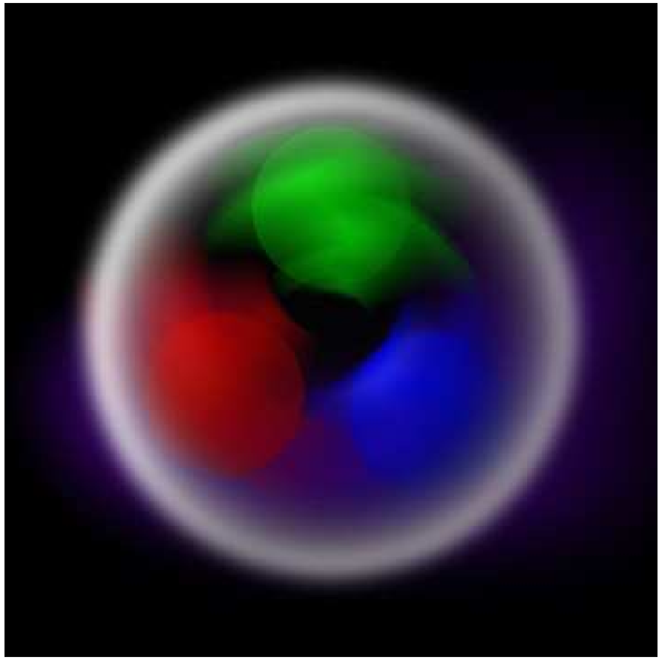
Electroweak Physics in the LHC Era: Tool or Target?

Research Training Group Münster

Annual Retreat 2015

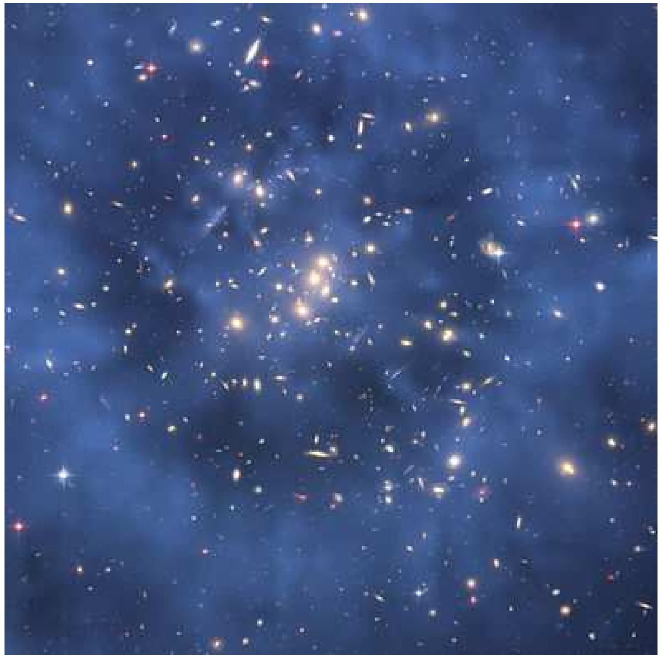
Barbara Jäger
University of Tübingen

Strong and Weak Interactions . . .



. . . from Hadrons . . .

. . . to Dark Matter



the world's largest hadron collider . . .

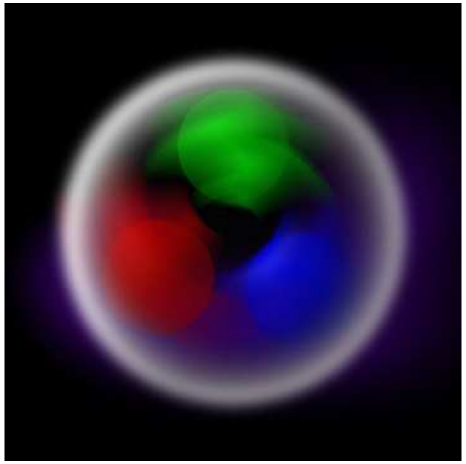
. . . the Large Hadron Collider (LHC) at CERN

how to calculate cross sections for the LHC

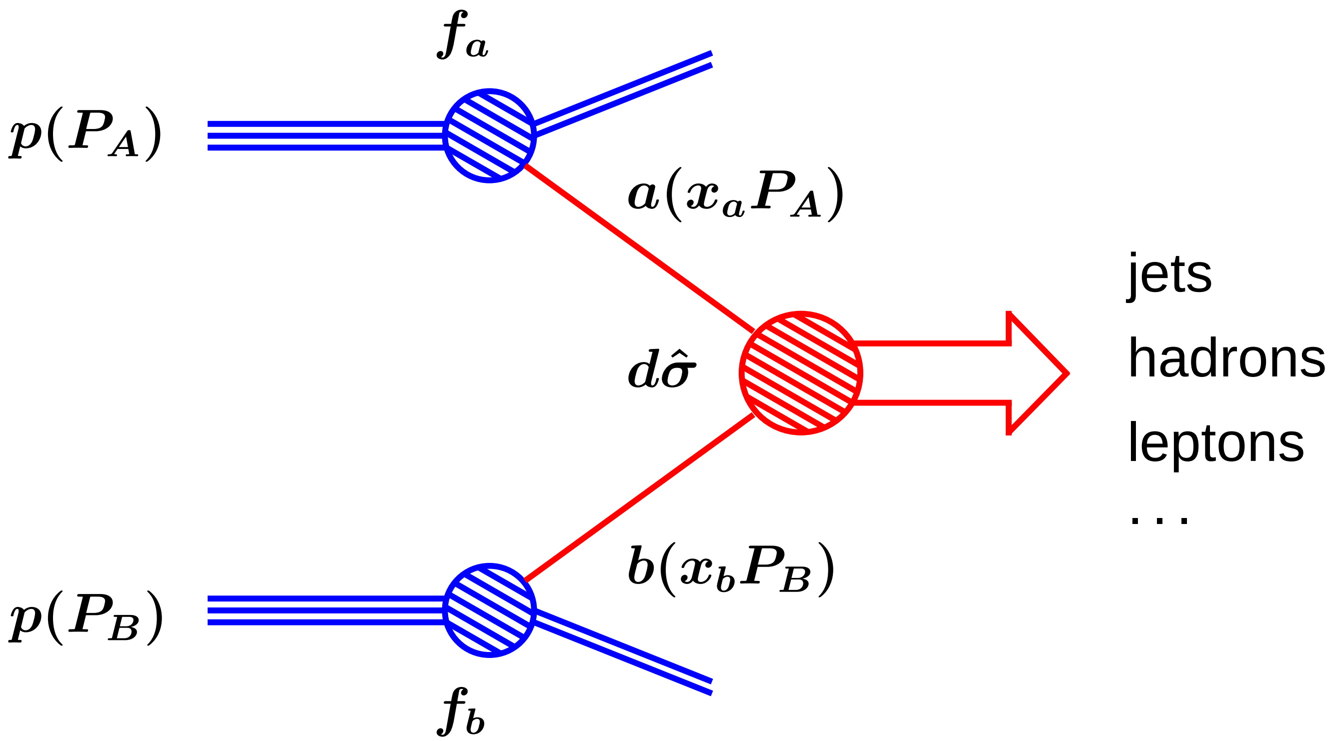
- high energies $\to$ can calculate QCD processes perturbatively
- EW coupling: sufficiently small for perturbation theory
- Feynman rules $\to$ in principle calculate
  any process at any order in perturbation theory
- but: perturbative calculations for quarks and gluons

☞ have to connect

partons $\leftrightarrow$ protons

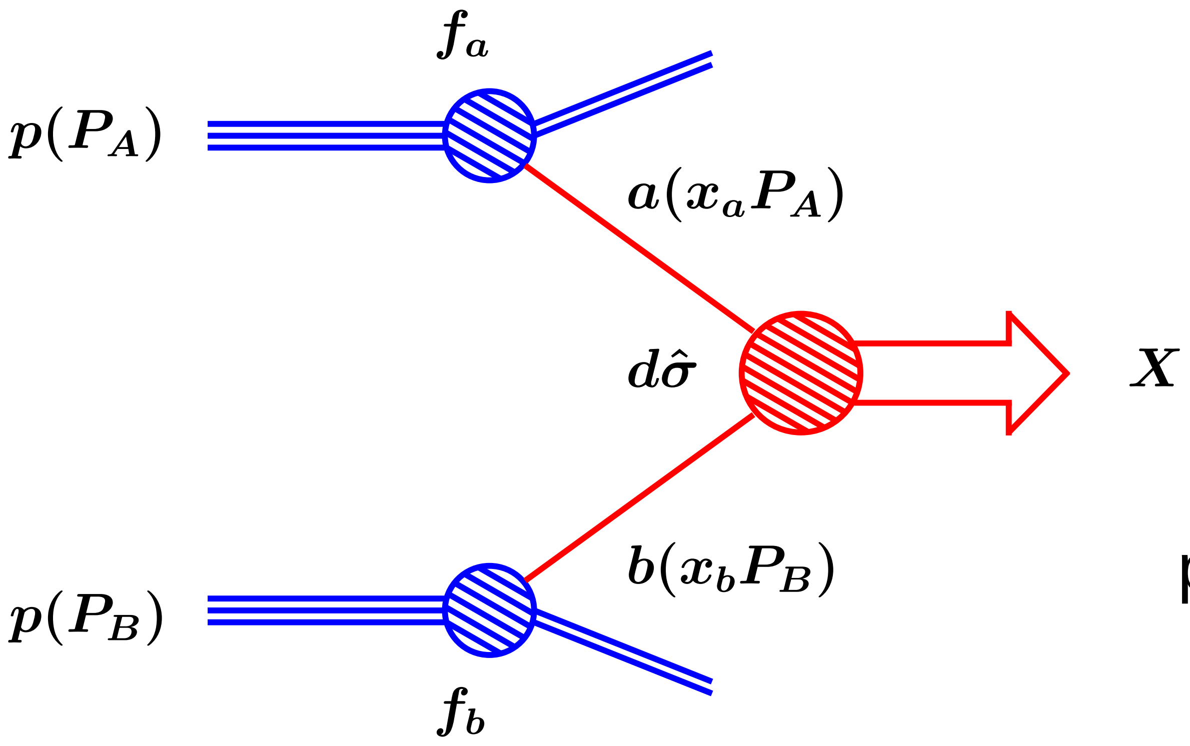


hadron-hadron collision



$$d\sigma^{pp\to X} = \sum_{a,b} \int_0^1 dx_a \int_0^1 dx_b \, f_a(x_a, \mu_F) f_b(x_b, \mu_F) \times d\hat{\sigma}^{ab\to X}(x_a P_A, x_b P_B, \mu_F, \mu_R)$$

