

Vector Boson Scattering (VBS) at the LHC:
QCD-/EW-Production and -Corrections

$$pp \rightarrow e^+ \nu_e \mu^+ \nu_\mu jj + X$$

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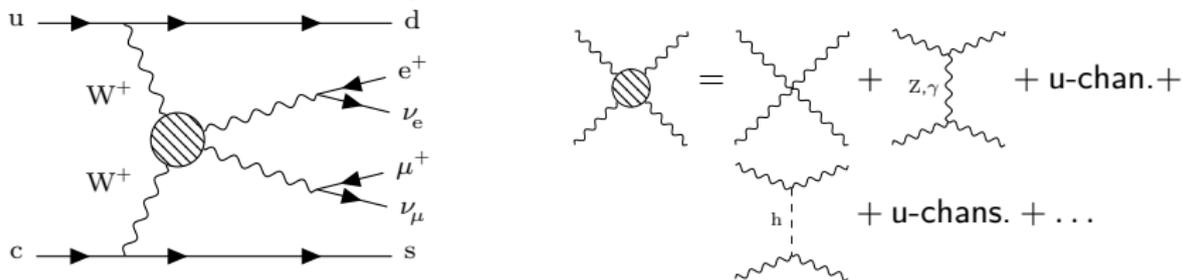
Albert-Ludwigs-Universität Freiburg

Zurich, Aug 25



Outline

- 1 Motivation: $pp \rightarrow e^+ \nu_e \mu^+ \nu_\mu jj + X$
- 2 Leading Order and Cross Sections
- 3 QCD and EW Corrections

Why study $pp \rightarrow e^+ \nu_e \mu^+ \nu_\mu jj + X$?

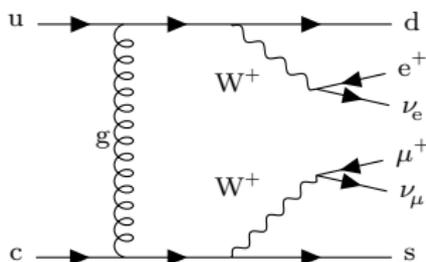
- Vector Boson Scattering (VBS): cancellations between diagrams for longitudinally polarized vector bosons—without Higgs ME can become arbitrarily large (\rightarrow Lee–Qigg–Thacker bound $m_h \lesssim 1 \text{ TeV}$)
- study EW symmetry breaking (EWSB)
- quartic gauge boson couplings (QGC) \rightarrow anomalous gauge couplings?

Similar processes:

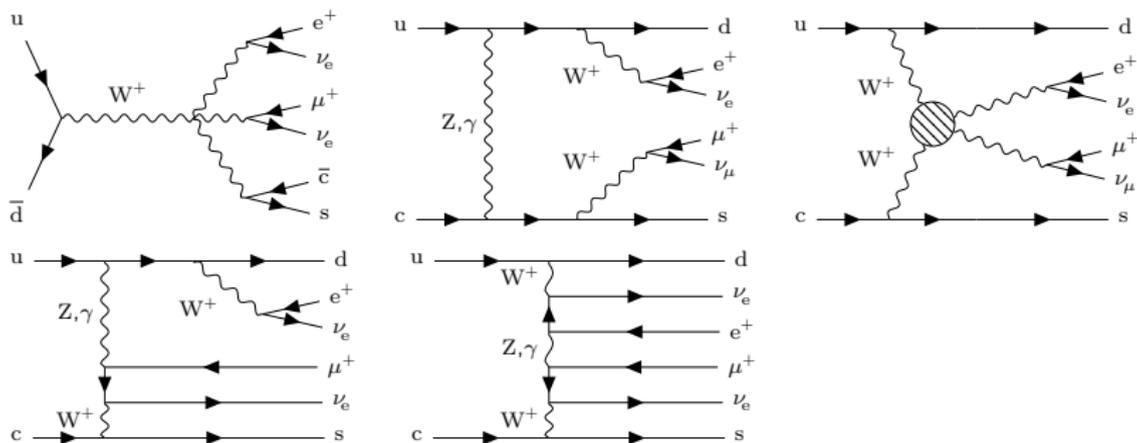
- lower cross section ($\sim 1 \text{ fb}$) than opposite-sign W -scattering, but background can be efficiently suppressed
- $pp \rightarrow e \bar{\nu}_e \mu \bar{\nu}_\mu jj + X$: MEs obtained by charge conjugation, but lower luminosity due to protons having positive charge
- $pp \rightarrow \{e \nu_e e \nu_e, \mu \nu_\mu \mu \nu_\mu\} jj + X \approx 0.5 \times$ (different leptons)

LO: QCD Production ($\alpha_s^2 \alpha^4$)

Representative diagram for \mathcal{M}_{QCD}



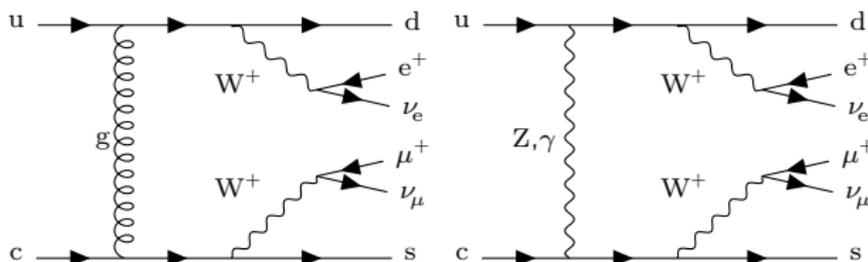
- surprisingly simple: 8 (16) diagrams for $uc \rightarrow e^+ \nu_e \mu^+ \nu_\mu ds$
($uu \rightarrow e^+ \nu_e \mu^+ \nu_\mu dd$)
- only double-resonant diagrams
- no gluons in the initial state (charge)

