Precision Diboson Observables for the LHC

Marat Freytsis

University of Oregon

Rencontres de Moriond QCD, March 19–26, 2016

based on arXiv:1510.08451 (accepted by JHEP)
with Chris Frye, Jakub Scholtz, Matt Strassler

Why precision? Why dibosons?

- entering the era of precision Higgs physics
- ... but not all EW physics easy to tie to Higgs measurements
  - BSM might not be easy to connect either
    whither 750 GeV?
- non-Higgs precision measurements at the LHC are the next frontier

Why precision? Why dibosons?

- entering the era of precision Higgs physics
- …but not all EW physics easy to tie to Higgs measurements
  - BSM might not be easy to connect either
    whither 750 GeV?
- non-Higgs precision measurements at the LHC are the next frontier
- large part of this effort hinges on precision calculations
  many talks here: D. Heymes, M. Worek, A. Huss, F. Dreyer, S. Kallweit …
- but clever choices of observables can also help
  cf. hadronic, Higgs decay ratios
- diboson rates related by $SU(2)_L \times U(1)_Y$ relations
  - broken at low energies, but restored above the EW scale
  - is there any way to take advantage of this?

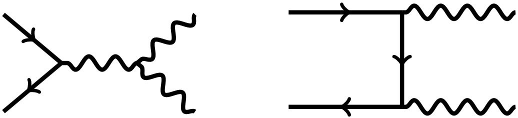
Plan

- Leading order
  - Structure of partonic cross sections
  - Ratio observables
- Next-to-leading order
  - NLO corrections for $\sigma(\gamma\gamma)$, $\sigma(Z\gamma)$, $\sigma(ZZ)$
  - Photon isolation and gluon fusion
- Experimental benefits

(Nearly) massless gauge bosons at high $\sqrt{s}$

expand around unbroken $SU(2)_L \times U(1)_Y$ (gauge bosons: w^a, b)

- corrections at $(m_{W,Z}/E)^2$



$$\mathbf{bb_1} \equiv \mathbf{bb} : \quad |bb\rangle$$

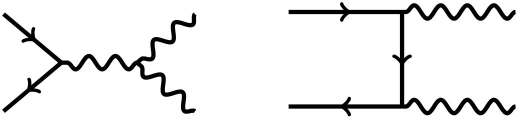
$$\mathbf{wb_3} \equiv \mathbf{wb} : \quad \{|w^+b\rangle\,,\ |w^3b\rangle\,,\ |w^-b\rangle\}$$

$$\mathbf{ww_1} : \quad |w^-w^+\rangle + |w^-w^+\rangle - |w^3w^3\rangle$$

$$\mathbf{ww_3} : \quad \{|w^+w^3\rangle - |w^3w^+\rangle\,,\ |w^+w^-\rangle - |w^-w^+\rangle\,, |w^3w^-\rangle - |w^-w^3\rangle\}$$

expand around unbroken $SU(2)_L \times U(1)_Y$ (gauge bosons: w^a, b)

- corrections at $(m_{W,Z}/E)^2$



(1) (2)

Schematically define coupling-stripped amplitudes:

$$a_1 = (2), \quad a_3 = (1) + (2)$$

Matrix elements of interest:

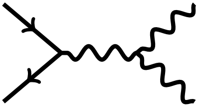
$$a_1 \sim \mathcal{M}(bb) \qquad \sim \mathcal{M}(ww_{\mathbf{1}}) \qquad \propto t\text{-}, u\text{-channel}$$

$$a_3 \sim \mathcal{M}(ww_{\mathbf{3}}) \qquad \propto s\text{-}, t\text{-}, u\text{-channel}$$

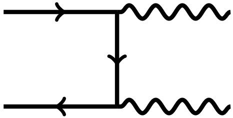
(Nearly) massless gauge bosons at high $\sqrt{s}$

expand around unbroken $SU(2)_L \times U(1)_Y$ (gauge bosons: w^a, b)

- corrections at $(m_{W,Z}/E)^2$



(1)



(2)

Schematically define coupling-stripped amplitudes:

$$a_1 = (2), \quad a_3 = (1) + (2)$$

Matrix elements of interest:

