Theory update on tZj

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TopWG meeting
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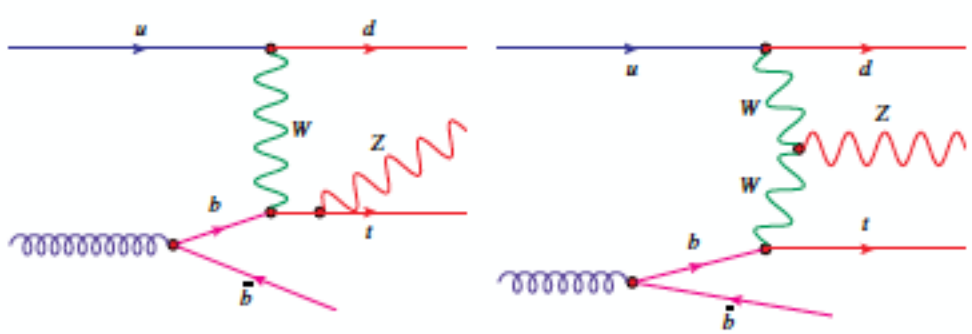
TOPWG November 2017

Signal samples & theory cross section

ATLAS

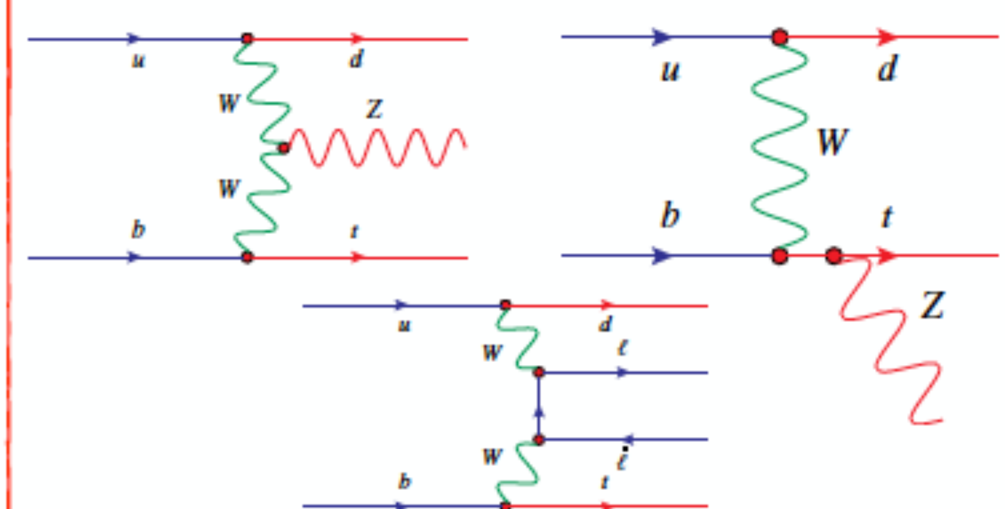
- Signal MC: LO rescaled to NLO.
- Theory cross section:
  - Z boson is forced to be on shell,
  - no cuts are applied,
  - 4-flavour scheme.
  - $\sigma_{NLO}(tZq)$ = 800 fb
    - ±6/7% scale



- Tau leptonic decays included.
- Different scale choice between ATLAS and CMS.
- Theory paper https://arxiv.org/abs/1302.3856
  - $\sigma_{NLO}(tZq) \sim$ 820 fb.

CMS

- Signal MC: NLO.
- Theory cross section:
  - Z boson can be off shell/γ* is also included,
  - m_{ll} > 30 GeV,
  - 5-flavour scheme (4FS for MC generation).
  - $\sigma_{NLO}(tllq)$ = 94 fb
    - ±2% scale
    - ±2.5% PDF



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Signal samples & theory cross section

	FS	Scale	Cuts	x-sec (fb)	notes
tllq	5	$\mu = \frac{1}{2}\Sigma\sqrt{E^2 - p_z^2}$	-	94	CMS default
tllq	4	$\mu = \frac{1}{2}\Sigma\sqrt{E^2 - p_z^2}$	-	76	4 vs 5 FS 20% effect
tllq	5	$\mu = \frac{1}{2}\Sigma\sqrt{E^2 - p_z^2}$	m_{ll} > 80 GeV	89	
tZ(→ll)q	5	$\mu = \frac{1}{2}\Sigma\sqrt{E^2 - p_z^2}$	-	86	effect of missing contributions from off-shell/γ* and extra diagrams
tZq	4	$\mu = 4\sqrt{m_b^2 + p_{T,b}^2}$	-	800	ATLAS default
tZq	4	$\mu = \frac{1}{2}\Sigma\sqrt{E^2 - p_z^2}$	-	690	scale 15% effect
tZq	5	$\mu = \frac{1}{2}\Sigma\sqrt{E^2 - p_z^2}$	-	860	4 vs 5 FS 20% effect

- Need to converge on a common setup.
  - Include or not γ* contribution → current thinking is to include it
  - If including γ*, need to fix an m(ll) requirement → 30 GeV seems reasonable from the experimental side
  - Whether to use 4FS or 5FS → current thinking is 5FS (expected to be more precise for inclusive XS)
  - Which scale to use → theory guidance appreciated

This talk: a first step to address these points

tZj in the SM: tools

MCFM: 5F calculation including top and Z decays
Campbell, Ellis and Röntsch: arXiv:1302.3856