LO: EW Production (α^6)Classes of diagrams for \mathcal{M}_{EW} 

- 93 (186) diagrams for $uc \rightarrow e^+ \nu_e \mu^+ \nu_\mu ds$ ($uu \rightarrow e^+ \nu_e \mu^+ \nu_\mu dd$)
- (triple-), double- (including VBS), single-, and non-resonant diagrams
- also no initial-state gluons (charge)
- no α_s in ME \rightarrow scale variation via μ_F in PDFs

LO: EW-QCD Interference, Color Suppression

Example term from $2 \operatorname{Re}(\mathcal{M}_{\text{QCD}} \mathcal{M}_{\text{EW}}^*)$



→ color part is $T_{ud}^a T_{cs}^a \delta_{ud} \delta_{cs} = \operatorname{Tr}(T^a) \operatorname{Tr}(T^a) = 0$

→ non-vanishing parts for identical quarks when they are crossed

→ therefore suppressed (see total cross section)

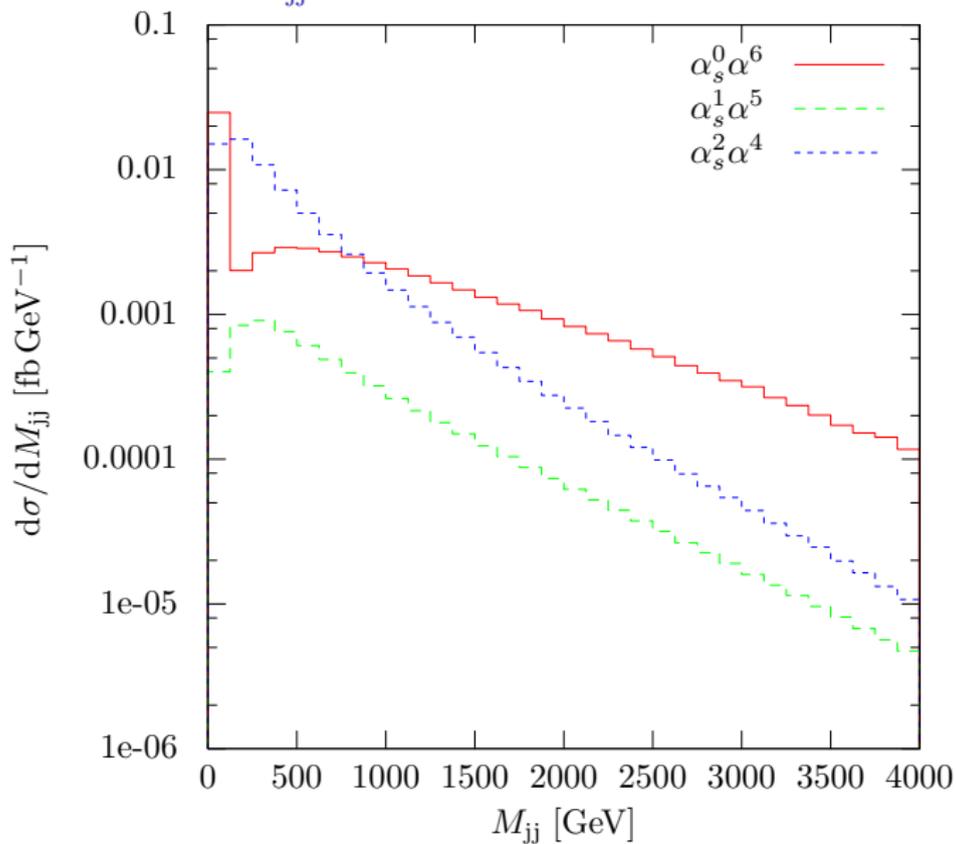
Motivates **VBF-approximation**: consider only t- and u-channel-like squared diagrams, no interferences, no s-channel diagrams in properly defined phase space

