Gluon-induced ZZ background to Higgs searches at the LHC

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A brief history of $gg \to ZZ$

$gg \to ZZ$ without decays:
- Dicus, Kao, Repko (1987)
- Glover, van der Bij (1989)

$gg \to ZZ$ with on-shell leptonic decays:
- Matsuura, van der Bij (1991)

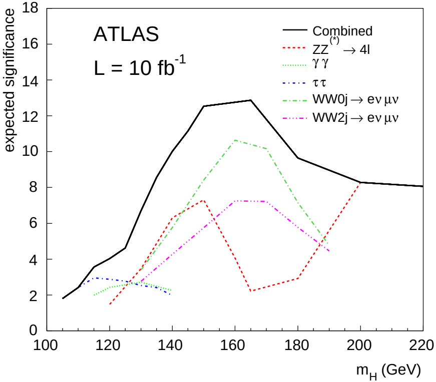
$gg \to ZZ$ with off-shell leptonic decays:
- Zecher, Matsuura, van der Bij (1994)

$gg \to (Z, \gamma^*)(Z, \gamma^*)$ with off-shell leptonic decays:
- Binoth, NK, Mertsch (2008)
- NK, in progress

- used by and cited in:
- ATLAS CSC Book, arXiv:0901.0512 [hep-ex]
- Campbell, Castaneda-Miranda, Fang, NK, Mellado, Wu, *Normalizing Weak Boson Pair Production at the LHC*, Phys. Rev. D80 (2009) 054023

Importance for LHC physics

- $H \to ZZ$ searches: dominant irreducible background is ZZ continuum production
- background to new physics searches with multi-lepton (+ jets) signatures (SUSY, ...)



• $gg \to VV$: new subprocess of $pp \to VV$ at NNLO
• but: large gluon-gluon luminosity at LHC and selection cuts enhance relative size of $gg \to WW$ and $gg \to ZZ$, $\mathcal{O}(10\%)$ effects

Calculation

$pp \to (Z,\gamma^*)(Z,\gamma^*) \to e^- e^+ \mu^- \mu^+$ at LO, NLO:

MCFM Campbell, K. Ellis (1999), amplitudes use Dixon, Kunszt, Signer (1998)
Note: s-channel diagrams switched off (even when `zerowidth=.false.`)

$gg \to (Z,\gamma^*)(Z,\gamma^*) \to e^- e^+ \mu^- \mu^+$ at LO:

two independent implementations of the 1-loop amplitudes
1) based on **Golem** Heinrich, Reiter, et al.
2) based on **FormCalc/LoopTools** Hahn
(using **FORM** Vermaseren) compared 1) and 2) at single PS point: good agreement
phase space integration with **OmniComp** Kauer

Input settings:

$\mu_R = \mu_F = M_Z$, CTEQ6L1 (LHAPDF, default $\alpha_s = 0.13$), G_μ scheme:
$m_Z = 91.188$ GeV, $\sin^2\theta_W = 0.222247$, $G_F = 1.16639 \cdot 10^{-5}$ GeV^{-2},
$\Gamma_Z = 2.49$ GeV, $m_t = 172.5$ GeV, $m_b = 4.75$ GeV

Cross sections (14 TeV)

$\sigma(pp \to (Z,\gamma^*)(Z,\gamma^*) \to e^-e^+\mu^-\mu^+)$ [fb], $\sqrt{s} = 14$ TeV				
gg	$q\bar{q}$		$\frac{\sigma_{\rm NLO}}{\sigma_{\rm LO}}$	$\frac{\sigma_{\rm LO+gg}}{\sigma_{\rm LO}}$
	LO	NLO		
$1.492(2)$	$7.343(1)$	$10.953(2)$	1.49	1.20

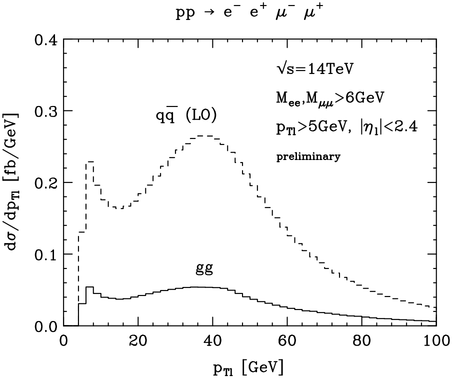
cuts: $p_{T\ell} > 20$ GeV, $|\eta_\ell| < 2.5$, 75 GeV $< M_{ee}, M_{\mu\mu} < 105$ GeV

