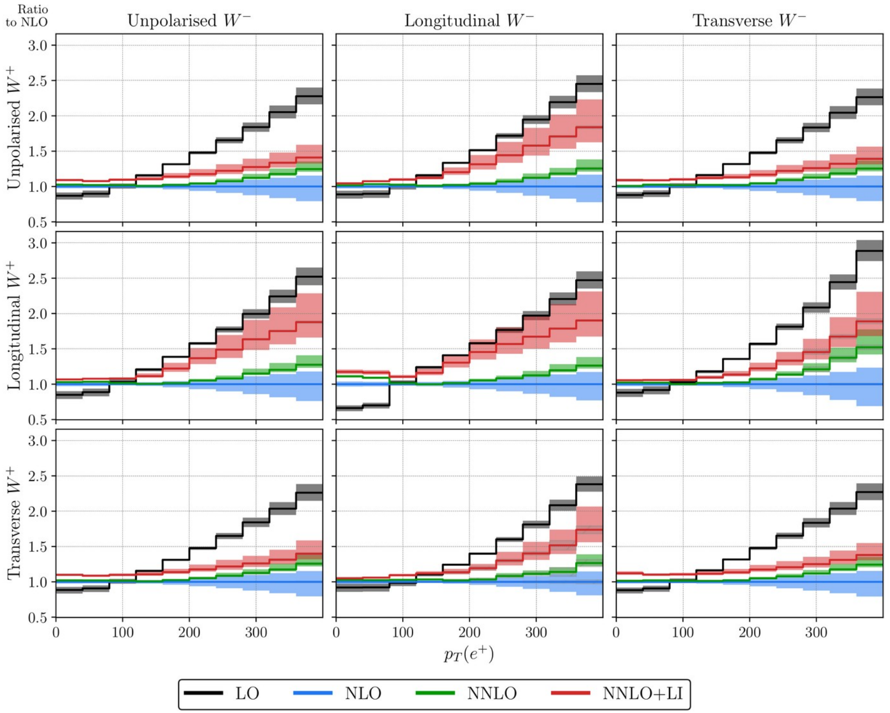
Polarised di-boson production



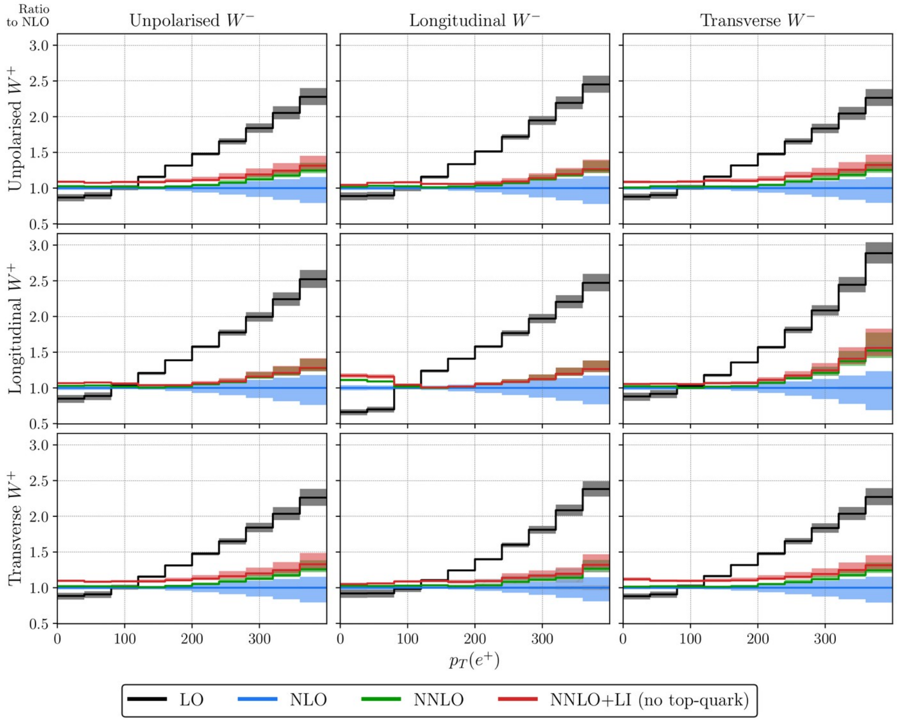


Loop induced gg → WW contributions

With top-quark loops in gg LI



Without top-quark loops in gg LI



Recent development: NLO+PS

NLO + PS

- SHERPA

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

  - Reproduction of fixed order results with approximation of virtuals
  - Study of impact of multiple hard emissions with multi-jet merging

- Powheg+Pythia

  Polarised-boson pairs at the LHC with NLOPS accuracy
  Pellicciolі, Zanderighi 2311.05220

  - Only small hower+hadronisation effects on polarization fractions

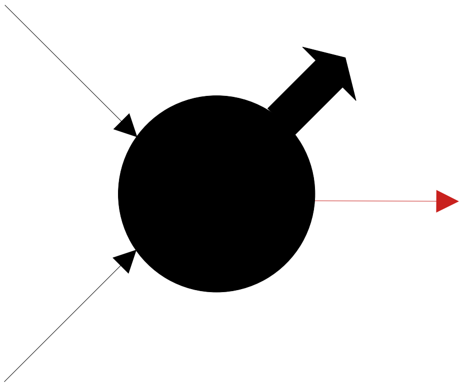
- Comparison effort among all MCs/fixed-order codes for $pp \to ZZ$

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

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

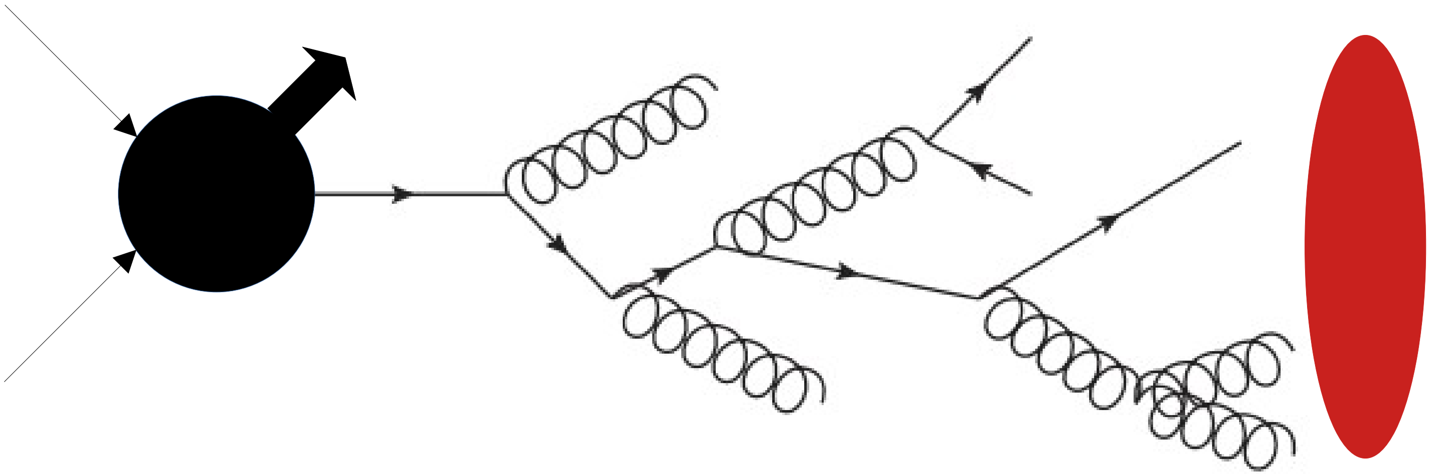
Heavy-flavour jets

Heavy flavour production (theory perspective)



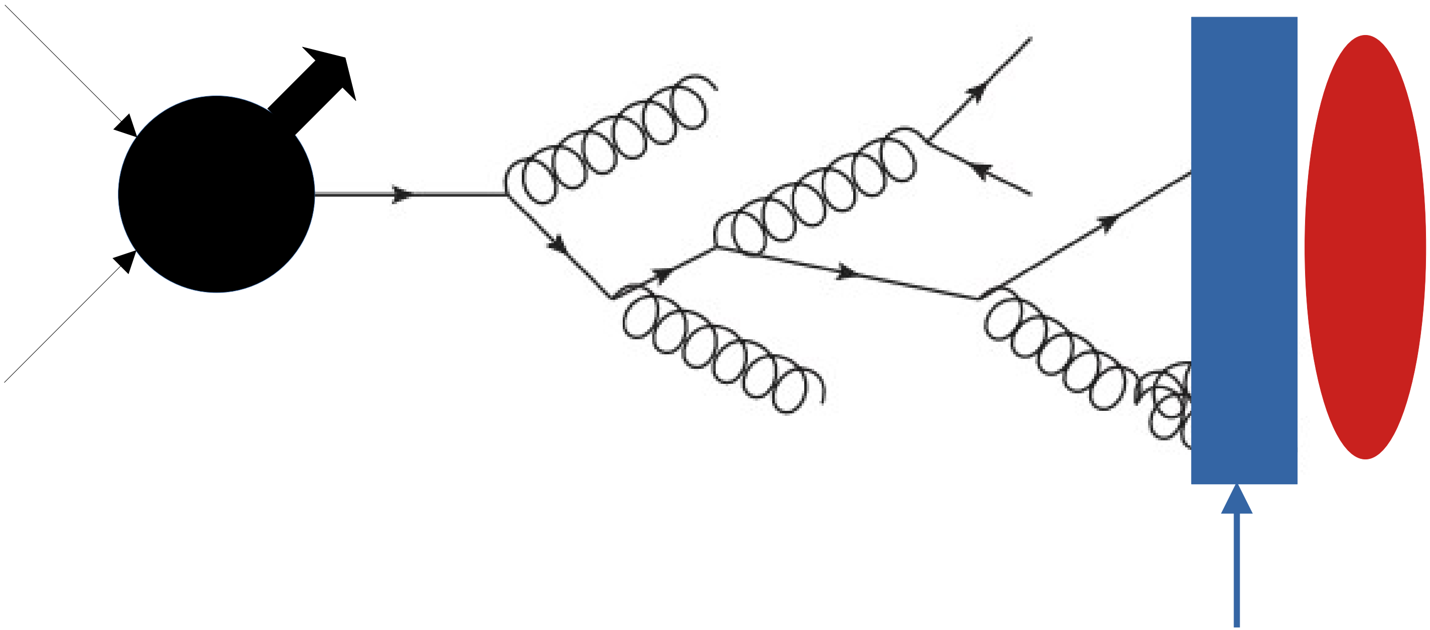
Process of interest here:
Production of a (massive) quark(s) of fixed flavour
(potentially with high transverse momentum: pT >> m)

Heavy flavour production (theory perspective)



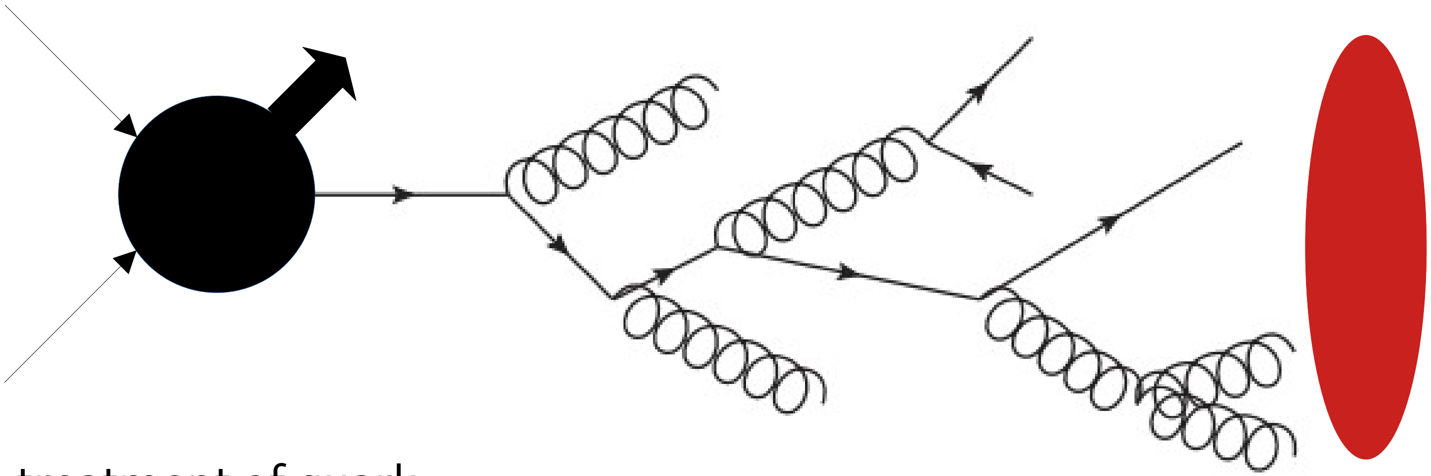
Reconstruction of jets to “approximate” the hard momentum

Heavy flavour production (theory perspective)



- Fragmentation/Hadronisation
- Partonic jet flavour: Quark-Hadron Duality
- Heavy B/D – hadron have a long life time:
  → experimental signature (displaced vertices)
  → distinguishable from "light" jets

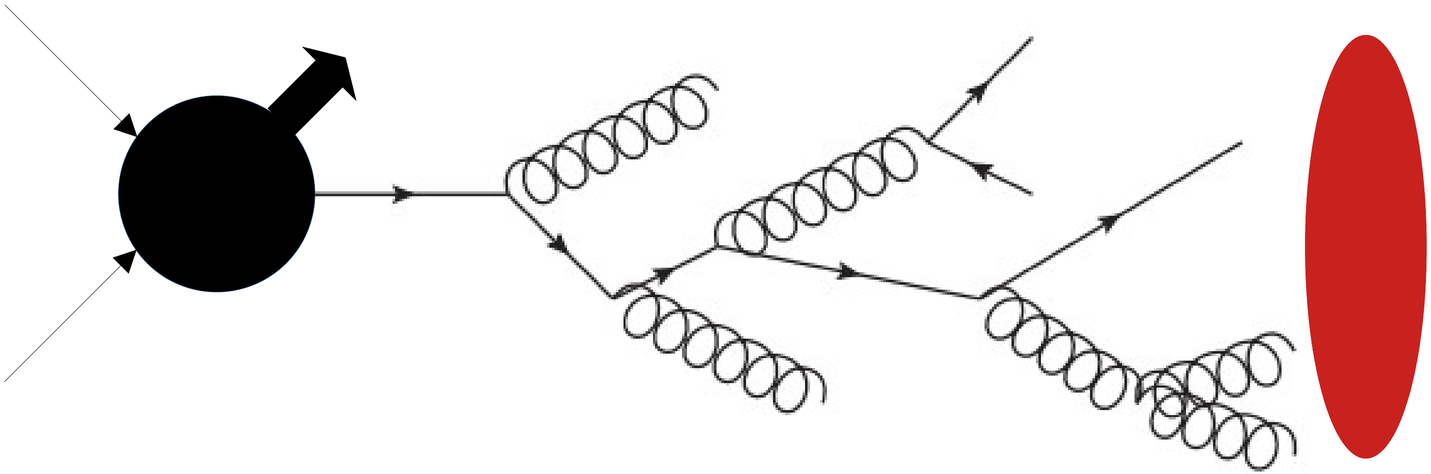
Heavy flavour production (theory perspective)



Massive treatment of quark

- Mass acts as IR regulator → no IR divergences from collinear splitting
- Price to pay: log(pT/m), how to treat PDFs (high Q^2 process due to V-boson)?
  → Resummation for reliable predictions
  → mostly limited to parton-showers (state-of-the-art: NLO+PS) or FONLL (needs also massless)
- Higher order calculations more difficult
- Some applications (like PDF fits) need fixed-order QCD at higher orders

Heavy flavour production (theory perspective)



High transverse momentum → massless quarks

- Consistent treatment with PDFs (high Q^2 → c/b quarks in DGLAP)
- Bonus: higher order calculations easier → NNLO QCD
- BUT: IR-safety more demanding due to collinear and soft flavoured particles
  → here the flavour algorithms come into the game
- This IR-safety issue → IR-sensitivity in massive and showered case

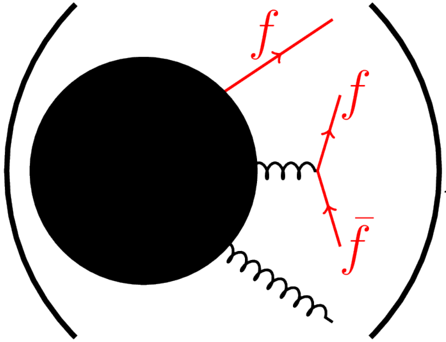
The IR-safety issue

Example NNLO:

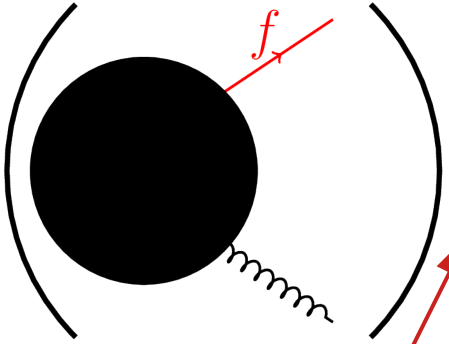
Double real matrix element

Double soft subtraction term:
Double soft function * tree ME

$d\sigma \ni d\Phi_{n+2}$



$F_{n+2} + \cdots + d\tilde{\Phi}_{n+2}\mathcal{S}_2$



F_n

Flavour structure depends on the angular configuration

IR safety:
Have to match in double soft limit

Fixed flavour structure

- If F(n+2) does not treat the flavour pair appropriately:
  → double soft singularity not subtracted

➔ Implies correlated treatment of kinematics and flavour information

Infrared safe definition of jet flavor, Banfi, Salam, Zanderighi hep-ph/0601139

The CMP algorithm

Infrared-safe flavoured anti-kT jets,
Czakon, Mitov, Poncelet 2205.11879

anti-kT: $d_{ij} = \min(k_{T,i}^{-2}, k_{T,j}^{-2}) R_{ij}^2 \qquad d_i = k_{T,i}^{-2}$

Proposed modification:

A soft term designed to modify the distance of flavoured pairs.

$$d_{ij}^{(F)} = d_{ij} \begin{cases} \mathcal{S}_{ij} & \text{i,j is flavoured pair} \\ 1 & \text{else} \end{cases} \qquad \text{where} \quad \mathcal{S}_{ij} \to 0 \quad \text{if } i,j \text{ are soft}$$

Original proposal:

$$\mathcal{S}_{ij} \equiv 1 - \theta\left(1 - \kappa_{ij}\right) \cos\left(\frac{\pi}{2}\kappa_{ij}\right) \quad \text{with} \quad \kappa_{ij} \equiv \frac{1}{a} \frac{k_{T,i}^2 + k_{T,j}^2}{2k_{T,\max}^2} .$$

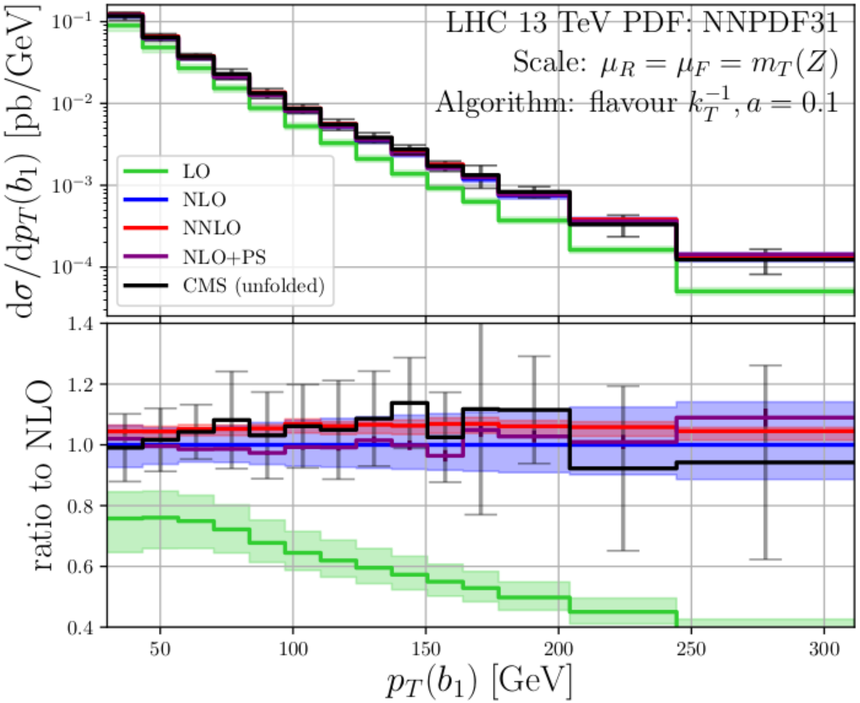
Issue when $E_i, E_j \gg 1 \quad \text{but} \quad p_{T,i}, p_{T,j} \ll 1$