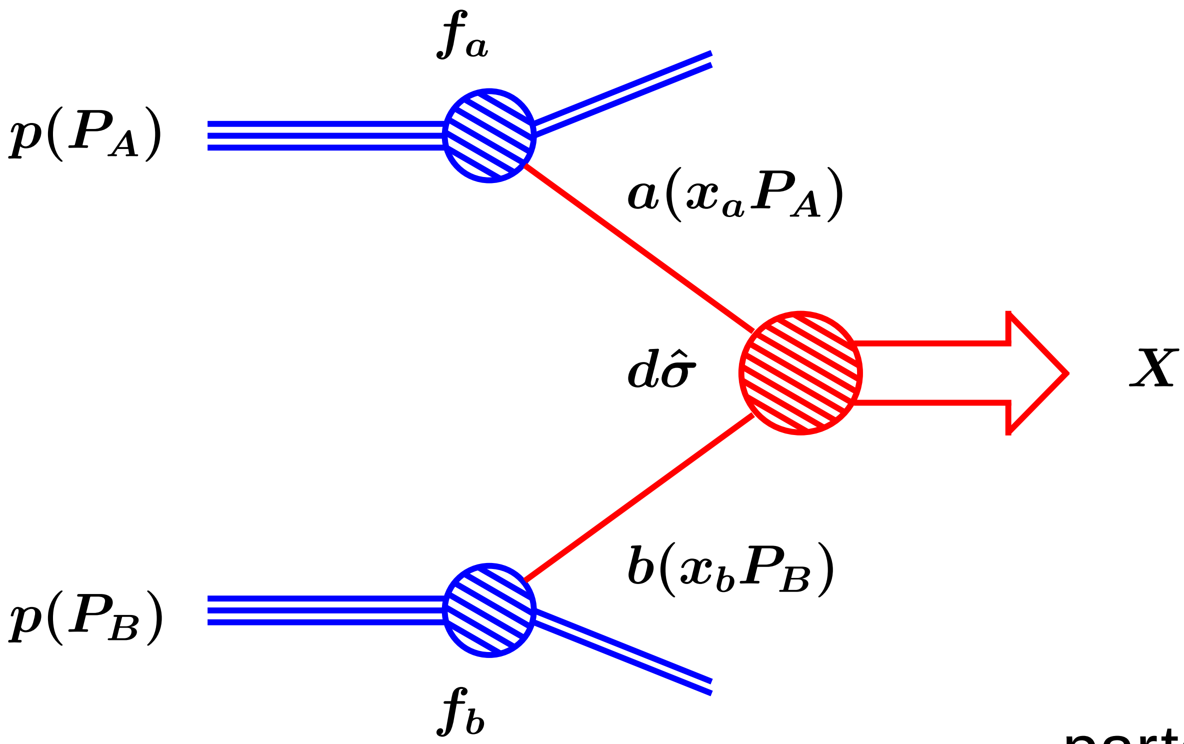
hadron-hadron collision



parton distribution functions

$$d\sigma^{pp\to X} = \sum_{a,b} \int_0^1 dx_a \int_0^1 dx_b\, f_a(x_a,\mu_F) f_b(x_b,\mu_F) \times d\hat{\sigma}^{ab\to X}(x_a P_A, x_b P_B, \mu_F, \mu_R)$$

hadron-hadron collision

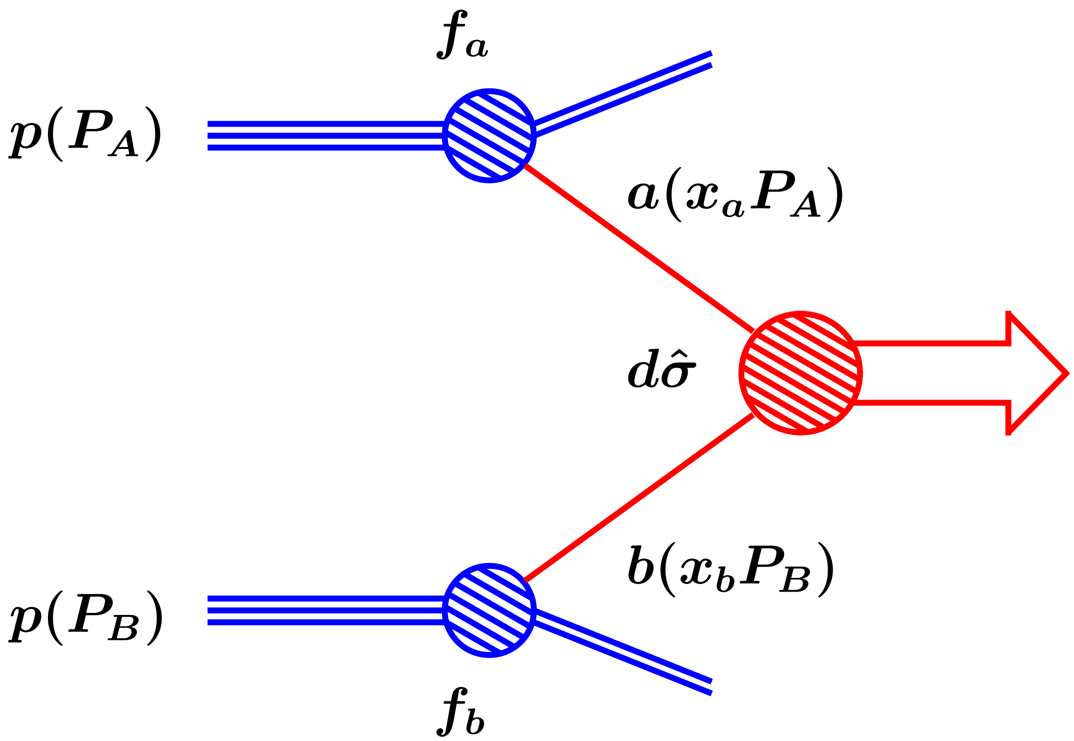


partonic cross section

$$d\sigma^{pp\to X} = \sum_{a,b} \int_0^1 dx_a \int_0^1 dx_b\, f_a(x_a,\mu_F) f_b(x_b,\mu_F)$$

$$\times d\hat{\sigma}^{ab\to X}(x_a P_A, x_b P_B, \mu_F, \mu_R)$$

hadron-hadron collision

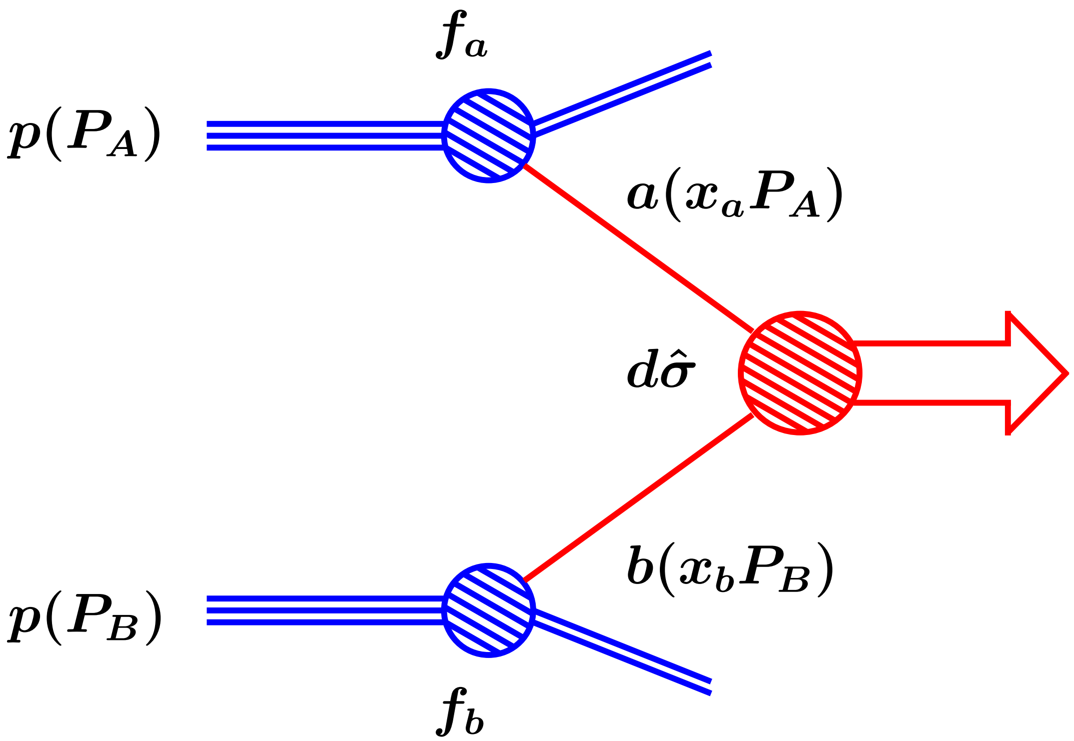


energy available for hard scattering:

$$\sqrt{\hat{s}} = \sqrt{x_a x_b S}$$

$$d\sigma^{pp\to X} = \sum_{a,b} \int_0^1 dx_a \int_0^1 dx_b \, f_a(x_a, \mu_F) f_b(x_b, \mu_F) \times d\hat{\sigma}^{ab\to X}(x_a P_A, x_b P_B, \mu_F, \mu_R)$$

factorization



foundation for predictive power of pQCD:

long-distance structure of hadrons

can be separated from

hard parton scattering

at specific scale μ_F

$$d\sigma^{pp\to X} = \sum_{a,b}\int_0^1 dx_a \int_0^1 dx_b\, f_a(x_a,\mu_F) f_b(x_b,\mu_F) \times d\hat{\sigma}^{ab\to X}(x_a P_A, x_b P_B, \mu_F, \mu_R)$$