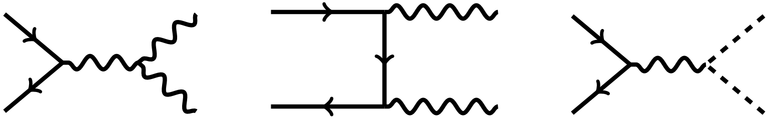
$$a_1 \sim \mathcal{M}(bb) \sim \mathcal{M}(wb) \sim \mathcal{M}(ww_{\mathbf{1}}) \qquad \propto t\text{-}, u\text{-channel}$$

$$a_3 \sim \mathcal{M}(ww_{\mathbf{3}}) \qquad \propto s\text{-}, t\text{-}, u\text{-channel}$$

(Nearly) massless gauge bosons at high $\sqrt{s}$

expand around unbroken $SU(2)_L \times U(1)_Y$ (gauge bosons: w^a, b)

- corrections at $(m_{W,Z}/E)^2$
- need ϕ^a goldstones to unitarize



(1) (2) (3)

Schematically define coupling-stripped amplitudes:

$$a_1 = (2), \quad a_3 = (1) + (2), \quad a_L = (3)$$

Matrix elements of interest:

$a_1 \sim \mathcal{M}(bb) \sim \mathcal{M}(wb) \sim \mathcal{M}(ww_{\mathbf{1}})$	$\propto t$-, u-channel
$a_3 \sim \mathcal{M}(ww_{\mathbf{3}})$	$\propto s$-, t-, u-channel
$a_L \sim \mathcal{M}(\phi\phi)$	$\propto s$-channel

Amplitudes
at high energies

boson statistics fix amplitudes under $\hat{t} \leftrightarrow \hat{u}$

- a_1, a_L symmetric
- a_3 antisymmetric

$\Longrightarrow a_3$ vanishes at threshold, $\mathrm{Re}(a_1^\dagger a_3)$ vanishes in asymmetries

$$
\begin{aligned}
|a_1|^2 &= \frac{\hat{t}}{\hat{u}} + \frac{\hat{u}}{\hat{t}} \\
2\mathrm{Re}(a_1^\dagger a_3) &= \frac{\hat{t} - \hat{u}}{2\hat{s}} + \frac{1}{4}\left(\frac{\hat{t}}{\hat{u}} - \frac{\hat{u}}{\hat{t}}\right) \\
|a_3|^2 &= \frac{\hat{u}\hat{t}}{4\hat{s}^2} - \frac{1}{8} + \frac{1}{32}\left(\frac{\hat{t}}{\hat{u}} + \frac{\hat{u}}{\hat{t}}\right) \\
|a_L|^2 &= \frac{\hat{u}\hat{t}}{4\hat{s}^2}
\end{aligned}
$$

Amplitudes
with mass corrections

boson statistics fix amplitudes under $\hat{t} \leftrightarrow \hat{u}$

- a_1, a_L symmetric
- a_3 antisymmetric

$\Longrightarrow a_3$ vanishes at threshold, $\mathrm{Re}(a_1^\dagger a_3)$ vanishes in asymmetries

$$
\begin{aligned}
|A_1|^2 &= (\hat{t}\hat{u} - m_1^2 m_2^2)\left(\frac{1}{\hat{t}^2} + \frac{1}{\hat{u}^2}\right) + \frac{2\hat{s}(m_1^2 + m_2^2)}{\hat{t}\hat{u}} \\
\mathrm{Re}(A_1^\dagger A_3) &= P_s\left(\hat{t}\hat{u} - m_1^2 m_2^2 - \hat{s}(m_1^2 + m_2^2)\right)\left(\frac{1}{\hat{u}} - \frac{1}{\hat{t}}\right) \\
&\quad + \frac{1}{4}(\hat{t}\hat{u} - m_1^2 m_2^2)\left(\frac{1}{\hat{u}^2} - \frac{1}{\hat{t}^2}\right) \\
|A_3|^2 &= \cdots \\
|A_L|^2 &= P_s^2\left(\hat{t}\hat{u} - m_1^2 m_2^2 + 2\hat{s}(m_1^2 + m_2^2)\right)
\end{aligned}
$$

finite m effects have uniform structure

$\gamma\gamma, Z\gamma, ZZ$ at LO

$$\frac{d\hat{\sigma}_{q\bar{q}\to V_0^1 V_0^2}}{d\hat{t}} = \frac{C_{q\bar{q}\to V_0^1 V_0^2}}{\hat{s}^2} |A_1|^2$$