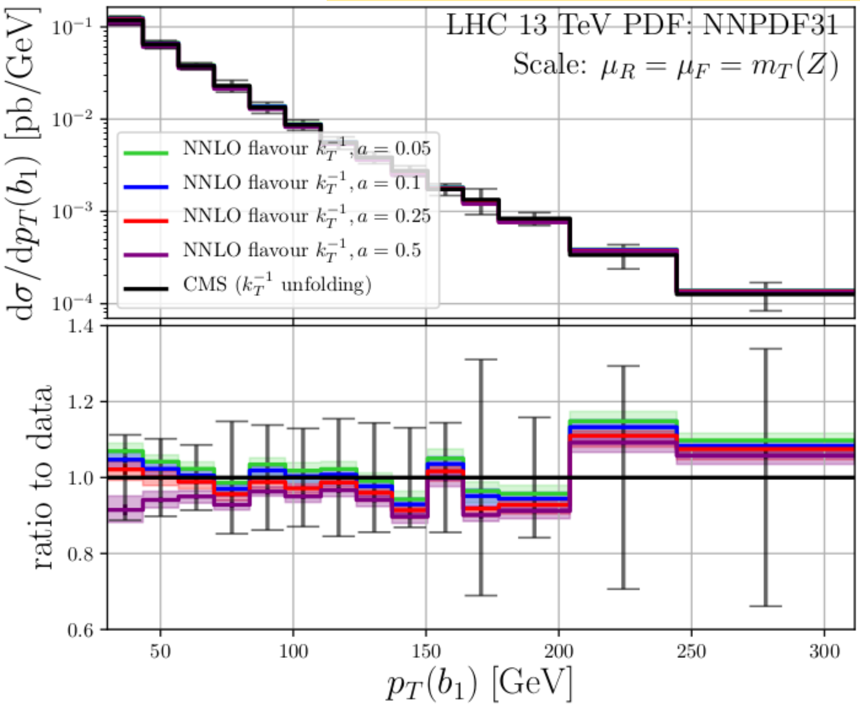
Variant IFN paper [2306.07314]

$$\mathcal{S}_{ij} \to \overline{\mathcal{S}}_{ij} = \mathcal{S}_{ij} \frac{\Omega_{ij}^2}{\Delta R_{ij}^2} \qquad \Omega_{ik}^2 \equiv 2\left[\frac{1}{\omega^2}\left(\cosh(\omega \Delta y_{ik}) - 1\right) - \left(\cos \Delta\phi_{ik} - 1\right)\right]$$

Z + bottom

Infrared-safe flavoured anti-kT jets,
Czakon, Mitov, Poncelet 2205.11879





MC-corrections based on NLO+PS

CMS data [1611.06507]

W + charm: collaboration with CMS

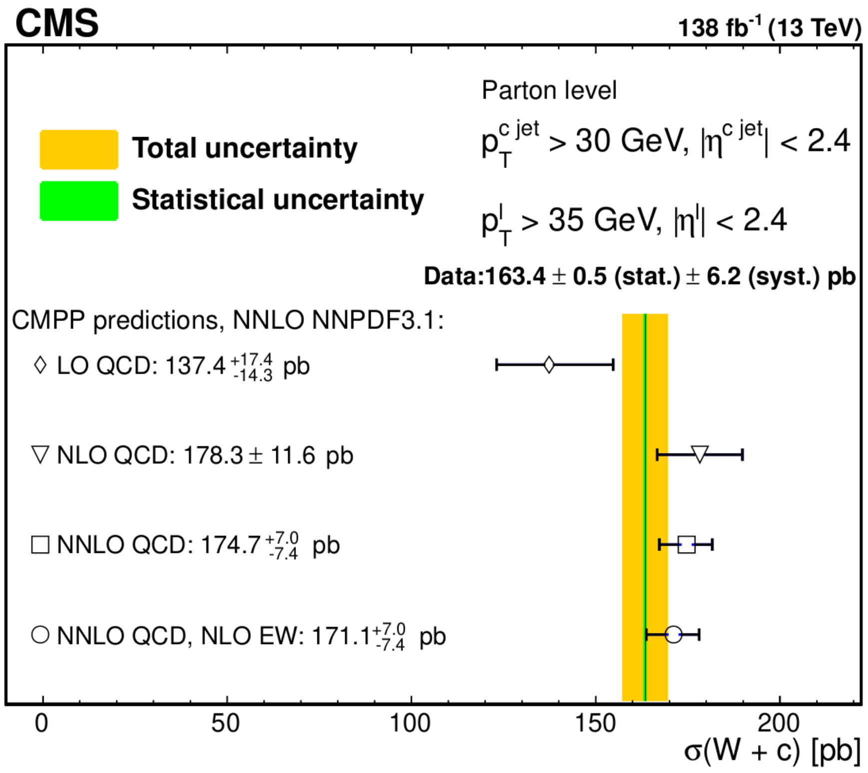
Measurement of the production cross section for a W boson in association with a charm quark in proton-proton collisions at Sqrt(s) = 13 TeV
CMS 2308.02285

Measurement of OS – SS cross-section unfolded to parton-level (anti-kT algorithm)

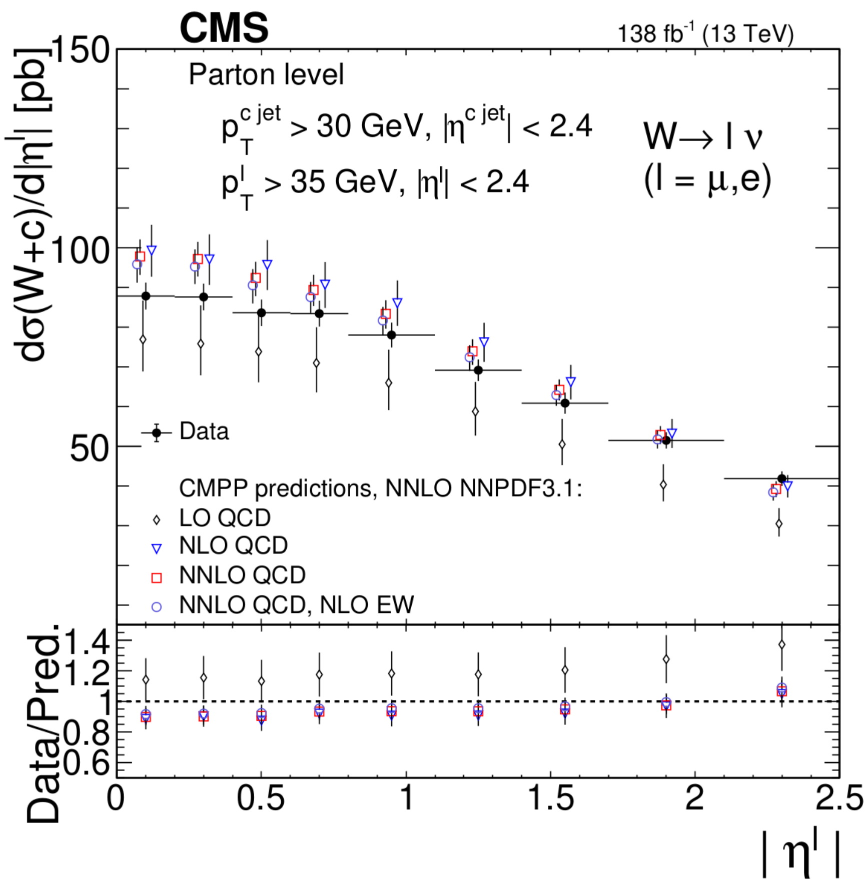
→ hadronisation and fragmentation corr. ~ 10%

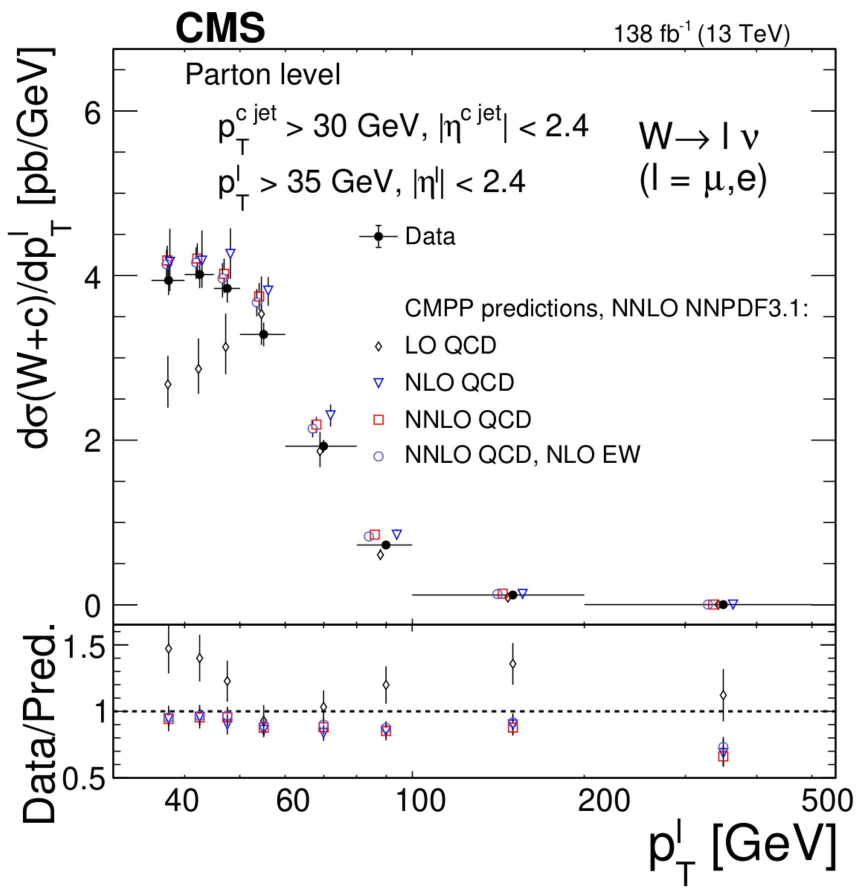
+ anti-kT → flv. Anti-kT correction on fixed-order

Not ideal but a full flv. Anti-kT unfolding was not feasible at that time…



W + charm: collaboration with CMS





New proposals for flavour-safe anti-kT jets

- Flavour with Soft-drop — **Practical Jet Flavour Through NNLO**
  Caletti, Larkoski, Marzani, Reichelt 2205.01109 — SDF
- Flavour anti-kT — **Infrared-safe flavoured anti-kT jets**,
  Czakon, Mitov, Poncelet 2205.11879 — CMP
- Fragmentation approach — **A Fragmentation Approach to Jet Flavor**
  Caletti, Larkoski, Marzani, Reichelt 2205.01117
  B-hadron production in NNLO QCD: application to LHC ttbar events with leptonic decays,
  Czakon, Generet, Mitov and Poncelet, 2102.08267
- Flavour dressing → standard anti-kT + flavour assignment — GHS
  QCD-aware partonic jet clustering for truth-jet flavour labelling
  Buckley, Pollard 1507.00508
  A dress of flavour to suit any jet
  Gauld, Huss, Stagnitto 2208.11138
- Interleaved flavour neutralisation — IFN
  Flavoured jets with exact anti-kT kinematics and tests of infrared and collinear safety
  Caola, Grabarczyk, Hutt, Salam, Scyboz, Thaler 2306.07314
- TBC…

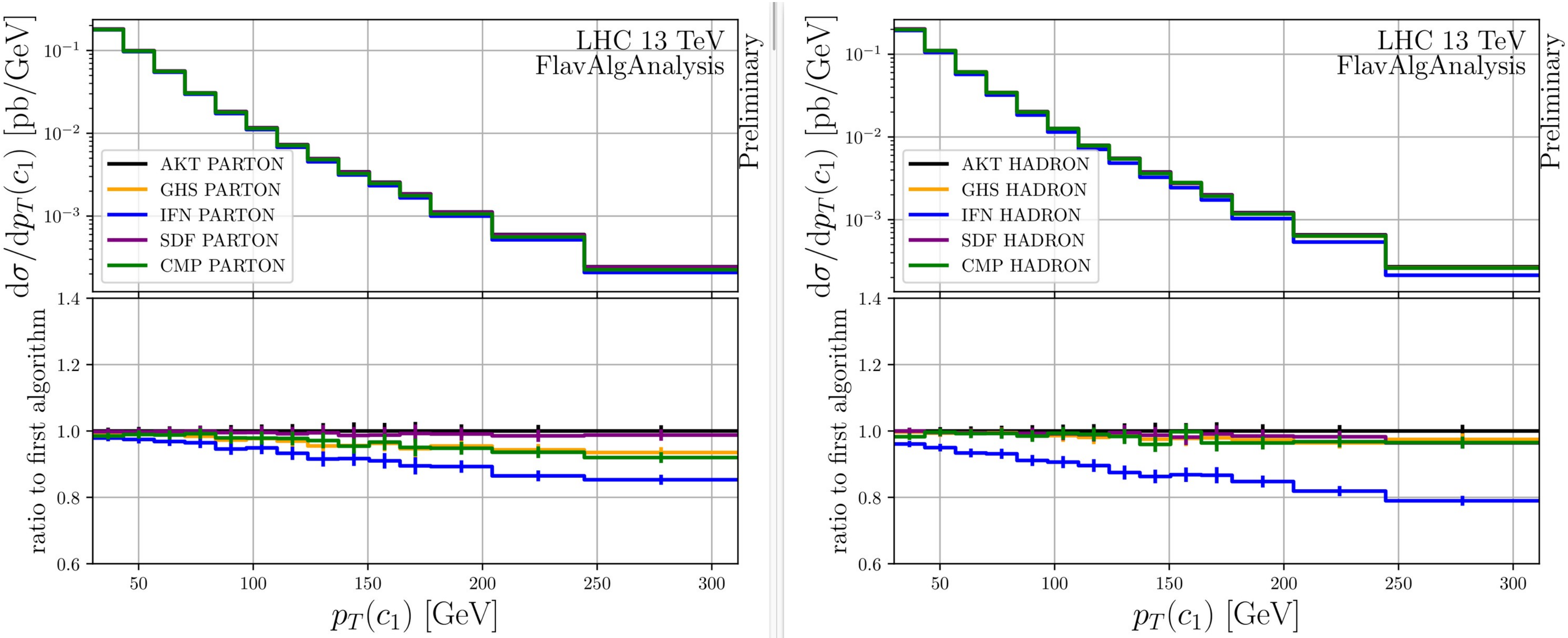
New proposals for flavour-safe anti-kT jets

Les Houches effort

- Recommendation on the usage of these algorithms
- Recommendation for flavoured jet definitions for phenomenology
- Phenomenological comparisons of these algorithms
  NLO+PS + NNLO QCD where possible:
  - pp → Z + b-jet / Z + c-jet (LHCb and CMS/ATLAS phase space)
  - pp → W+charm
  - pp → WH(→ bb)
- Estimation of impact on experimental flavour tagging

pT of leading charm-jet

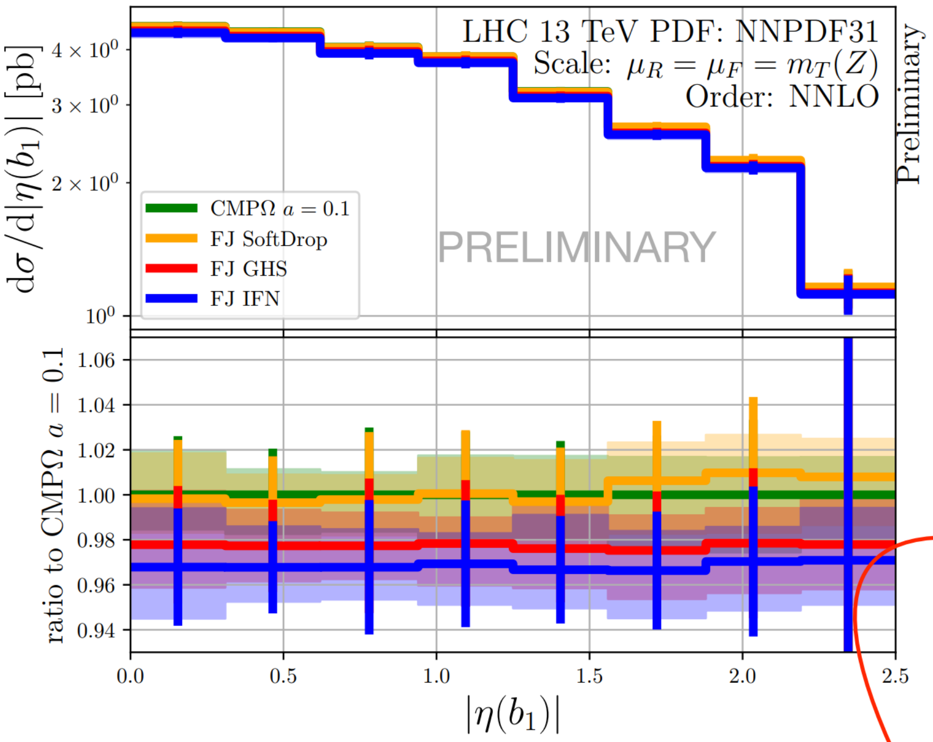
NLO+PS (SHERPA) for pp → Z + c-jet

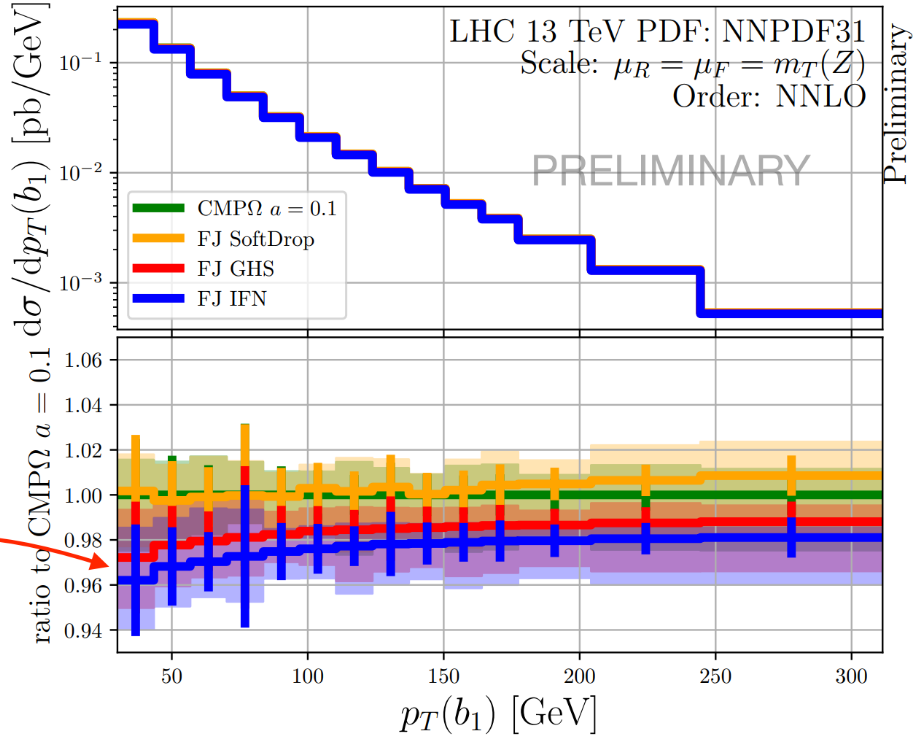


NNLO QCD comparisons

Calculations performed with sector-improved residue subtraction scheme
1408.2500 & 1907.12911

Les Houches Jet Flavour WG

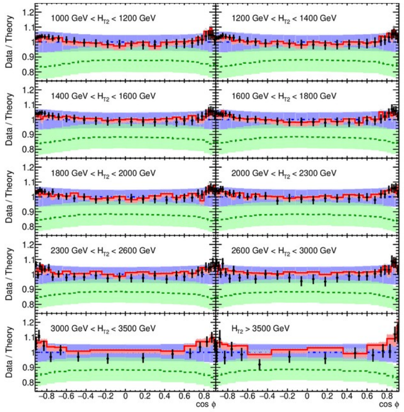




interesting shape difference at low p_t: it deserves further investigation!