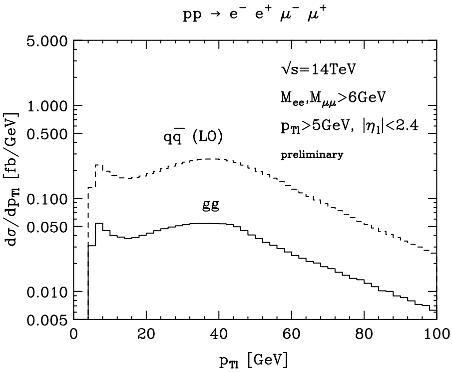
$\sigma(pp \to (Z,\gamma^*)(Z,\gamma^*) \to e^-e^+\mu^-\mu^+)$ [fb], $\sqrt{s} = 14$ TeV				
gg	$q\bar{q}$		$\frac{\sigma_{\rm NLO}}{\sigma_{\rm LO}}$	$\frac{\sigma_{\rm LO+gg}}{\sigma_{\rm LO}}$
	LO	NLO		
$16.3(1)$	$105.2(1)$	$118.9(2)$	1.13	1.15

cuts: $M_{ee}, M_{\mu\mu} > 5$ GeV

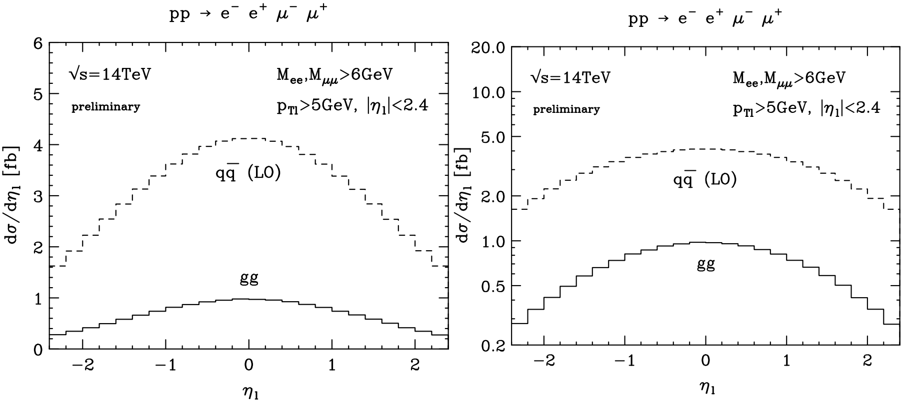
T. Binoth, NK, P. Mertsch, arXiv:0803.1154, arXiv:0807.0024

Lepton transverse momentum distribution (14 TeV)