$$\gamma = c_W\, b + s_W\, w^3,$$
$$Z = c_W\, w^3 - s_W b$$

$$\gamma\gamma, Z\gamma, ZZ \propto bb, wb, ww_{\mathbf{1}}$$

where

$$C_{q\bar{q}\to\gamma\gamma} = \frac{1}{2}\frac{\pi\alpha_2^2 s_W^4}{N_c}\, 2Q^4$$

$$C_{q\bar{q}\to Z\gamma} = \frac{\pi\alpha_2^2 s_W^2 c_W^2}{N_c}(L^2 Q^2 + R^2 Q^2)$$

$$C_{q\bar{q}\to ZZ} = \frac{1}{2}\frac{\pi\alpha_2^2 c_W^4}{N_c}\,(L^4 + R^4)$$

$\gamma\gamma, Z\gamma, ZZ$ at LO

$$\frac{d\hat{\sigma}_{q\bar{q}\to V_0^1 V_0^2}}{d\hat{t}} = \frac{C_{q\bar{q}\to V_0^1 V_0^2}}{\hat{s}^2} |A_1|^2$$

$$\gamma = c_W\, b + s_W\, w^3, \qquad Z = c_W\, w^3 - s_W b$$

$$\gamma\gamma, Z\gamma, ZZ \propto bb, wb, ww_{\mathbf{1}}$$

where

$$C_{q\bar{q}\to\gamma\gamma} = \frac{1}{2}\frac{\pi\alpha_2^2 s_W^4}{N_c}\, 2Q^4$$

$$C_{q\bar{q}\to Z\gamma} = \frac{\pi\alpha_2^2 s_W^2 c_W^2}{N_c}(L^2Q^2 + R^2Q^2)$$

$$C_{q\bar{q}\to ZZ} = \frac{1}{2}\frac{\pi\alpha_2^2 c_W^4}{N_c}\,(L^4 + R^4)$$

$$L = T_3 - Y_L t_W^2, \quad R = -Y_R t_W^2$$

$\gamma\gamma, Z\gamma, ZZ$ at LO

$$\frac{d\hat{\sigma}_{q\bar{q}\to V_0^1 V_0^2}}{d\hat{t}} = \frac{C_{q\bar{q}\to V_0^1 V_0^2}}{\hat{s}^2}\left|A_1\right|^2$$

$$\gamma = c_W\, b + s_W\, w^3,$$

$$Z = c_W\, w^3 - s_W b$$

$$\frac{d\sigma_{pp\to V_0^1 V_0^2}}{d\bar{m}_T} = \frac{1}{s}\int \frac{d\hat{s}}{\hat{s}^2}\left|\frac{d\hat{t}}{dm_T}\right|\left|A_1\right|^2 \underbrace{\sum_q C_{q\bar{q}\to V_0^1 V_0^2}\int dy\, f_q f_{\bar{q}}}_{\mathcal{L}_{12}(\hat{s})}$$

$$\gamma\gamma, Z\gamma, ZZ \propto bb, wb, ww_{\mathbf{1}}$$

where

$$C_{q\bar{q}\to\gamma\gamma} = \frac{1}{2}\frac{\pi\alpha_2^2 s_W^4}{N_c}\, 2Q^4$$

$$C_{q\bar{q}\to Z\gamma} = \frac{\pi\alpha_2^2 s_W^2 c_W^2}{N_c}(L^2Q^2 + R^2Q^2)$$

$$C_{q\bar{q}\to ZZ} = \frac{1}{2}\frac{\pi\alpha_2^2 c_W^4}{N_c}(L^4 + R^4)$$

$$L = T_3 - Y_L t_W^2, \quad R = -Y_R t_W^2$$

$\gamma\gamma, Z\gamma, ZZ$ at LO

$$\frac{d\hat{\sigma}_{q\bar{q}\to V_0^1 V_0^2}}{d\hat{t}} = \frac{C_{q\bar{q}\to V_0^1 V_0^2}}{\hat{s}^2} |A_1|^2$$