MG5_aMC: possibility for 5F and 4F scheme calculations

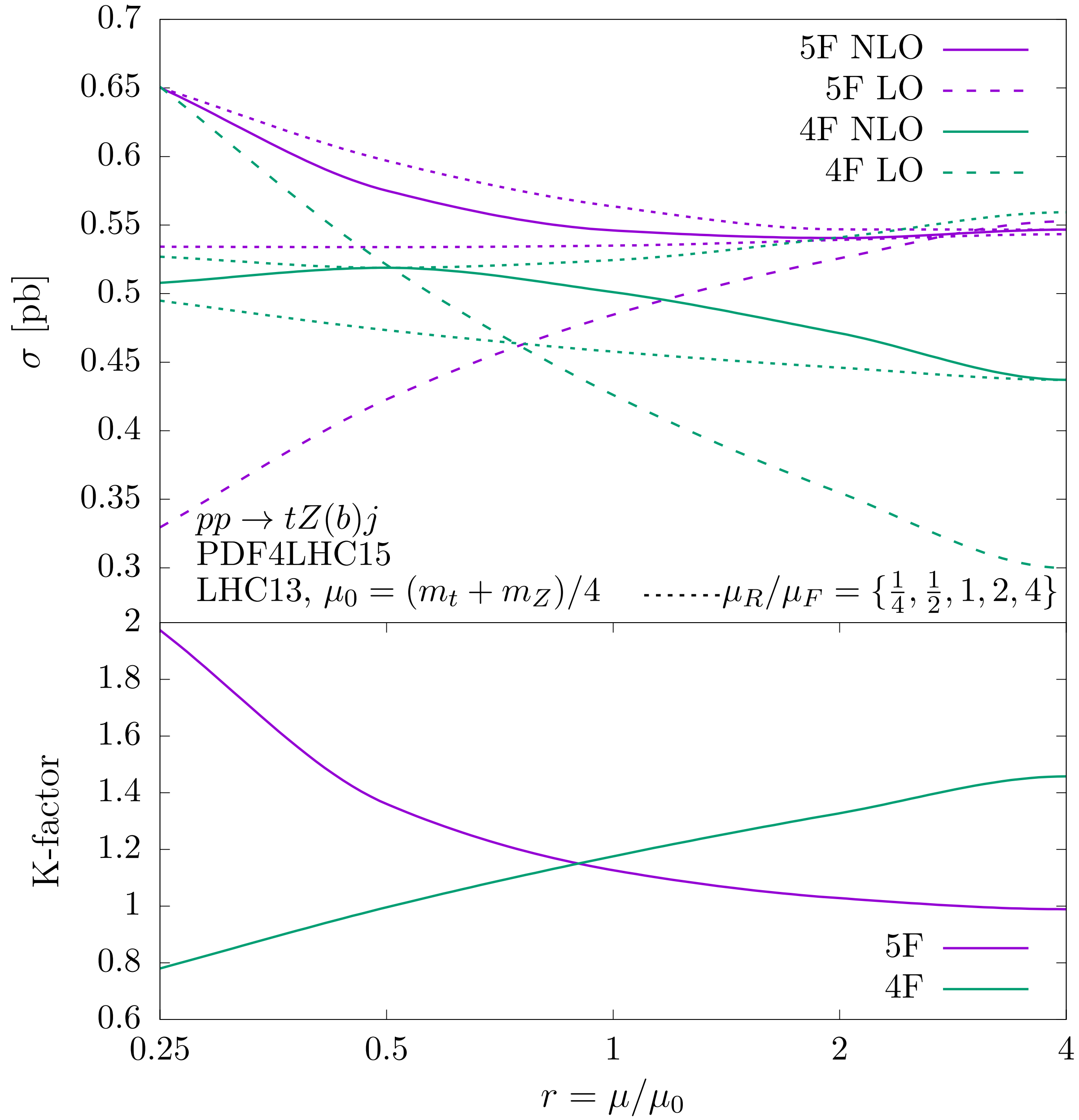
```
import model loop_sm
generate p p > t z b~ j $$ w+ w- [QCD]
output tZjsm4F

import model loop_sm-no_b_mass
generate p p > t Z j $$ w+ w- [QCD]
output tZjsm5F
```

Similarly for anti-top

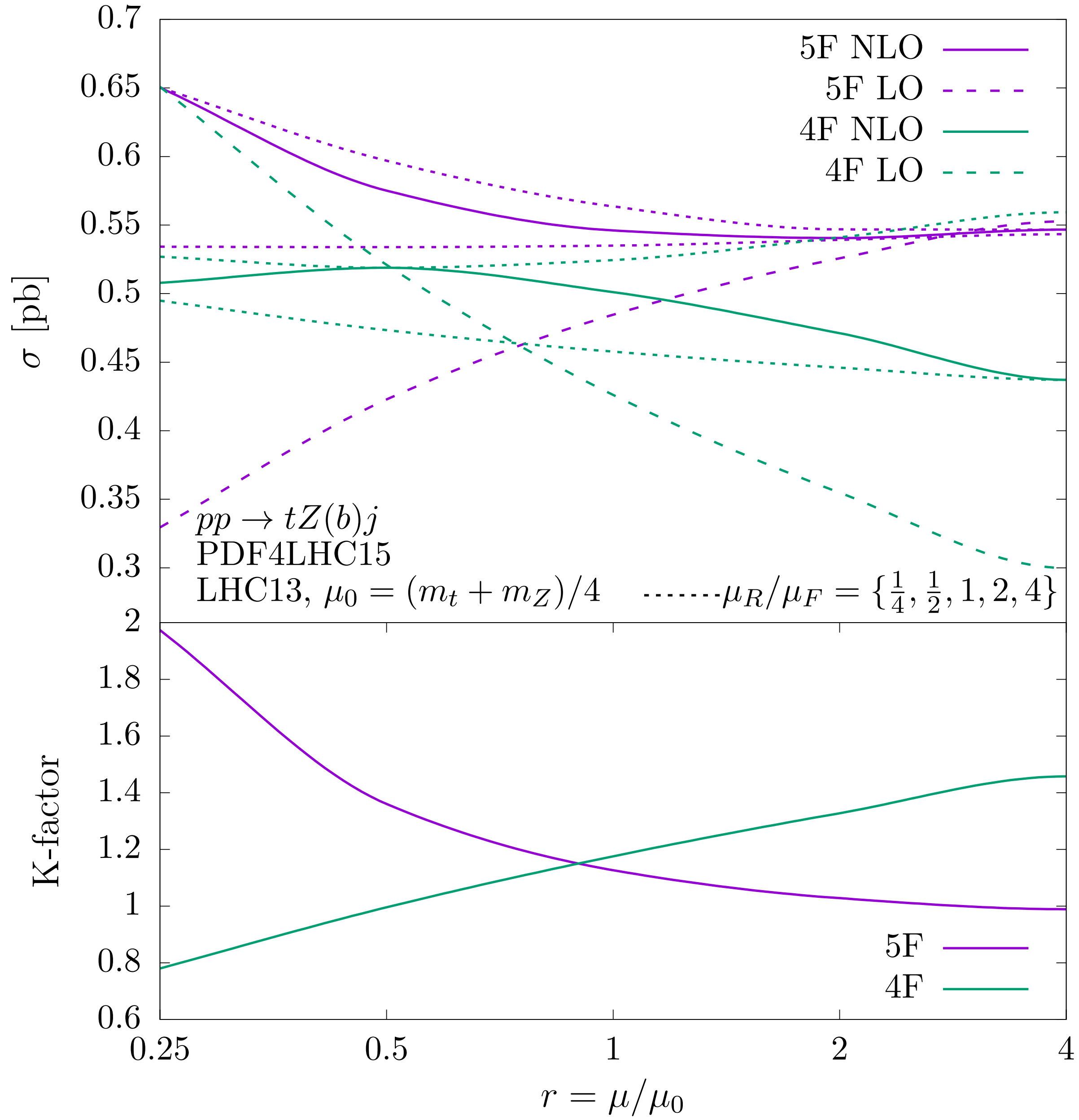
Both codes give the fully differential NLO results in relatively short runtimes

