Full NLO corrections to 3-jet production and R_{32} at the LHC

Max Reyer

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Advisor:
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UNI FREIBURG

Masse und Symmetrien nach der Entdeckung des Higgs-Teilchens am LHC
GRK 2044

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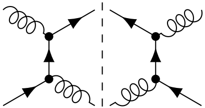
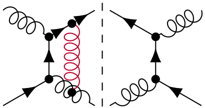
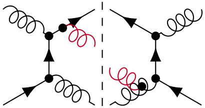
Outline

Jet Production at QCD LO and NLO

- among most abundant processes at LHC
  - ⇒ allows for multi-differential measurements into high-p_{T} regions
- important SM background and BSM searching ground
- determination of PDFs and α_s at high scales Q^2

2-jet production in QCD:

$a, b, c, d, e \in \{g, q\}$

LO (Born)	$a + b \rightarrow c + d$	α_S^2	
NLO (virtual)	$a + b \rightarrow c + d$	α_S^3	
NLO (real)	$a + b \rightarrow c + d + e$	α_S^3	

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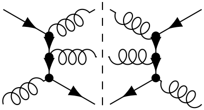
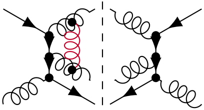
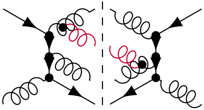
LO (Born)	$a + b \to c + d + e$	α_S^3	
NLO (virtual)	$a + b \to c + d + e$	α_S^4	
NLO (real)	$a + b \to c + d + e + f$	α_S^4	

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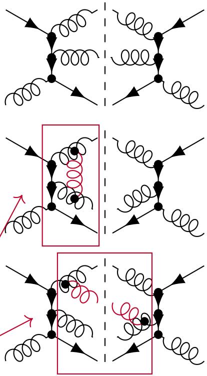


infrared (IR) singularities $\to$ dipole subtraction

Existing Studies of Jet Production

- NLO QCD up to 5 final state jets
  [Ellis *et al.*, 1992] [Nagy, 2003] [Badger *et al.*, 2014]
  [Giele *et al.*, 1993] [Bern *et al.*, 2012]
- NLO QCD combined with parton showers
  [Alioli *et al.*, 2011] [Höche *et al.*, 2012]
- NNLO QCD 2-jet
  [Currie *et al.*, 2016] [Ridder *et al.*, 2019]
  [Currie *et al.*, 2017] [Czakon *et al.*, 2019] (full color)
- NNLO QCD 3-jet
  [Czakon *et al.*, 2021] (double-virtual in leading color)
- pure weak corrections for 2-jet (no γ; $\mathcal{O}\left(\alpha_s^2\alpha\right)$, $\mathcal{O}\left(\alpha_s\alpha\right)$, $\mathcal{O}\left(\alpha^2\right)$)
  [Dittmaier *et al.*, 2012]
- full SM NLO for 2-jet
  [Frederix *et al.*, 2017]
- full SM NLO for 3-jet, inclusive cross section
  [Frederix *et al.*, 2018]
- full SM NLO for 3-jet, (double) differential
  [MR *et. al., 2019*]

3/2-Jet Ratios and α_S Determination

- examples:

$$R_{32}(Q^2) = \frac{\mathrm{d}\sigma_{3j}/\mathrm{d}Q^2}{\mathrm{d}\sigma_{2j}/\mathrm{d}Q^2},$$

$$R_{\Delta\phi}(Q^2, \Delta\phi_{\mathrm{max}}) = \frac{\mathrm{d}\sigma_{2j}(\Delta\phi_{12} < \Delta\phi_{\mathrm{max}})/\mathrm{d}Q^2}{\mathrm{d}\sigma_{2j}/\mathrm{d}Q^2}, \quad (2\pi/3 < \Delta\phi_{\mathrm{max}} < \pi).$$

[Wobisch *et al.*, 2013]

- ratios reduce uncertainties
  - experimental: luminosity, jet energy scale, ...
  - theory: PDFs, factorizing higher-order contributions, ...