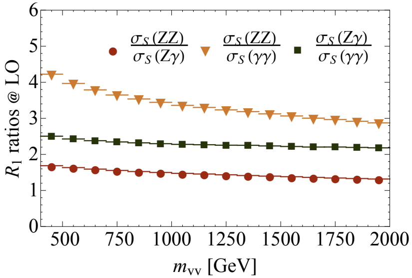
$$\frac{d\sigma_{pp\to V_0^1 V_0^2}}{d\bar{m}_T} = \frac{1}{s} \int \frac{d\hat{s}}{\hat{s}^2} \left|\frac{d\hat{t}}{dm_T}\right| |A_1|^2 \underbrace{\sum_q C_{q\bar{q}\to V_0^1 V_0^2} \int dy\, f_q f_{\bar{q}}}_{\mathcal{L}_{12}(\hat{s})}$$

$$\gamma = c_W\, b + s_W\, w^3,$$
$$Z = c_W\, w^3 - s_W b$$

$$\gamma\gamma, Z\gamma, ZZ \propto bb, wb, ww_1$$

where

$V_1^0 V_2^0$	$\mathcal{L}_{12}^u \cdot 10^5$	$\mathcal{L}_{12}^d \cdot 10^5$
$\gamma\gamma$	1.2	0.07
$Z\gamma$	2.2	0.7
ZZ	1.6	3.3



$\gamma\gamma, Z\gamma, ZZ$ at LO

$$\frac{d\hat{\sigma}_{q\bar{q}\to V_0^1 V_0^2}}{d\hat{t}} = \frac{C_{q\bar{q}\to V_0^1 V_0^2}}{\hat{s}^2} |A_1|^2$$

$$\frac{d\sigma_{pp\to V_0^1 V_0^2}}{d\bar{m}_T} = \frac{1}{s}\int \frac{d\hat{s}}{\hat{s}^2}\left|\frac{d\hat{t}}{dm_T}\right| |A_1|^2 \underbrace{\sum_q C_{q\bar{q}\to V_0^1 V_0^2}\int dy\, f_q f_{\bar{q}}}_{\mathcal{L}_{12}(\hat{s})}$$

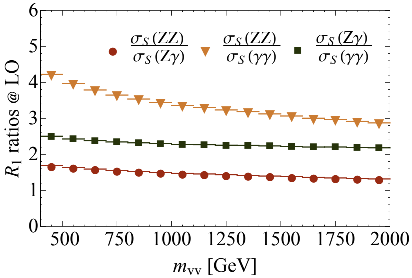
$$\gamma = c_W\, b + s_W\, w^3,$$
$$Z = c_W\, w^3 - s_W b$$

$$\gamma\gamma, Z\gamma, ZZ \propto bb, wb, ww_1$$

where

$V_1^0 V_2^0$	$\mathcal{L}_{12}^u \cdot 10^5$	$\mathcal{L}_{12}^d \cdot 10^5$
$\gamma\gamma$	1.2	0.07
$Z\gamma$	2.2	0.7
ZZ	1.6	3.3

PDFs mostly cancel – $u\bar{u}$ dominates



$W^\pm\gamma$, $W^\pm Z$ at LO

$W^\pm\gamma$ and $W^\pm Z$ built from wb and $ww_3 \implies$ Need A_1 and A_3.

Need A_L for $\phi^\pm\phi^3$ component of $W^\pm Z$.

$$\frac{d\hat{\sigma}_{u\bar{d}\to W^\pm\gamma}}{d\hat{t}} = \frac{\pi|V_{ud}|^2\alpha_2^2 s_W^2}{N_c\hat{s}^2}\left(\frac{Y_L^2}{2}|A_1|^2 \pm 2Y_L\mathrm{Re}(A_1^\dagger A_3) + |A_3|^2\right)$$

$$\frac{d\hat{\sigma}_{u\bar{d}\to W^\pm Z}}{d\hat{t}} = \frac{\pi|V_{ud}|^2\alpha_2^2}{N_c\hat{s}^2}\left(\frac{s_W^4 Y_L^2}{2c_W^2}|A_1|^2 \mp 2s_W^2 Y_L\mathrm{Re}(A_1^\dagger A_3) + 4c_W^2|A_3|^2 + \frac{1}{2}|A_L|^2\right)$$

$W^{\pm}\gamma$, $W^{\pm}Z$ at LO

$W^{\pm}\gamma$ and $W^{\pm}Z$ built from wb and ww_3 $\Longrightarrow$ Need A_1 and A_3.