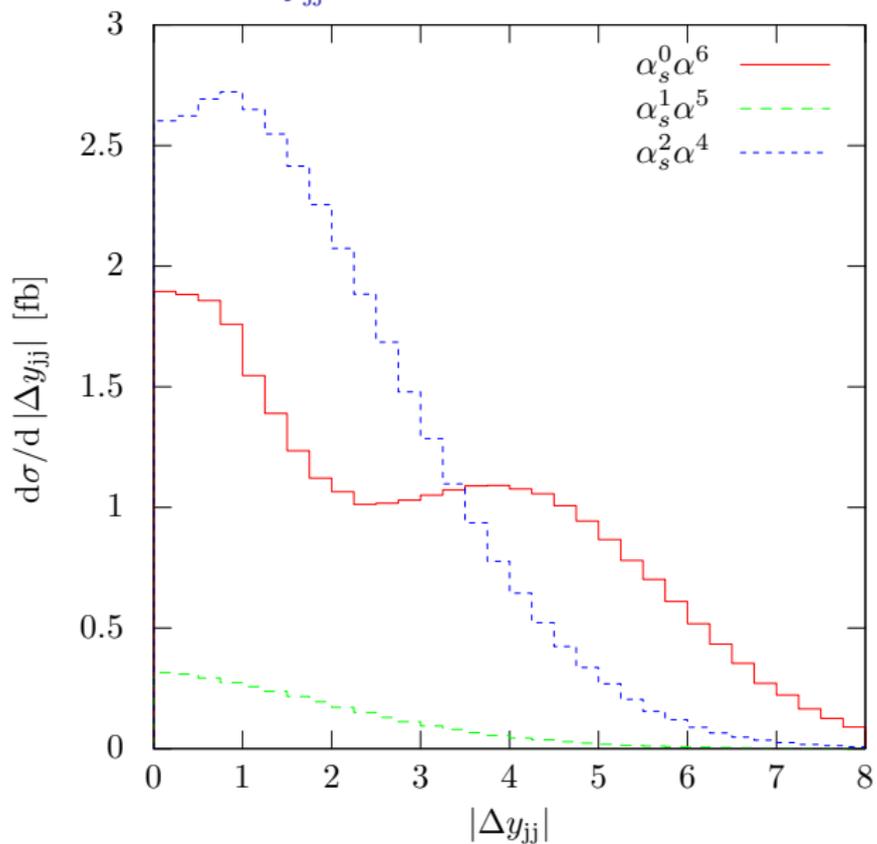
Total Cross Section: $pp \rightarrow e\bar{\nu}_e \mu\bar{\nu}_\mu jj + X$

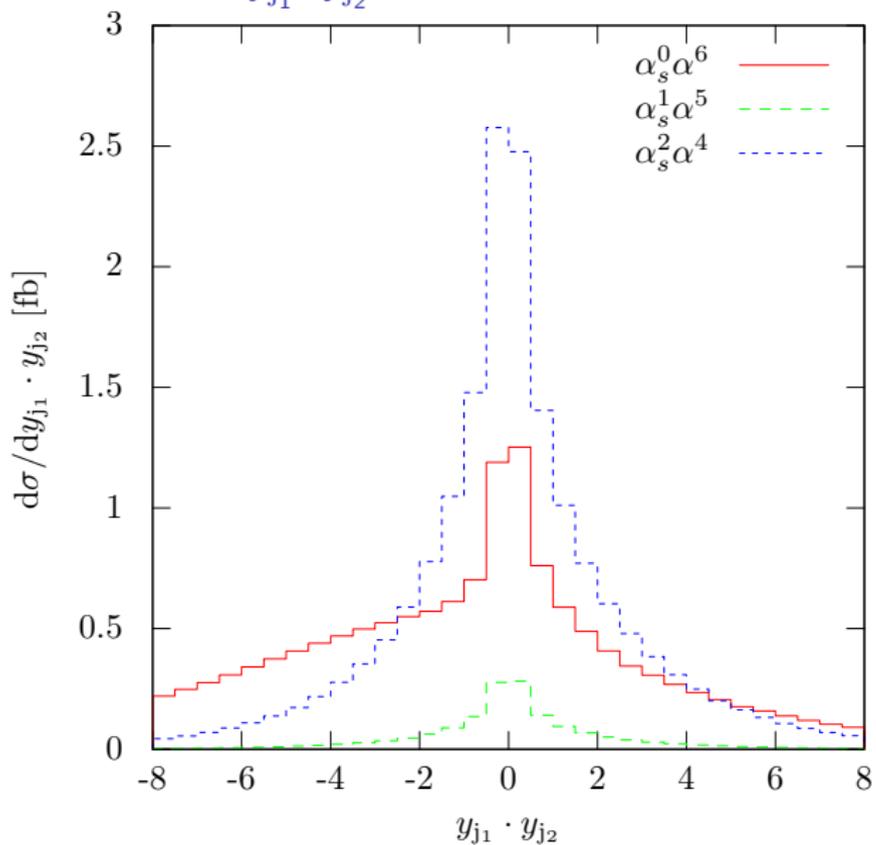
- $\sqrt{s} = 13 \text{ TeV}$
- no cuts: total cross section exists
- two k_T jets with $D = 0.7$
- MSTW2008 pdfs
- $\mu_R = \mu_F = M_W$
- Complex mass scheme:

$$\alpha = \frac{\sqrt{2}M_W^2 G_\mu}{\pi} \left(1 - \frac{M_W^2}{M_Z^2} \right), \quad \cos^2 \theta_w = \frac{M_W^2 - iM_W\Gamma_W}{M_Z^2 - iM_Z\Gamma_Z} \quad (1)$$

- four massless quarks, diagonal CKM matrix

Jet Distributions: M_{jj} 

Jet Distributions: Δy_{jj} 

Jet Distributions: $y_{j_1} \cdot y_{j_2}$ 

Cross Section for $pp \rightarrow e^+ \nu_e \mu^+ \nu_\mu jj + X$ with VBS cuts

- ≥ 2 jets with $p_{T,j} > 20 \text{ GeV}$ and $|y_j| < 4.5$

- VBF cuts:

- $M_{jj} > 600 \text{ GeV}$
- $\Delta y_{jj} = |y_{j_1} - y_{j_2}| > 4$
- $y_{j_1} \cdot y_{j_2} < 0$