4F/5F comparison



- 5F tZj results cross-checked between MCFM and MG5_aMC: agreement to the per mille level for the inclusive cross section at various scales
- A central scale choice of $(m_t+m_Z)/4$ inspired by the tHj study Demartin et al. arXiv:1504.00611
- PDF4LHC15 pdfs used, 5F and 4F variants accordingly

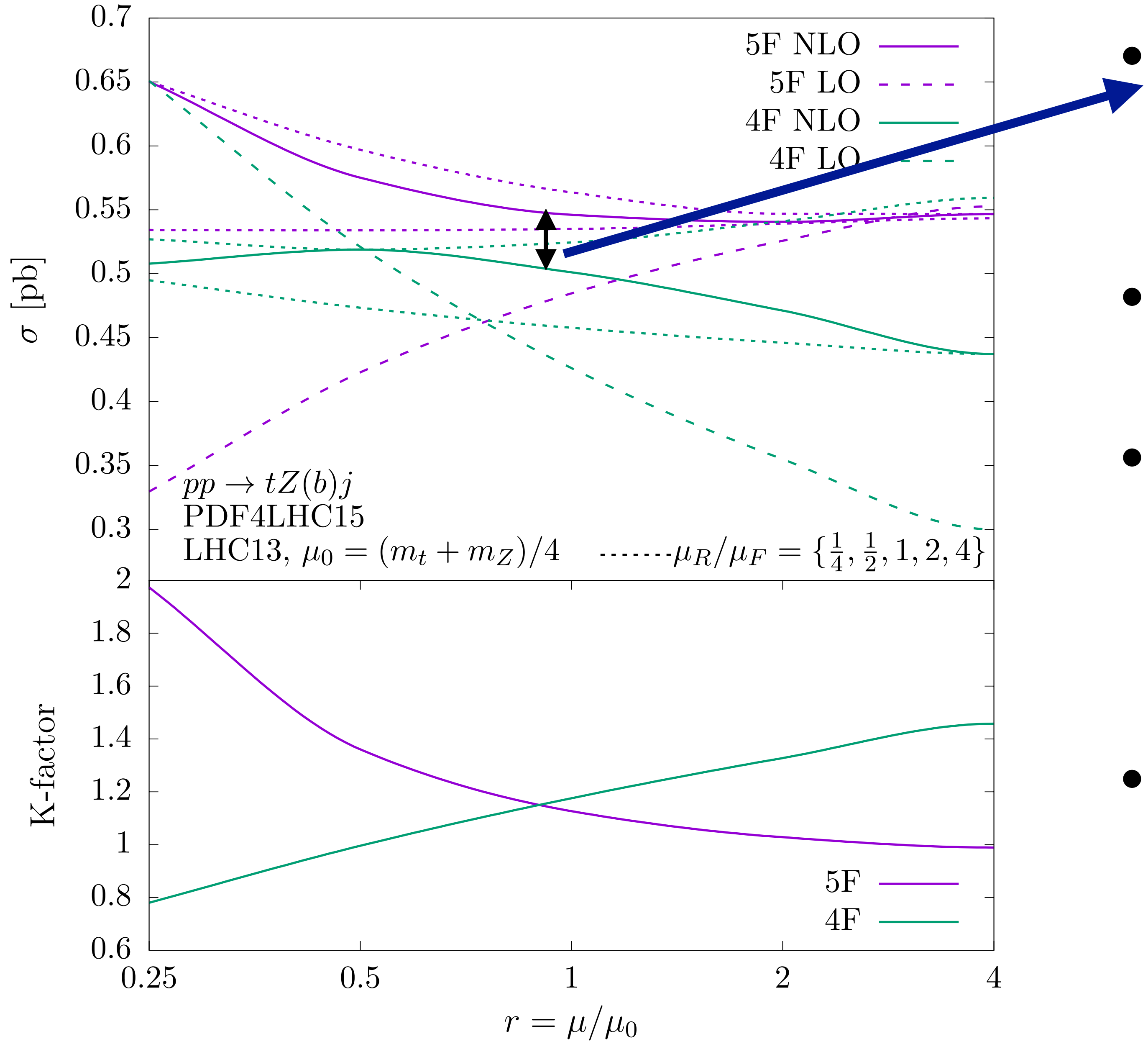
4F/5F comparison



- Central choice appears to minimise the 4F-5F difference at NLO
- 5F NLO scale dependence and K-factor become flatter at $\mu > \mu_0$
- Independent variation of renormalisation and factorisation scales around μ_0 gives additional bands (dotted lines)
- Varying mb up and down by 0.5 GeV for 4F gives a ~4% uncertainty in the cross section

Best central prediction and uncertainty to be decided

4F/5F comparison



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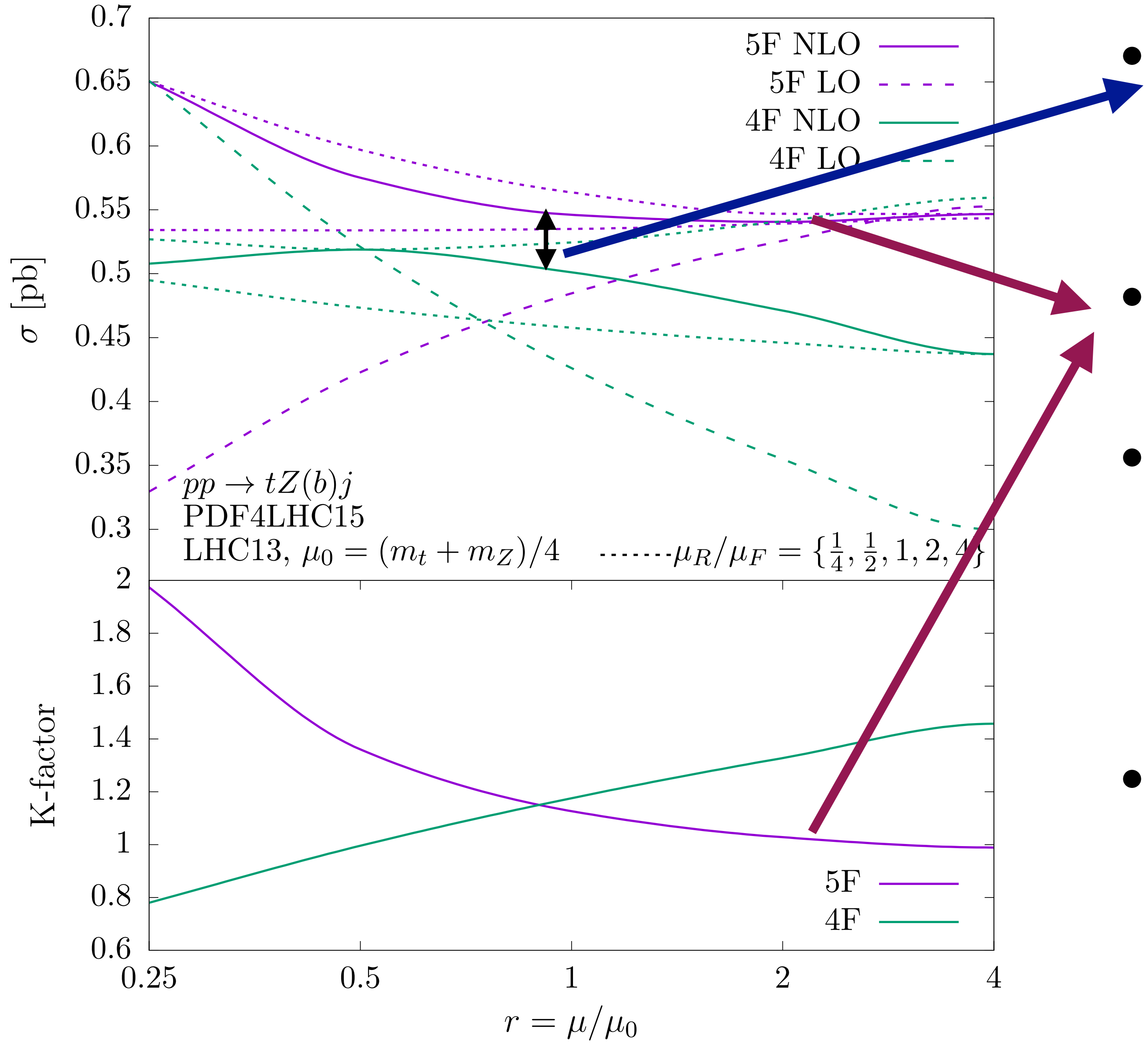