“electroweak physics” – definition:

a : electroweak processes

(dominated by electroweak interactions)

b : electroweak corrections

(can be applied to any process;

particulary important for electroweak processes)

this talk: abbreviate electroweak as “EW”

EW corrections: why worry?

- LHC-2 is operating at 13 TeV

  $\longrightarrow$ reach energy range (more) sensitive to EW effects;
  EW corrections ($\delta_{\mathbf{EW}}$) can reach some 10%

- integrated LHC luminosity will reach several 100 fb^{-1}

  $\longrightarrow$ many measurements at few-percent level
  (= typical size of EW corrections)

- planned high-precision measurements:

  EW parameters, (anomalous) couplings,...
  $\longrightarrow$ $\delta_{\mathbf{EW}}$ is crucial ingredient

EW corrections: generic features

naive expectation:

$\alpha \sim \alpha_s^2 \rightarrow$ NLO EW $\sim$ NNLO QCD ?

but: systematic enhancements possible, e.g.:

- kinematic effects
- photon emission $\rightarrow$ mass-singular logs, e.g. $\frac{\alpha}{\pi} \ln\left(\frac{Q}{m_\mu}\right)$
- high energies $\rightarrow$ EW Sudakov logs, e.g. $\frac{\alpha}{\pi} \ln^2\left(\frac{Q}{M_W}\right)$

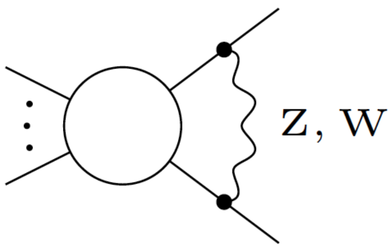
EW corrections: Sudakov logarithms

typical $2 \to 2$ process: at high energy
EW corrections enhanced by large logs

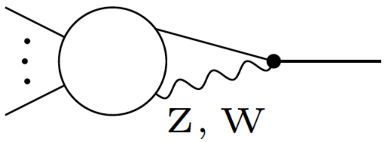
$$\ln^2\left(\frac{Q^2}{M_W^2}\right) \sim 25 \text{ @ energy scale of 1 TeV}$$

universal origin of leading EW logs:

mass singularities in virtual corrections related to external lines



soft and collinear virtual gauge bosons: $\to$ double logs



soft or collinear virtual gauge bosons: $\to$ single logs

EW corrections: Sudakov logarithms

compare to QED / QCD:

IR singularities of virtuals canceled
by real-emission contributions

electroweak bosons massive

$\rightarrow$ real radiation experimentally distinguishable

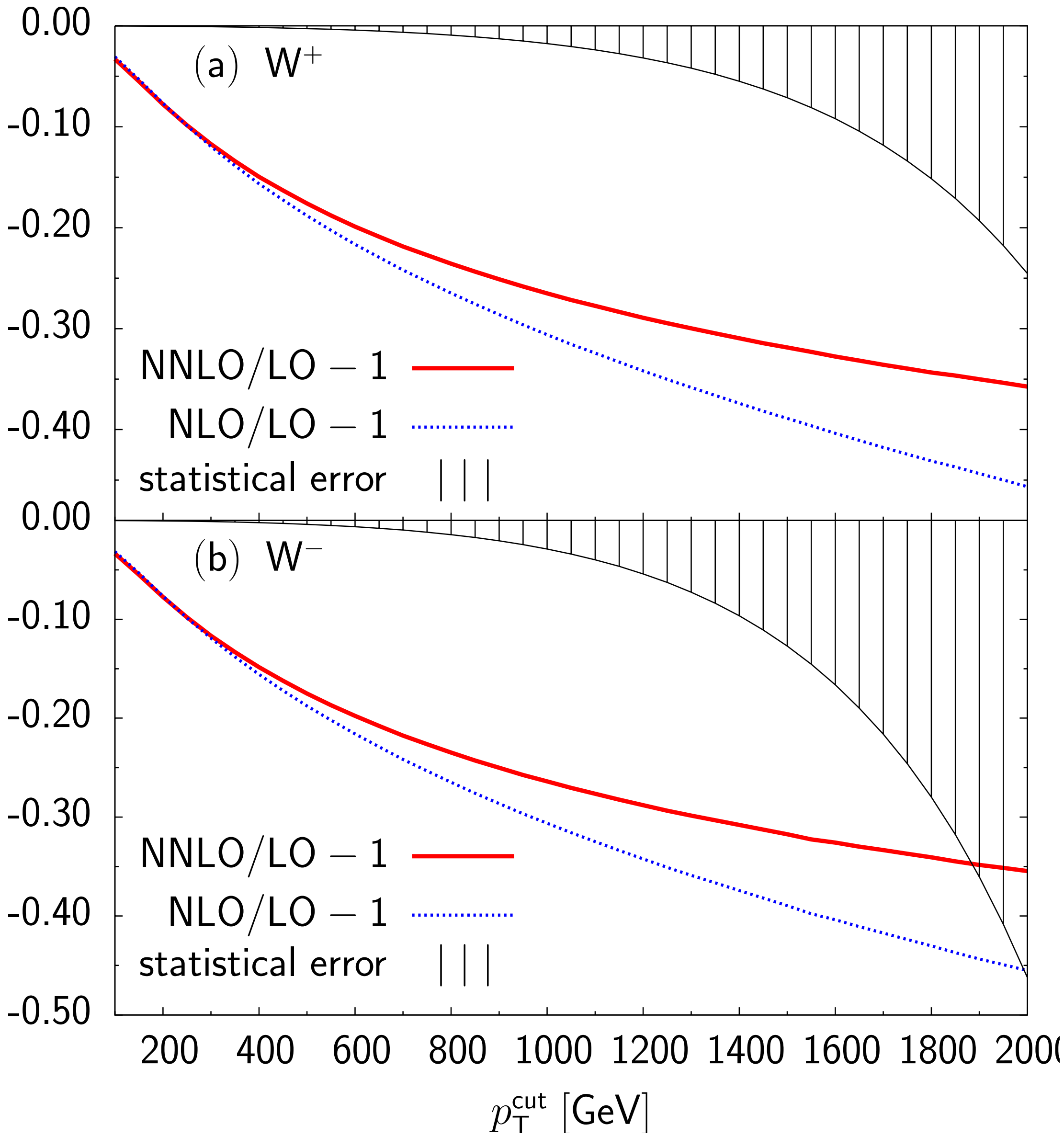
non-Abelian charges of W, Z are open

$\rightarrow$ Bloch-Nordsieck theorem not applicable

M. Ciafaloni, P. Ciafaloni, Comelli; Beenakker, Werthenbach; Denner, Pozzorini; Kühn et al., Baur; . . .

impact of EW Sudakov logarithms

Kulesza et al. (2007)



$pp \to Wj$ at 14 TeV:

tails of distributions receive large corrections!

input parameter schemes

SM input parameters: $\alpha_s, \alpha, M_W, M_Z, M_H, m_f, V_{\text{CKM}}$

EW sector: freedom in choice of α to

- avoid sensitivity to non-perturbative effects
- minimize universal EW corrections

schemes: fix M_W, M_Z, choose α:

- $\alpha(0)$ scheme: external photons
- $\alpha(M_Z)$ scheme: internal photons at high energies ($\gamma^\star$)
- G_μ scheme: W, Z bosons; $\alpha_{G_\mu} = \frac{\sqrt{2}G_\mu M_W^2}{\pi}\left(1 - \frac{M_W^2}{M_Z^2}\right)$

nota bene:

- global choice of α in gauge-invariant contributions mandatory
- weak mixing angle $\sin\theta_W$ no free parameter for fixed M_W, M_Z
- Yukawa couplings are uniquely fixed by fermion masses

EW effects in PDFs

collinear splittings $q \to q\gamma$, $\gamma \to q\bar{q}$ lead to quark mass singularities $\sim \alpha \log m_q \to$ factorize into redefined PDFs $\to \mathcal{O}(\alpha)$ corrections to all PDFs and new photon PDF