- Lepton cuts:

- $p_{T,\ell} > 20 \text{ GeV}$
- $|y_\ell| < 2.5$
- $\Delta R_{j\ell} > 0.4$
- $\Delta R_{\ell\ell} > 0.1$

- Lepton centrality:

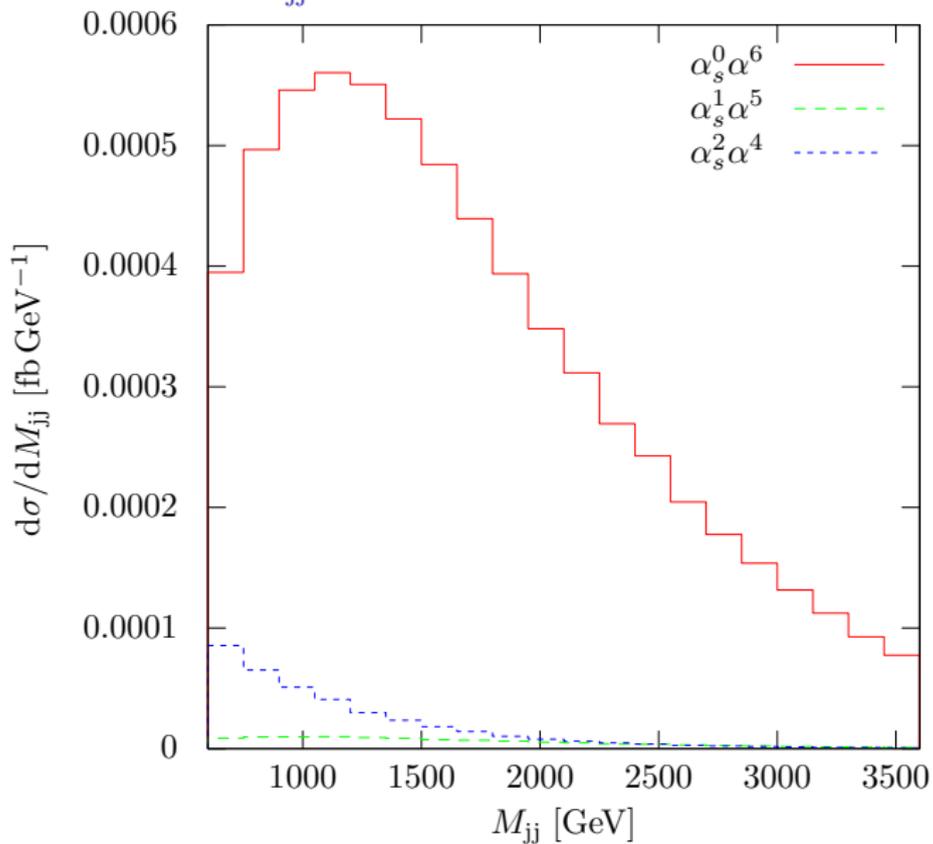
- $\min\{y_{j_1}, y_{j_2}\} < y_\ell < \max\{y_{j_1}, y_{j_2}\}$

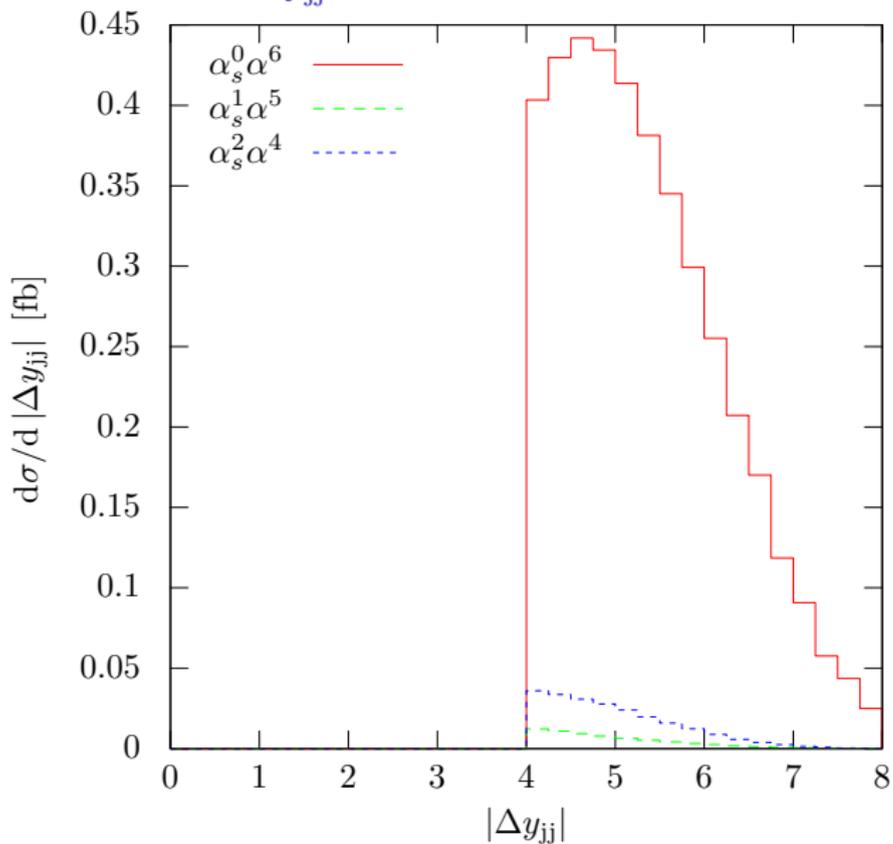
- Scale choice: $\mu = \sqrt{p_{T,j_1} \cdot p_{T,j_2}}$