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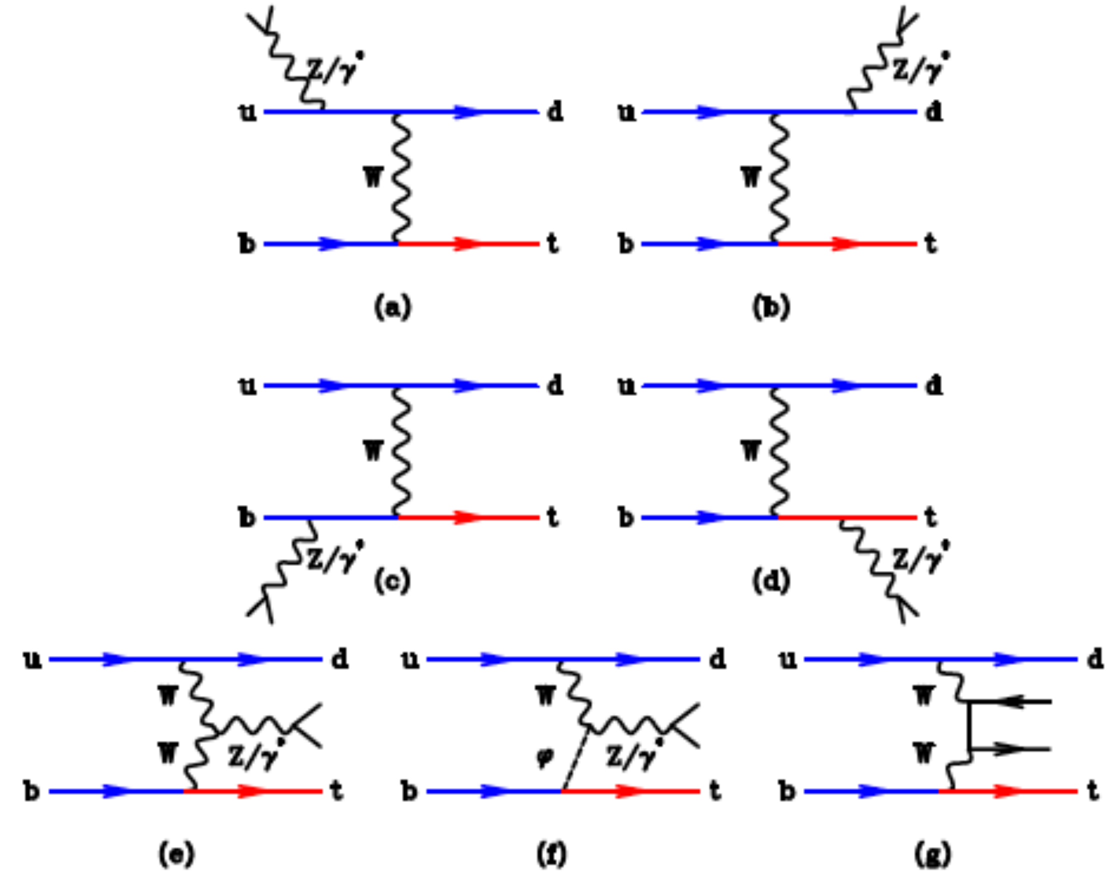
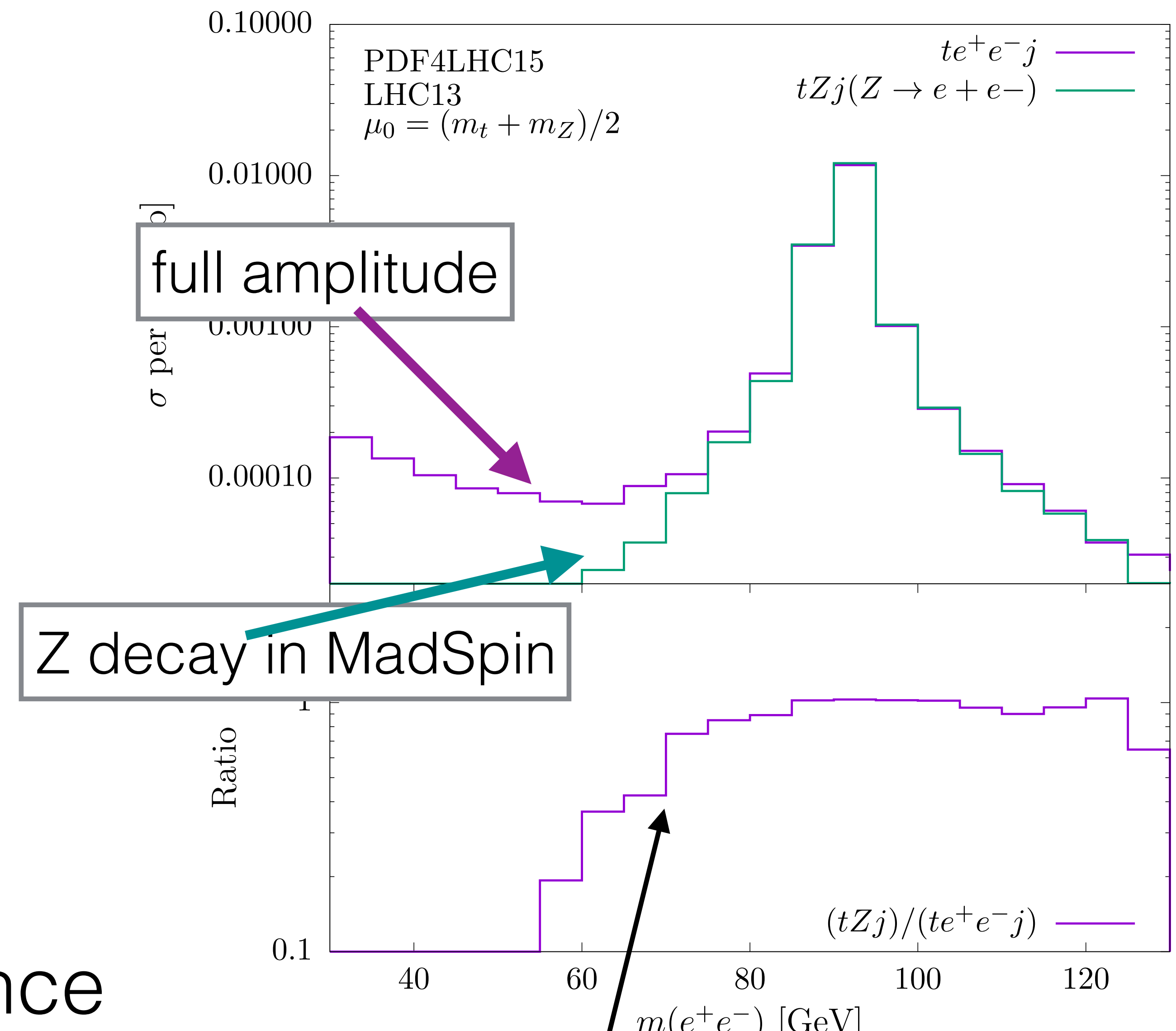
Best central prediction and uncertainty to be decided