HighTEA

HighTEA



= ~100 MCPUh

How to make this more efficient/environment-friendly/accessible/faster?

for your freshly brewed analysis

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

HighTEA: High energy Theory Event Analyser
[2304.05993]

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Basic idea

- Database of precomputed “Theory Events”
  - **Equivalent to a full fledged computation**
  - Currently this means partonic fixed order events
  - Extensions to included showered/resummed/hadronized events is feasible
  - (Partially) Unweighting to increase efficiency
- Analysis of the data through an user interface
  - Easy-to-use
  - Fast
  - Flexible:
    - Observables from basic 4-momenta
    - Free specification of bins
    - Renormalization/Factorization Scale variation
    - PDF (member) variation
    - Specify phase space cuts

Not so new idea:
LHE [Alwall et al ‘06],
Ntuple [BlackHat ‘08’13],

Factorizations

Factorizing renormalization and factorization scale dependence:

$$w_s^{i,j} = w_{\text{PDF}}(\mu_F, x_1, x_2) w_{\alpha_s}(\mu_R) \left(\sum_{i,j} c_{i,j} \ln\left(\mu_R^2\right)^i \ln\left(\mu_F^2\right)^j \right)$$

PDF dependence:

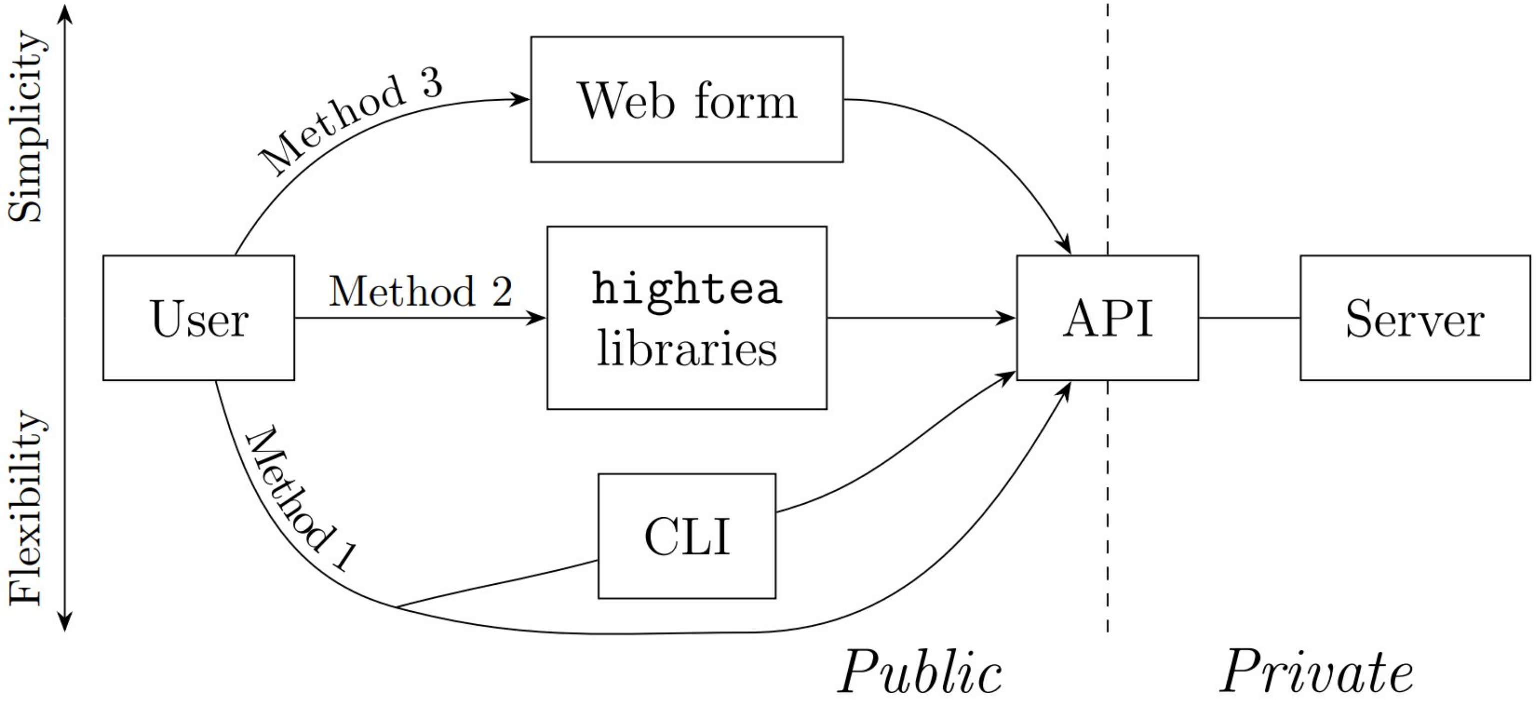
$$w_{\text{PDF}}(\mu, x_1, x_2) = \sum_{ab \in \text{channel}} f_a(x_1, \mu) f_b(x_2, \mu)$$

α_s dependence:

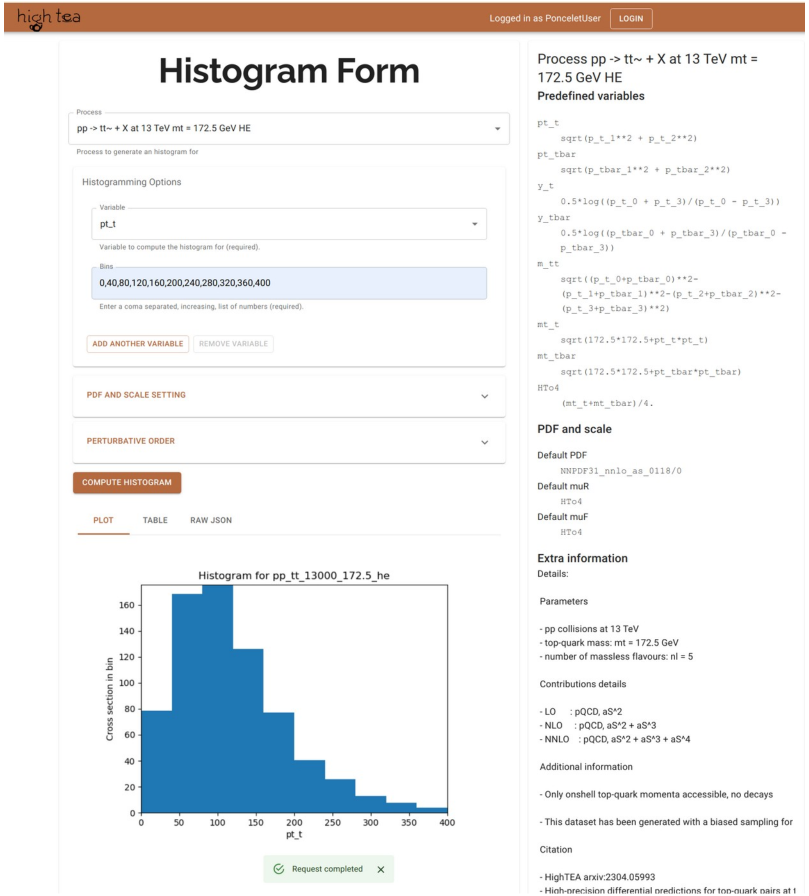
$$w_{\alpha_s}(\mu) = (\alpha_s(\mu))^m$$

Allows **full control over scales and PDF**

HighTEA interface



HighTEA webform



Allows for basic computation

- Predefined observables only
- PDF/scales/binning/order
- Very simplified presentation
- Mainly a demo/debug tool

HighTEA Python framework

hightea-client and *hightea-plottting*

(try it yourself `pip install hightea-client hightea-plotting`)

Python libraries that provides routines to

- Interact with the HighTEA server in an easy way
- Analyse the output
- Plotting

```
job = hightea('Example-ttbar-simple',directory=USERDIR)     # define new job
job.process('pp_tt_13000_172.5')                            # specify process for job
```

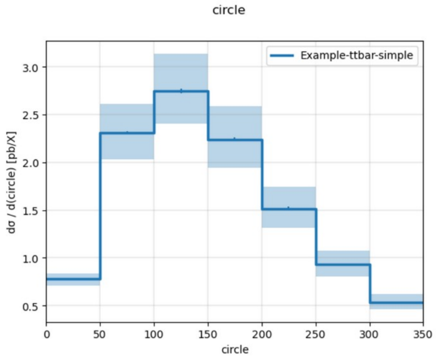
Show hidden output

```
job.define_new_variable('circle',                              # specify a new variable
                        'sqrt(pt_t**2+pt_tbar**2)')
job.contribution('NLO')                                        # specify contribution
job.scales('m_tt','m_tt*2')                                    # choose renormalization and factorizatior
job.pdf('CT14nnlo')                                            # choose pdf
job.observable('circle',[0.,50.,100.,150.,200.,250.,300.,350.]) # specify binning: variable and bin edges
job.scale_variation('3-point')                                 # add scale variation
```

```
job.request()
```

Show hidden output

```
plot(job.result());
```

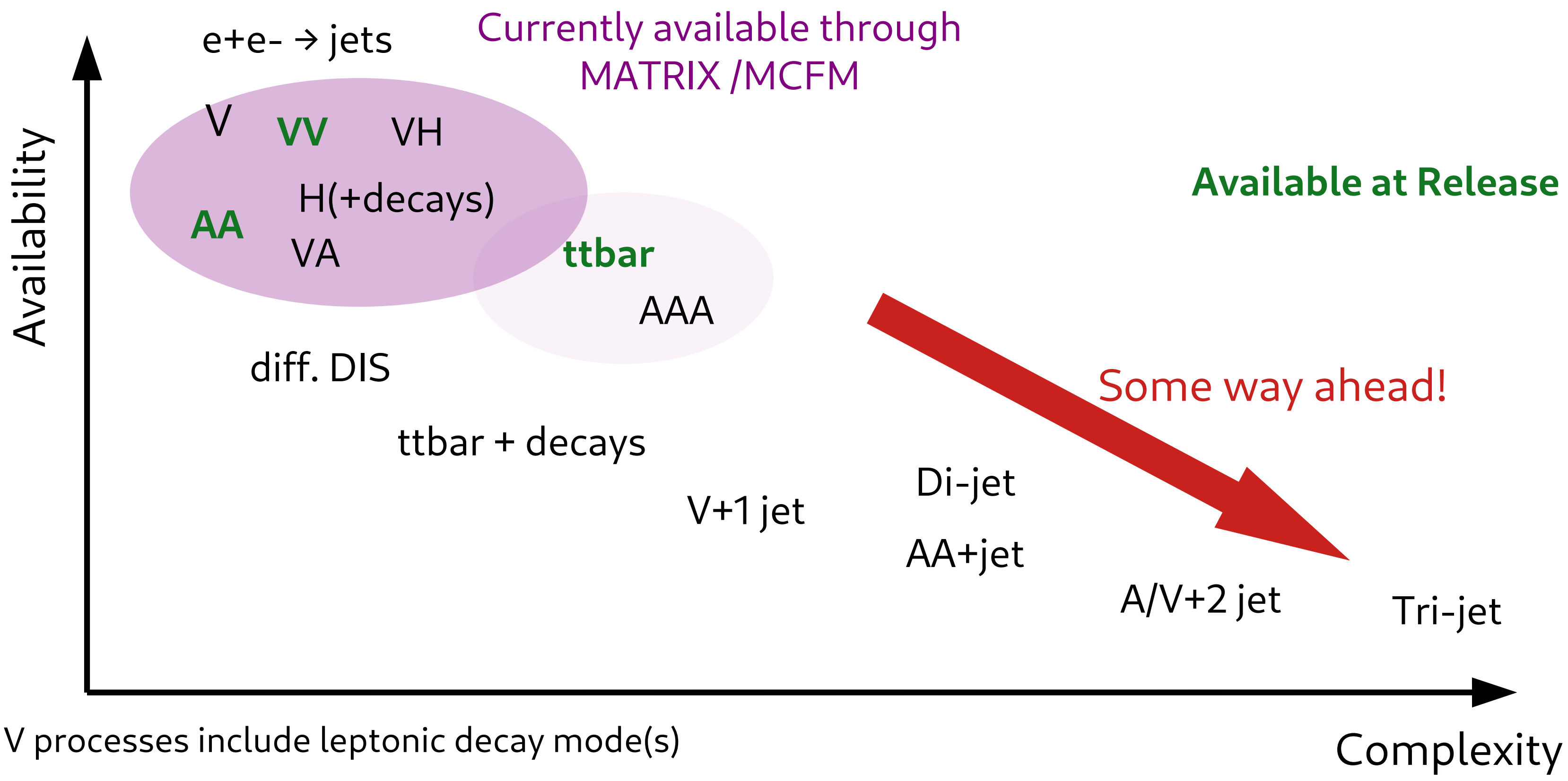



```
job.show_result()
```

```
Name                       :  Example-ttbar-simple
Contributions              :  ['NLO']
muR                        :  m_tt
muF                        :  m_tt*2
pdf                        :  CT14nnlo , 0
fiducial xsection [pb]     :    5.910E+02
  mc-error [pb] ([%])      :  2.3E+00 (3.9E-01)
sys. unc. [pb] ([%])       : scale (3)
                           :  +8.4E+01 (1.4E+01) / -7.5E+01 (1.3E+01)
Histogram     : circle
 bin1 low  | bin1 high | sigma [pb]  | mc-err [pb] ([%]) | scale (3) [pb] ([%])                      |
 0.000E+00 | 5.000E+01 |   3.894E+01 | 6.7E-01 (1.7E+00) | +2.7E+00 (7.0E+00) / -3.3E+00 (8.5E+00) |
 5.000E+01 | 1.000E+02 |   1.155E+02 | 9.1E-01 (7.9E-01) | +1.5E+01 (1.3E+01) / -1.4E+01 (1.2E+01) |
 1.000E+02 | 1.500E+02 |   1.374E+02 | 1.1E+00 (8.1E-01) | +2.0E+01 (1.4E+01) / -1.7E+01 (1.3E+01) |
 1.500E+02 | 2.000E+02 |   1.120E+02 | 1.0E+00 (9.0E-01) | +1.7E+01 (1.5E+01) / -1.5E+01 (1.3E+01) |
 2.000E+02 | 2.500E+02 |   7.582E+01 | 9.2E-01 (1.2E+00) | +1.2E+01 (1.5E+01) / -1.0E+01 (1.3E+01) |
```

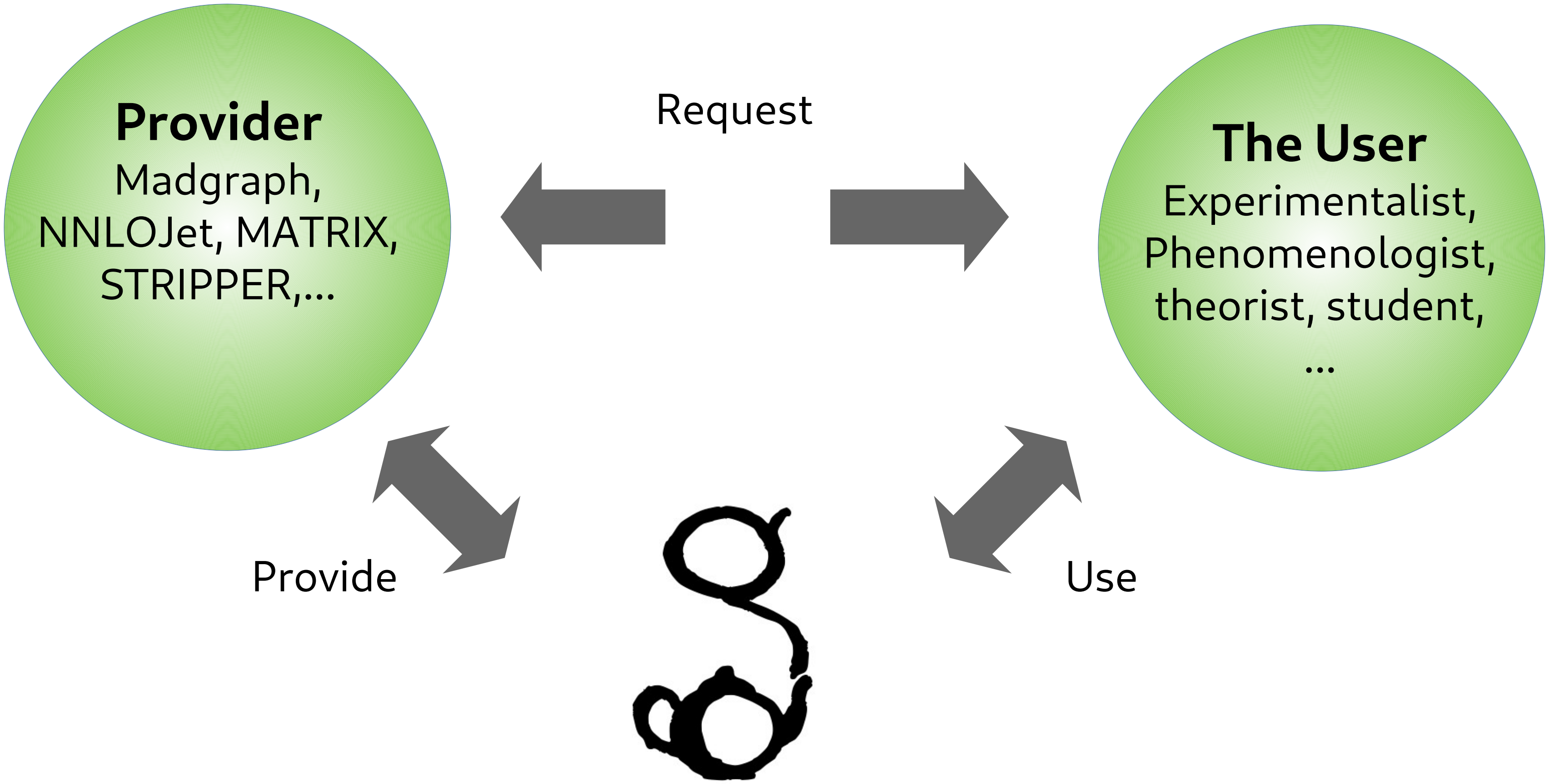
Available Processes

Processes currently implemented in our STRIPPER framework through NNLO QCD



* V processes include leptonic decay mode(s)

The Vision


Provider
Madgraph,
NNLOJet, MATRIX,
STRIPPER,...
Request
The User
Experimentalist,
Phenomenologist,
theorist, student,
...
Provide
Use

Summary

Summary

- Precision phenomenology is staple of LHC physics
  → but requires higher-order corrections!
  → NNLO QCD or even higher orders are needed to keep up with experimental precision

- Two pheno examples:

  Polarization of EW bosons
  → Higher-order modify shapes and lead to reduction of scale uncertainties

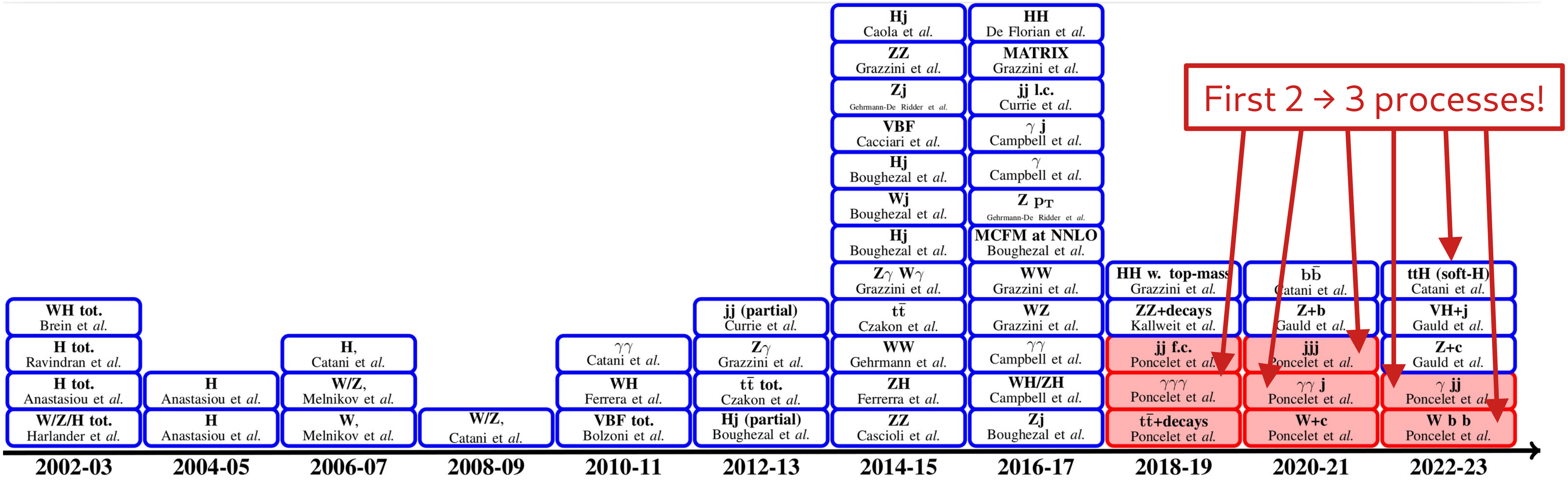
  Heavy flavour jets
  → New singularity structures “reveal” issues with flavoured jet definitions
  → New flavoured algorithms