Need A_L for $\phi^{\pm}\phi^3$ component of $W^{\pm}Z$.

$$\frac{d\hat{\sigma}_{u\bar{d}\to W^{\pm}\gamma}}{d\hat{t}} = \frac{\pi|V_{ud}|^2\alpha_2^2 s_W^2}{N_c\hat{s}^2}\left(\frac{Y_L^2}{2}|A_1|^2 \pm 2Y_L\mathrm{Re}(A_1^\dagger A_3) + |A_3|^2\right)$$

$$\frac{d\hat{\sigma}_{u\bar{d}\to W^{\pm}Z}}{d\hat{t}} = \frac{\pi|V_{ud}|^2\alpha_2^2}{N_c\hat{s}^2}\left(\frac{s_W^4 Y_L^2}{2c_W^2}|A_1|^2 \mp 2s_W^2 Y_L\mathrm{Re}(A_1^\dagger A_3) + 4c_W^2|A_3|^2 + \frac{1}{2}|A_L|^2\right)$$

Numerically small
$\Longrightarrow W\gamma/WZ \sim \tan^2\theta_W$

$W^\pm\gamma$, $W^\pm Z$ at LO

$W^\pm\gamma$ and $W^\pm Z$ built from wb and $ww_3 \Longrightarrow$ Need A_1 and A_3.

Need A_L for $\phi^\pm\phi^3$ component of $W^\pm Z$.

$$\frac{d\hat\sigma_{u\bar d\to W^\pm\gamma}}{d\hat t} = \frac{\pi|V_{ud}|^2\alpha_2^2 s_W^2}{N_c\hat s^2}\left(\frac{Y_L^2}{2}|A_1|^2 \pm \cancel{2Y_L \mathrm{Re}(A_1^\dagger A_3)} + \cancel{|A_3|^2}\right)$$

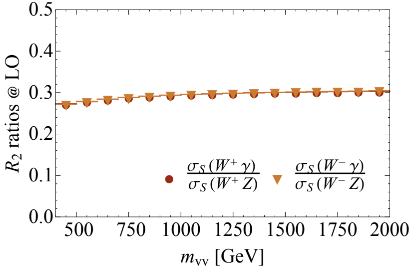
$$\frac{d\hat\sigma_{u\bar d\to W^\pm Z}}{d\hat t} = \frac{\pi|V_{ud}|^2\alpha_2^2}{N_c\hat s^2}\left(\frac{s_W^4 Y_L^2}{2c_W^2}|A_1|^2 \mp \cancel{2s_W^2 Y_L \mathrm{Re}(A_1^\dagger A_3)} + \cancel{4c_W^2|A_3|^2} + \frac{1}{2}|A_L|^2\right)$$

Numerically small

$\Longrightarrow W\gamma/WZ \sim \tan^2\theta_W$

Radiation zero at threshold

$\Longrightarrow W\gamma/WZ \sim 0.19$

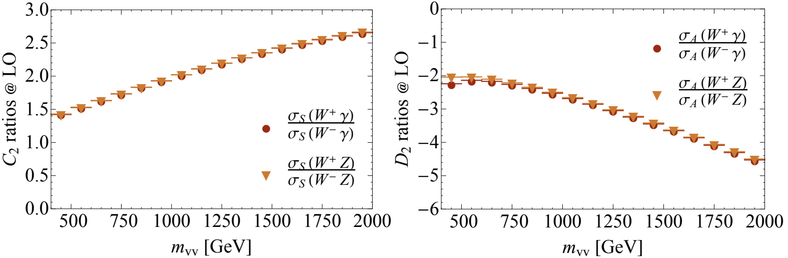


$W^\pm\gamma$, $W^\pm Z$

CP symmetry controls $W^- V^0$ rates:

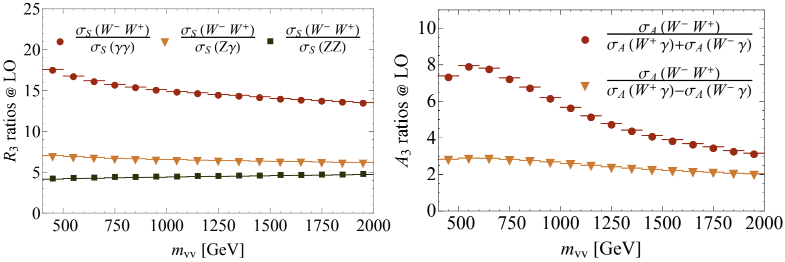
$$d\hat{\sigma}_S(u\bar{d} \to W^+ V^0) = d\hat{\sigma}_S(d\bar{u} \to W^- V^0)$$

$$d\hat{\sigma}_A(u\bar{d} \to W^+ V^0) = -d\hat{\sigma}_A(d\bar{u} \to W^- V^0)$$



W^+W^- built from ww_1, ww_3, $\phi^+\phi^-$ Very similar to $W^\pm\gamma$

$$\frac{\sigma_A(W^+W^-)}{a\sigma_A(W^+\gamma)+b\sigma_A(W^-\gamma)} \sim \frac{\mathcal{L}^A_{u\bar{u}}-\mathcal{L}^A_{d\bar{d}}}{4|V_{ud}|^2 s_W^2 Y_L(a\mathcal{L}^A_{u\bar{d}}-b\mathcal{L}^A_{d\bar{u}})}$$



Beyond leading order

- QCD cancellations?
  - how large are the shifts?
  - $SU(2)_L \times U(1)_Y$ relations help – where do they fail?
  - residual uncertainties?
- EW corrections?
- Big issue: the radiation zero
  - LO relations may receive large corrections where present
- Start with $V_1^0 V_2^0$
  - No radiation zero
  - Fully reconstructed (only $Z \to \ell^+\ell^-$ here)
  - Good statistics (ZZ tougher)

NLO corrections to diboson production

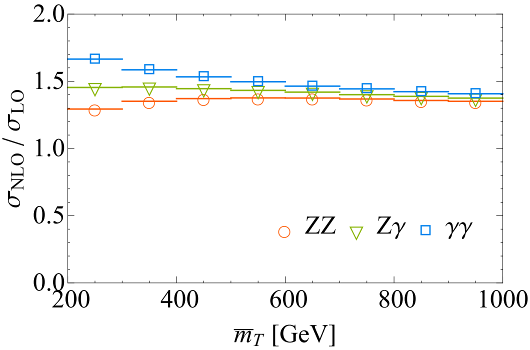
EW processes at LHC typically have large $O(\alpha_s)$ corrections

$qg \to V_1 V_2 q$ appears at $O(\alpha_s)$, and $f_g \gg f_{\bar{q}}$

Large uncertainties if distributions are “effectively LO” somewhere in PS

$$\bar{m}_T = \frac{1}{2}(m_{T1} + m_{T2}) = \text{min. } E \text{ at } \theta_{CM} = \pi/2$$

Radiation can never reduce this variable



NLO corrections to diboson production

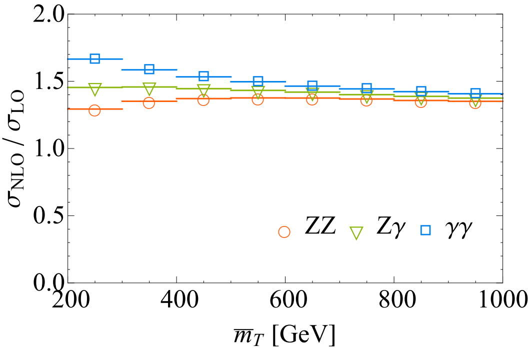
EW processes at LHC typically have large $O(\alpha_s)$ corrections

$qg \to V_1 V_2 q$ appears at $O(\alpha_s)$, and $f_g \gg f_{\bar{q}}$

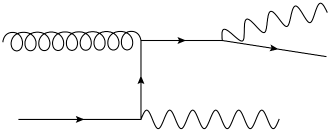
Choose cuts to avoid generating large logs anywhere in phase space

$$H_T < \frac{1}{2} p^V_{T,\mathrm{min}}, \quad p^V_{T,\mathrm{min}} > \frac{1}{2} p^V_{T,\mathrm{max}}$$