Including Z decays: $t\ell^+\ell^-j$



Can the additional contributions be ignored?



Virtual photon contribution

Diagrams with TGC and WW scattering enter

All needed for gauge-invariance

Quickly becomes important for $|m-m_Z|>20$ GeV

$t\ell^+\ell^- j$

Both Monte-Carlos allow computing this at NLO, including all contributions

MG5_aMC

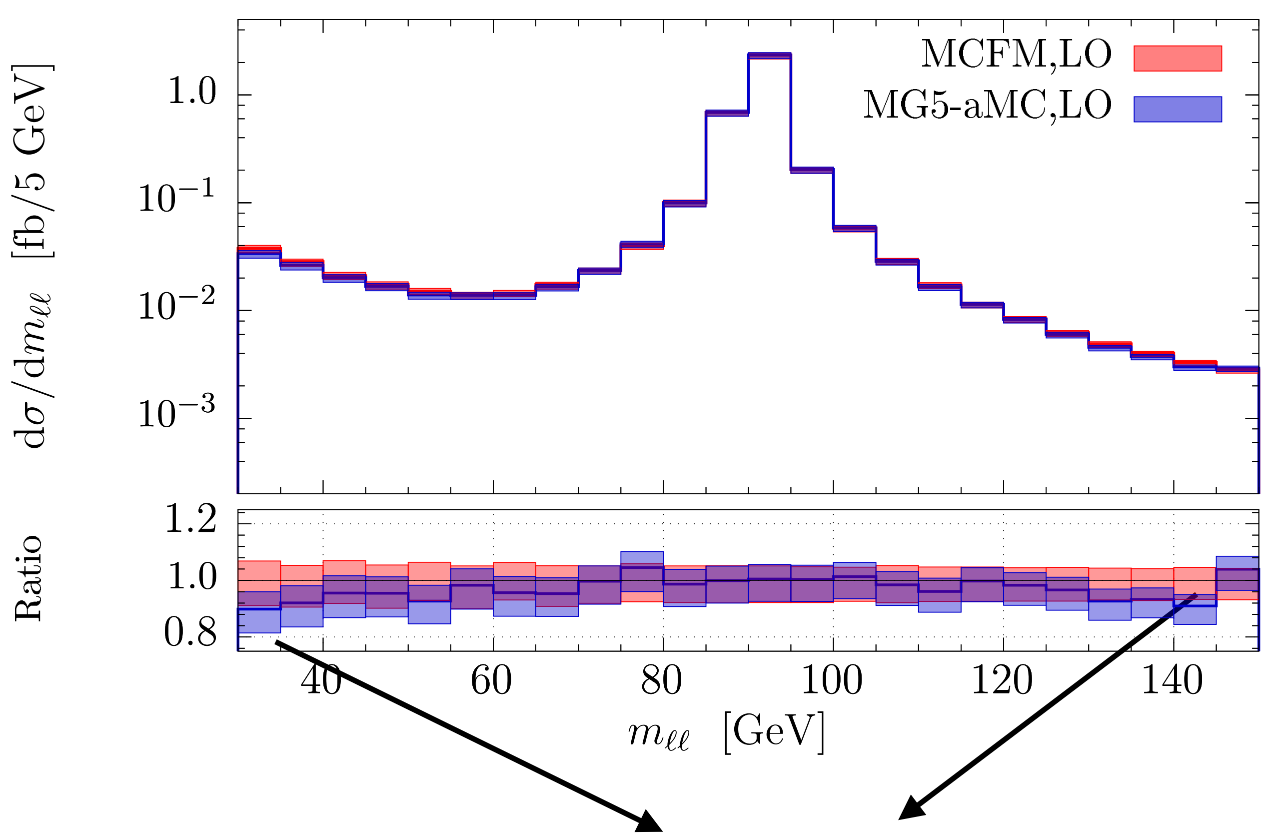
Z width included in a gauge-invariant way