- HighTEA
  → Tool to provide fast and easy access to higher-order calculations

Backup

Theory predictions with higher-order corrections

The NNLO QCD revolution



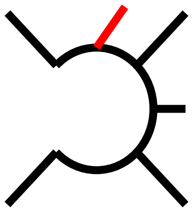
Next-to-leading order case

$$\hat{\sigma}_{ab}^{(1)} = \hat{\sigma}_{ab}^{\mathrm{R}} + \hat{\sigma}_{ab}^{\mathrm{V}} + \hat{\sigma}_{ab}^{\mathrm{C}}$$

KLN theorem
sum is finite for sufficiently inclusive observables and regularization scheme independent

Each term separately infrared (IR) divergent:

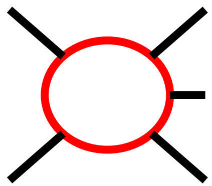
Real corrections:



$$\hat{\sigma}_{ab}^{\mathrm{R}} = \frac{1}{2\hat{s}} \int \mathrm{d}\Phi_{n+1} \left\langle \mathcal{M}_{n+1}^{(0)} \middle| \mathcal{M}_{n+1}^{(0)} \right\rangle \mathrm{F}_{n+1}$$

Phase space integration over unresolved configurations

Virtual corrections:

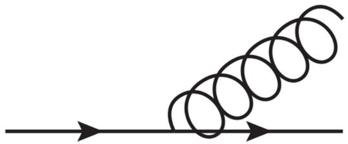


$$\hat{\sigma}_{ab}^{\mathrm{V}} = \frac{1}{2\hat{s}} \int \mathrm{d}\Phi_{n}\, 2\mathrm{Re} \left\langle \mathcal{M}_{n}^{(0)} \middle| \mathcal{M}_{n}^{(1)} \right\rangle \mathrm{F}_{n}$$

Integration over loop-momentum
(UV divergences cured by renormalization)

IR singularities in real radiation

$$\hat{\sigma}_{ab}^{\mathrm{R}} = \frac{1}{2\hat{s}} \int \mathrm{d}\Phi_{n+1} \left\langle \mathcal{M}_{n+1}^{(0)} \middle| \mathcal{M}_{n+1}^{(0)} \right\rangle \mathrm{F}_{n+1}$$

$\ni \mathrm{d}\Phi_1$ 

$$\sim \int_0 \mathrm{d}E\mathrm{d}\theta \frac{1}{E(1-\cos\theta)} f(E, \cos(\theta))$$

Finite function

Divergent

Regularization in Conventional Dimensional Regularization (CDR) $d = 4 - 2\epsilon$

$$\to \int_0 \mathrm{d}E\mathrm{d}\theta \frac{1}{E^{1-2\epsilon}(1-\cos\theta)^{1-\epsilon}} f(E, \cos(\theta)) \sim \frac{1}{\epsilon^2} + \ldots$$

Cancellation against similar divergences in

$$\hat{\sigma}_{ab}^{\mathrm{V}} = \frac{1}{2\hat{s}} \int \mathrm{d}\Phi_n \, 2\mathrm{Re} \left\langle \mathcal{M}_n^{(0)} \middle| \mathcal{M}_n^{(1)} \right\rangle \mathrm{F}_n$$

How to extract these poles? Slicing and Subtraction

Central idea: Divergences arise from infrared (IR, soft/collinear) limits → Factorization!

Slicing

$$\hat{\sigma}^{\mathrm{R}}_{ab} = \frac{1}{2\hat{s}} \int_{\delta(\Phi)\geq\delta_c} \mathrm{d}\Phi_{n+1} \left\langle \mathcal{M}^{(0)}_{n+1} \middle| \mathcal{M}^{(0)}_{n+1} \right\rangle \mathrm{F}_{n+1} + \frac{1}{2\hat{s}} \int_{\delta(\Phi)<\delta_c} \mathrm{d}\Phi_{n+1} \left\langle \mathcal{M}^{(0)}_{n+1} \middle| \mathcal{M}^{(0)}_{n+1} \right\rangle \mathrm{F}_{n+1}$$

$$\approx \frac{1}{2\hat{s}} \int_{\delta(\Phi)\geq\delta_c} \mathrm{d}\Phi_{n+1} \left\langle \mathcal{M}^{(0)}_{n+1} \middle| \mathcal{M}^{(0)}_{n+1} \right\rangle \mathrm{F}_{n+1} + \frac{1}{2\hat{s}} \int \mathrm{d}\Phi_n \, \tilde{M}(\delta_c)\mathrm{F}_n + \mathcal{O}(\delta_c)$$

$$\ldots + \hat{\sigma}^{\mathrm{V}}_{ab} = \text{finite}$$

Subtraction

$$\hat{\sigma}^{\mathrm{R}}_{ab} = \frac{1}{2\hat{s}} \int \left(\mathrm{d}\Phi_{n+1} \left\langle \mathcal{M}^{(0)}_{n+1} \middle| \mathcal{M}^{(0)}_{n+1} \right\rangle \mathrm{F}_{n+1} - \mathrm{d}\tilde{\Phi}_{n+1} \, \mathcal{S}\mathrm{F}_n \right) + \frac{1}{2\hat{s}} \int \mathrm{d}\tilde{\Phi}_{n+1} \, \mathcal{S}\mathrm{F}_n$$

$$\frac{1}{2\hat{s}} \int \mathrm{d}\tilde{\Phi}_{n+1} \, \mathcal{S}\mathrm{F}_n = \frac{1}{2\hat{s}} \int \mathrm{d}\Phi_n \, \mathrm{d}\Phi_1 \, \mathcal{S}\mathrm{F}_n$$

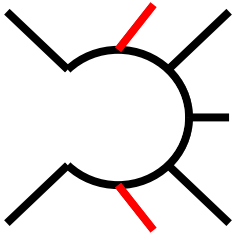
Phase space factorization
→ momentum mappings

Most popular NLO QCD schemes:
CS [hep-ph/9605323],
FKS [hep-ph/9512328]

→ Basis of modern event simulation

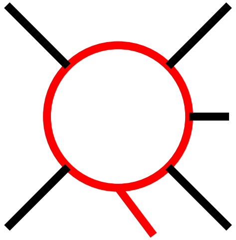
Partonic cross section beyond NLO

$$\hat{\sigma}_{ab}^{(2)} = \hat{\sigma}_{ab}^{\mathrm{VV}} + \hat{\sigma}_{ab}^{\mathrm{RV}} + \hat{\sigma}_{ab}^{\mathrm{RR}} + \hat{\sigma}_{ab}^{\mathrm{C2}} + \hat{\sigma}_{ab}^{\mathrm{C1}}$$



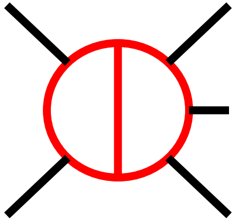
Real-Real

$$\hat{\sigma}_{ab}^{\mathrm{RR}} = \frac{1}{2\hat{s}} \int \mathrm{d}\Phi_{n+2} \left\langle \mathcal{M}_{n+2}^{(0)} \middle| \mathcal{M}_{n+2}^{(0)} \right\rangle \mathrm{F}_{n+2}$$



Real-Virtual

$$\hat{\sigma}_{ab}^{\mathrm{RV}} = \frac{1}{2\hat{s}} \int \mathrm{d}\Phi_{n+1}\, 2\mathrm{Re} \left\langle \mathcal{M}_{n+1}^{(0)} \middle| \mathcal{M}_{n+1}^{(1)} \right\rangle \mathrm{F}_{n+1}$$



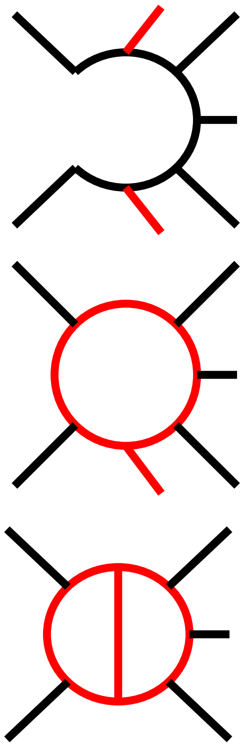
Virtual-Virtual

$$\hat{\sigma}_{ab}^{\mathrm{VV}} = \frac{1}{2\hat{s}} \int \mathrm{d}\Phi_{n} \left(2\mathrm{Re} \left\langle \mathcal{M}_{n}^{(0)} \middle| \mathcal{M}_{n}^{(2)} \right\rangle + \left\langle \mathcal{M}_{n}^{(1)} \middle| \mathcal{M}_{n}^{(1)} \right\rangle \right) \mathrm{F}_{n}$$

$\hat{\sigma}_{ab}^{\mathrm{C2}} = (\text{double convolution})\, \mathrm{F}_n$ $\hat{\sigma}_{ab}^{\mathrm{C1}} = (\text{single convolution})\, \mathrm{F}_{n+1}$

Partonic cross section beyond NLO

$$\hat{\sigma}^{(2)}_{ab} = \hat{\sigma}^{\mathrm{VV}}_{ab} + \hat{\sigma}^{\mathrm{RV}}_{ab} + \hat{\sigma}^{\mathrm{RR}}_{ab} + \hat{\sigma}^{\mathrm{C2}}_{ab} + \hat{\sigma}^{\mathrm{C1}}_{ab}$$



Technically substantially more complicated!

Main bottlenecks:

- Real - real → overlapping singularities
  Many possible limits → good organization principle needed
- Real - virtual → stable matrix elements
- Virtual - virtual → complicated case-by-case analytic treatment

Slicing and Subtraction

Slicing

- Conceptually simple
- Recycling of lower computations
- Non-local cancellations/power-corrections
  → computationally expensive

NNLO QCD schemes

qT-slicing [Catani’07],
N-jettiness slicing [Gaunt‘15/Boughezal‘15]

Subtraction

- Conceptually more difficult
- Local subtraction → efficient
- Better numerical stability
- Choices:
  - Momentum mapping
  - Subtraction terms
  - Numerics vs. analytic

Antenna [Gehrmann’05-’08],
Colorful [DelDuca‘05-’15],
Sector-improved residue subtraction [Czakon’10-’14’19]
Projection [Cacciari‘15],
Nested collinear [Caola’17],
Geometric [Herzog‘18],
Unsubtraction [Aguilera-Verdugo’19],
…

Minimal sector-improved residue subtraction

Single-jet inclusive rates with exact color at $\mathcal{O}(\alpha_s^4)$
Czakon,Hameren,Mitov,**Poncelet**, JHEP 10 (2019), 262

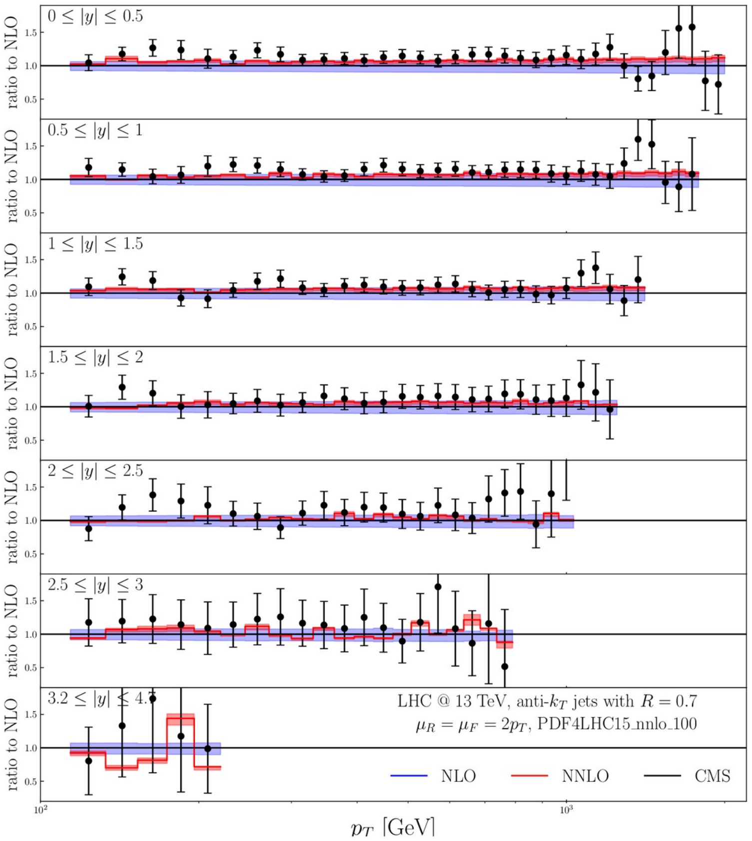
Refined formulation of the
sector-improved residue subtraction

- New phase space parametrisation
  → minimization of subtraction kinematics
  → improved computational efficiency/stability

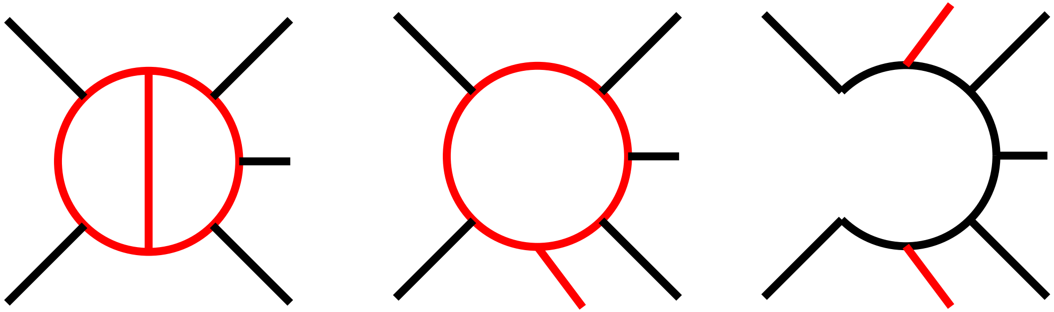
- Improved sector decomposition

- New 4 – dimensional formulation

- First application: inclusive jet production
  → demonstrates that the **scheme is complete**
  → no approximations



Sector-improved residue subtraction



Sector decomposition I

Considering working in CDR:

→ Virtuals are usually done in this regularization: $\hat{\sigma}_{ab}^{VV} = \sum_{i=-4}^{0} c_i \epsilon^i + \mathcal{O}(\epsilon)$

→ Can we write the real radiation as such expansion?

→ Difficult integrals, analytical impractical (except very simple observables)!

→ Numerics not possible, integrals are divergent → ε-poles!

How to extract these poles? → Sector decomposition!

Divide and conquer the phase space:

$$1 = \sum_{i,j} \left[\sum_k \mathcal{S}_{ij,k} + \sum_{k,l} \mathcal{S}_{i,k;j,l} \right] \rightarrow \hat{\sigma}_{ab}^{\mathrm{RR}} = \frac{1}{2\hat{s}} \int \mathrm{d}\Phi_{n+2} \sum_{i,j} \left[\sum_k \mathcal{S}_{ij,k} + \sum_{k,l} \mathcal{S}_{i,k;j,l} \right] \left\langle \mathcal{M}_{n+2}^{(0)} \middle| \mathcal{M}_{n+2}^{(0)} \right\rangle \mathrm{F}_{n+2}$$

Sector decomposition II

Divide and conquer the phase space

- Each $\mathcal{S}_{i,k}$ (NLO), $\mathcal{S}_{ij,k}/\mathcal{S}_{i,k;j,l}$ (NNLO) has simpler divergences:
  - Soft limits of partons i and j
  - Collinear w.r.t partons k (and l) of partons i and j

$$\mathcal{S}_{i,k} = \frac{1}{D_1 d_{i,k}} \quad D_1 = \sum_{ik} \frac{1}{d_{i,k}} \qquad d_{i,k} = \frac{E_i}{\sqrt{s}}(1-\cos\theta_{ik})$$

- Parametrization w.r.t. reference parton makes divergences explicit

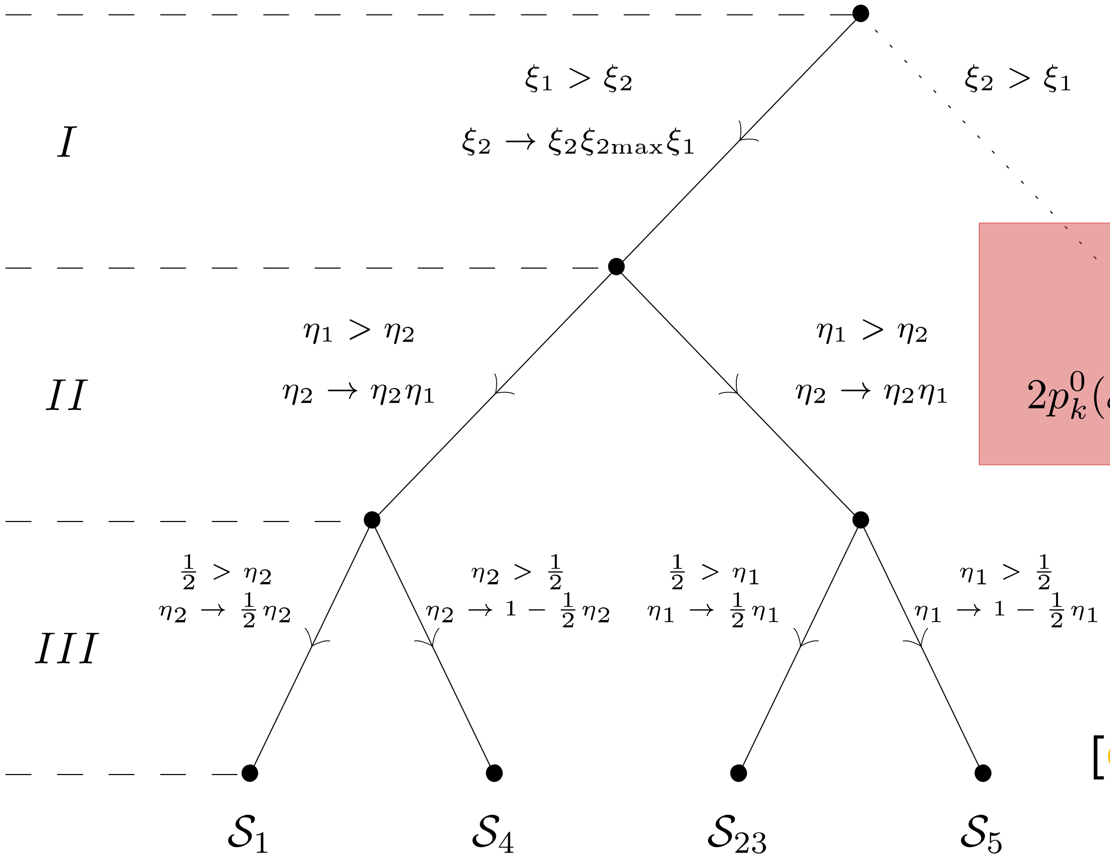
$$\hat{\eta}_i = \tfrac{1}{2}(1-\cos\theta_{ik}) \in [0,1] \qquad \hat{\xi}_i = \frac{u_i^0}{u_{\max}^0} \in [0,1]$$

- Example: Splitting function

$$\sim \frac{1}{s_{ik}} P(z) \qquad s_{ik} = (p_i + p_k)^2 = 2 p_k^0 u_{\max}^0 \xi_i \eta_i \qquad \sim \frac{1}{\eta_i \xi_i}$$

Sector decomposition II – triple collinear factorization

Three particle invariant does not factorize trivially:



Double soft factorization:

$$\theta(u_i^0 - u_j^0) + \theta(u_i^0 - u_j^0)$$

$$(p_k + u_i + u_j)^2 =$$

$$2p_k^0(\xi_i \eta_i u_{\max}^{0,i} + \xi_j \eta_j u_{\max}^{0,j} + \xi_i \xi_j \frac{u_{max}^{0,i} u_{max}^{0,j}}{p_k^0} \angle(u_i, u_j))$$

[Czakon'10,Caola'17]