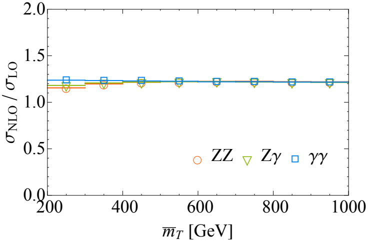
Fixed order calculation reliable



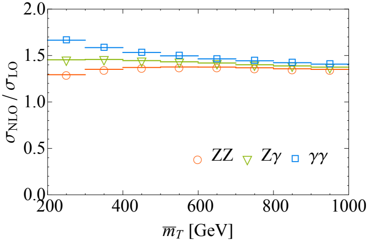
Complications in QCD corrects



divergence in qg process when $q\gamma$ are collinear
cut region out of phase space, or absorb into fragmentation function
large logarithm after regulation $\Longrightarrow$ need tight γ isolation

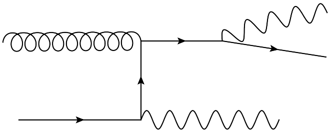


tight isolation



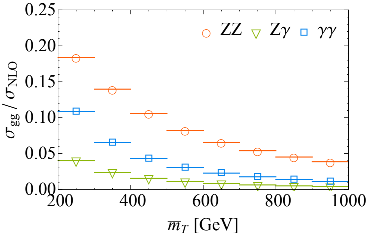
loose isolation

Complications in QCD corrects



divergence in qg process when $q\gamma$ are collinear
cut region out of phase space, or absorb into fragmentation function
large logarithm after regulation $\Longrightarrow$ need tight γ isolation

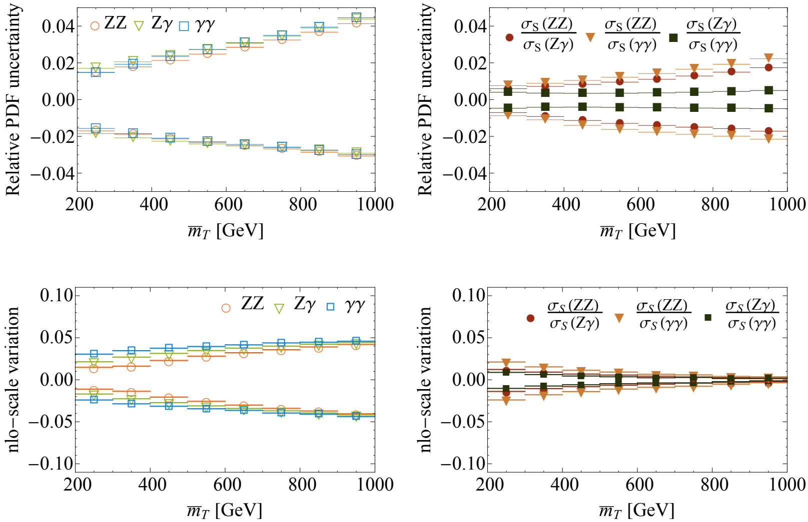
$gg \to V_1^0 V_2^0$
$\Longrightarrow$ formally NNLO, numerically large