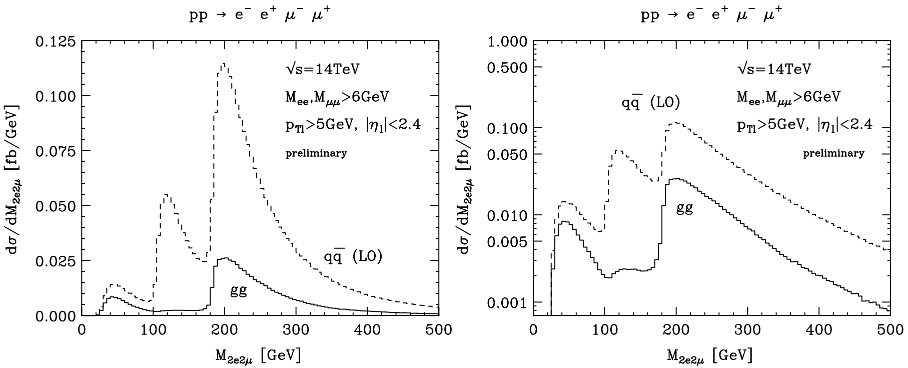




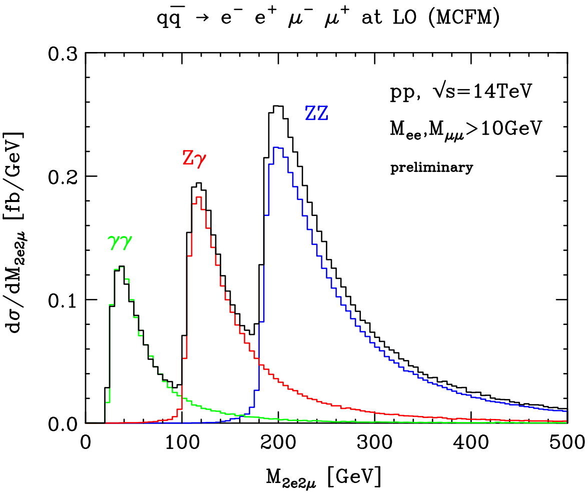
Lepton pseudorapidity distribution (14 TeV)



ZZ invariant mass distribution (14 TeV)

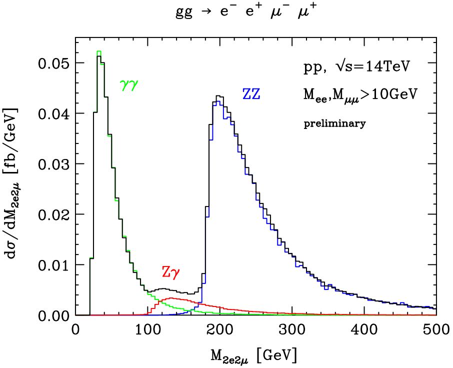


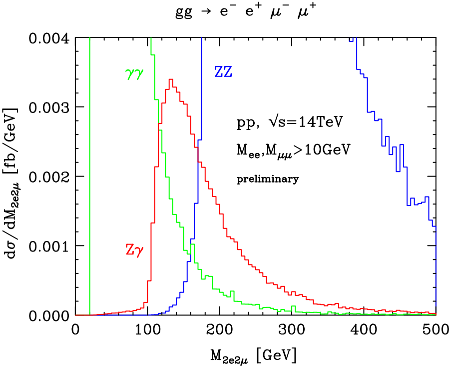
Contributions for $q\bar{q} \to (Z, \gamma^*)(Z, \gamma^*)$



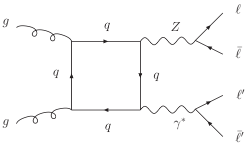
$\gamma^*\gamma^*$: 15%, $Z\gamma^*$: 29%, ZZ: 56%

Contributions for $gg \to (Z, \gamma^*)(Z, \gamma^*)$



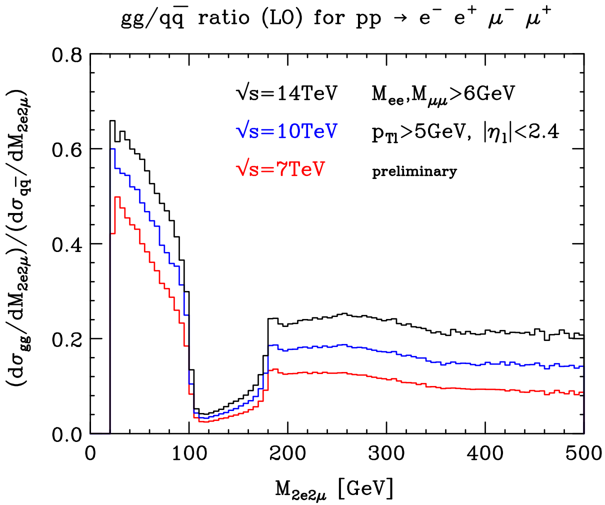


$\gamma^*\gamma^*$: 30%, $Z\gamma^*$: 5%, ZZ: 65%



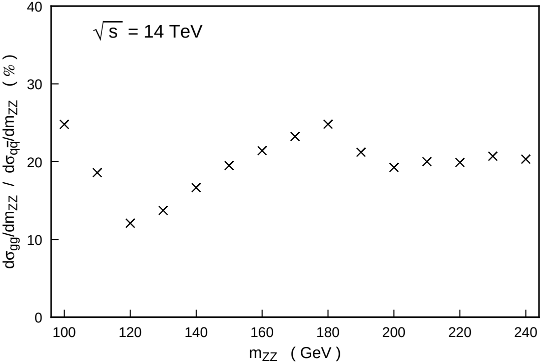
axial vector coupling of Z boson does not contribute to $gg \to Z\gamma^*$ (Furry's theorem for closed loops)