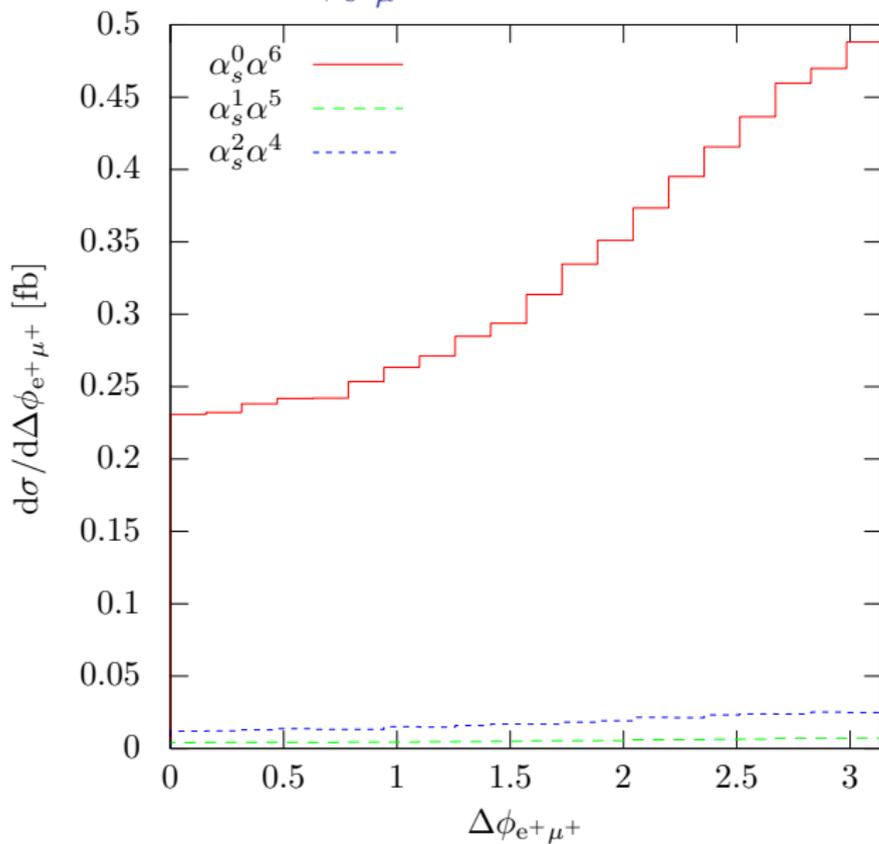
→ Effective suppression of backgrounds:

- $\frac{\sigma_{\frac{s}{s_0}}^2 \alpha^4}{\sigma_{\alpha^6}} \approx 18$
- $\frac{\sigma_{\frac{s}{s_0}}^1 \alpha^5}{\sigma_{\alpha^6}} \approx 62$

and VBF approximation very good: $\frac{\sigma_{\alpha^6}^{\text{VBF}}}{\sigma_{\alpha^6}} \sim 0.01 \%$

Jet Distributions: M_{jj} 

Jet Distributions: Δy_{jj} 

Lepton Distributions: $\phi_{e^+\mu^+}$ 

Overview of QCD and EW Corrections

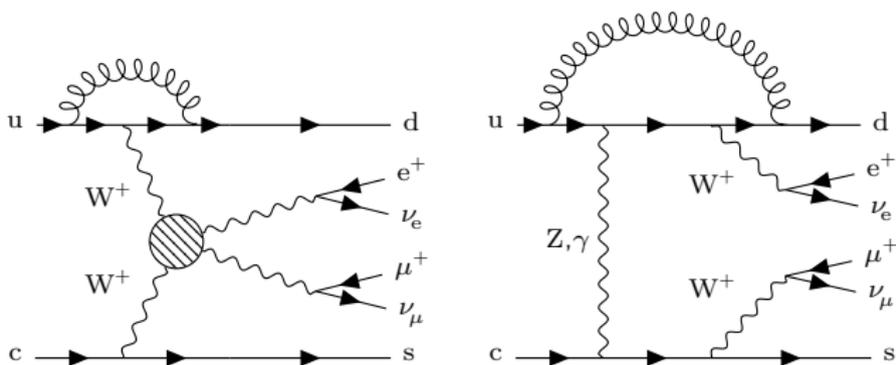
QCD < EW at LO, maybe similar situation at NLO? In any case: Sudakov and collinear logs large for high invariants (\rightarrow Talk given by [S. Uccirati](#)) \rightarrow need EW corrections

\rightarrow QCD/EW corrections to QCD/EW production yields four different coupling orders:

Order	Name	
$\alpha_s^3 \alpha^4$	QCD to QCD \times QCD	Melia, Melnikov, Röntsch, Zanderighi '10
$\alpha_s^2 \alpha^5$	Mixed	unknown
$\alpha_s \alpha^6$	{ Mixed QCD to EW \times EW	color-suppressed, probably small Jeager, Oleari, Zeppenfeld '09 Denner, Hosekova, Kallweit '12
α^7	EW to EW \times EW	unknown, supposed to be relevant