Both effects decrease in importance at high energy

Uncertainties: σ vs. R_{1i}

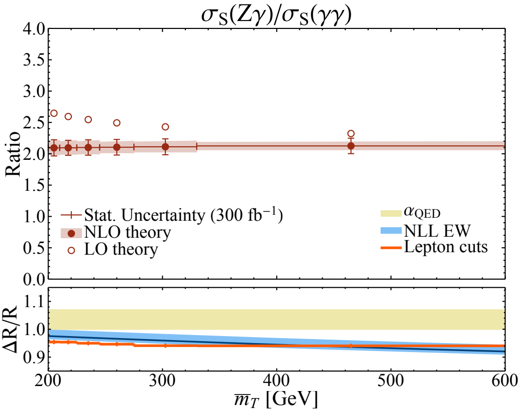
PDFs and scale choices



both PDF and scale uncertainties at the 1–2% level in ratios

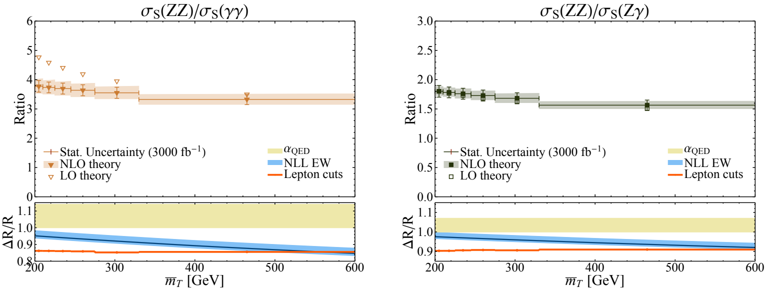
Predicted ratios

$Z\gamma/\gamma\gamma$ at 300 fb^{-1}



Predicted ratios

The other ratios at 3000 fb^{-1}



Summary & outlook

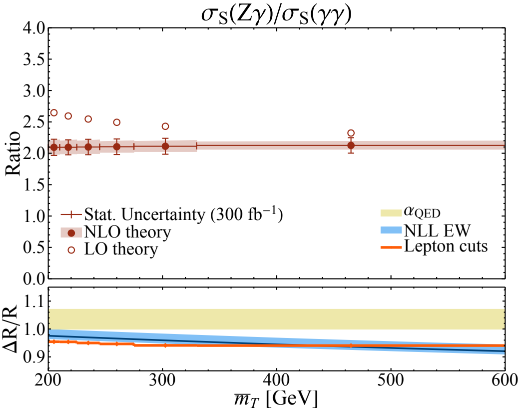
$SU(2)_L \times U(1)_Y$ structure of diboson rates at LO suggests points to studying certain observables

ratio observables based on this structure:
- low uncertainties, small QCD corrections
- candidates for (even) high(er)-precision calculation

certainly useful for SM studies

need to see if sensitivity to new physics improved
- reliable characterization of new resonances?
- increased sensitivity to non-resonant effects?

Ratios for precision! Ratios for understanding!



Backup slides

Variable bin widths

Problem: very few Z decays to leptons

V_1V_2	$N_f + N_b$	$N_f - N_b$
$\gamma\gamma$	12 000	0
$Z\gamma$	2000	0
ZZ	220	0
$W^+\gamma$	3300	−500
$W^-\gamma$	2100	220
W^+Z	790	33
W^-Z	520	−16
W^-W^+	9500	−430

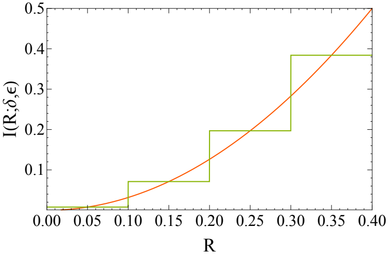
Choose bin widths for 5% statistical uncertainty.
$R_{1a} = \sigma_S(Z\gamma)/\sigma_S(\gamma\gamma)$ not statistics limited with 300 fb^{-1}
Others will have to wait until 3000 fb^{-1}

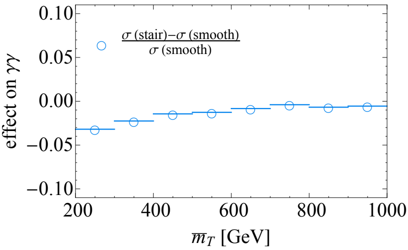
Staircase isolation

"Practical" smooth-come isolation:

- stairs of width $\Delta R = 0.1$
- heights match smooth cone at midpoint
- never take heights below 25 GeV (pileup/resolution)

Minimize sensitivity to fragmentation functions, protect against large log at small cutoff. Experimentally viable.





Uncertainty budget

Effect	R_{1a} ($Z\gamma/\gamma\gamma$)	R_{1b} ($ZZ/\gamma\gamma$)	R_{1c} ($ZZ/Z\gamma$)	Comments
$qq \to VVqq$	2–3%	3–3.5%	1.5–2.5%	extrapolating $p^j_{T,\min} \to 0$
μ_R, μ_F (gg)	0.5–1%	1%	1–2%	uses NLO $gg \to \gamma\gamma$
μ_R, μ_F (NLO)	0.5–1%	1.5–2.5%	1–1.5%	varied independently
PDF	0.5%	1–1.5%	0.5–1%	MSTW2008 using MCFM
γ isolation	$< 0.1\%$	$< 0.1\%$	$< 0.1\%$	Uncertainty in frag. fun.
α_{QED}	7%	14%	7%	Fully correlated
EW (LL)	$^{+2\%}_{-1\%}$	$^{+3\%}_{-1\%}$	$^{+2\%}_{-1\%}$	EFT scale uncertainty