M_{ZZ} distribution: $gg/q\bar{q}$ ratio (7, 10, 14 TeV)



Comparison with Zecher, Matsuura, van der Bij

approximate agreement expected for $M_{ZZ} \geq 200$ GeV points:



$gg/q\bar{q} \to ZZ$ (no γ^*) $\to \mu^-\mu^+\mu^-\mu^+$ at LO (points average over 10 GeV M_{ZZ} bins)

$p_{T\ell} > 10$ GeV, $|\eta_\ell| < 2.5$, $p_{TZ} > 2$ GeV ($m_t = 140$ GeV, $m_b = 4.89$ GeV)

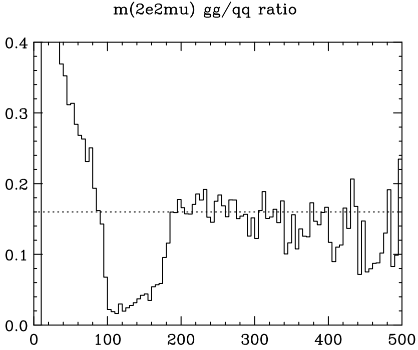
C. Zecher, T. Matsuura, J. J. van der Bij, Z. Phys. C64 (1994) 219, arXiv:hep-ph/940429

Summary and Outlook

- $gg \to ZZ$ and WW backgrounds should be included in LHC studies
- GG2WW: **final** version (2.4.0) public
- GG2ZZ: version 1.0.0 public (limitation: technical cuts for double precision stability affect low M_{ZZ} predictions)
- immediate steps: make version 1.1.0 public (no technical cuts), confirm: $gg \to ZZq\bar{q}$ (tree-level) is small Adamson, de Florian, Signer (2002), include Higgs signal and study signal-background interference
- scale uncertainty $\mu_R, \mu_F \in \{M_Z/2, 2M_Z\}$: gg: 20%, $q\bar{q}$ NLO (LO): 4% (7%)
- currently: $pp \to ZZ$ at NLO + $gg \to ZZ$ at LO
- better: $pp \to ZZ$ at NNLO (includes $gg \to ZZ$ at LO)
- or: $pp \to ZZ$ at NLO + $gg \to ZZ$ at NLO
- better still: $pp \to ZZ$ at NNLO + $gg \to ZZ$ NLO correction
- best, but not any time soon: $pp \to ZZ$ at NNNLO (includes $gg \to ZZ$ at NLO)
- in parallel: explore data-driven methods to reduce uncertainties

Backup Slides

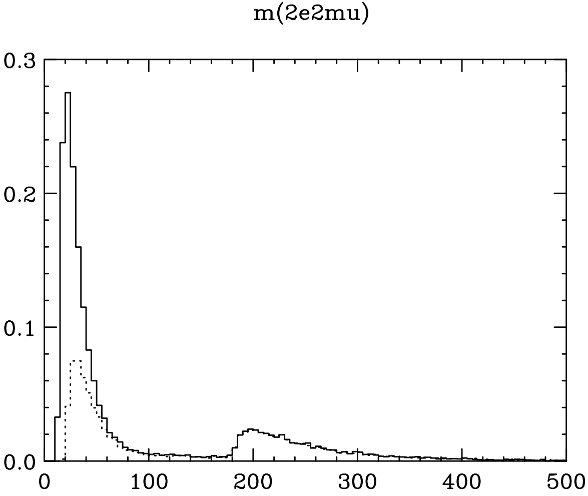
$gg/q\bar{q}$ ratio depends on lepton cuts:



left: $M_{ee}, M_{\mu\mu} > 6$ GeV, **right**: $M_{ee}, M_{\mu\mu} > 6$ GeV, $p_{T\ell} > 5$ GeV, $|\eta_\ell| < 2.4$

$\sqrt{s} = 14$ TeV

Technical cuts in gg2ZZ-1.0.0 only affect $M_{ee\mu\mu} < 100$ GeV region:



$\sqrt{s} = 10$ TeV, $M_{ee}, M_{\mu\mu} > 6$ GeV, **dotted**: gg2ZZ-1.0.0 (with technical cuts: $p_{TZ} > 2$ GeV, except if M_{ee} or $M_{\mu\mu} < 36.5$ GeV: then $p_{TZ} > 7$ GeV)