MRST2004QED: first PDF set with $\mathcal{O}(\alpha)$ corrections

NNPDF2.3QED (2013): NNPDF set with $\mathcal{O}(\alpha)$ corrections

- currently best PDF prediction at (N)NLO QCD + NLO QED
- PDF samples for error estimate provided
- photon PDF fitted to DIS and Drell-Yan data $(10^{-5} \lesssim x \lesssim 10^{-1})$

  lack of experimental information for large x

  (constrain via $\gamma\gamma \to \mu^+\mu^-$ or W^+W^- in the future?)
- small $\mathcal{O}(\alpha)$ ambiguity still remains

electroweak physics at the LHC

- improved determination of electroweak parameters:

  $$M_W,\, m_{\mathrm{top}},\, \sin^2\theta_W,\, M_H$$

  $\rightarrow$ improved precision tests of electroweak SM
  or its extensions (like MSSM)

- improved measurement of gauge-boson self-interactions
  (triple and quartic gauge couplings)

- discovery of the Higgs boson and study of its properties

- study of strong electroweak interactions (if relevant)

- search for physics beyond electroweak SM (if relevant)

how to access selected SM properties

- improved measurement of the W-boson mass:

$$pp \to W \to \ell\nu_\ell + X$$

- improved measurement of the effective weak mixing angle:

$$pp \to Z \to \ell\ell + X$$

- improved measurement of non-Abelian triple gauge couplings:

$$pp \to WW, WZ, ZZ$$
$$pp \to W\gamma, Z\gamma$$

- measurement of (anomalous?) quartic gauge couplings:

$$pp \to VVV, VV\gamma$$
$$pp \to VVjj \text{ (vector-boson scattering)}$$

- determination of the Higgs boson's properties:

various production and decay modes

new physics at the LHC

new physics may reveal itself by:

- ✥ spectacular new signatures that are easily distinguishable from SM

  example: new resonance in $pp \to \mu^+\mu^-$ (like a Z')
  but: so far nothing of this sort found

- ✥ less spectacular signatures with SM background (e.g. excess)

  example: missing energy in production of SUSY particles
  ☞ need SM prediction

- ✥ (small) deviations from SM predictions

  examples: anomalous couplings,
  contributions of heavy fermions via loop processes
  ☞ need precise SM prediction

in the absence of striking new signatures, to distinguish new physics from SM effects need precise predictions of SM processes!

what theorists need to provide

... precise experiments require adequate theoretical predictions:

- NLO QCD corrections:
  basically needed for all hard scattering processes at the LHC

- NNLO QCD corrections:
  needed for some processes like single W/Z production

- NLO EW corrections:
  generically $\mathcal{O}(\alpha) \sim \mathcal{O}(\alpha_s^2)$, but systematic enhancements by
  - logarithms $\sim \ln^n(M_W/Q)$ at high scales Q
  - kinematic effects from photon radiation off leptons

- more precision might be relevant for some processes
  (NNLO EW corrections, resummation,
  QCD$\times$EW interference effects ...)

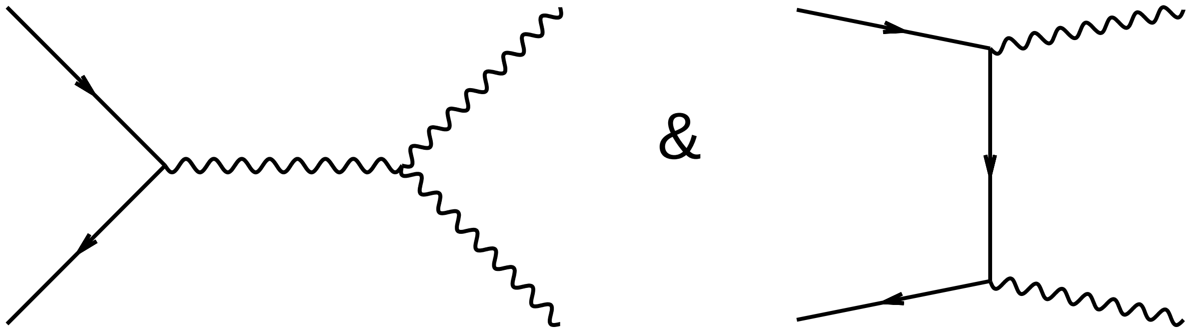
“electroweak physics”

electroweak processes

(here: will present a biased selection)

- gauge boson pair production
- multi gauge boson production
- vector boson scattering

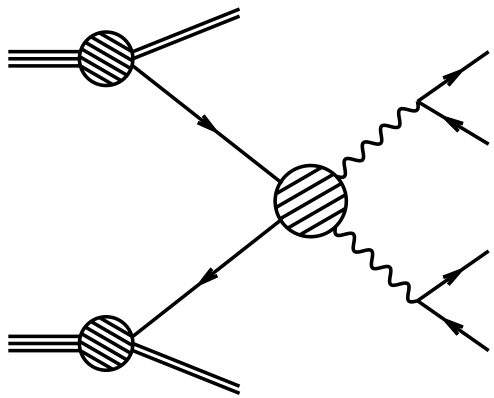
gauge-boson pair production



probe non-Abelian structure of the SM at high energies:

- (anomalous) triple-gauge-boson couplings
- dynamics of longitudinal massive gauge bosons

gauge-boson pair production



$$pp \to VV \to 4f$$

constitutes important class of
background processes to:

- the Higgs search in the mode $pp \to H \to VV \to 4f$
- new physics searches with leptons+$\not{E}_T$ signatures
  (e.g. SUSY-particle pair production)

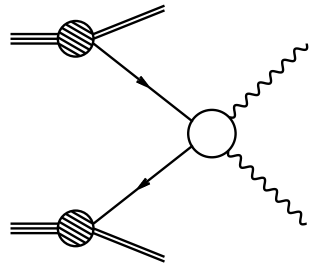
gauge-boson pair production @ NLO QCD

$h_1 h_2 \to ZZ$:

Ohnemus, Owens (1991) / Mele, Nason, Ridolfi (1991)

$h_1 h_2 \to W^{\pm} Z$:

Ohnemus (1991) / Frixione, Nason, Ridolfi (1992)



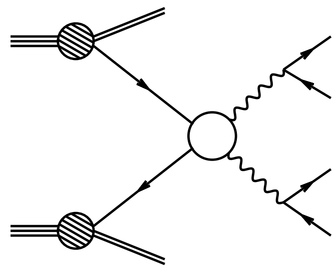
$h_1 h_2 \to W^{+} W^{-}$:

Ohnemus (1991) / Frixione (1993)

including leptonic decays:

analytical expressions:

Dixon, Kunszt, Signer (1998) / Baur, Han, Ohnemus (1996)



implementation in public code `MCFM`:

Campbell, Ellis (1999)

gauge-boson pair production @ NLO QCD

$$pp \to W^+(\to e^+\nu_e)W^-(\to \mu^-\overline{\nu}_\mu)$$

$\sqrt{s}$ [TeV] and cuts	σ^{LO} [fb]	σ^{NLO} [fb]	K-factor
7 (basic)	144	249	1.73
7 (Higgs)	7.14	15.19	2.13
14 (basic)	296	566	1.91
14 (Higgs)	13.7	34.7	2.53

numbers taken from `MCFM`: *Campbell, Ellis, Williams (2011)*

gauge-boson pair production @ NLO QCD

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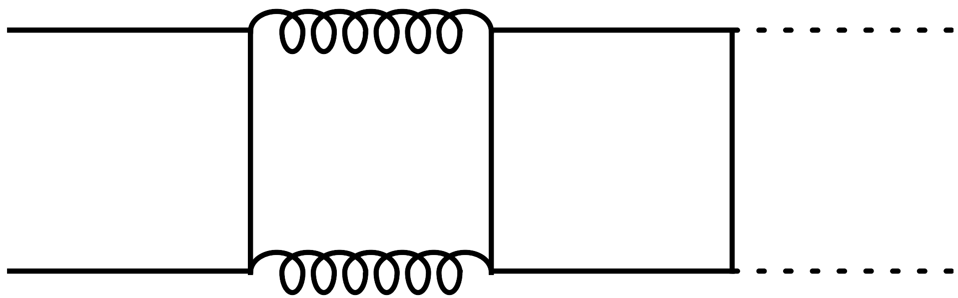
- size of NLO-QCD corrections is large and cut-dependent
- not expected from variation of central scale
  $M_W/2 \leq \mu_f \leq 2M_W$ at LO (← qg channels)