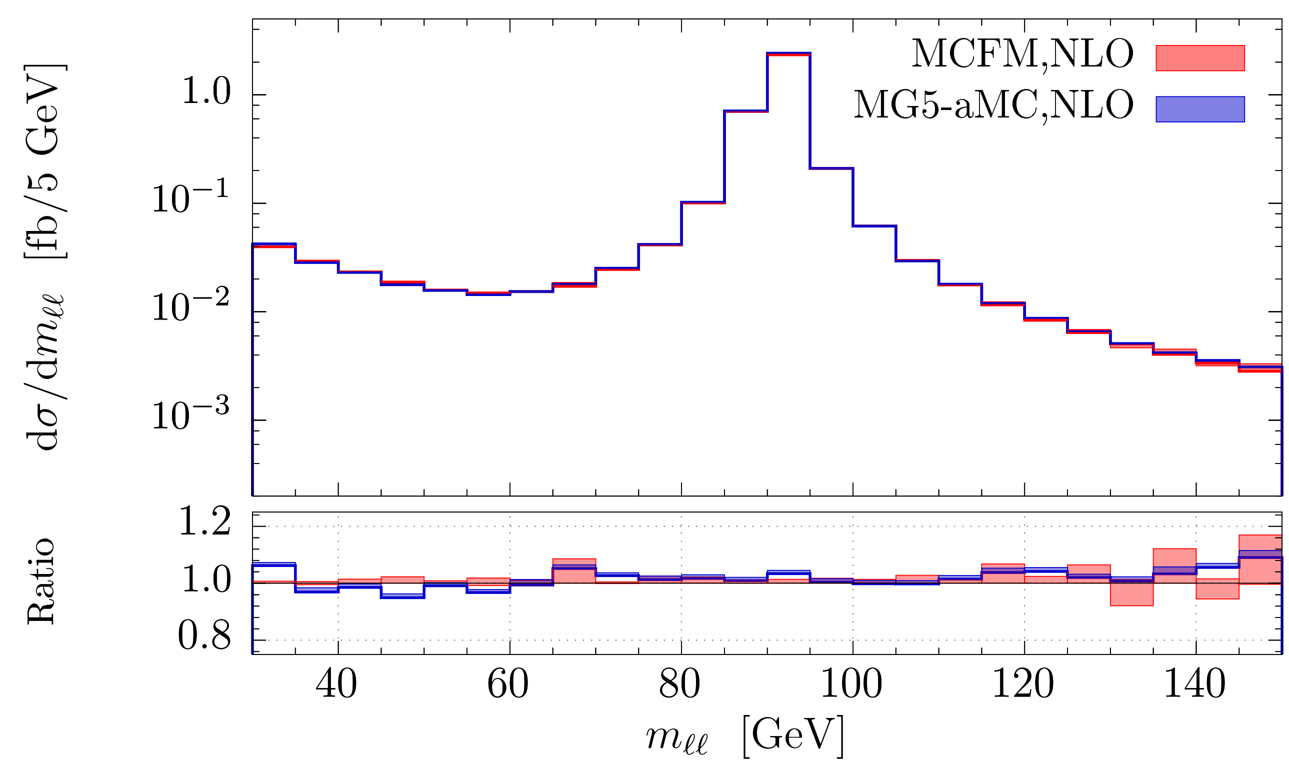
```
import model loop_sm-no_b_mass
set complex_mass_scheme True
generate p p > t j e+ e- $$w+ w- QED=4 QCD=0 [QCD]
output tjelelnlo
```

$$m_k \longrightarrow \sqrt{m_k^2 - i m_k \Gamma_k}$$

MCFM uses the Baur-Zeppenfeld scheme

Propagator: $D_Z(s_{34}) = \dfrac{1}{s_{34} - m_Z^2}$ Amplitude multiplied by: $\left(\dfrac{s_{34} - m_Z^2}{s_{34} - m_Z^2 + i m_Z \Gamma_Z}\right)$