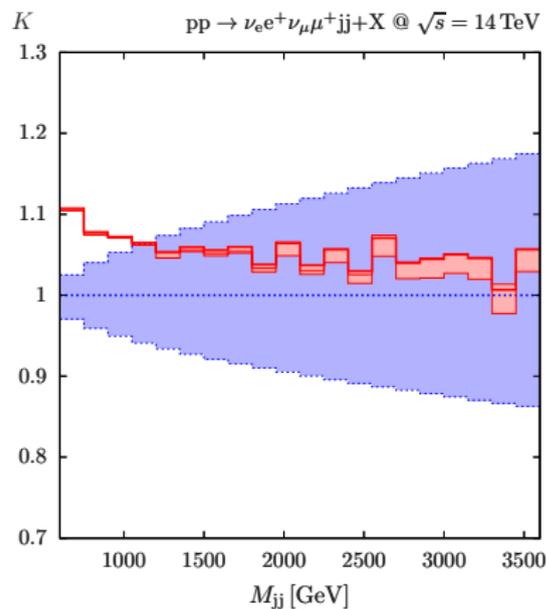
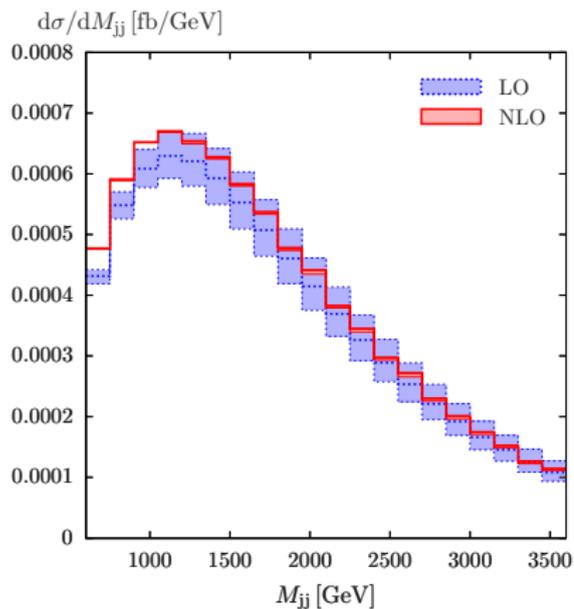
QCD Corrections to EW Production: $\text{Re}(\mathcal{M}_{EW}^{\alpha_s} \mathcal{M}_{EW}^*)$

Example diagrams of $\mathcal{M}_{EW}^{\alpha_s}$

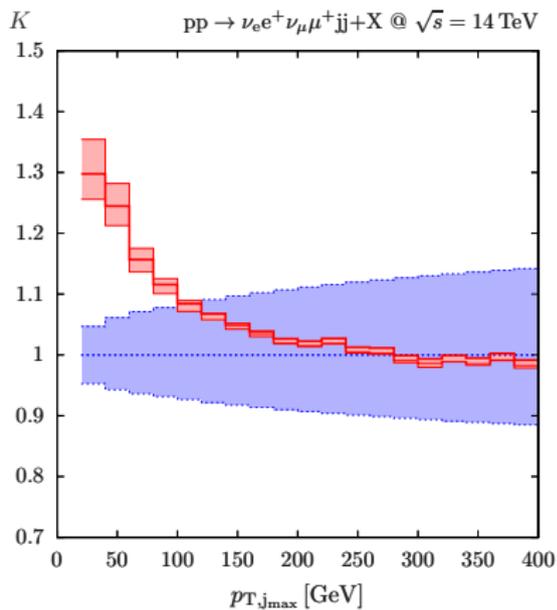
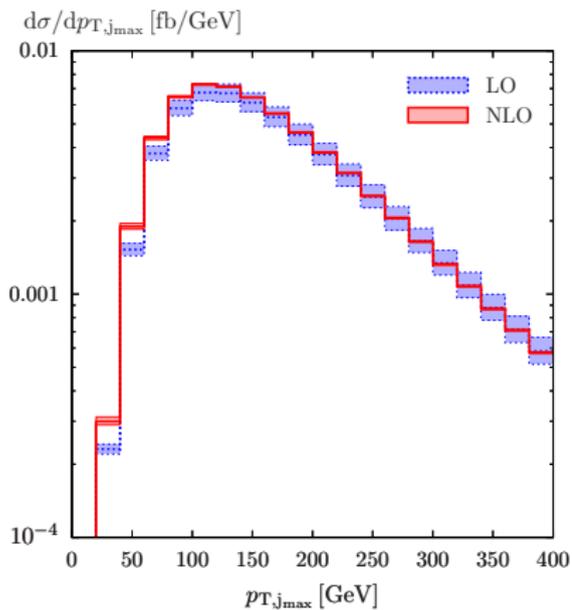