- R_{32}, $R_{\Delta\phi}$ are approximately proportional to $\alpha_s(Q^2)$

  ⇒ allow for measurement in various bins of Q^2

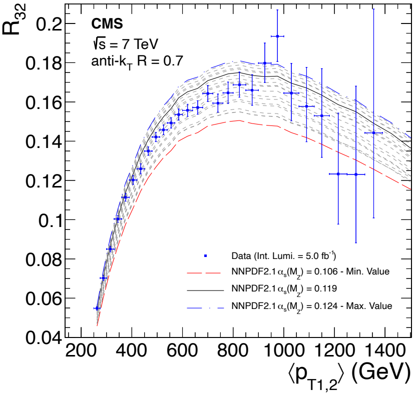
  [Abazov *et al.*, 2012] [Chatrchyan *et al.*, 2013] [Aaboud *et al.*, 2018]

  ⇒ fit theory predictions to data, by varying the α_s input

  ⇒ test for RGE running of $\alpha_s(Q^2)$

Collaboration with CMS on EW NLO corrections for $R_{\Delta\phi}$ variant!

3/2-Jet Ratios and α_S Determi



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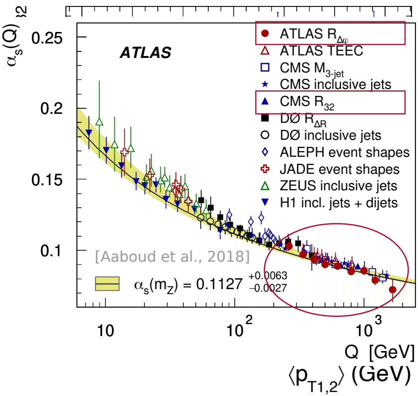

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Features of Electroweak (EW) NLO

- EW NLO: contributions with additional power of $\alpha \sim 1\%$ w.r.t. to LO

$\Rightarrow$ $W^\pm, Z$ in loops:

$\Rightarrow$ IR finite Sudakov logs $\sim \alpha \log^2\left(\frac{Q^2}{m_V^2}\right) \sim 10\%$ @ 1TeV

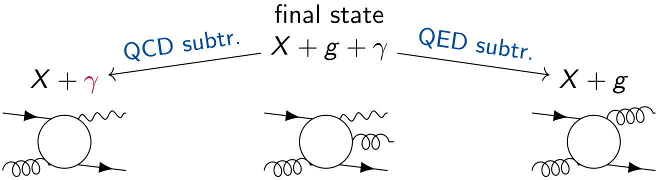
$\Rightarrow$ γ in loops: IR QED divergences

$\Rightarrow$ real γ radiation required for cancellation

$\Rightarrow$ add γ to jet clustering

$\Rightarrow$ perform QED dipole subtraction [Dittmaier, 2000]

- simultaneous QCD and QED subtraction $\rightarrow$ distinct Born processes



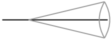
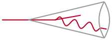
$\Rightarrow$ forces γ in process definition already at LO

External Photons and Jet Observables in EW NLO

- theory: jet definition needs to include γ (QED IR cancellations)
- experiment: distinction between jets and γ desired (different process)

$\Rightarrow$ IR safe removal of "photon jets" is non-trivial!

- example: cut on photonic energy fraction z_γ inside jet $\Rightarrow$ not IR safe
  - $q \to q\gamma$ splittings (q and collinear $q\gamma$-pair are distinguished)

 $z_\gamma < z_{\text{cut}}$  $z_\gamma \geq z_{\text{cut}}$,

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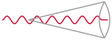
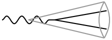
 $z_\gamma \geq z_{\text{cut}}$  $z_\gamma < z_{\text{cut}}$,

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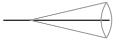
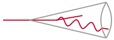
     $z_\gamma < z_{\text{cut}}$  $z_\gamma \geq z_{\text{cut}}$,

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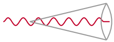
     $z_\gamma \geq z_{\text{cut}}$  $z_\gamma < z_{\text{cut}}$,

- proper description requires non-perturbative physics, provided by
  - $q \to q\gamma$: fragmentation functions $D_{q\to\gamma}$ [Glover *et al.*, 1994], [Buskulic *et al.*, 1996]
  - $\gamma \to q\bar{q}$: conversion function $D_{\gamma\to\text{had}}$ [Denner *et al.*, 2019]