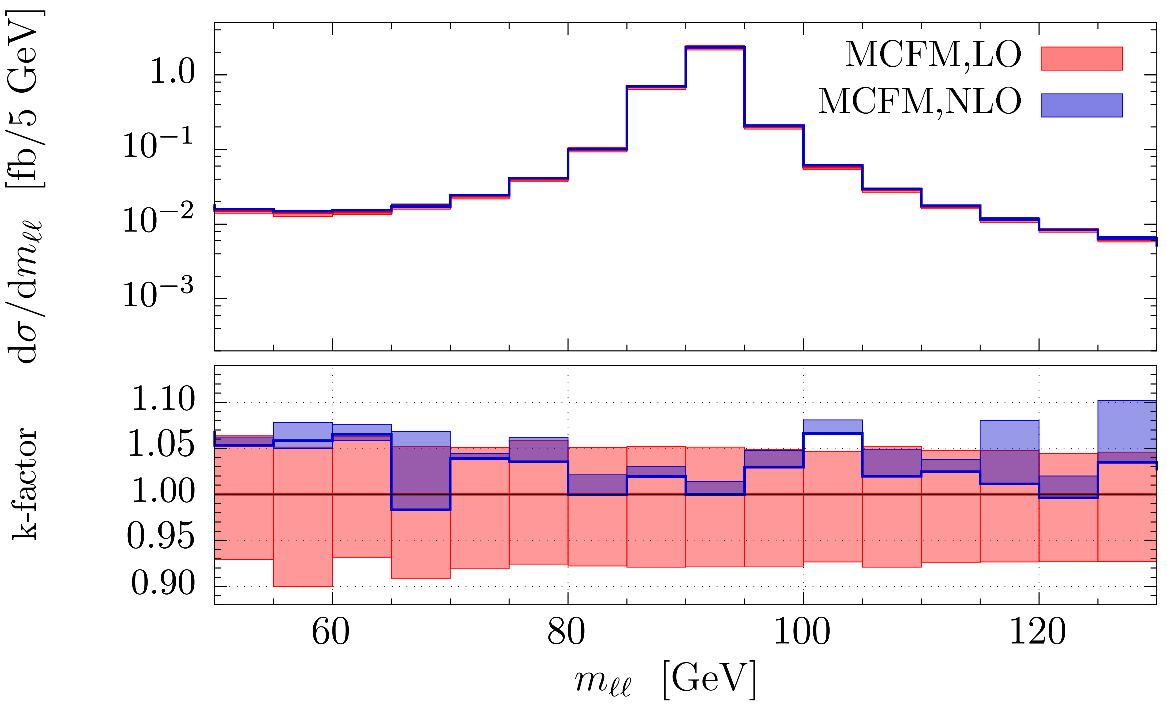


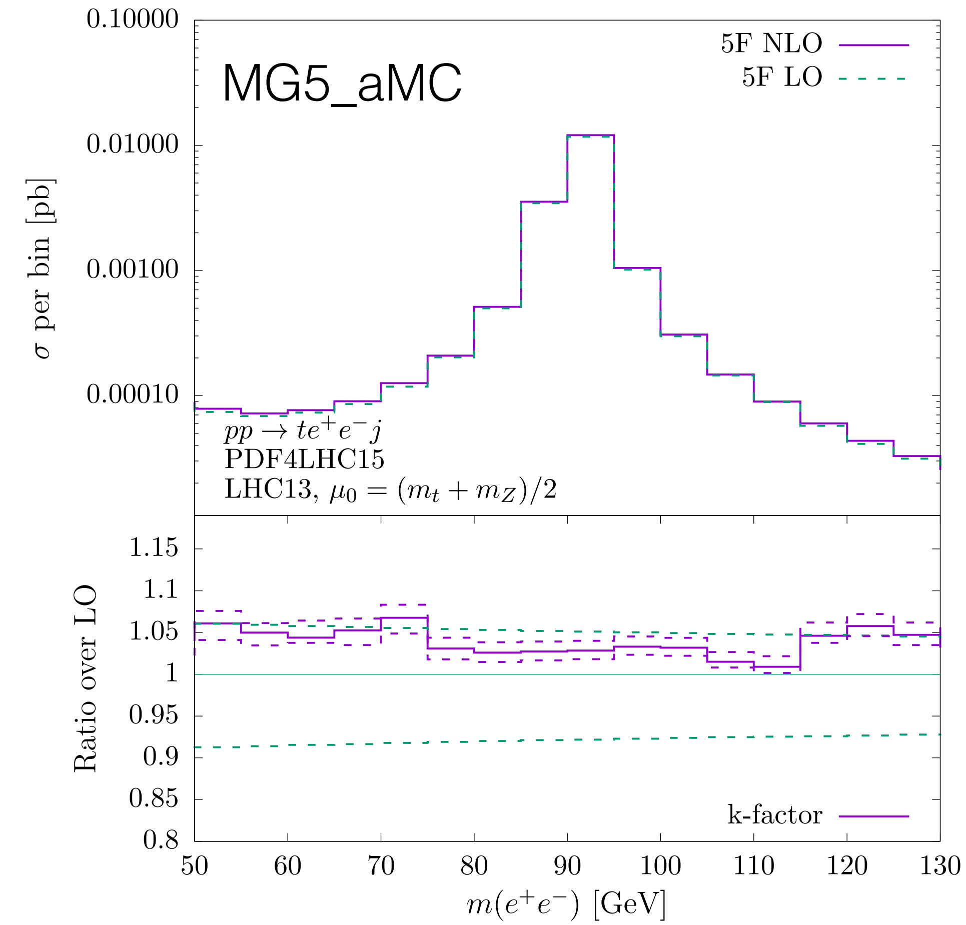
small differences in the tails

No systematic difference at NLO

Differential k-factors

$t\ell^+\ell^- j$





Differential k-factors: flat
Significant reduction of the scale uncertainties

Summary

Available so far:

- Comparison between MG5_aMC and MCFM, shows agreement, both at the inclusive and differential level for the 5F scheme
- Both tools include off-shell and interference effects, which should be used by the experimental groups to ensure a good description beyond the Z-mass peak
- Comparison between 4F and 5F scheme and scale variations show theoretical uncertainties under control (at the 10% level)

Further steps

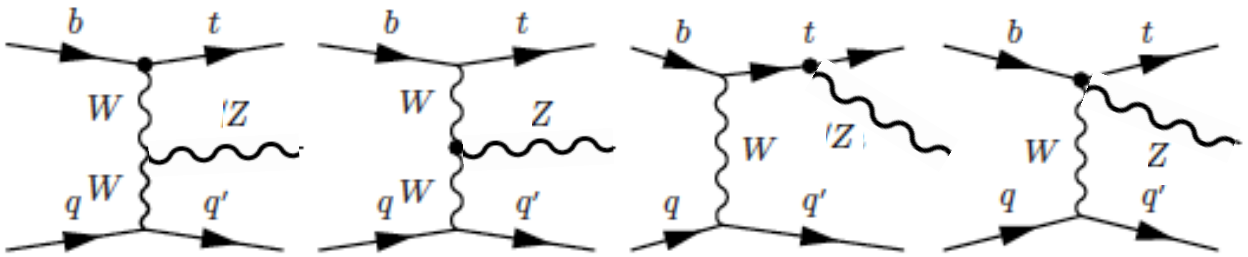
- Combine 4F/5F to obtain a recommendation for the inclusive cross-section: central value and associated uncertainties: see for example the suggestion for tHj in arXiv:1504.00611

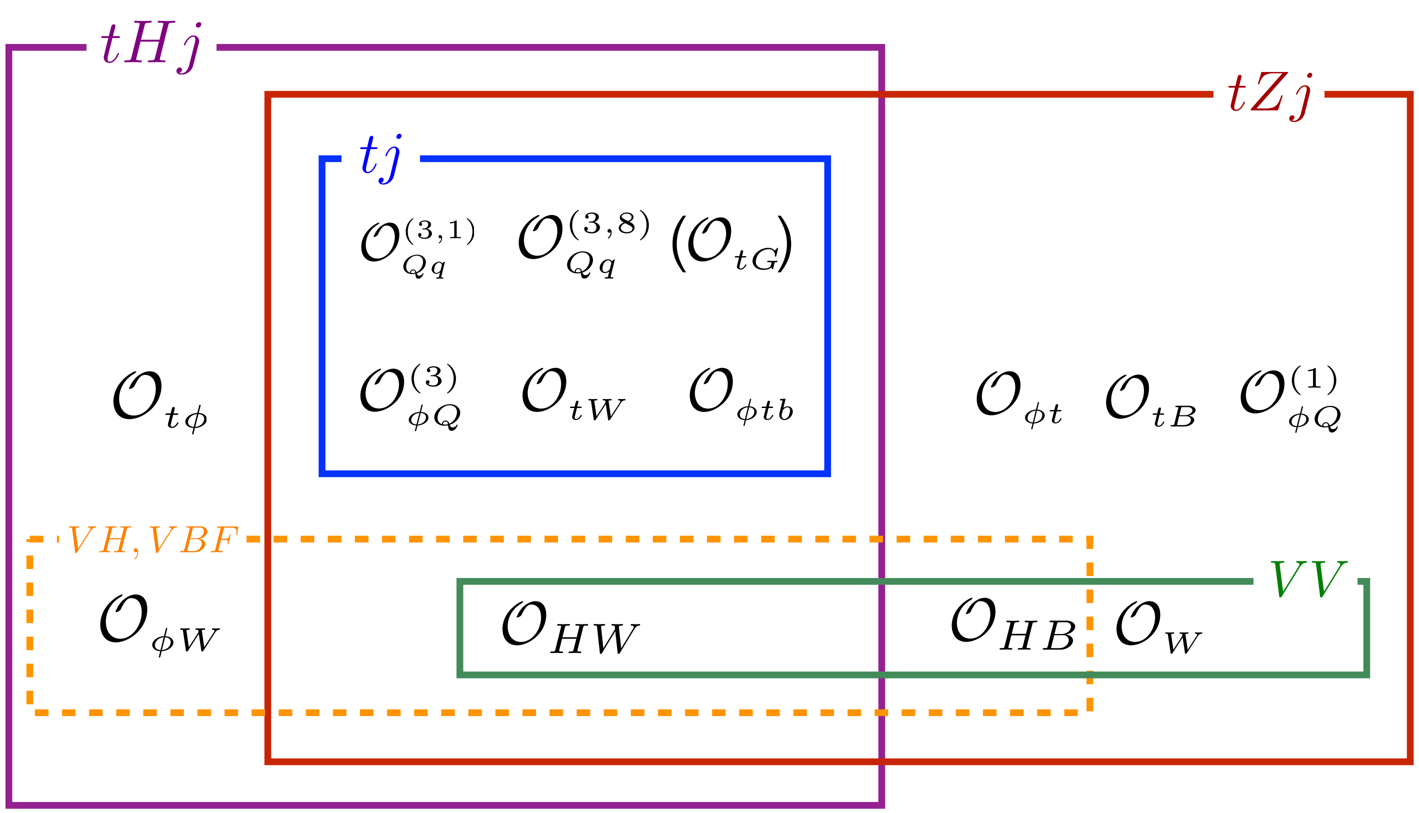
$$\sigma_{\mathrm{NLO}} = (\sigma^+ + \sigma^-)/2\,, \quad \delta_{\mu+\mathrm{FS}} = (\sigma^+ - \sigma^-)/2$$