Sector decomposition III

Factorized singular limits in each sector:

$$\frac{1}{2\hat{s}}\int \mathrm{d}\Phi_{n+2}\,\mathcal{S}_{kl,m}\left\langle \mathcal{M}^{(0)}_{n+2}\middle|\mathcal{M}^{(0)}_{n+2}\right\rangle \mathrm{F}_{n+2} = \sum_{\text{sub-sec.}}\int \mathrm{d}\Phi_n \prod \mathrm{d}x_i \underbrace{x_i^{-1-b_i\epsilon}}_{\text{singular}} \mathrm{d}\tilde{\mu}(\{x_i\}) \underbrace{\prod x_i^{a_i+1}\langle \mathcal{M}_{n+2}|\mathcal{M}_{n+2}\rangle}_{\text{regular}} \mathrm{F}_{n+2}$$

$$x_i \in \{\eta_1, \xi_1, \eta_2, \xi_2\}$$

Regularization of divergences:

$$x^{-1-b\epsilon} = \underbrace{\frac{-1}{b\epsilon}}_{\text{pole term}} + \underbrace{\left[x^{-1-b\epsilon}\right]_+}_{\text{reg. + sub.}}$$

$$\int_0^1 \mathrm{d}x\,\left[x^{-1-b\epsilon}\right]_+ f(x) = \int_0^1 \frac{f(x)-f(0)}{x^{1+b\epsilon}}$$

Finite NNLO cross section

$$\hat{\sigma}_{ab}^{\mathrm{RR}} = \frac{1}{2\hat{s}} \int \mathrm{d}\Phi_{n+2} \left\langle \mathcal{M}_{n+2}^{(0)} \middle| \mathcal{M}_{n+2}^{(0)} \right\rangle \mathrm{F}_{n+2}$$

$$\hat{\sigma}_{ab}^{\mathrm{RV}} = \frac{1}{2\hat{s}} \int \mathrm{d}\Phi_{n+1}\, 2\mathrm{Re} \left\langle \mathcal{M}_{n+1}^{(0)} \middle| \mathcal{M}_{n+1}^{(1)} \right\rangle \mathrm{F}_{n+1}$$

$$\hat{\sigma}_{ab}^{\mathrm{VV}} = \frac{1}{2\hat{s}} \int \mathrm{d}\Phi_{n} \left(2\mathrm{Re} \left\langle \mathcal{M}_{n}^{(0)} \middle| \mathcal{M}_{n}^{(2)} \right\rangle + \left\langle \mathcal{M}_{n}^{(1)} \middle| \mathcal{M}_{n}^{(1)} \right\rangle \right) \mathrm{F}_{n}$$

$$\hat{\sigma}_{ab}^{\mathrm{C1}} = (\text{single convolution})\, \mathrm{F}_{n+1}$$

$$\hat{\sigma}_{ab}^{\mathrm{C2}} = (\text{double convolution})\, \mathrm{F}_{n}$$

↓ sector decomposition and master formula

$$x^{-1-b\epsilon} = \underbrace{\frac{-1}{b\epsilon}}_{\text{pole term}} + \underbrace{\left[x^{-1-b\epsilon}\right]_+}_{\text{reg. + sub.}}$$

$$\left(\sigma_F^{RR}, \sigma_{SU}^{RR}, \sigma_{DU}^{RR}\right) \quad \left(\sigma_F^{RV}, \sigma_{SU}^{RV}, \sigma_{DU}^{RV}\right) \quad \left(\sigma_F^{VV}, \sigma_{DU}^{VV}, \sigma_{FR}^{VV}\right) \quad \left(\sigma_{SU}^{C1}, \sigma_{DU}^{C1}\right) \quad \left(\sigma_{DU}^{C2}, \sigma_{FR}^{C2}\right)$$

↓ re-arrangement of terms → 4-dim. formulation [Czakon'14,Czakon'19]

$$\underline{\left(\sigma_F^{RR}\right)} \quad \underline{\left(\sigma_F^{RV}\right)} \quad \underline{\left(\sigma_F^{VV}\right)} \quad \underline{\left(\sigma_{SU}^{RR}, \sigma_{SU}^{RV}, \sigma_{SU}^{C1}\right)} \quad \underline{\left(\sigma_{DU}^{RR}, \sigma_{DU}^{RV}, \sigma_{DU}^{VV}, \sigma_{DU}^{C1}, \sigma_{DU}^{C2}\right)} \quad \underline{\left(\sigma_{FR}^{RV}, \sigma_{FR}^{VV}, \sigma_{FR}^{C2}\right)}$$

separately finite: ε poles cancel

Improved phase space generation

Phase space cut and differential observable introduce

mis-binning : mismatch between kinematics in subtraction terms

→ leads to increased variance of the integrand

→ slow Monte Carlo convergence

New phase space parametrization [Czakon'19]:

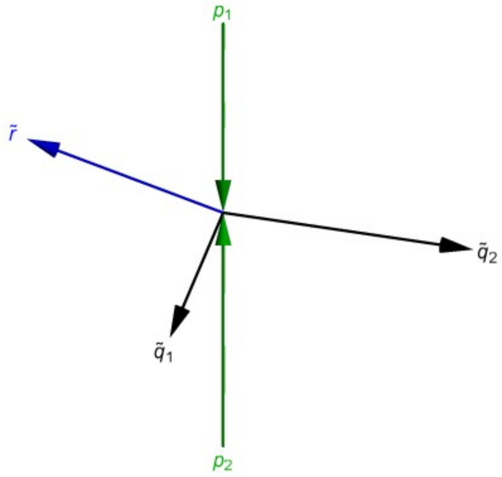
Minimization of # of different subtraction kinematics in each sector

Improved phase space generation

New phase space parametrization:

Minimization of # of different subtraction kinematics in each sector

Mapping from n+2 to n particle phase space: $\{P, r_j, u_k\} \to \left\{\tilde{P}, \tilde{r}_j\right\}$



Requirements:

- Keep direction of reference r fixed
- Invertible for fixed u_i: $\left\{\tilde{P}, \tilde{r}_j, u_k\right\} \to \{P, r_j, u_k\}$
- Preserve Born invariant mass: $q^2 = \tilde{q}^2\,,\ \ \tilde{q} = \tilde{P} - \sum_{j=1}^{n_{fr}} \tilde{r}_j$

Main steps:

- Generate Born configuration
- Generate unresolved partons u_i
- Rescale reference momentum $r = x\tilde{r}$
- Boost non-reference momenta of the Born configuration

Improved phase space generation

New phase space parametrization:

Minimization of # of different subtraction kinematics in each sector

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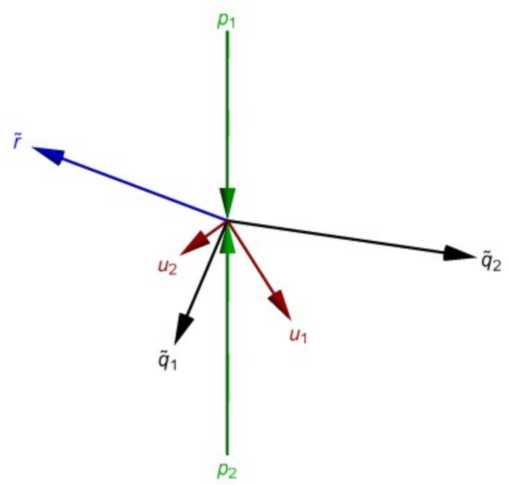

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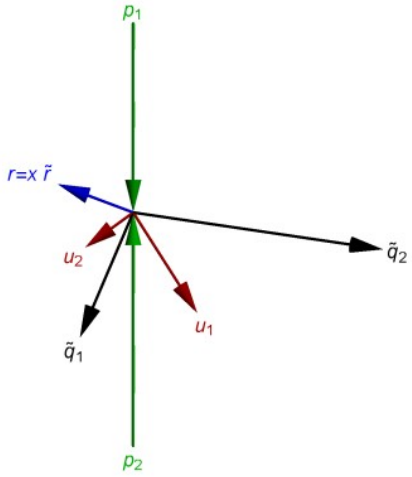

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- Keep direction of reference r fixed
- Invertible for fixed u_i : $\left\{\tilde{P}, \tilde{r}_j, u_k\right\} \to \{P, r_j, u_k\}$
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Improved phase space generation

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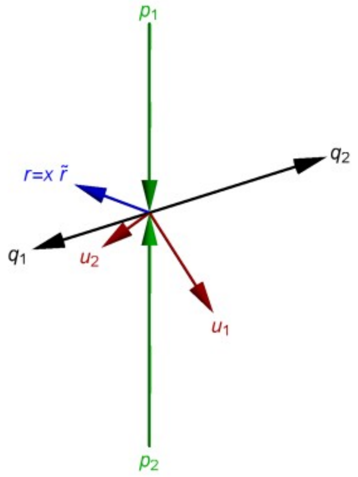


Requirements:

- Keep direction of reference r fixed
- Invertible for fixed u_i : $\left\{\tilde{P}, \tilde{r}_j, u_k\right\} \to \{P, r_j, u_k\}$
- Preserve Born invariant mass: $q^2 = \tilde{q}^2\,, \quad \tilde{q} = \tilde{P} - \sum_{j=1}^{n_{fr}} \tilde{r}_j$

Main steps:

- Generate Born configuration
- Generate unresolved partons u_i
- Rescale reference momentum $r = x\tilde{r}$
- Boost non-reference momenta of the Born configuration

t'HV corrections

Observables: Implemented by infrared safe measurement function (MF) F_m

Infrared property in STRIPPER context:

- $\{x_i\} \to 0 \leftrightarrow$ single unresolved limit
  $\Rightarrow \mathrm{F}_{n+2} \to \mathrm{F}_{n+1}$
- $\{x_i\} \to 0 \leftrightarrow$ double unresolved limit
  $\Rightarrow \mathrm{F}_{n+2} \to \mathrm{F}_{n}$
  $\Rightarrow \mathrm{F}_{n+1} \to \mathrm{F}_{n}$

Tool for new formulation in the 't Hooft Veltman scheme:

Parameterized MF $\mathrm{F}^{\alpha}_{n+1}$

- $\mathrm{F}^{\alpha}_{n} \equiv 0$ for $\alpha \neq 0$
  (NLO MF)
- 'arbitrary' F^{0}_{n}
  (NNLO MF)
- $\alpha \neq 0 \Rightarrow \mathrm{DU} = 0$ and SU separately finite

Example: $F^{\alpha}_{n+1} = F_{n+1}\Theta_{\alpha}(\{\alpha_i\})$
with $\Theta_{\alpha} = 0$ if some $\alpha_i < \alpha$

t'HV corrections

$$\sigma_{SU} = \sigma_{SU}^{RR} + \sigma_{SU}^{RV} + \sigma_{SU}^{C1} \qquad \text{where} \qquad \sigma_{SU}^{c} = \int \mathrm{d}\Phi_{n+1} \left(I_{n+1}^{\mathrm{c}} F_{n+1} + I_{n}^{\mathrm{c}} F_{n} \right)$$

NLO measurement function ($\alpha \neq 0$):

$$\int \mathrm{d}\Phi_{n+1} \left(I_{n+1}^{\mathrm{RR}} + I_{n+1}^{\mathrm{RV}} + I_{n+1}^{\mathrm{C1}} \right) F_{n+1}^{\alpha} = \text{finite in 4 dim.}$$

All divergences cancel in d-dimensions:

$$\sum_{c} \int \mathrm{d}\Phi_{n+1} \left[\frac{I_{n+1}^{c,(-2)}}{\epsilon^2} + \frac{I_{n+1}^{c,(-1)}}{\epsilon} \right] F_{n+1}^{\alpha} \equiv \sum_{c} \mathcal{I}^{c} = 0$$

t'HV corrections

$$\sigma_{SU} = \sigma_{SU}^{RR} + \sigma_{SU}^{RV} + \sigma_{SU}^{C1} \underbrace{-\mathcal{I}^{RR} - \mathcal{I}^{RV} - \mathcal{I}^{C1}}_{=0}$$

$$\begin{aligned}
\sigma_{SU}^{c} - \mathcal{I}^{c} = & \int \mathrm{d}\Phi_{n+1} \left\{ \left[\frac{I_{n+1}^{c,(-2)}}{\epsilon^2} + \frac{I_{n+1}^{c,(-1)}}{\epsilon} + I_{n+1}^{c,(0)} \right] F_{n+1} + \left[\frac{I_{n}^{c,(-2)}}{\epsilon^2} + \frac{I_{n}^{c,(-1)}}{\epsilon} + I_{n}^{c,(0)} \right] F_{n} \right\} \\
& - \int \mathrm{d}\Phi_{n+1} \left[\frac{I_{n+1}^{c,(-2)}}{\epsilon^2} + \frac{I_{n+1}^{c,(-1)}}{\epsilon} \right] F_{n+1} \Theta_{\alpha}(\{\alpha_i\}) \\
= & \int \mathrm{d}\Phi_{n+1} \left[\frac{I_{n+1}^{c,(-2)} F_{n+1} + I_{n}^{c,(-2)} F_{n}}{\epsilon^2} + \frac{I_{n+1}^{c,(-1)} F_{n+1} + I_{n}^{c,(-1)} F_{n}}{\epsilon} \right] (1 - \Theta_{\alpha}(\{\alpha_i\})) \\
& + \int \mathrm{d}\Phi_{n+1} \left[I_{n+1}^{c,(0)} F_{n+1} + I_{n}^{c,(0)} F_{n} \right] + \int \mathrm{d}\Phi_{n+1} \left[\frac{I_{n}^{c,(-2)}}{\epsilon^2} + \frac{I_{n}^{c,(-1)}}{\epsilon} \right] F_{n} \Theta_{\alpha}(\{\alpha_i\})
\end{aligned}$$

$$=: \underbrace{Z^{c}(\alpha)}_{\text{integrable, zero volume for } \alpha \to 0} + \underbrace{C^{c}}_{\text{no divergencies}} + \underbrace{N^{c}(\alpha)}_{\text{only } F_n \to \text{DU}}$$

t'HV corrections

Looks like slicing, but it is slicing *only* for divergences
$\to$ no actual slicing parameter in result

Powerlog-expansion:

$$N^c(\alpha) = \sum_{k=0}^{\ell_{\max}} \ln^k(\alpha) N_k^c(\alpha)$$

- all $N_k^c(\alpha)$ regular in α
- start expression independent of $\alpha \Rightarrow$ all logs cancel
- only $N_0^c(0)$ relevant

Putting parts together:

$$\sigma_{SU} - \sum_c N_0^c(0) \text{ and } \sigma_{DU} + \sum_c N_0^c(0)$$

are finite in 4 dimension

$\Downarrow$

SU contribution: $\sigma_{SU} - \sum_c N_0^c = \sum_c C^c$
original expression σ_{SU} in 4-dim without poles, no further ϵ pole cancellation

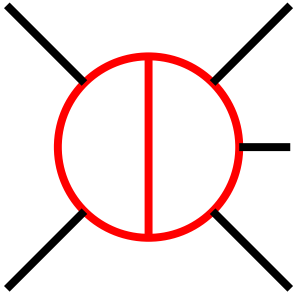
C++ framework

- Formulation allows efficient algorithmic implementation → STRIPPER
- **High degree of automation**:
  - Partonic processes (taking into account all symmetries)
  - Sectors and subtraction terms
  - Interfaces to Matrix-element providers + O(100) hardcoded: AvH, OpenLoops, Recola, NJET, HardCoded

    → In practice: Only two-loop matrix elements required
- **Broad range of applications** through additional facilities:
  - Narrow-Width & Double-Pole Approximation
  - Fragmentation
  - Polarised intermediate massive bosons
  - (Partial) Unweighting → Event generation for **HighTEA**
  - Interfaces: FastNLO, FastJet

Two-loop five-point amplitudes

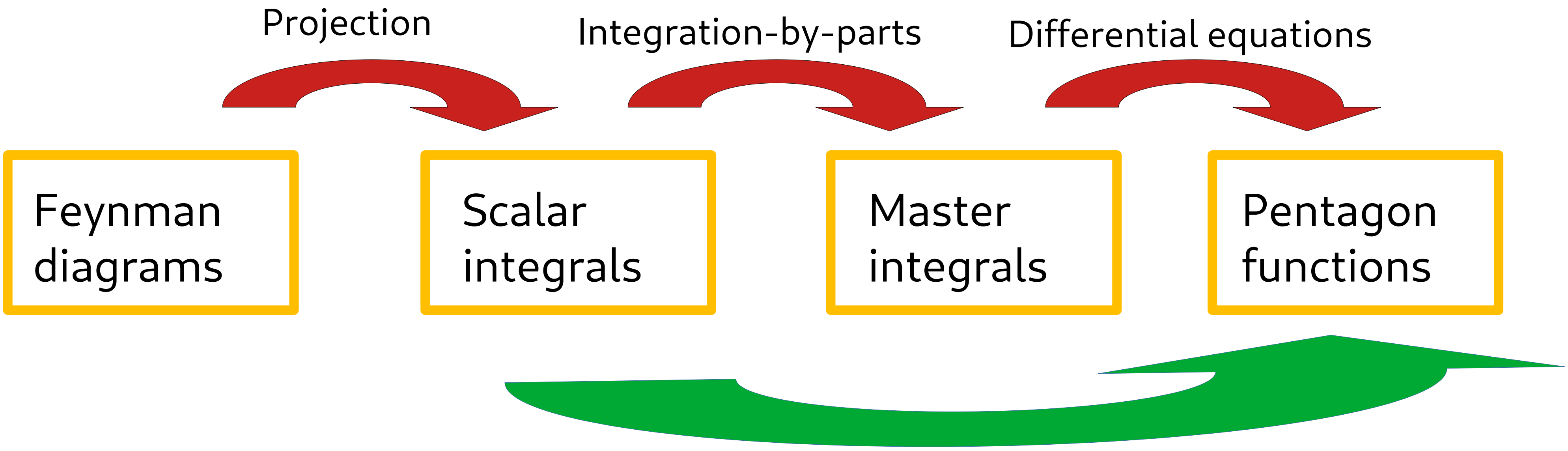
Massless:
[Chawdry'19'20'21] (3A+2j,2A+3j)
[Abreu'20'21] (3A+2j,5j)
[Agarwal'21] (2A+3j)
[Badger'21'23] (5j,gggAA,jjjjA)



1 external mass:
[Abreu'21] (W+4j)
[Badger'21'22] (Hqqgg,W4q,Wajjj)
[Hartanto'22] (W4q)

Overview

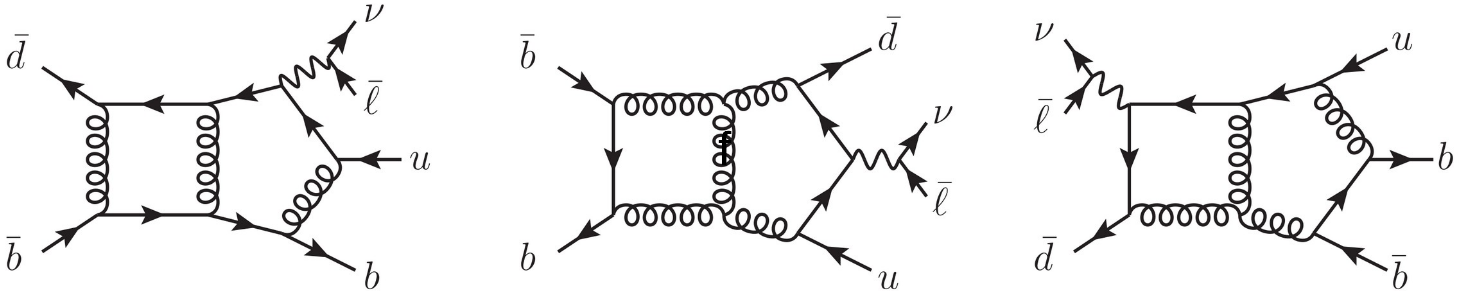
Old school approach:



Automated framework using finite fields to avoid expression swell based on FiniteFlow [Peraro'19]

Projection to scalar integrals

Generate diagrams (contributing to leading-colour) with QGRAF



Factorizing decay: $A_6^{(L)} = A_5^{(L)\mu} D_\mu P$ $\quad M_6^{2(L)} = \sum_{\text{spin}} A_6^{(0)^*} A_6^{(L)} = M_5^{(L)\mu\nu} D_{\mu\nu} |P|^2$

Projection on scalar functions (FORM+Mathematica):
→ anti-commuting γ_5 + Larin prescription

$$M_5^{(L)\mu\nu} = \sum_{i=1}^{16} a_i^{(L)} v_i^{\mu\nu}$$

➡ $a_i^{(L)} = a_i^{(L),\text{even}} + \text{tr}_5 a_i^{(L),\text{odd}}$ $\quad a_i^{(L),p} = \sum_i c_{j,i}(\{p\},\epsilon)\mathcal{I}(\{p\},\epsilon)$

Integration-By-Parts reduction

$$a_i^{(L),p} = \sum_i c_{j,i}(\{p\},\epsilon)\mathcal{I}(\{p\},\epsilon)$$

→ prohibitively large number of integrals

$$\mathcal{I}_i(\{p\},\epsilon) \equiv \mathcal{I}(\vec{n_i},\{p\},\epsilon) = \int \frac{\mathrm{d}^d k_1}{(2\pi)^d}\frac{\mathrm{d}^d k_2}{(2\pi)^d}\prod_{k=1}^{11} D_k^{-n_{i,k}}(\{p\},\{k\})$$