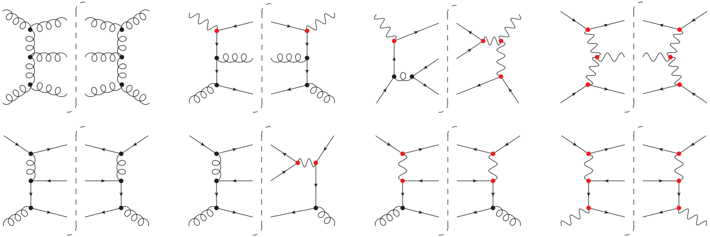
  $\Rightarrow$ contain IR-singular perturbative parts

  $\Rightarrow$ combine with IR singularities from real process

2/3-Jet Production at EW NLO and Full SM NLO

- External particles: $a, b \in \{g, q, \gamma\}$ and $c, d, e, f \in \{g, q, \gamma, l, \nu\}$

	process:	$\alpha_s^n \alpha^m$
2-jet:	$a + b \rightarrow c + d\,[+e]$	$n + m = 2, 3$
3-jet:	$a + b \rightarrow c + d + e\,[+f]$	$n + m = 3, 4$



$\mathcal{O}(\alpha_s^3)$	$\mathcal{O}(\alpha_s^2\alpha)$	$\mathcal{O}(\alpha_s\alpha^2)$	$\mathcal{O}(\alpha^3)$
LO_0	LO_1	LO_2	LO_3
"LO"	← "subleading LO" →		

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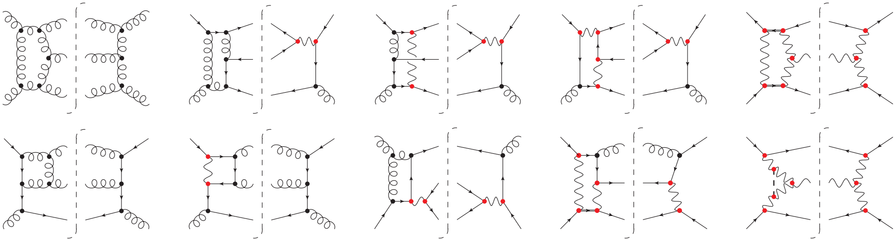


$\mathcal{O}(\alpha_s^4)$	$\mathcal{O}(\alpha_s^3\alpha)$	$\mathcal{O}(\alpha_s^2\alpha^2)$	$\mathcal{O}(\alpha_s\alpha^3)$	$\mathcal{O}(\alpha^4)$
$\Delta\mathrm{NLO}_0$	$\Delta\mathrm{NLO}_1$	$\Delta\mathrm{NLO}_2$	$\Delta\mathrm{NLO}_3$	$\Delta\mathrm{NLO}_4$
"QCD NLO"	"EW NLO"	← "subleading NLO" →		

2/3-Jet Production at EW NLO and Full SM NLO

jet definition and fiducial phase space cuts:

- require 3 resp. 2 anti-k_{T} jets, $R = 0.4$, democratic [input: g, q, γ, l]

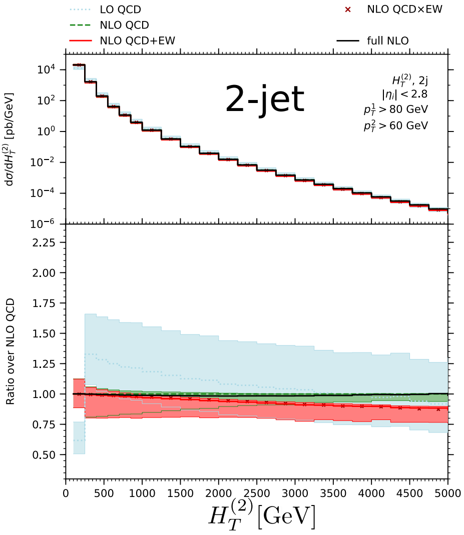
$$|\eta| < 2.8; \qquad p_T^1 \geq 80\text{GeV}, \qquad p_T^{i\geq 2} \geq 60\text{GeV}$$