use VBF approximation: no gluons between both quark lines

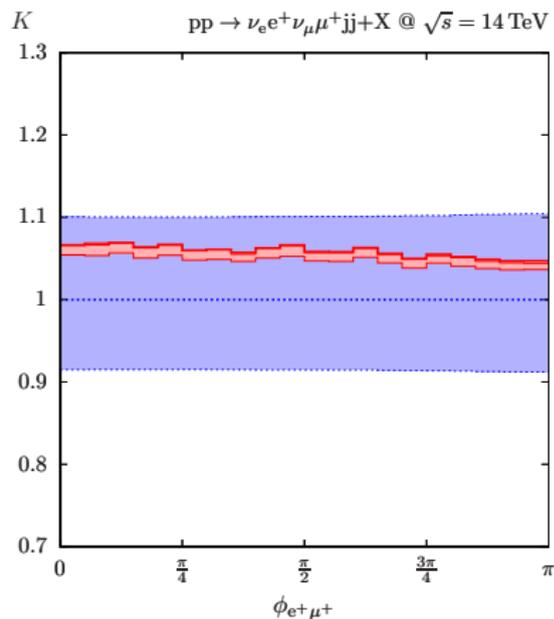
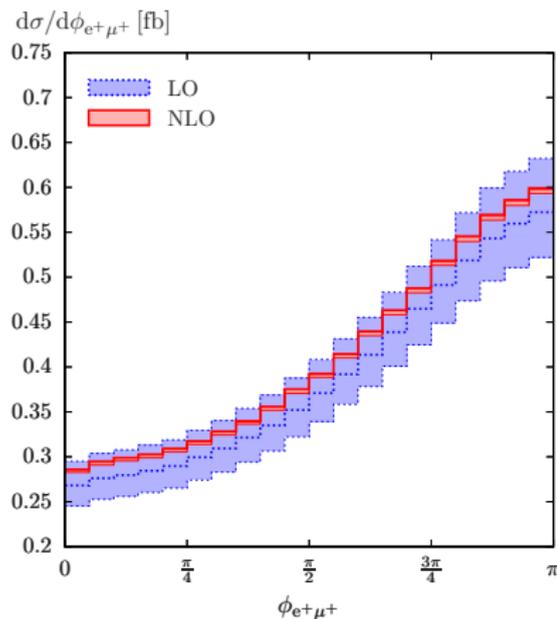
Jet Distributions: M_{jj}



Denner, Hosekova, Kallweit '12

Jet Distributions: $p_{T,j_{\max}}$ 

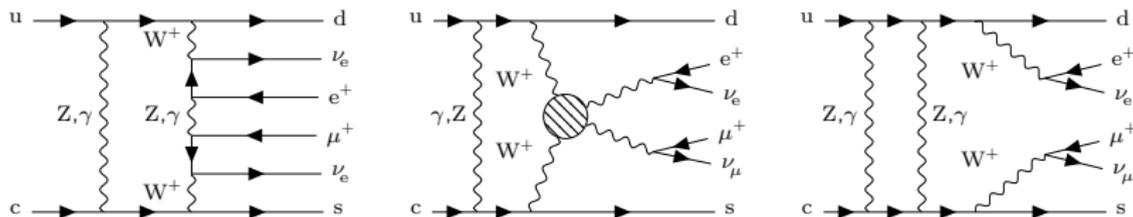
Denner, Hosekova, Kallweit '12

Lepton Distributions: $\phi_{e^+\mu^+}$ 

Denner, Hosekova, Kallweit '12

Outlook: Order- α^7 Corrections — Overview

Example diagrams: \mathcal{M}_{EW}^α



Exact calculation probably not feasible in the near future. Instead:

- Use double-pole approximation (DPA) dividing (gauge-invariantly) the virtual corrections into
 - ① factorizable,
 - ② non-factorizable pieces (\rightarrow backup slides, arxiv:1511.01698),
 - ③ and pieces (tripe-, single-, non-resonant) that are typically small (or not \rightarrow talk by L. Salfelder)
- Calculate real correction exactly
- Match real/virtual contributions with proper insertion terms

Outlook: Order- α^7 Corrections — Factorizable Corrections

Similar to Narrow-width approximation, but

- uses both full phase space k_i , and
- projection $\{k_i\} \mapsto \{\hat{k}_i\}$ where the resonances (both W^+) are on-shell

→ matrix element reads:

$$\mathcal{M}_{\text{virt, fact, PA}} = \sum_{\lambda_1, \lambda_2} \left(\prod_{i=1}^2 \frac{1}{K_i} \right) \left[\mathcal{M}_{\text{virt}}^{\text{pp} \rightarrow W^+ W^+ jj} \mathcal{M}_{\text{LO}}^{W^+ \rightarrow e^+ \nu_e} \mathcal{M}_{\text{LO}}^{W^+ \rightarrow \mu^+ \nu_\mu} \right. \\ \left. + \mathcal{M}_{\text{LO}}^{\text{pp} \rightarrow W^+ W^+ jj} \mathcal{M}_{\text{virt}}^{W^+ \rightarrow e^+ \nu_e} \mathcal{M}_{\text{LO}}^{W^+ \rightarrow \mu^+ \nu_\mu} + \right. \\ \left. \mathcal{M}_{\text{LO}}^{\text{pp} \rightarrow W^+ W^+ jj} \mathcal{M}_{\text{LO}}^{W^+ \rightarrow e^+ \nu_e} \mathcal{M}_{\text{virt}}^{W^+ \rightarrow \mu^+ \nu_\mu} \right] \{W \text{ on shell}\}$$

with $K_i = k_{W_i}^2 - M_W^2 + iM_W \Gamma_W$ (off-shell)

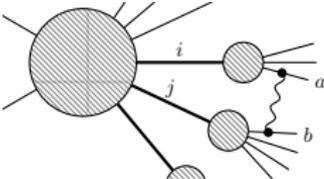
→ Problem now effectively $2 \rightarrow 4$.