Integration-By-Parts identities connect different integrals → system of equations
→ only a small number of independent "master" integrals

$$0 = \int \frac{\mathrm{d}^d k_1}{(2\pi)^d}\frac{\mathrm{d}^d k_2}{(2\pi)^d} l_\mu \frac{\partial}{\partial l^\mu}\prod_{k=1}^{11} D_k^{-n_{i,k}}(\{p\},\{k\}) \quad \text{with} \quad l \in \{p\}\cap\{k\}$$

LiteRed (+ Finite Fields)

$$\longrightarrow \quad a_i^{(L),p} = \sum_i d_{j,i}(\{p\},\epsilon)\mathrm{MI}(\{p\},\epsilon)$$

Master integrals & finite remainder

Differential Equations: $\mathrm{d}\vec{\mathrm{MI}} = \mathrm{d}A(\{p\},\epsilon)\vec{\mathrm{MI}}$

Canonical basis: $\mathrm{d}\vec{\mathrm{MI}} = \epsilon \mathrm{d}\tilde{A}(\{p\})\vec{\mathrm{MI}}$

[Remiddi, 97]
[Gehrmann, Remiddi, 99]
[Henn, 13]

Simple iterative solution

$$\mathrm{MI}_i = \sum_w \epsilon^w \tilde{\mathrm{MI}}_i^w \quad \text{with} \quad \tilde{\mathrm{MI}}_i^w = \sum_j c_{i,j} m_j$$

Chen-iterated integrals
"Pentagon"-functions

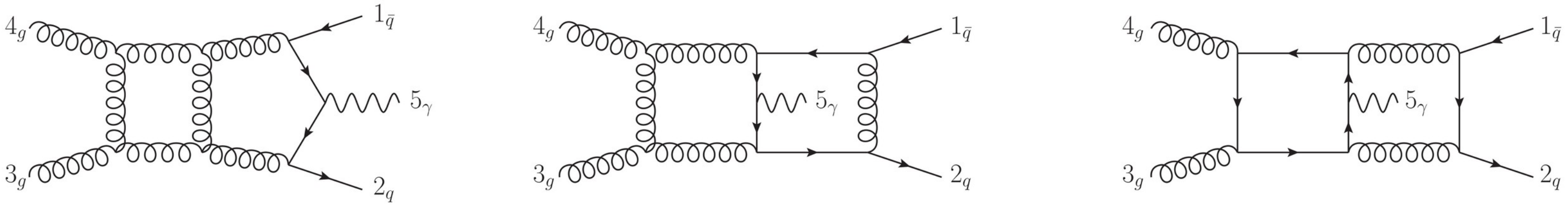
[Chicherin, Sotnikov, 20]
[Chicherin, Sotnikov, Zoia, 21]

Putting everything together (and removing of IR poles):

$$f_i^{(L),p} = a_i^{(L),p} - \text{poles} \qquad f_i^{(L),p} = \sum_j c_{i,j}(\{p\}) m_j + \mathcal{O}(\epsilon)$$

Reconstruction of Amplitudes

[Badger'21]



$A^{(2),N_c^2}_{34;q}, A^{(2),N_c}_{\delta;q}$ $A^{(2),1}_{34;q}, A^{(2),N_c}_{\delta;q}, A^{(2),1/N_c}_{\delta;q}$ $A^{(2),N_c}_{34;l}, A^{(2),1/N_c}_{34;l}, A^{(2),1/N_c^2}_{\delta;l}$

New optimizations

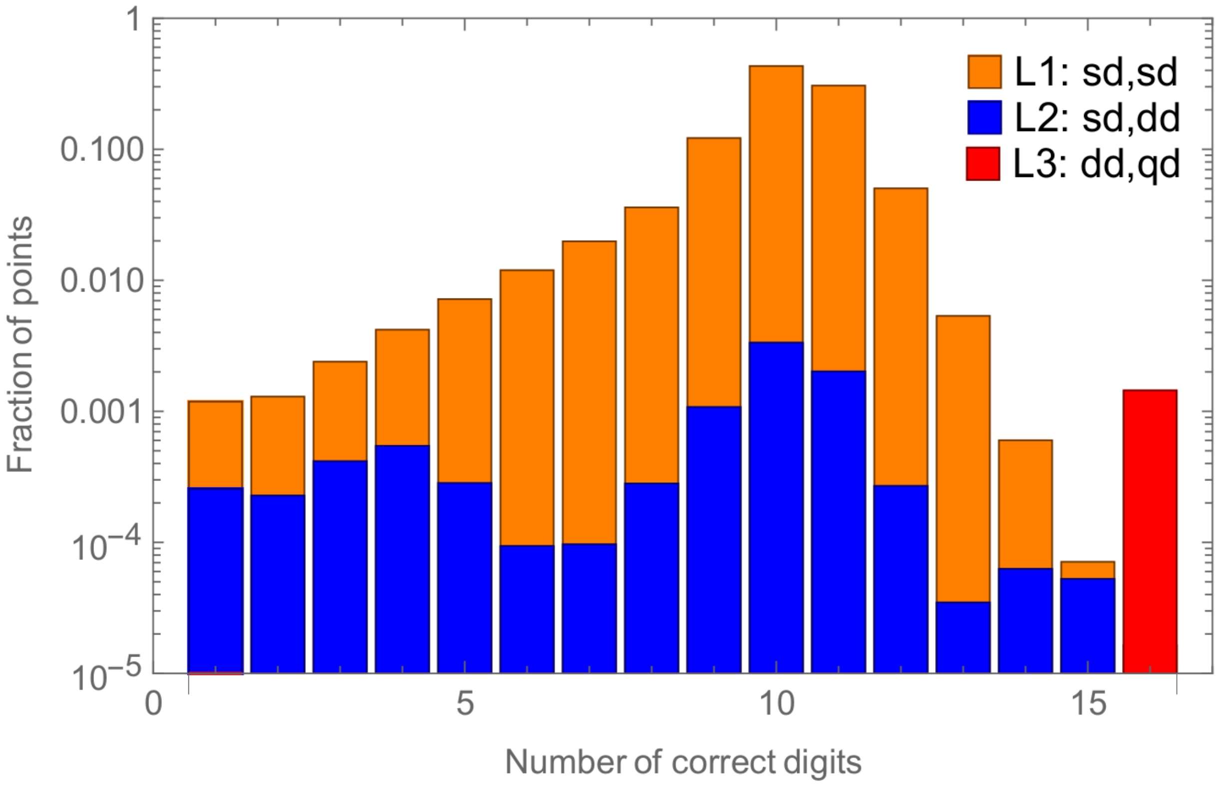
- Syzygy's to simplify IBPs
- Exploitation of Q-linear relations
- Denominator Ansaetze
- On-the-fly partial fractioning

amplitude	helicity	original	stage 1	stage 2	stage 3	stage 4
$A^{(2),1}_{34;q}$	$-++-+$	94/91	74/71	74/0	22/18	22/0
$A^{(2),1}_{34;q}$	$-+-++$	93/89	90/86	90/0	24/14	18/0
$A^{(2),1/N_c^2}_{34;q}$	$-++-+$	90/88	73/71	73/0	23/18	22/0
$A^{(2),1/N_c^2}_{34;q}$	$-+-++$	90/86	86/82	86/0	24/14	19/0
$A^{(2),1/N_c}_{34;l}$	$-+-++$	89/82	74/67	73/0	27/14	20/0
$A^{(2),1/N_c}_{34;l}$	$-++-+$	85/81	61/58	60/0	27/18	20/0
$A^{(2),N_c^2}_{34;q}$	$-+-++$	58/55	54/51	53/0	20/16	20/0

Massive reduction of complexity

Two-loop matrix element stability

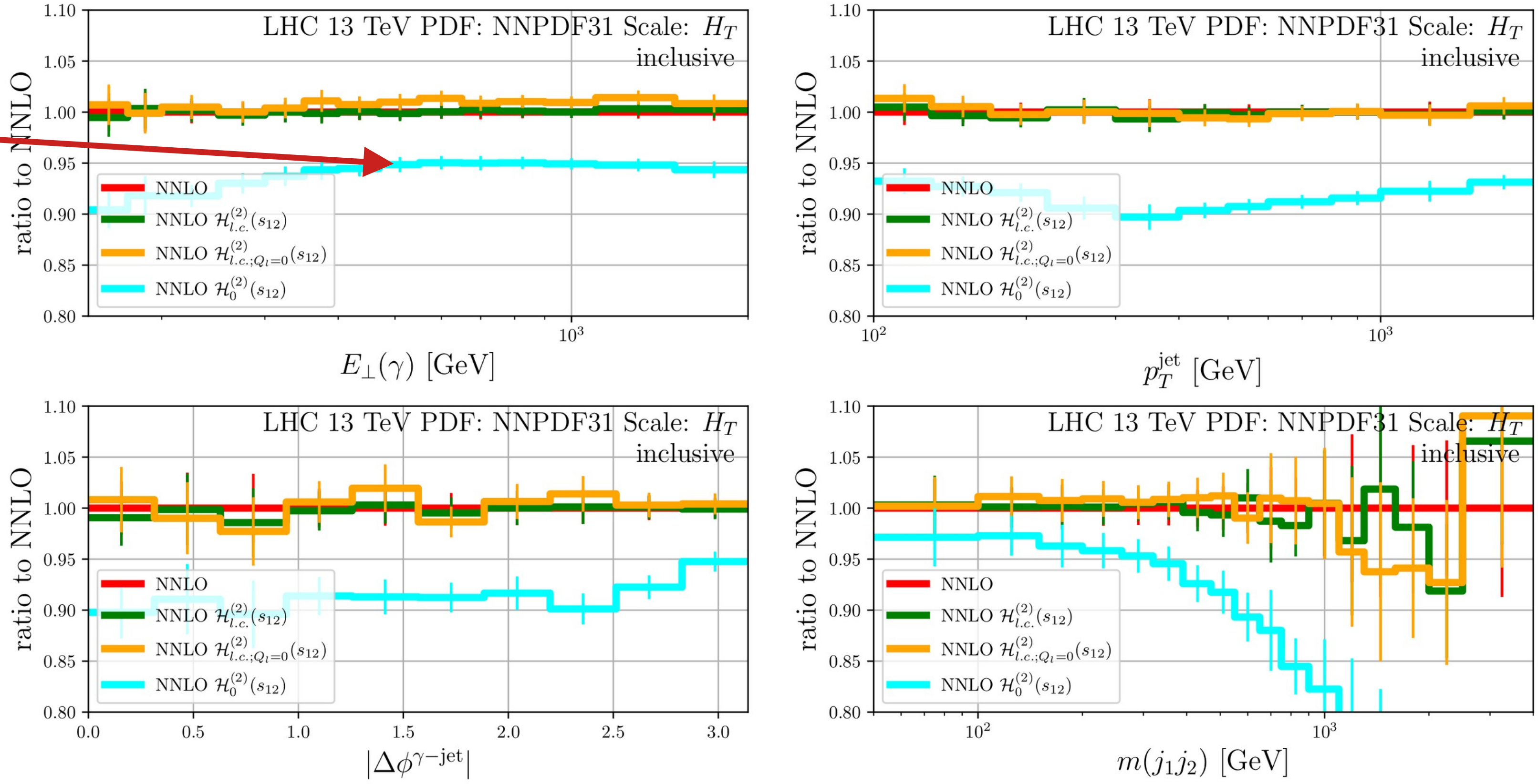
- Stable evaluation requires high floating point precision for rational functions
- In rarer cases higher precision "Pentagon" functions necessary
- 2.2 million events needed → fast evaluation essential



Quality of leading colour the approximation

Two-loop contribution
~ 5-10%
wrt. full NNLO
(scheme dep.)

"Leading colour"
Approximation
"Error" = O(~1%)
wrt full NNLO



Polarized EW bosons

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, Pelliccioli 2006.14867
NLO QCD predictions for doubly-polarized WZ production at the LHC,
Denner, Pelliccioli 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, Pelliccioli 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, Pelliccioli 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
Pelliccioli, Zanderighi 2311.05220
NLO EW corrections to polarised W+W- production and decay at the LHC
Denner, Haitz, Pelliccioli 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

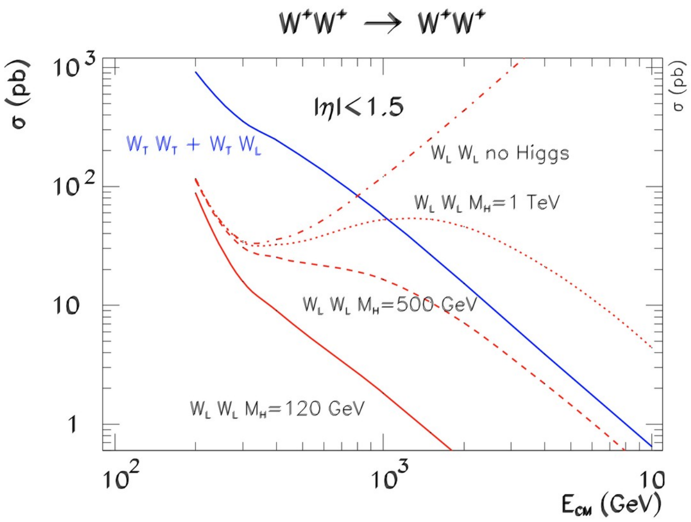
- Polarised VBS (so far LO):
  W boson polarization in vector boson scattering at the LHC,
  Ballestrero, Maina, Pellicciolі 1710.09339
  Polarized vector boson scattering in the fully leptonic WZ and ZZ channels at the LHC,
  Ballestrero, Maina, Pellicciolі 1907.04722
  Automated predictions from polarized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

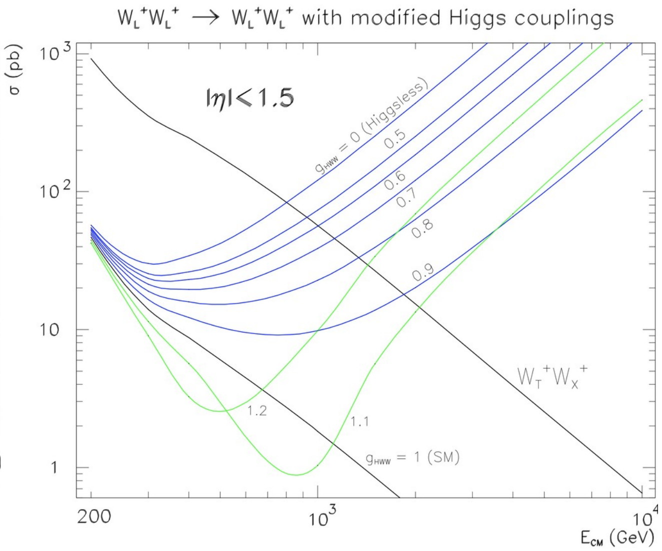
Longitudinal Vector-Boson-Scattering (VBS)

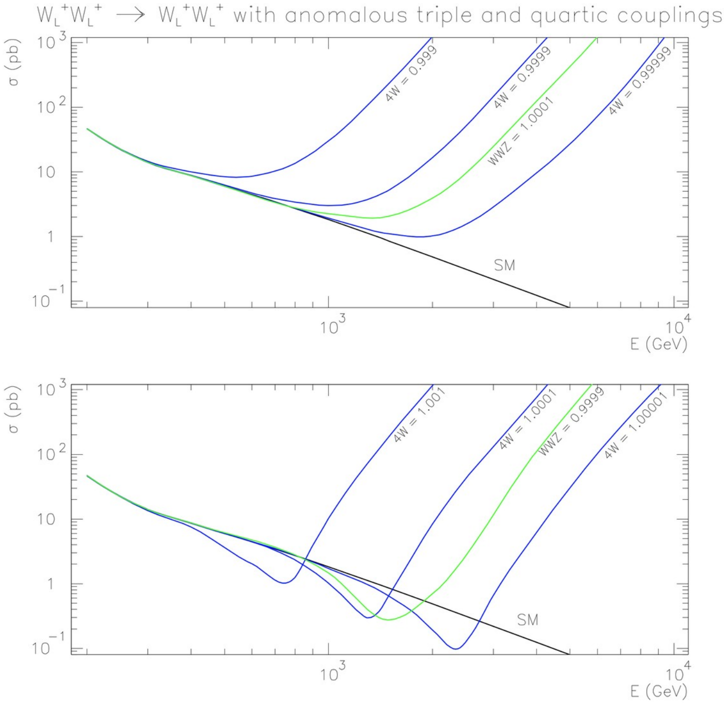
The Higgs boson and the physics of WW scattering before and after Higgs discovery
M. Szleper 1412.8367

Sensitivity to the Higgs mass



Modified HVV, VVV, VVVV couplings





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:

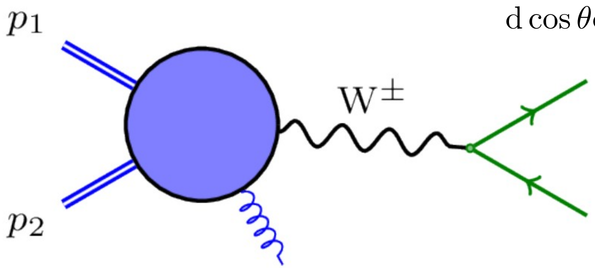
$$\phi = U^{-1}(\pi^i)\phi, \qquad W_\mu = U^{-1}W_\mu U - \frac{i}{g_W}U^{-1}\partial_\mu U$$

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

- Restores renormalizability and unitarity

Angular coefficients

Angular decomposition of 2-body W decay:



$$\frac{d\sigma}{d\cos\theta\, d\phi\, dX} = \frac{d\sigma}{dX}\frac{3}{16\pi}\Big[(1+\cos^2\theta) + \frac{A_0}{2}(1-3\cos^2\theta) + A_1 \sin 2\theta\cos\phi + \frac{A_2}{2}\sin^2\theta\cos 2\phi$$
$$+ A_3\sin\theta\cos\phi + A_4\cos\theta + A_5\sin^2\theta\sin 2\phi + A_6\sin 2\theta\sin\phi + A_7\sin\theta\sin\phi\Big]$$

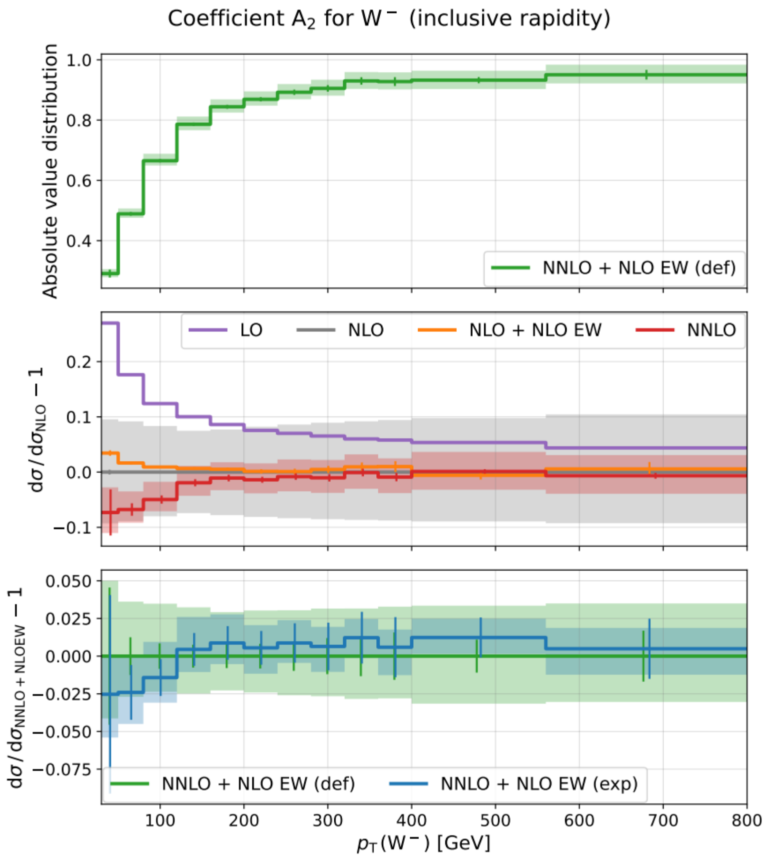
After azimuthal integration:
$$\frac{1}{\sigma}\frac{d\sigma}{\cos\theta} = \frac{3}{4}\sin\theta f_0 + \frac{3}{8}(1-\cos\theta)^2 f_L + \frac{3}{8}(1+\cos\theta)^2 f_R$$