- reject 'lepton jets': $|\eta_j| < 2.5$ and net lepton number $\neq 0$
  - $\Rightarrow$ collinear same-flavor lepton pairs survive (IR safety!)
  - $\Rightarrow$ leptons outside CMS tracker survive
  - $\Rightarrow$ after rejection, impact of final state leptons numerically irrelevant

computation:

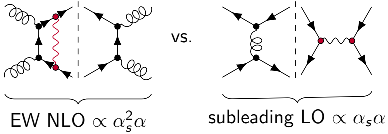
- Fully automated: Sherpa interfaced to Recola
  [Schönherr, 2018; Biedermann *et al.*, 2017]
- pp @ 13 TeV, PDF: `NNPDF31_nlo_as_0118_luxqed`
- scale choice $\mu_R = \mu_F = \frac{1}{2}\hat{H}_{\mathrm{T}}$, 7-point scale variations
- G_μ scheme, complex mass scheme
  [Denner *et al.*, 1999] [Denner *et al.*, 2005] [Denner *et al.*, 2020]

$H_{\mathrm{T}}^{(2)}$-Spectra (input distributions to R_{32})



- large negative Sudakov-type EW NLO corrections
- accidental cancellation of EW NLO with subleading LO and NLO

⇒ highly dependent on:
  - observable definition
  - fiducial phase space



(c.f. [Dittmaier *et al.*, 2012])

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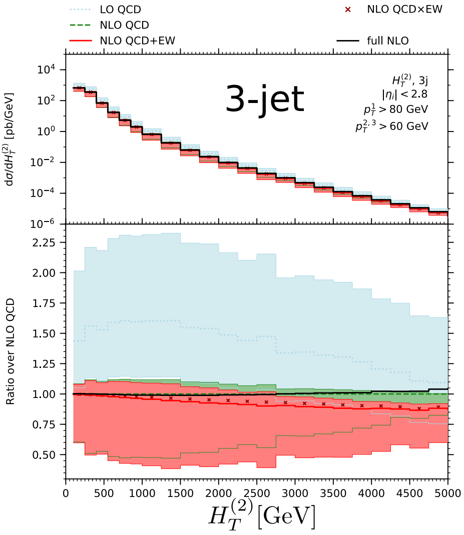

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⇒ highly dependent on:
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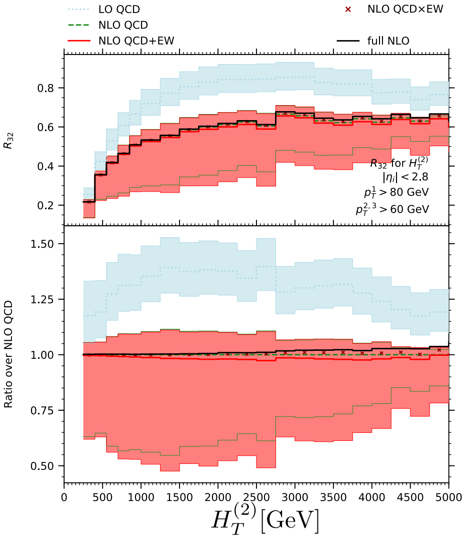
  - fiducial phase space

- in 3-jet sample at high $H_{\mathrm{T}}^{(2)}$:
  - ⇒ 3rd jet predominantly soft
  - ⇒ factorizing higher order corrections
  - ⇒ similar EW corrections in 2-jet and 3-jet sample