towards NNLO QCD for $pp \to VV$



✔ 2-loop master integrals for $\bar{q}q \to VV$

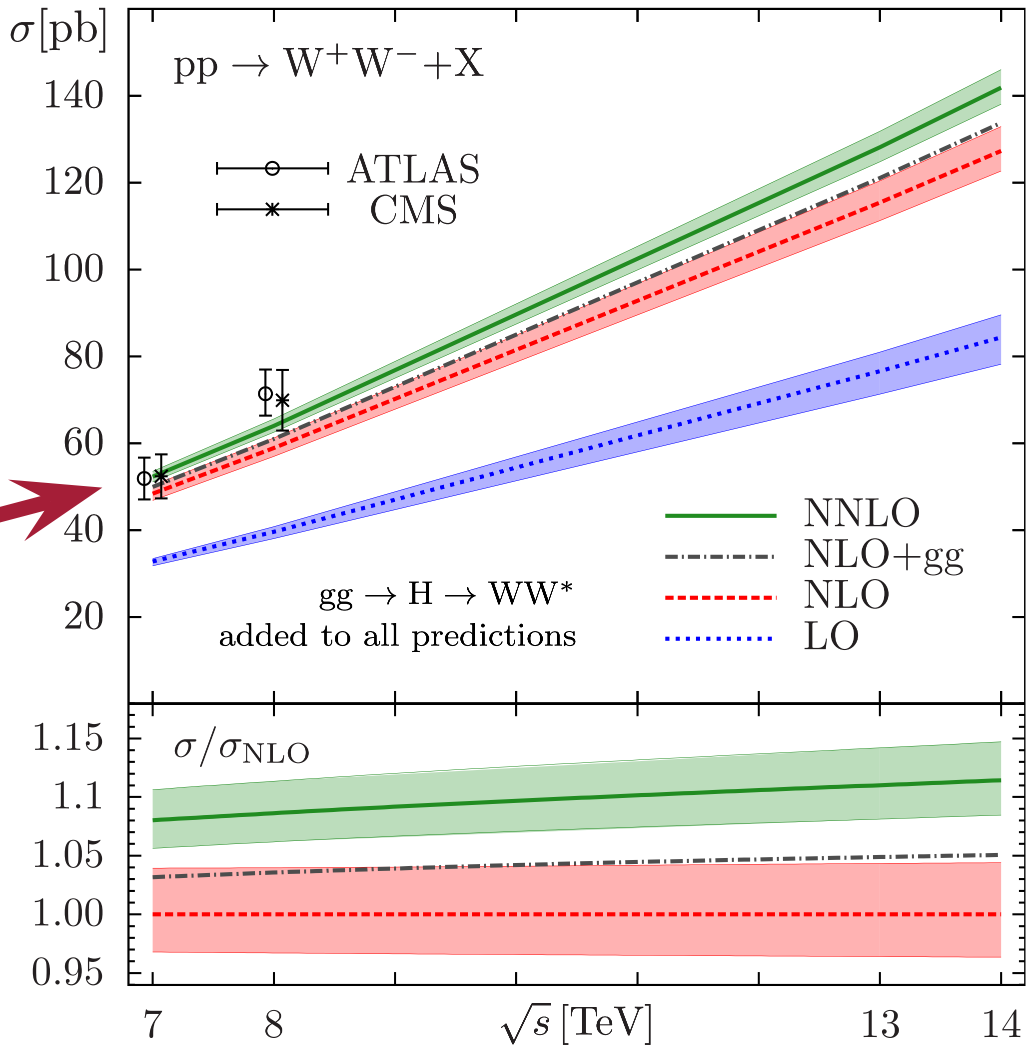
Gehrmann, Tancredi, Weihs (2013)

Gehrmann, von Manteuffel, Tancredi, Weihs (2014)

$pp \to WW$ @ NNLO QCD!

Gehrmann et al. (08/2014)

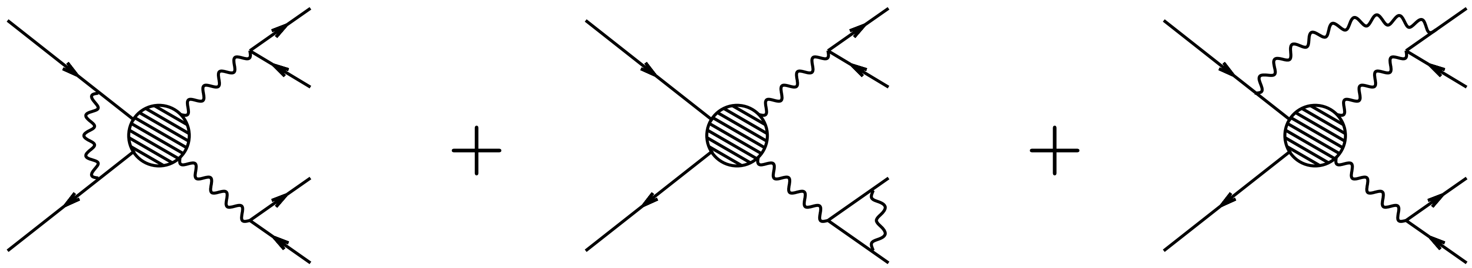
note:
improved agreement with LHC data



gauge-boson pair production beyond LO EW

$pp \to VV \to$ 4 leptons: $\mathcal{O}(\alpha)$ corrections

more challenging than QCD corrections:



$\to$ first step: employ approximations:

- retain only universal logarithms that are large at high energies
- double pole approximation for gauge bosons

Accomando, Denner, Pozzorini, Kaiser (2001-2004)

new physics effects in VV production

most general contribution to Lagrangian for WWV interaction, compatible with C and P conservation:

$$\mathcal{L}_{WWV} = g_{WWV}\Big[ig_1^V(W^*_{\mu\nu}W^{\mu}V^{\nu} - W_{\mu\nu}W^{*\,\mu}V^{\nu}) + i\kappa^V W^*_{\mu}W_{\nu}V^{\mu\nu} + i\frac{\lambda^V}{M_W^2}W^*_{\rho\mu}W^{\mu}_{\nu}V^{\nu\rho}\Big]$$

supplied by form factors to tame unitarity violations at high energies:

$$\Delta g \to \frac{\Delta g}{(1+M_{VV}^2/\Lambda^2)^2}$$

LEP bounds:

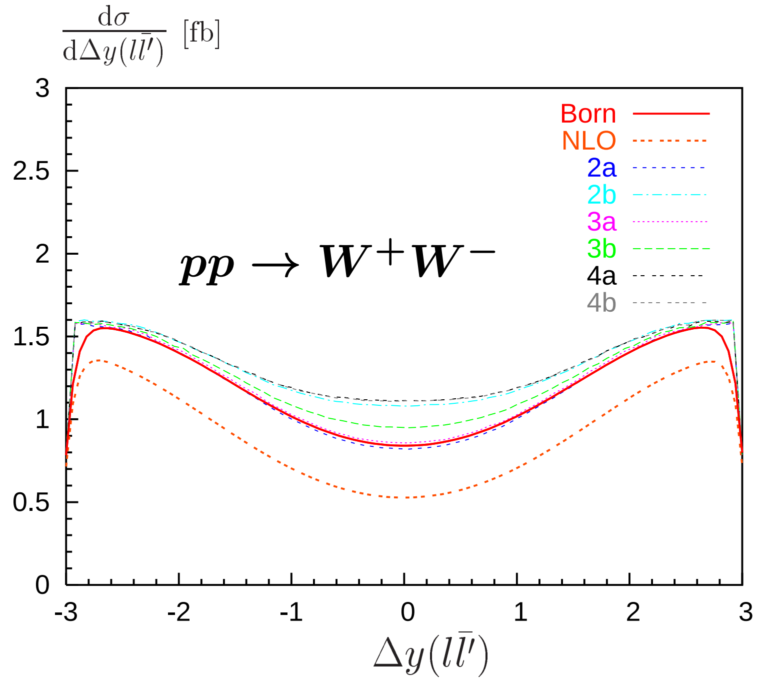
$$\Delta g_1^Z = (-0.054, 0.028),\ \ \Delta\kappa^\gamma = (-0.117, 0.067),$$
$$\Delta\lambda^Z = \Delta\lambda^\gamma = (-0.07, 0.012)$$

(SM: $g_1^V = \kappa^V = 1$ and $\lambda^V = 0$)

higher order or new physics effects?

parameterize new physics by anomalous triple gauge boson couplings λ, $\Delta\kappa_\gamma$, Δg_1^Z

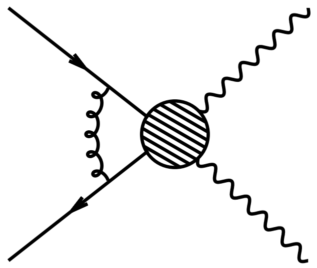
Accomando, Kaiser (2005)



Scenario	λ	Δg_1^Z	$\Delta\kappa_\gamma$
Born/NLO EW	0	0	0
2a/2b	0	± 0.02	0
3a/3b	0	0	± 0.04
4a/4b	± 0.02	0	0

missing EW corrections can fake anomalous triple-gauge boson couplings

on-shell gauge-boson pair production @ NLO EW



$\mathcal{O}(\alpha)$ corrections to

$pp \to VV$

Bierweiler, Kasprzik, Kühn, Uccirati (2012-2013)

Baglio, Ninh, Weber (2013)

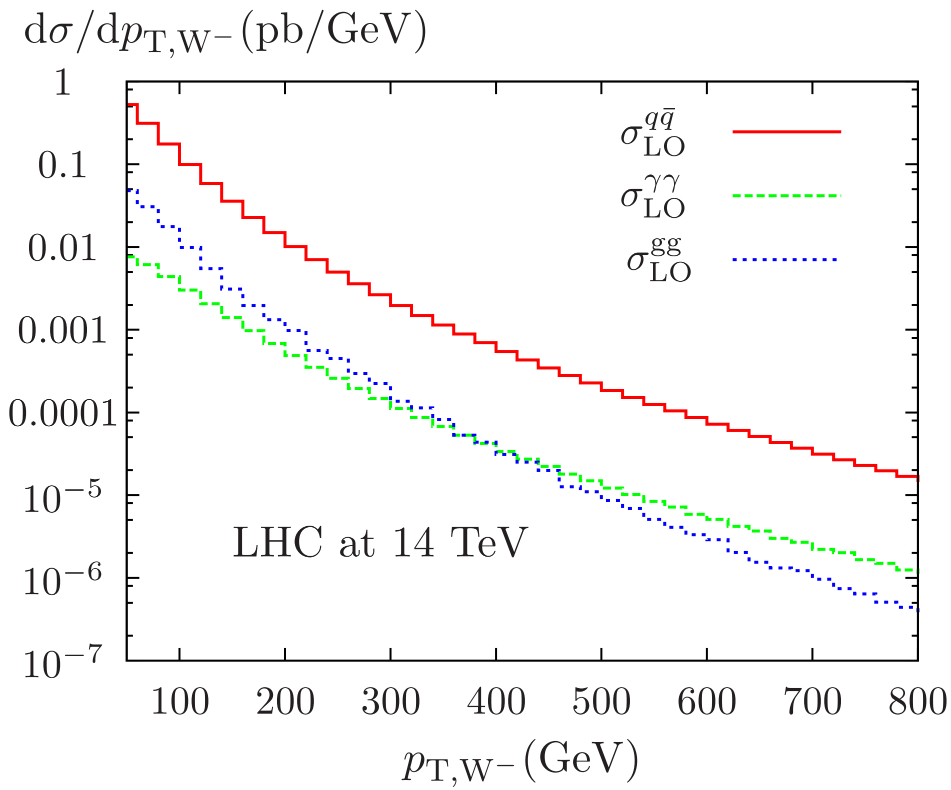
$\to$ EW corrections negative and small for inclusive x-secs,