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:

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



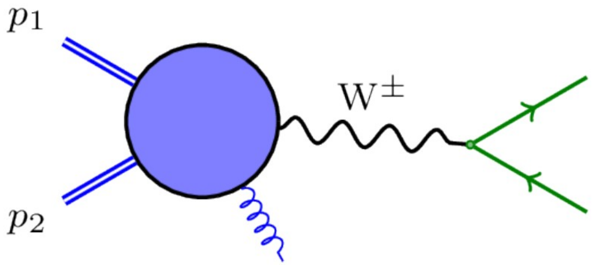
Angular coefficients in W+j production at the LHC with high precision
Pellen, Poncelet, Popescu, Vitos, 2204.12394

Angular coefficients, practical considerations

This simple idea suffers from:

- Fiducial phase space requirements on the leptons:
  → Interferences do not cancel
  → Correspondence between fractions (f_0, f_L, f_R) and angular distributions broken.
- Higher order corrections to decay (QED radiation 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

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 W+jet: 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 $p_T(j) \geq 30\ \mathrm{GeV}$

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

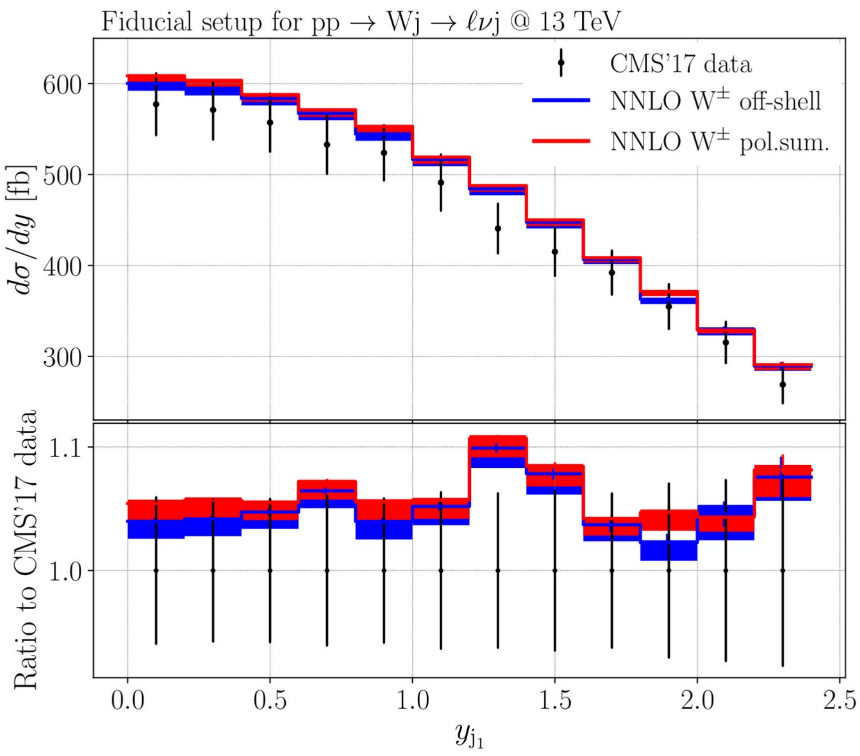
Technical aspects:

- 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]

Extraction of polarisation fractions

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

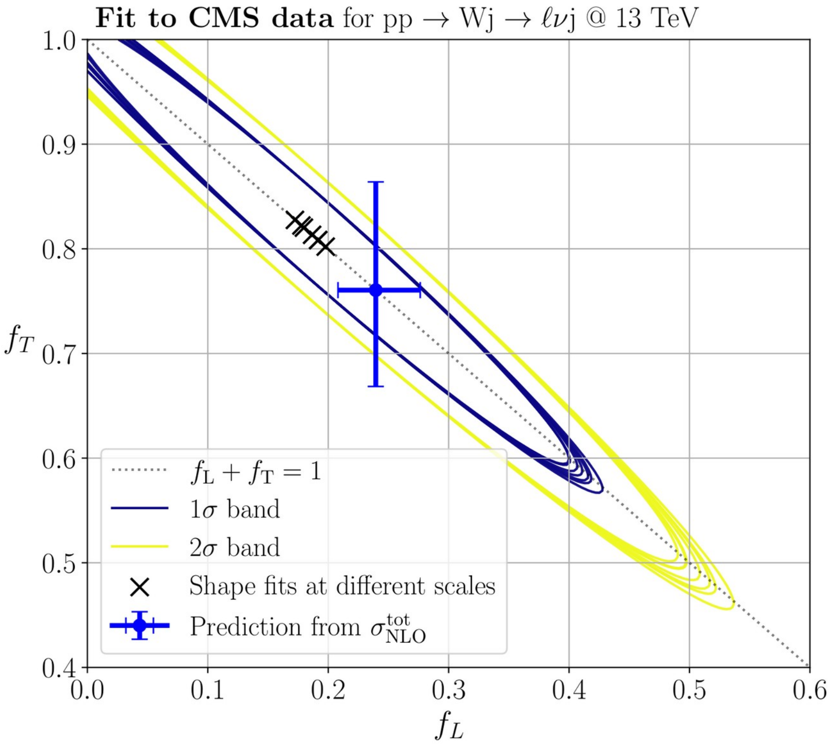
- $\Delta\phi(\ell, j_1) \geq 0.3$
- $25 \text{ GeV} \leq p_T(\ell) < 70 \text{ GeV}$
- $\cos(\theta^*_\ell) \geq -0.75$
- $|y(j_1)| \leq 2$

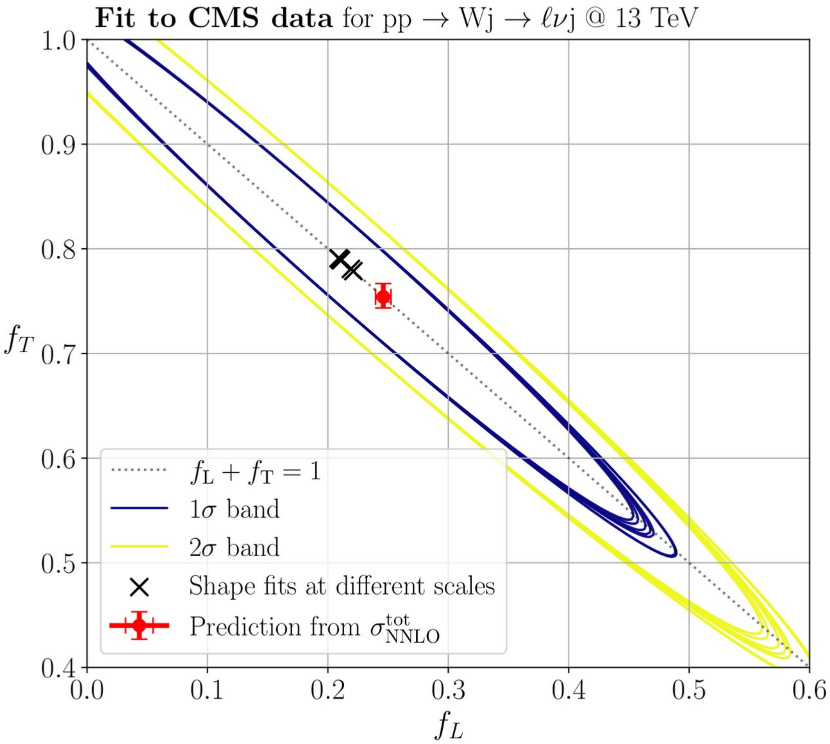


W+jet : fit to CMS data

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

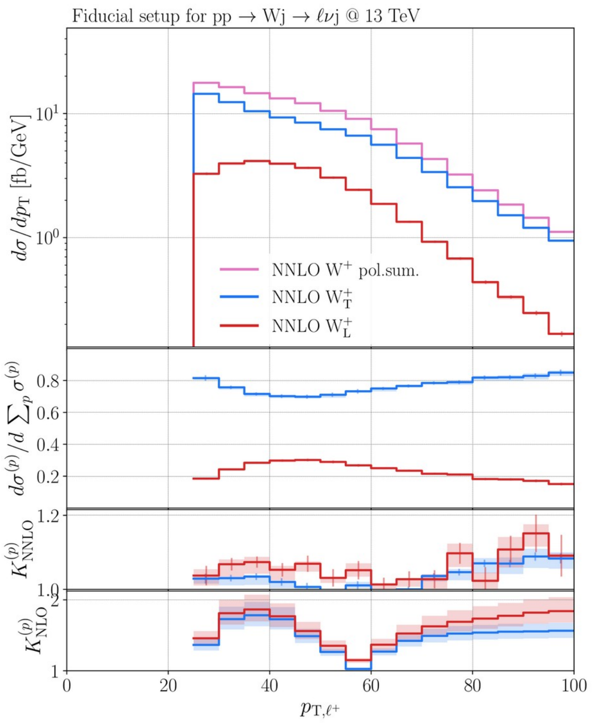
→ dominated by experimental uncertainties (no correlations available)



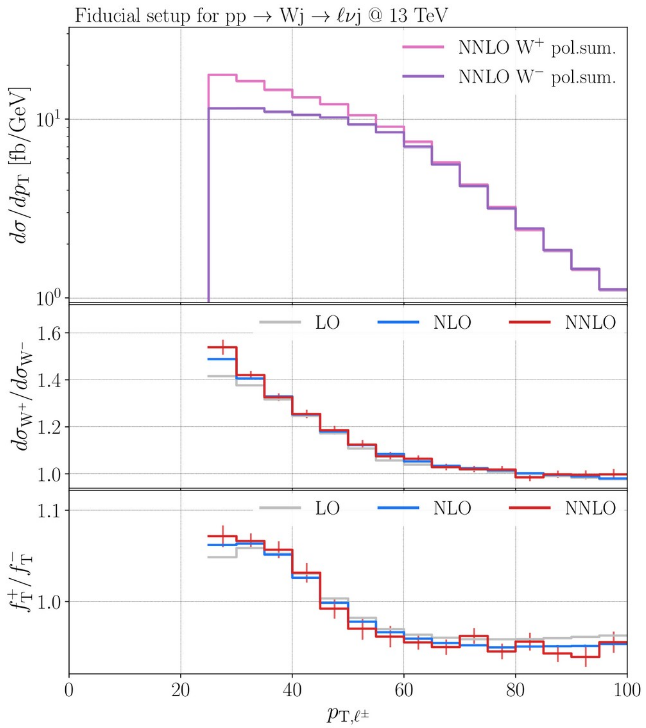


Example: lepton transverse momentum

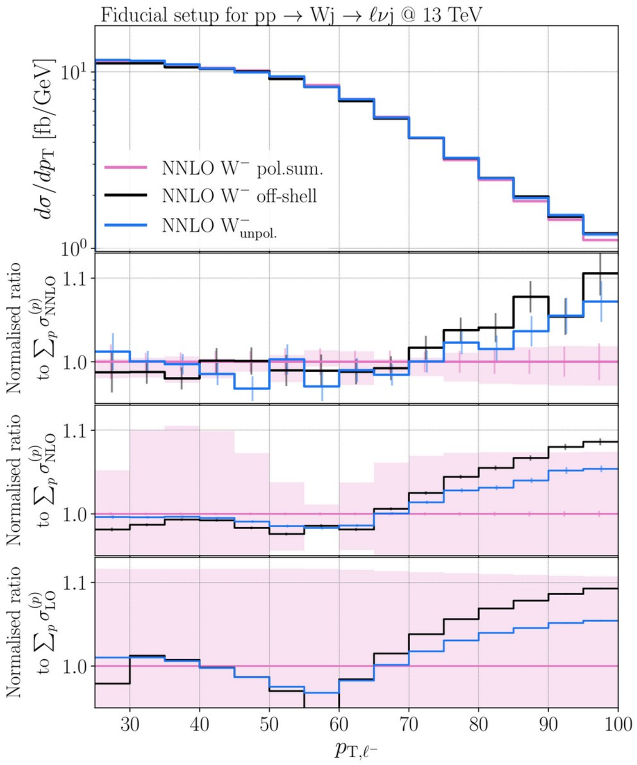
Perturbative corrections



Charge differences



Off-shell/Interference effects



Status of polarization calculations

Process	LO	NLO	NLO EW	NNLO	+ PS
pp → WW	X	X	X	X	X
pp → ZZ	X	X	X		X
pp → WZ	X	X	X		X
pp → W/Z	X	X	X	Ang.	X
pp → W+j	X	X	(X)	X	
pp → Z+j	X	Ang.		Ang.	
VBS	X	X			

(Collection of papers in the backup)

Ang. = angular coefficients

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 (reweighted by pol. tree MEs)
- Comparison with multi-jet merged calculations

Comparison with fixed order

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

W^+Z	$\sigma^{\rm NLO}$ [fb]	Fraction [%]	K-factor	$\sigma^{\rm nLO+PS}_{\rm SHERPA}$ [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)

Polarised NLO+PS: POWHEG

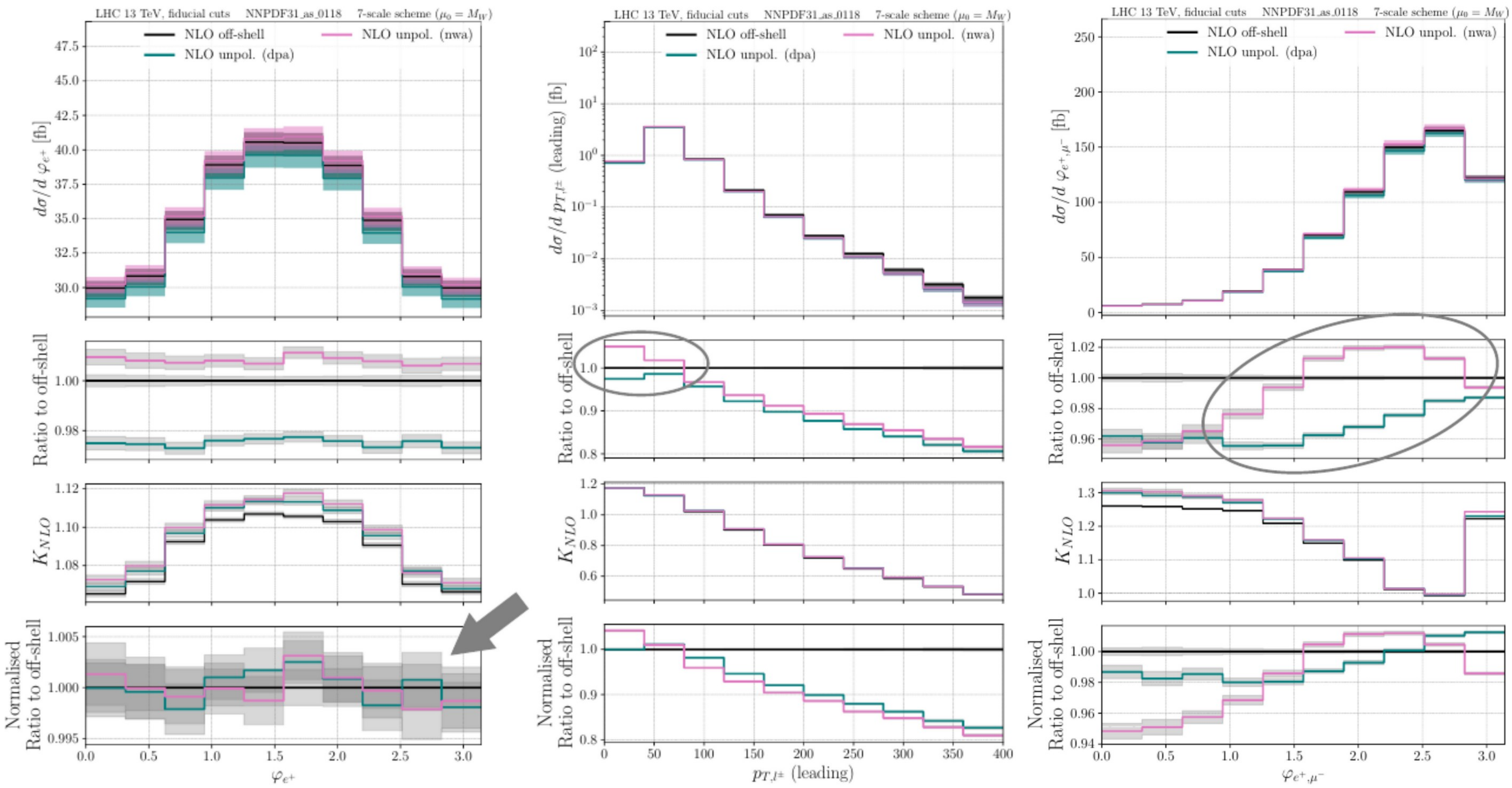
Polarised-boson pairs at the LHC with NLOPS accuracy
Pellicciolі, Zanderighi 2311.05220

- NLO QCD + PS in POWHEG-BOX-RES framework
- Study of PS (Pythia8) + hadronisation effects on fractions and differential distributions WW/WZ/ZZ

→ 1-5% effect on distributions, but generally small impact on fractions (~1% effects)

state	σ[fb] LHE	ratio [/unp., %] LHE	σ[fb] PS+hadr	ratio [/unp., %] PS+hadr
Inclusive setup				
full off-shell	$98.36(3)^{+4.8\%}_{-3.9\%}$	101.20	$95.27(3)^{+4.9\%}_{-3.9\%}$	101.28
unpolarised	$97.20(3)^{+4.8\%}_{-3.9\%}$	100	$94.07(3)^{+4.9\%}_{-3.9\%}$	100
LL	$4.499(2)^{+2.8\%}_{-2.3\%}$	$4.63^{+0.13}_{-0.13}$	$4.359(2)^{+2.8\%}_{-2.2\%}$	$4.63^{+0.13}_{-0.13}$
LT	$13.151(4)^{+7.0\%}_{-5.7\%}$	$13.53^{+0.28}_{-0.27}$	$12.730(5)^{+7.0\%}_{-5.7\%}$	$13.53^{+0.28}_{-0.28}$
TL	$12.724(4)^{+7.3\%}_{-5.9\%}$	$13.09^{+0.32}_{-0.31}$	$12.314(5)^{+7.4\%}_{-5.9\%}$	$13.09^{+0.31}_{-0.32}$
TT	$66.88(2)^{+4.0\%}_{-3.3\%}$	$68.81^{+0.47}_{-0.51}$	$64.74(2)^{+4.1\%}_{-3.2\%}$	$68.82^{+0.46}_{-0.51}$
interference	-0.058	-0.06	-0.069	-0.06