Summary

- $pp \rightarrow e^+ \nu_e \mu^+ \nu_\mu jj + X$ can be used to study QGC, EWSB
- Background process can be efficiently suppressed by VBS cuts
- QCD corrections typically $\sim 5\text{--}10\%$
- EW corrections: Not yet available. Use DPA for the virtual part and calculate (non-)factorizable corrections

Non-Factorizable Corrections (I)

At 1-loop there are **resonant contributions** different from the factorizable ones:
Non-factorizable corrections, e.g. from

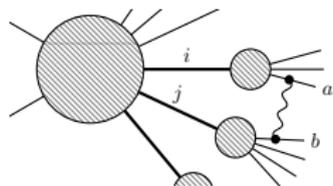


$$\sim \left[\mathcal{M}_{\text{LO,PA}} \int \frac{d^D q}{(2\pi)^D} \frac{K_i}{q^2 + 2q\bar{k}_i + K_i} \right. \\ \left. \times \frac{K_j}{q^2 - 2q\bar{k}_j + K_j} \frac{1}{q^2 - m_\gamma^2} \frac{1}{q^2 + 2qk_a} \frac{1}{q^2 - 2qk_b} \right]_{\{\bar{k}_i^2 = M_i^2\}}$$

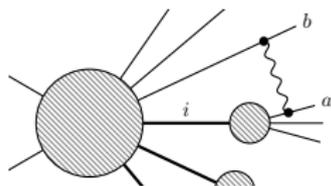
with $K_i = \bar{k}_i^2 - M_i^2 + iM_i\Gamma_i$

- this is a purely soft effect \rightarrow consider loops with photons
- “non-factorizable” concerns the structure of the resonant propagators, not the diagrams!

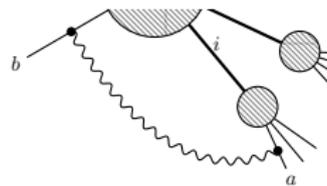
NLO: Non-Factorizable Corrections (II)



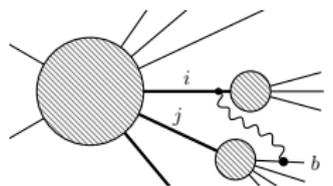
(a) ff'



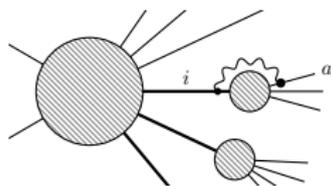
(b) nf



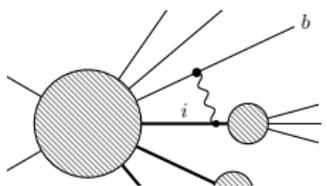
(c) if



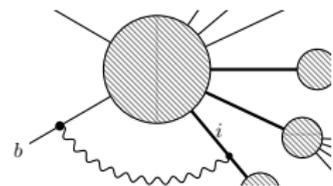
(d) mf'



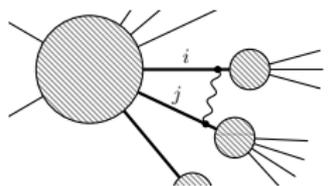
(e) mf



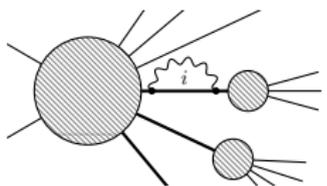
(f) mn



(g) im



(h) mm'



(i) mm

NLO: Non-Factorizable Corrections (III)

Non-factorizable corrections factor from LO:

$$\mathcal{M}_{\text{virt,nfact,PA}} = \mathcal{M}_{\text{LO,PA}} \delta_{\text{nfact}}$$

δ_{nfact} is universal, for arbitrary number r of resonances and non-resonant particles:

$$\begin{aligned} \delta_{\text{nfact}} = & - \sum_{i=1}^r \sum_{j=i+1}^r \sum_{a \in R_i} \sum_{b \in R_j} \sigma_a \sigma_b Q_a Q_b \frac{\alpha}{\pi} \Re \{ \Delta \} \\ & - \sum_{i=1}^r \sum_{a \in R_i} \sum_{b \in N \cup I} \sigma_a \sigma_b Q_a Q_b \frac{\alpha}{\pi} \Re \{ \Delta' \} \end{aligned}$$

with

$$\begin{aligned} \Delta(i, a; j, b) &= \Delta_{\text{mm}} + \Delta_{\text{mf}} + \Delta_{\text{mm}'} + \Delta_{\text{mf}'} + \Delta_{\text{ff}'}, \\ \Delta'(i, a; b) &= \Delta'_{\text{mm}} + \Delta'_{\text{mf}} + \Delta_{\text{xf}} + \Delta_{\text{xm}}, \end{aligned}$$

$$\begin{aligned} d\sigma_{\text{virt}} &\approx d\sigma_{\text{virt,nfact,PA}} + d\sigma_{\text{virt,fact,PA}} \\ &= d\phi_n \left(2\Re \{ \mathcal{M}_{\text{LO,PA}}^* \mathcal{M}_{\text{virt,fact,PA}} \} + |\mathcal{M}_{\text{LO,PA}}|^2 \delta_{\text{nfact}} \right) \end{aligned}$$