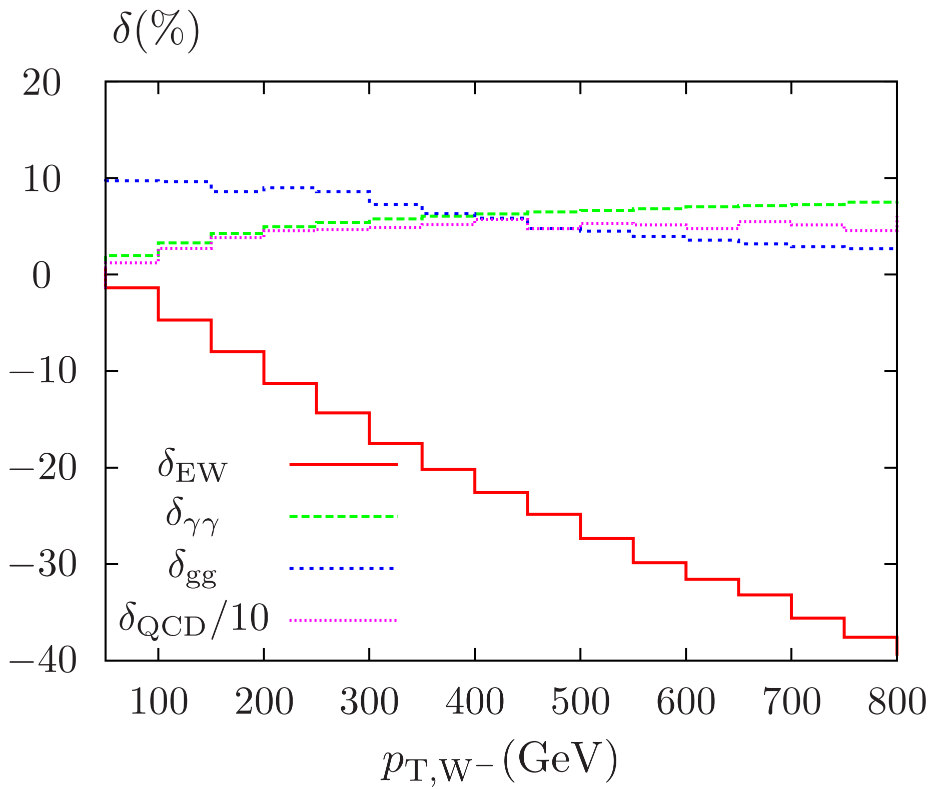
but can be large and negative in tails of distributions

(universal Sudakov logarithms)

on-shell gauge-boson pair production @ NLO EW

Bierweiler, Kasprzik, Kühn, Uccirati (2012)





NLO-EW beyond the on-shell approximation

leading order: full off-shell calculation

- light quark contributions ($q = u, d, c, s$)
- $b\bar{b}$-induced contributions ($< 2\%$)
- photon-induced contributions ($< 1\%$)

real-emission and virtual contributions:

for light quark channels use full off-shell calculation or double pole approximation

(analogous to Racoon approach for $e^+e^- \to 4$ fermions

[Denner, Dittmaier, Roth, Wackeroth (1999-2002)])

$pp \to WW \to \ell\nu\ell\nu$: cross section contributions

Billoni et al. (2013)

	$\sigma^{\mathrm{LO}}_{\bar{q}q}$ [fb]	$\delta_{\bar{q}q}$ [%]	$\delta_{q\gamma}$ [%]	$\delta_{\gamma\gamma}$ [%]	$\delta_{\bar{b}b}$ [%]
LHC14	412.5(1)	-2.7	0.6	0.7	1.7
LHC8	236.83(5)	-2.8	0.5	0.8	0.9
ATLAS cuts	163.84(4)	-3.0	-0.3	1.0	1.0

ATLAS inspired cuts:

$p_{T,\ell} > 20$ GeV, $|y_\ell| < 2.5$

$p^{\mathrm{leading}}_{T,\ell} > 25$ GeV, $E^{\mathrm{miss}}_T > 25$ GeV,

$R_{e\mu} > 0.1$, $M_{e\mu} > 10$ GeV

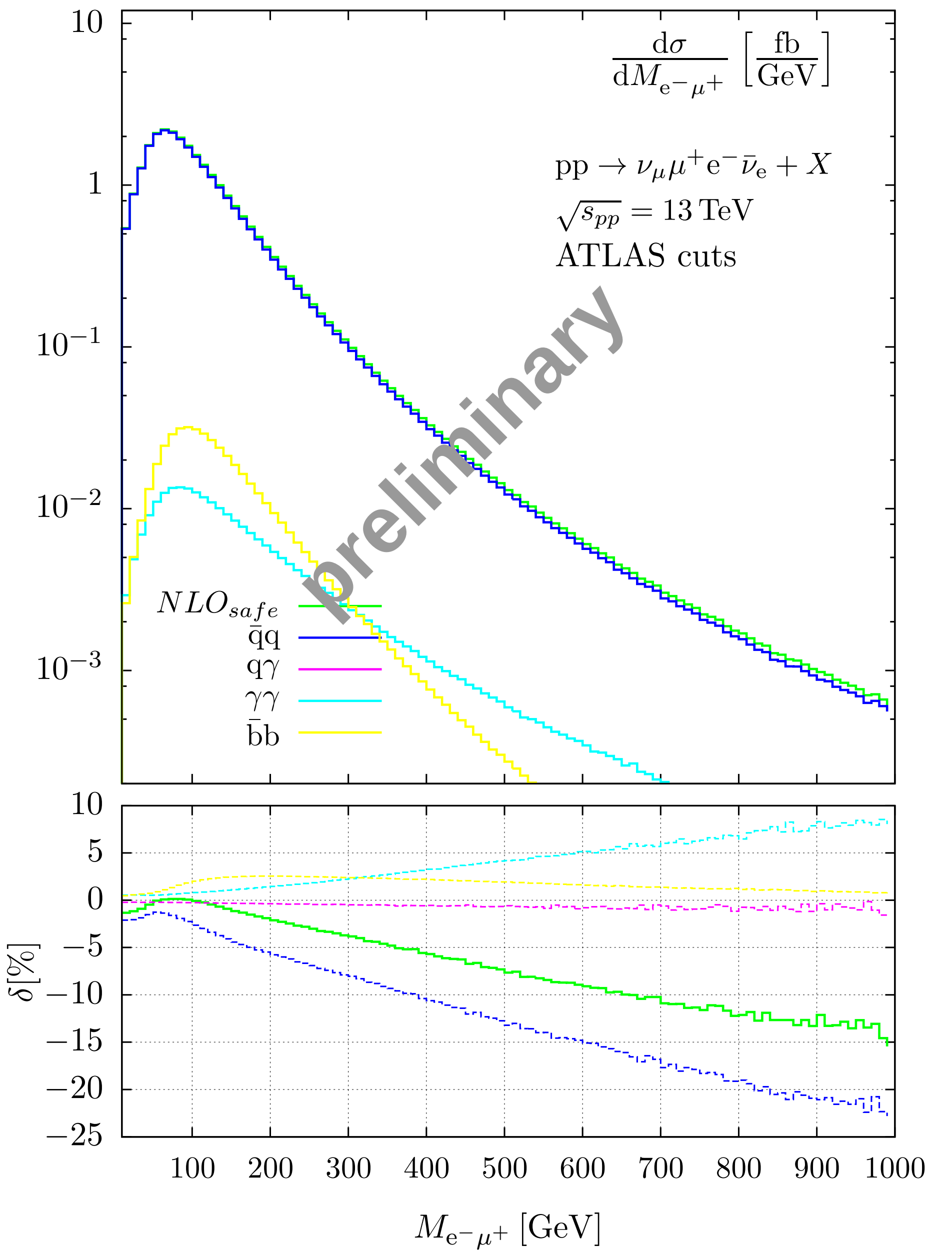
jet veto: not jets with $p_{T,j} > 25$ GeV

minimal cuts:

$p_{T,\ell} > 20$ GeV, $|y_\ell| < 2.5$

jet veto: $p_{T,j} > 100$ GeV

invariant mass of the lepton system



full NLO EW calculation:

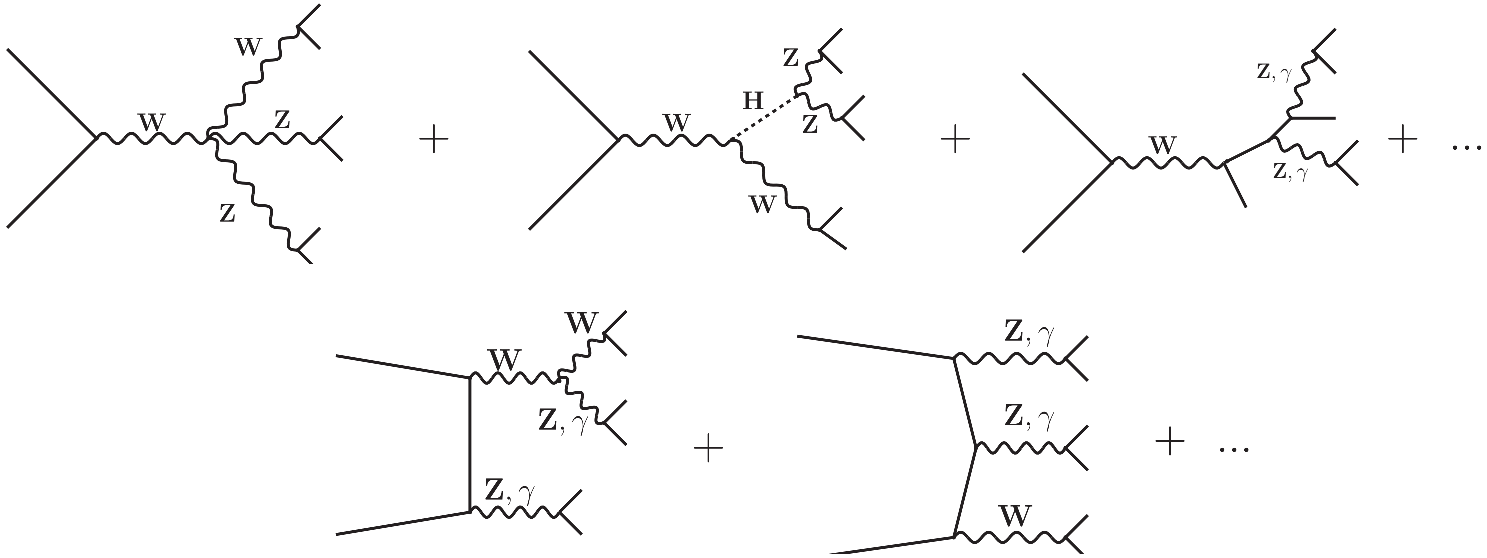
gives full control

on lepton distributions

and correlations

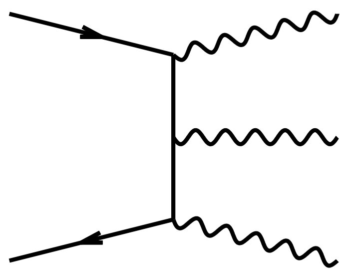
[Biedermann, Denner, Dittmaier, Hofer, B.J.]

triboson production



- SM background for new physics signatures with multi-leptons$+\not{p}_T$
- sensitive to (anomalous) triple and quartic gauge boson couplings
- NLO QCD corrections are large and strongly depend on observable and phase space region (drastically underestimated by LO scale variations)

triboson production @ NLO QCD



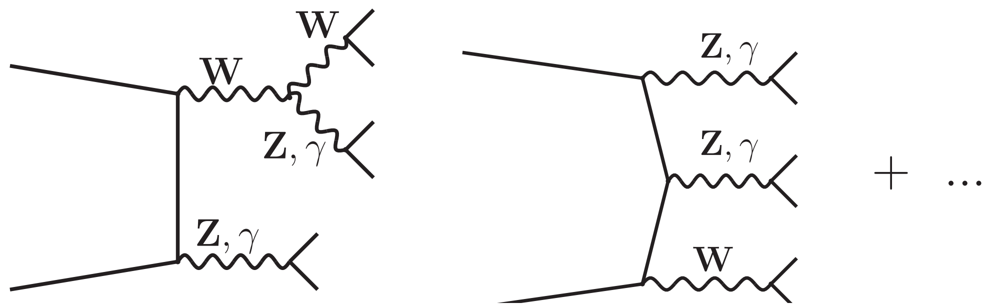
on-shell production

$pp \to ZZZ$:
Lazopoulos, Melnikov, Petriello (2007)

$pp \to VVV$:
Binoth, Ossola, Papadopoulos, Pittau (2008)

$pp \to W\gamma\gamma$:
Baur, Wackeroth, Weber (2010)

$pp \to WWZ$ (NLO QCD and EW):
Nhung, Ninh, Weber (2013)



including leptonic decays
and off-shell effects

$pp \to VVV$:
Campanario, Hankele, Oleari, Prestel, Rauch, Rzehak, Zeppenfeld (2007-2011)

example: $pp \to W^+W^-Z$ with decays

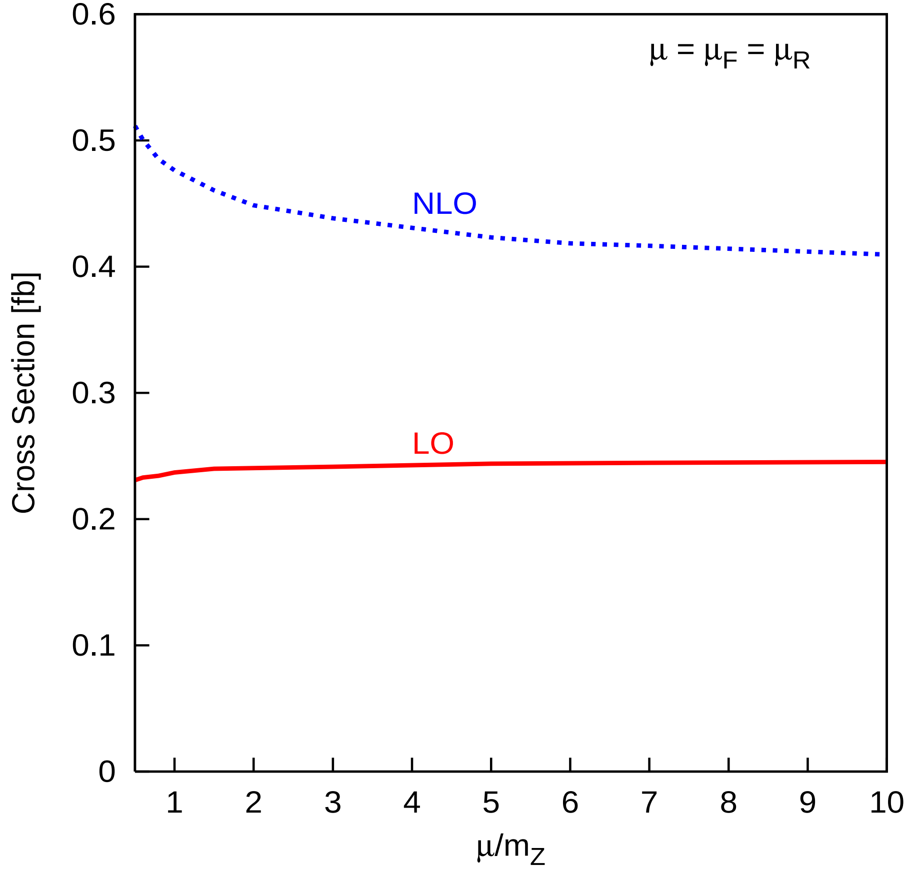
Hankele, Zeppenfeld (2007)

LO: very mild scale dependence

LO is $\mathcal{O}(\alpha_s^0)$,
PDFs probed in regions
with small μ_f dependence

but large QCD corrections with

$$\frac{\sigma^{NLO}}{\sigma^{LO}} \sim 1.7 \div 2.2$$

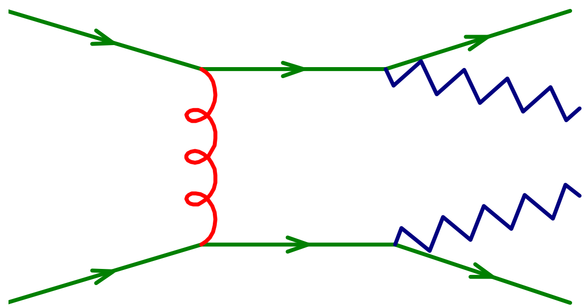


gauge-boson pairs in association with two jets

QCD-induced production

W^+W^+jj & W^+W^-jj:

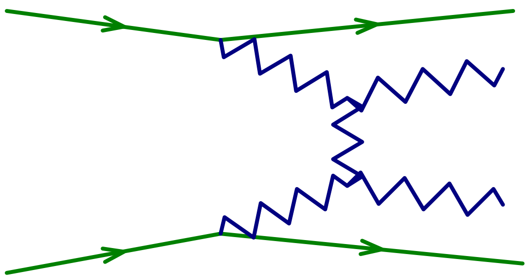
Melia, Melnikov, Rontsch, Zanderighi (2010-2011)



EW production

all $VVjj$ channels:

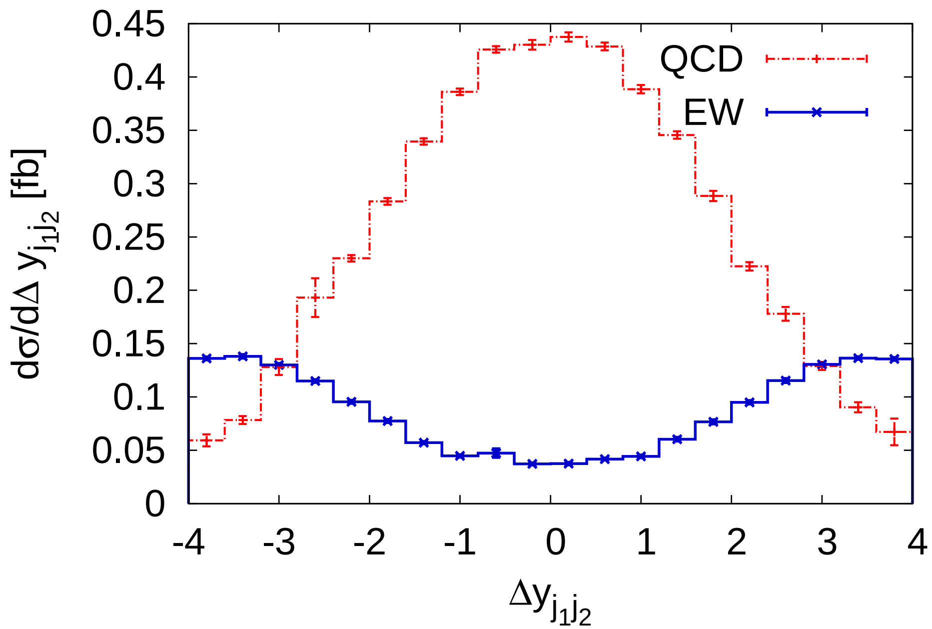
Bozzi, Oleari, Zeppenfeld, B.J. (2006-2009)

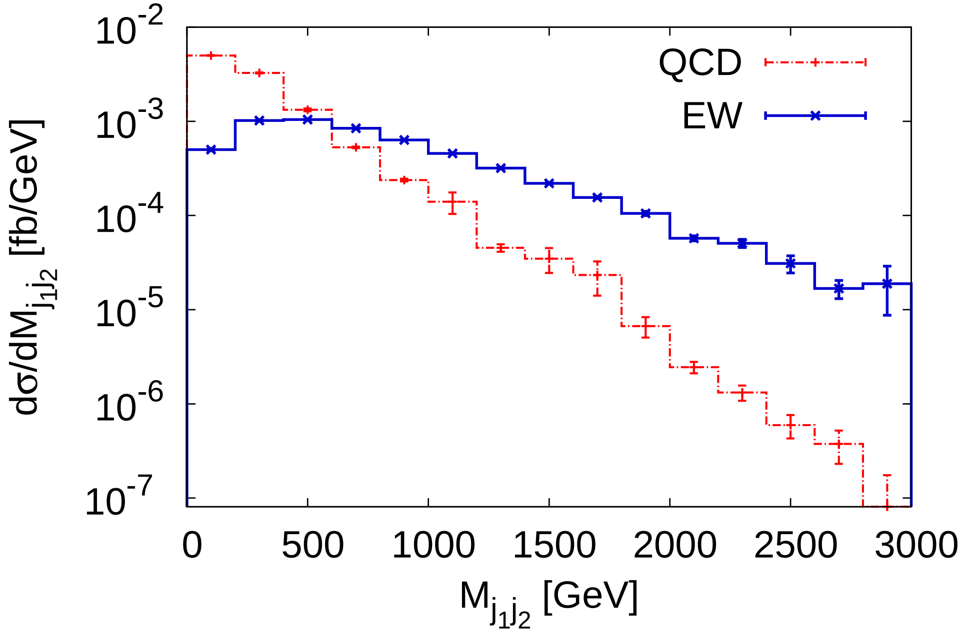


- W^+W^+jj ➠ distinct signature: same-sign leptons $+\not{E}_T+$ 2 jets
- W^+W^+jj ➠ test ground for multiple parton interactions
- $VVjj$ ➠ important backgrounds to search for Higgs and BSM in VBF channel

$pp \to W^+W^+jj$: QCD versus EW production

Zanderighi, B.J. (2011)





- $\sqrt{s} = 7$ TeV
- basic jet cuts only
- NLO-QCD accuracy

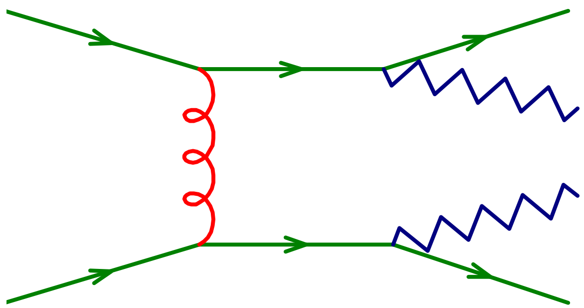
$pp \to W^+W^+jj$ in the POWHEG-BOX

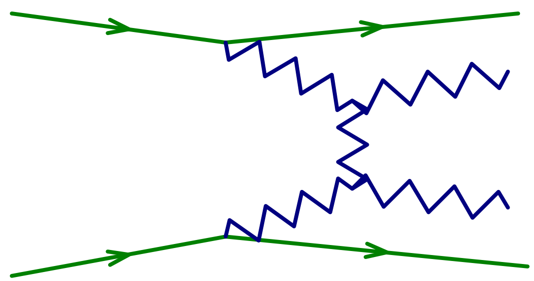
QCD-induced production

Melia, Melnikov, Rontsch, Zanderighi (2010);
Melia, Nason, Rontsch, Zanderighi (2011)

EW production

Oleari, Zeppenfeld, B.J. (2009);
Zanderighi, B.J. (2011)





NLO results with basic jet cuts only ($p_T^{\text{tag}} > 20$ GeV):

$\sigma_{\text{QCD}}^{\text{inc}} = 2.12$ fb

$\sigma_{\text{EW}}^{\text{inc}} = 1.097$ fb

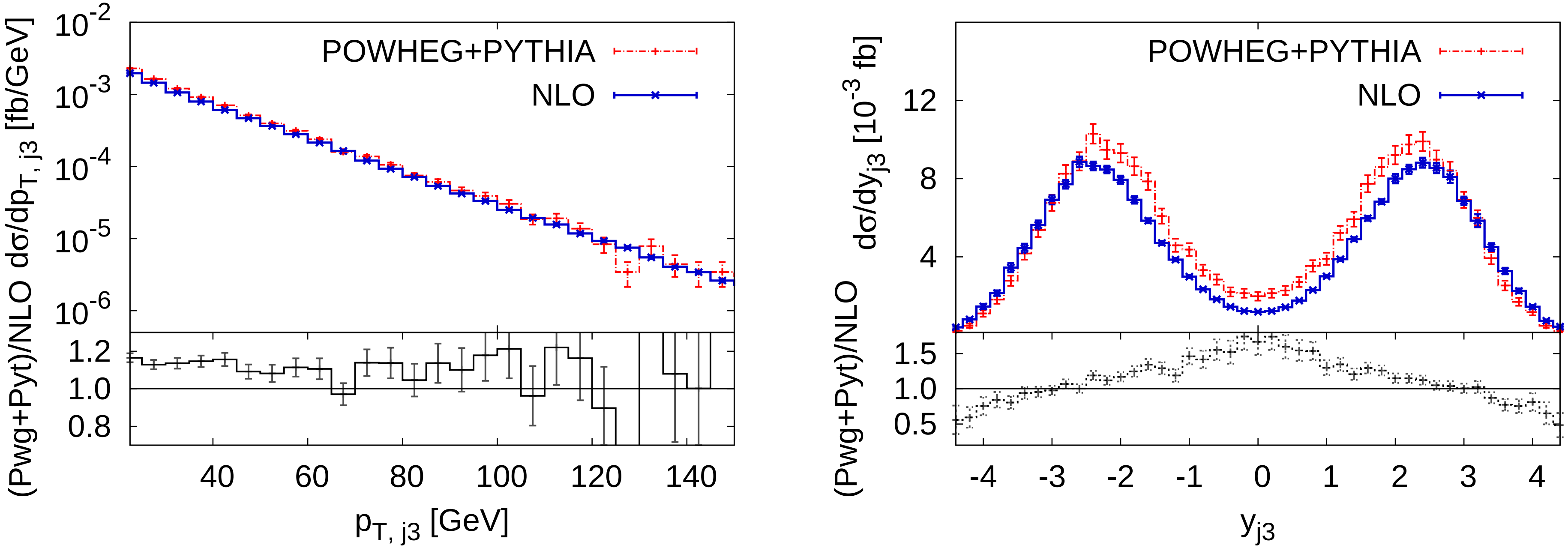
NLO results with VBF cuts:

$\sigma_{\text{QCD}}^{\text{cuts}} = 0.0074$ fb

$\sigma_{\text{EW}}^{\text{cuts}} = 0.201$ fb

$pp \to W^+W^+jj$ in the POWHEG-BOX

Zanderighi, B.J. (2011)



good agreement between parton-level NLO calculation and POWHEG matched with PYTHIA for many observables

typical for VBF processes: little jet activity at central rapidities
$\rightarrow$ exploited by central-jet veto techniques

note: parton-shower effects slightly enchance central jet activity

summary

- EW physics at the LHC is tool and target at the same time
- discussed selected processes:

  $$\boldsymbol{Vj},\ \boldsymbol{VV},\ \boldsymbol{VVjj},\ \boldsymbol{VVV}$$

- provide powerful probes of the structure of the Standard Model

  e.g. triple and quartic gauge boson couplings

- serve as important backgrounds

  . . . to searches for the Higgs boson
  . . . to searches for new physics

conclusions

impact of radiative corrections can be large and dependent on experimental selection criteria

↓

- to achieve precision required by experiment:
  - consider QCD and EW corrections
  - disregard (on-shell, high-energy, . . .) approximations
  - match to parton-shower programs

- calculations for selected processes advanced, several public tools available:

`MCFM, vbfnlo, POWHEG-BOX, ...`

Thank
You.