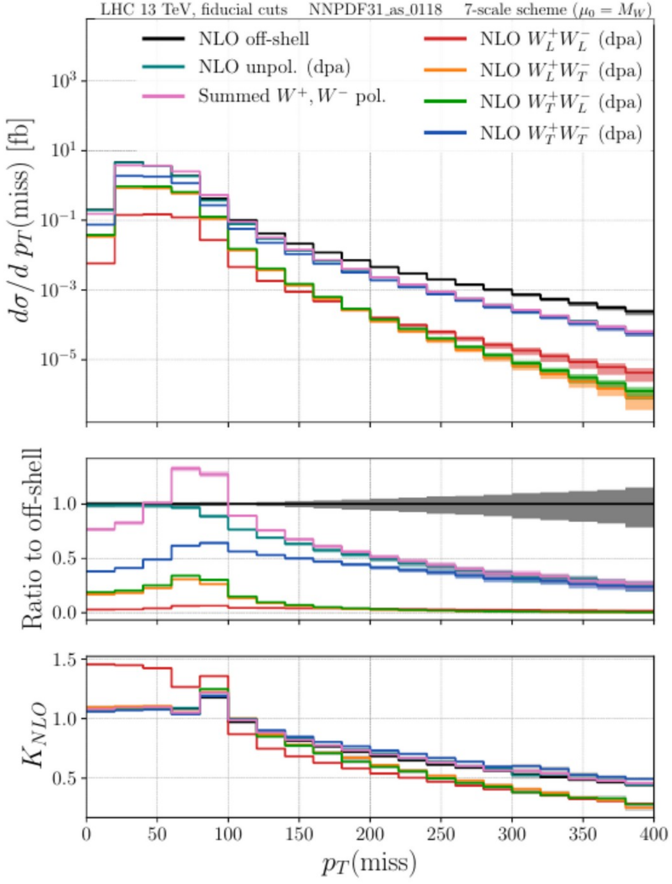
NWA vs. DPA

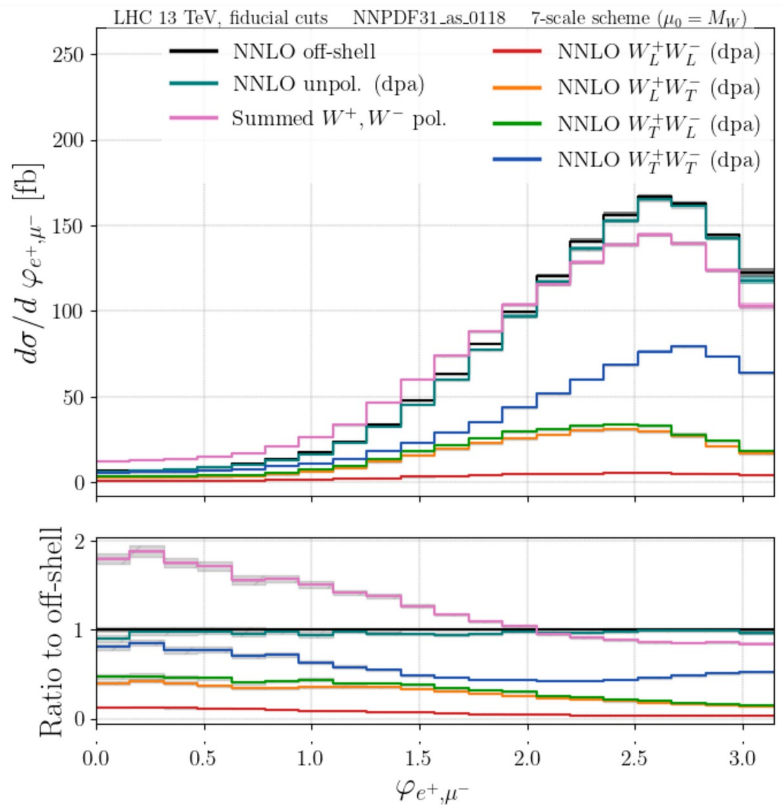


LHC 13 TeV, fiducial cuts NNPDF31_as_0118 7-scale scheme ($\mu_0 = M_W$)
NLO off-shell
NLO unpol. (nwa)
NLO unpol. (dpa)
$d\sigma/d\,\varphi_{e^+}$ [fb]
$d\sigma/d\,p_{T,l^\pm}$ (leading) [fb]
$d\sigma/d\,\varphi_{e^+,\mu^-}$ [fb]
Ratio to off-shell
K_{NLO}
Normalised Ratio to off-shell
φ_{e^+}
$p_{T,l^\pm}$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

Interference and off-shell effects

Large off-shell effect from single-resonant contributions





Large interference effects through phase space constraints

Take home messages

- Precise (and accurate) SM predictions for polarized cross section are important to pin down the longitudinal component.
- NLO QCD/EW (+PS) are the state-of-the-art for polarized EW boson processes
  → few process are available at NNLO QCD
- Looking at higher-orders NNLO QCD
  - Scale dependence can mimic signal → NNLO QCD needed to reduce these effects
  - Loop-induced contributions: ‘LO’ at NNLO → needs partial N3LO QCD
- What’s next? → Phenomenology, benchmark new tools (Powheg, SHERPA, Madgraph)
  - NNLO QCD for VV, (+ NLO EW), providing templates through high tea
  - + SMEFT

NNLO QCD polarized WW production

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

STRIPPER

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

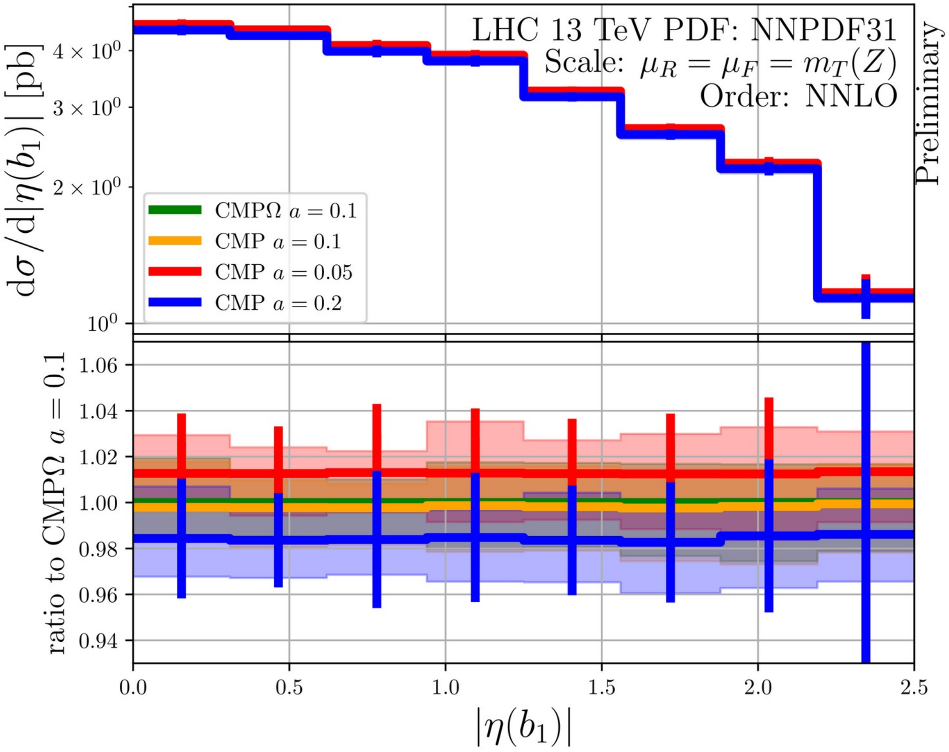
- Leptons: $p_T(\ell) \geq 27$ GeV $|y(\ell)| < 2.5$ $m(\ell\bar{\ell}) > 55$ GeV
- Missing transverse momentum: $p_{T,\text{miss}} = p_T(\nu_e + \bar{\nu}_\mu) \geq 20$ GeV
- Jet-veto: $p_T(j) > 35$ GeV $|y(j)| < 4.5$

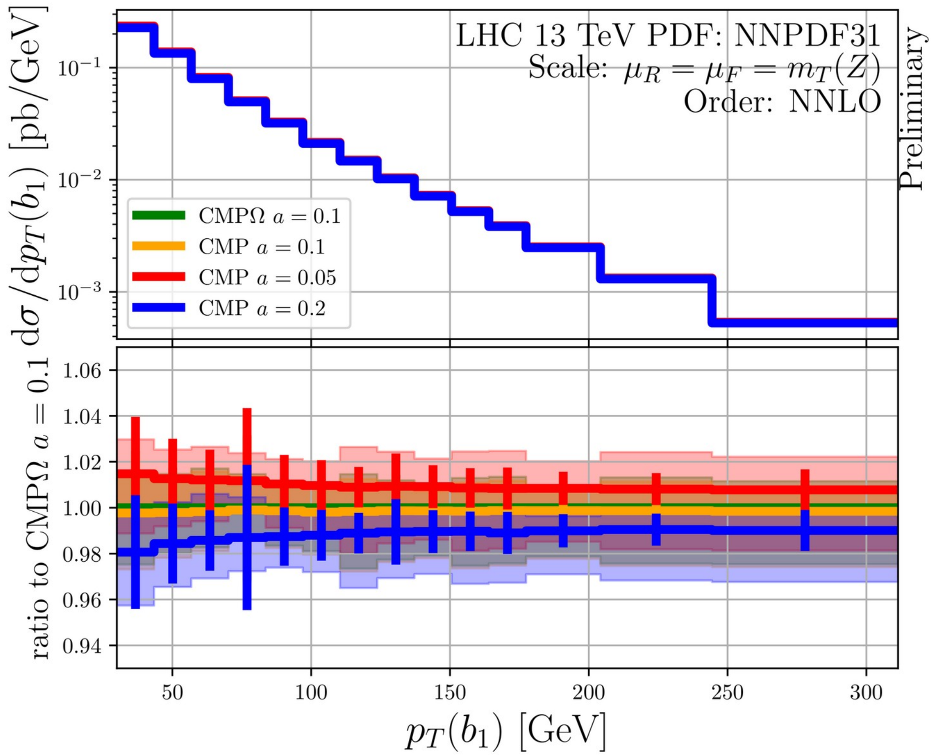
Heavy flavoured jets

Differences to CMPΩ

Calculations performed with sector-improved residue subtraction scheme
1408.2500 & 1907.12911

Les Houches Jet Flavour WG

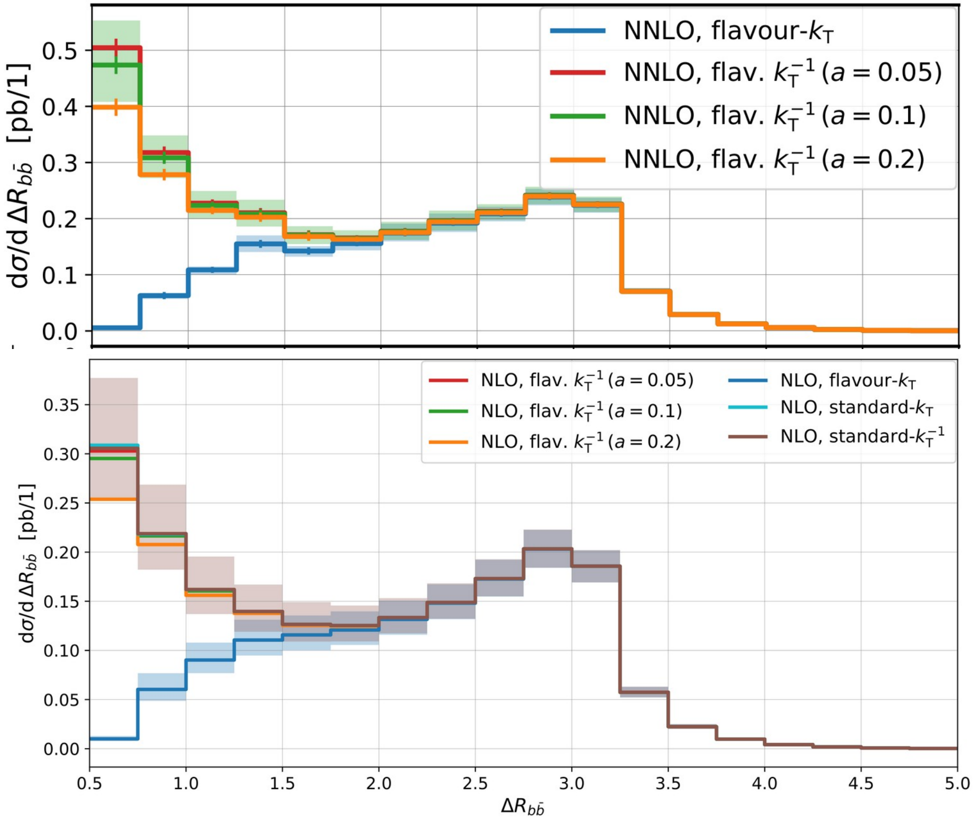


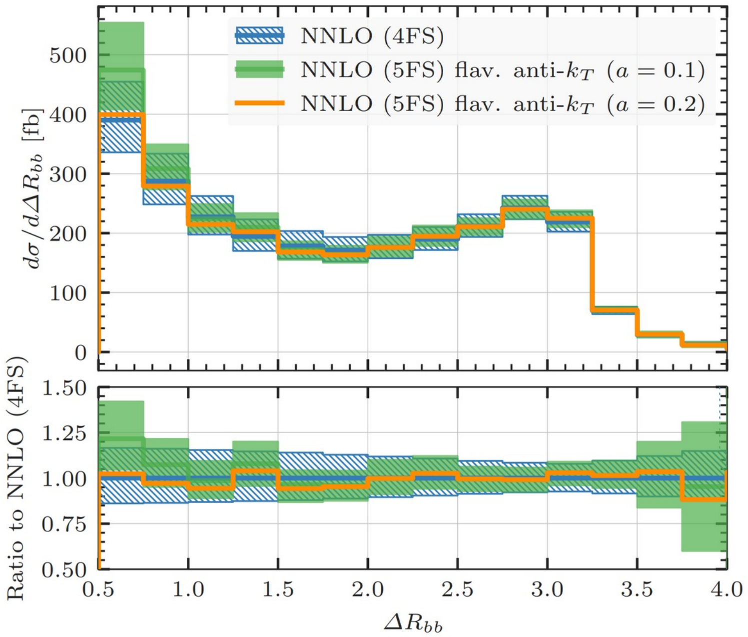


Negligible difference between CMPΩ and CMP at NNLO

W + bottom pair: $pp \to Wb\bar{b} + X$

Flavour anti-kT algorithm applied to Wbb production at the LHC
Hartanto, **Poncelet**, Popescu, Zoia 2209.03280

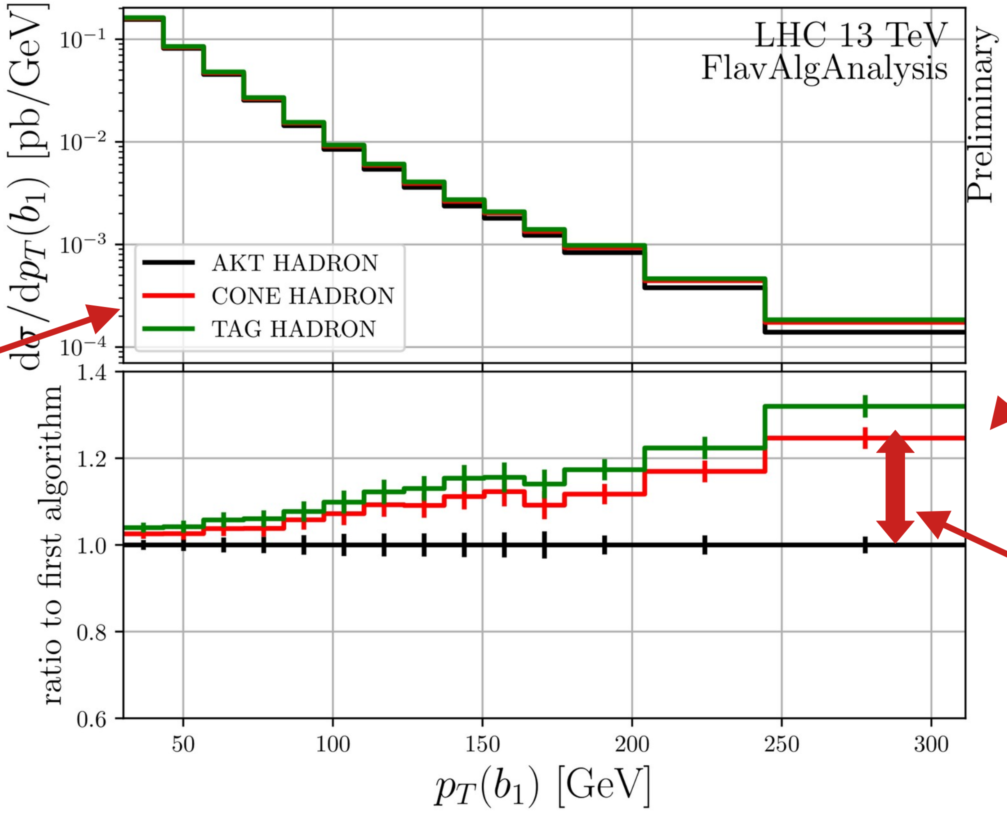




4 FS vs. 5 FS [Buonocore 2212.04954]
→ CMP and anti-kT close

Comparison anti-kT tagging

- AKT ($b\bar{b} = g$)
- CONE <=> ATLAS
- TAG <=> CMS

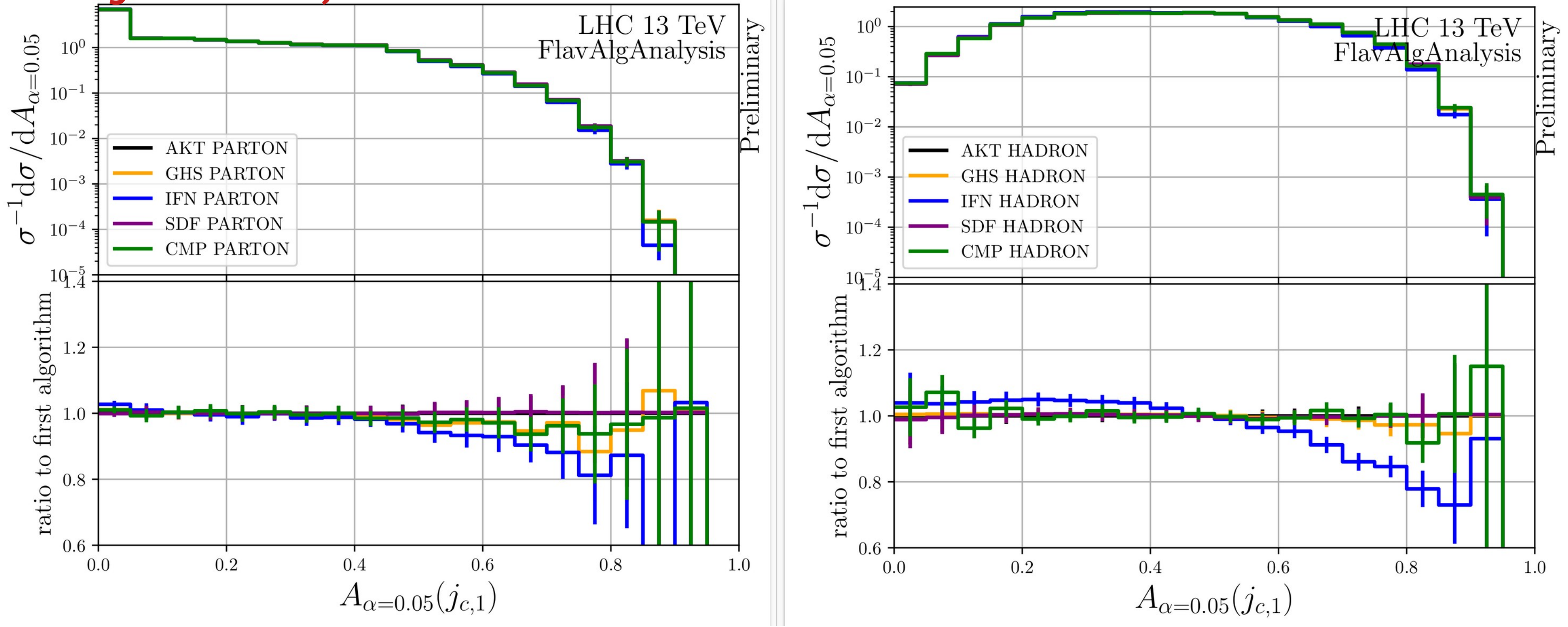


Note:
comparable results for
ATLAS and CMS tagging

1) Impact of double tags?
$g \to b\bar{b}$

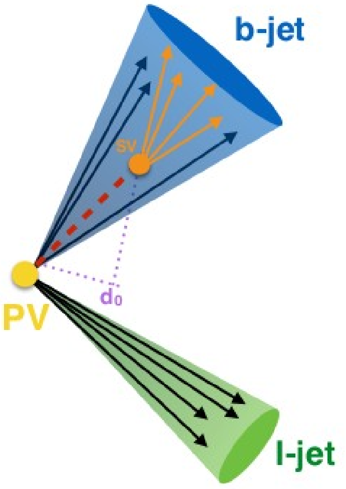
LesHouches: JSS - Angularity

Leading flavoured jet



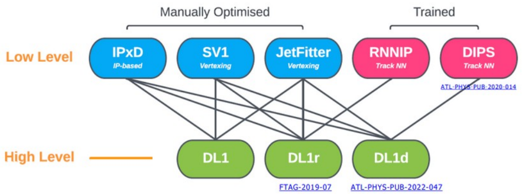
Impact on experimental b/c-tagging

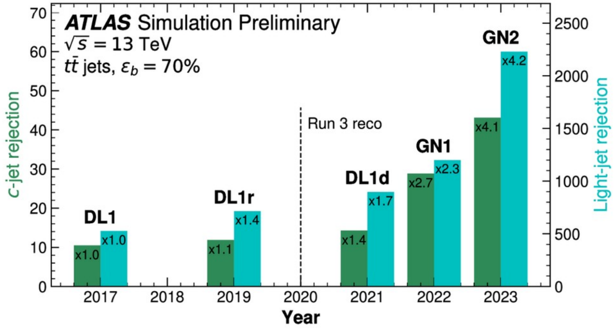
Displaced vertices



Credit: Arnaud Duperrin (DIS23 talk)

ML taggers





Where does the training data come from?

MC → Ghost tagging

1) it contains at least one B/D
FO: IR-unsafe because
$g \to b\,\bar{b}$ splitting

2) within dR < R of jet axis
FO: IR-unsafe because
soft wide angle emission

3) with pT > pT_cut
FO: collinear unsafe
b → b g splitting

“Truth” labelling used in MC samples, used to train the NN