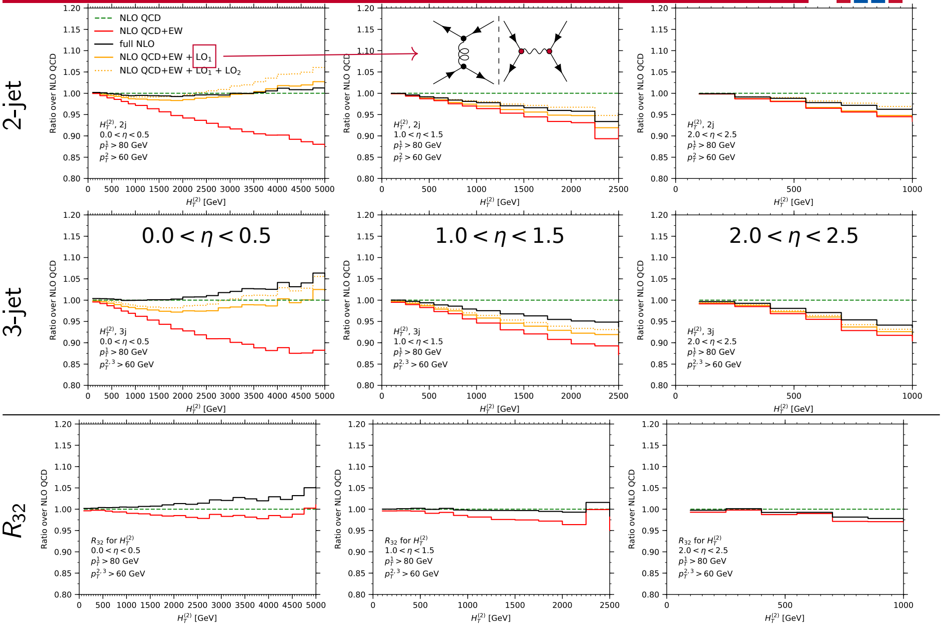
R_{32} Result



- small corrections from EW NLO
  - ⇒ factorizing EW corrections between 3-jet and 2-jet distributions
  - ⇒ beyond accidental cancellation
  - ⇒ stable w.r.t. cuts e.g. on

$$\eta := |\eta_1 - \eta_2|/2$$

Dependence on $\eta := |\eta_1 - \eta_2|/2$



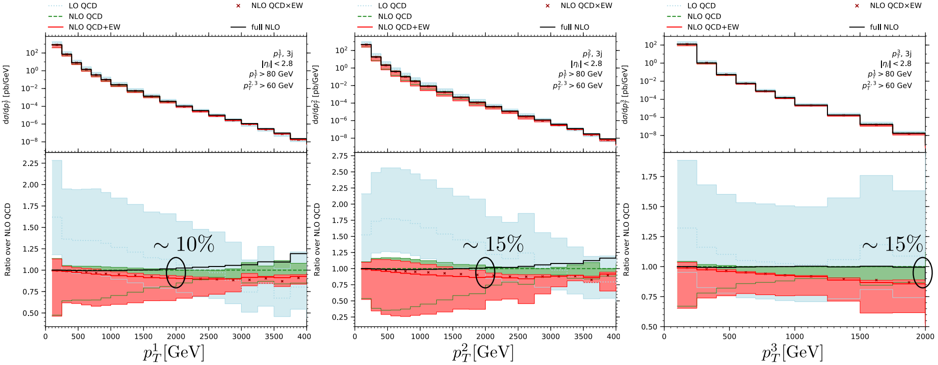
Summary:

- Definition of jets is non-trivial at EW NLO
- EW NLO corrections in 2/3-jet production
  - at high $H_{\mathrm{T}}^{(2)}$ competitive with QCD NLO
  - large accidental compensations in p_{T}-type distributions
  - systematically cancel in $R_{32}(H_{\mathrm{T}}^{(2)})$

Outlook:

- provide CMS with EW NLO corrections to $R_{\Delta\phi}$
- implementation of conversion function $D_{\gamma\to\text{had}}$
- multijet merging in EW_{virt} approximation [Kallweit *et al.*, 2016]

BACKUP: p_T-Spectra

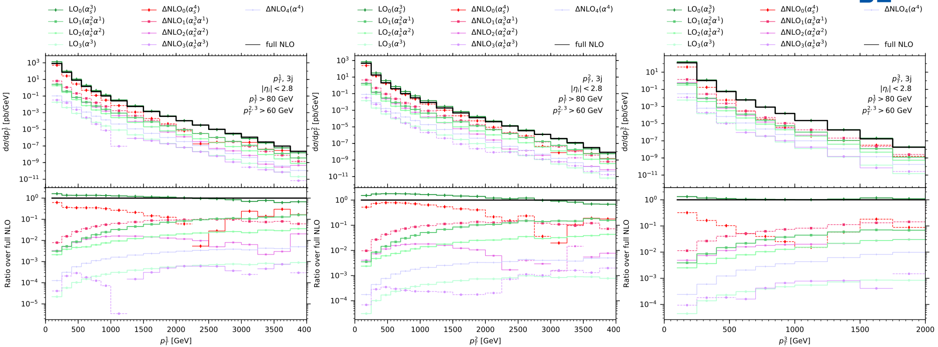


- large negative Sudakov-type EW NLO corrections

at 2TeV in	p_T^1	p_T^2	p_T^3
$\Delta\mathrm{NLO}_1[\%]$	-10	-15	-15

- larger for subleading p_T

BACKUP: p_{T}-spectra



- nomenclature for n-jet XS:

$$\mathcal{O}\left(\sigma_{nj}^{\mathrm{LO}_i}\right) = \alpha_s^{n-i}\alpha^i, \qquad \mathcal{O}\left(\sigma_{nj}^{\Delta\mathrm{NLO}_i}\right) = \alpha_s^{n+1-i}\alpha^i,$$

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- combination of QCD and EW NLO:

additive:
$$\sigma_{nj}^{\text{NLO QCD+EW}} = \sigma_{nj}^{\text{LO}_0} + \sigma_{nj}^{\Delta\text{NLO}_0} + \sigma_{nj}^{\Delta\text{NLO}_1}$$

multiplicative:
$$\sigma_{nj}^{\text{NLO QCD}\times\text{EW}} = \sigma_{nj}^{\text{LO}_0}\left(1 + \frac{\sigma_{nj}^{\Delta\text{NLO}_0}}{\sigma_{nj}^{\text{LO}_0}}\right)\left(1 + \frac{\sigma_{nj}^{\Delta\text{NLO}_1}}{\sigma_{nj}^{\text{LO}_0}}\right)$$

- estimate of unknown $\mathcal{O}(\alpha_s\alpha)$ NNLO corrections:

$$\sigma_{\text{QCD}\times\text{EW}}^{\text{NLO}} - \sigma_{\text{QCD+EW}}^{\text{NLO}} = \frac{\delta\sigma_{\text{QCD}}^{\text{NLO}} \times \delta\sigma_{\text{EW}}^{\text{NLO}}}{\sigma^{\text{LO}}}$$

$\mathrm{EW}_{\mathrm{virt}}$ approximation

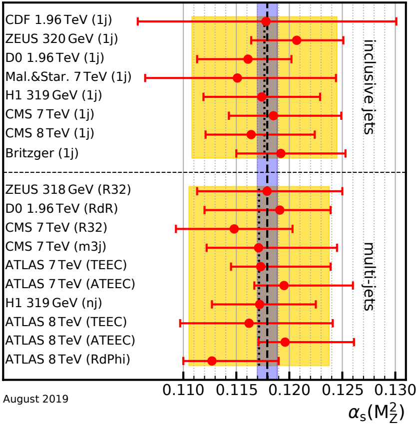
- multijet merging in $\mathrm{EW}_{\mathrm{virt}}$ approximation: [Kallweit *et al.*, 2016]

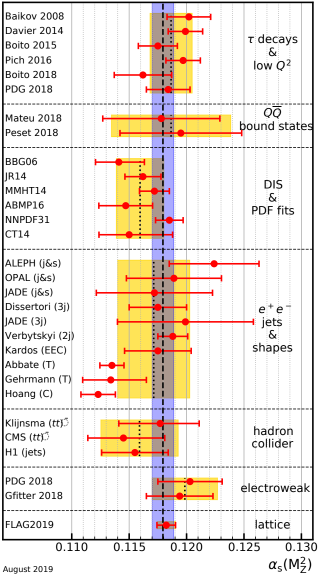
$$\mathrm{d}\sigma_{\mathrm{NLO\,EW_{virt}}} = \left[B(\Phi_n) + V_{\mathrm{EW}}(\Phi_n) + I_{\mathrm{EW}}(\Phi_n)\right]\mathrm{d}\Phi_n$$

$\Rightarrow$ no double counting issue
$\Rightarrow$ EW-NLO accurate multijet merging with LO complexity

Uncertainties in $\alpha_s(M_Z^2)$ Determination

[Workman, 2022]





R_{32} at NNLO QCD

[Czakon *et al.*, 2021]