$$\sigma^+ = \max_{\mu\in[\mu_0/2,\,2\mu_0]} \left\{ \sigma^{4\mathrm{F}}_{\mathrm{NLO}}(\mu)\,,\, \sigma^{5\mathrm{F}}_{\mathrm{NLO}}(\mu) \right\},$$
$$\sigma^- = \min_{\mu\in[\mu_0/2,\,2\mu_0]} \left\{ \sigma^{4\mathrm{F}}_{\mathrm{NLO}}(\mu)\,,\, \sigma^{5\mathrm{F}}_{\mathrm{NLO}}(\mu) \right\}.$$

- More detailed study of scale variations? Dynamical scales? Any input will be appreciated
- Study of differences between 4F and 5F in the signal PS region?
- EFT interpretations

tZj in the EFT





σ [fb]	LO	NLO	K-factor
σ_{SM}	$660.8(4)^{+13.7\%}_{-9.6\%} \pm 9.7\%$	$839.1(5)^{+1.1\%}_{-5.1\%} \pm 1.0\%$	1.27
σ_{W}	$-7.87(7)^{+8.4\%}_{-12.6\%} \pm 9.7\%$	$-8.77(8)^{+8.5\%}_{-4.3\%} \pm 1.1\%$	1.12
$\sigma_{W,W}$	$34.58(3)^{+8.2\%}_{-3.9\%} \pm 13.0\%$	$43.80(4)^{+6.6\%}_{-15.1\%} \pm 2.8\%$	1.27
σ_{tB}	$2.23(2)^{+14.7[0.9]\%}_{-10.7[1.0]\%} \pm 9.4\%$	$2.94(2)^{+2.3[0.4]\%}_{-3.0[0.7]\%} \pm 1.1\%$	1.32
$\sigma_{tB,tB}$	$2.833(2)^{+10.5[1.7]\%}_{-6.3[1.9]\%} \pm 11.1\%$	$4.155(3)^{+4.7[0.9]\%}_{-10.1[1.4]\%} \pm 1.7\%$	1.47
σ_{tW}	$2.66(4)^{+18.8[0.9]\%}_{-15.3[1.0]\%} \pm 11.4\%$	$13.0(1)^{+15.8[2.1]\%}_{-22.8[0.0]\%} \pm 1.2\%$	4.90
$\sigma_{tW,tW}$	$48.16(4)^{+10.0[1.7]\%}_{-5.8[1.9]\%} \pm 11.3\%$	$80.00(4)^{+7.9[1.3]\%}_{-14.7[1.6]\%} \pm 1.9\%$	1.66
$\sigma_{\varphi dtR}$	$4.20(1)^{+14.9\%}_{-10.9\%} \pm 9.3\%$	$4.94(2)^{+3.4\%}_{-6.7\%} \pm 1.0\%$	1.18
$\sigma_{\varphi dtR,\varphi dtR}$	$0.3326(3)^{+13.6\%}_{-9.5\%} \pm 9.6\%$	$0.4402(5)^{+3.7\%}_{-9.3\%} \pm 1.0\%$	1.32
$\sigma_{\varphi Q}$	$14.98(2)^{+14.5\%}_{-10.5\%} \pm 9.4\%$	$18.07(3)^{+2.3\%}_{-1.6\%} \pm 1.0\%$	1.21
$\sigma_{\varphi Q,\varphi Q}$	$0.7442(7)^{+14.1\%}_{-10.0\%} \pm 9.5\%$	$1.028(1)^{+2.8\%}_{-7.3\%} \pm 1.0\%$	1.38
$\sigma_{\varphi Q^{(3)}}$	$130.04(8)^{+13.8\%}_{-9.8\%} \pm 9.5\%$	$161.4(1)^{+0.9\%}_{-4.8\%} \pm 1.0\%$	1.24
$\sigma_{\varphi Q^{(3)},\varphi Q^{(3)}}$	$17.82(2)^{+11.7\%}_{-7.5\%} \pm 10.5\%$	$23.98(2)^{+3.7\%}_{-9.3\%} \pm 1.4\%$	1.35
$\sigma_{\varphi tb}$	0	0	–
$\sigma_{\varphi tb,\varphi tb}$	$2.949(2)^{+10.5\%}_{-6.2\%} \pm 11.1\%$	$4.154(4)^{+5.1\%}_{-11.2\%} \pm 1.8\%$	1.41
σ_{HW}	$-5.16(6)^{+7.8\%}_{-12.0\%} \pm 10.5\%$	$-6.88(8)^{+6.4\%}_{-2.0\%} \pm 1.4\%$	1.33
$\sigma_{HW,HW}$	$0.912(2)^{+9.4\%}_{-5.2\%} \pm 12.0\%$	$1.048(2)^{+5.2\%}_{-12.8\%} \pm 2.1\%$	1.15
σ_{HB}	$-3.015(9)^{+9.9\%}_{-13.9\%} \pm 9.5\%$	$-3.76(1)^{+5.2\%}_{-1.0\%} \pm 1.0\%$	1.25
$\sigma_{HB,HB}$	$0.02324(6)^{+12.7\%}_{-8.5\%} \pm 9.9\%$	$0.02893(6)^{+2.3\%}_{-7.5\%} \pm 1.1\%$	1.24
σ_{tG}	$0.45(2)^{+93.0\%}_{-148.8\%} \pm 4.9\%$		–
$\sigma_{tG,tG}$	$2.251(4)^{+20.9\%}_{-30.0\%} \pm 2.5\%$		–
$\sigma_{Qq^{(3,1)}}$	$-393.5(5)^{+8.1\%}_{-12.3\%} \pm 10.0\%$	$-498(1)^{+8.9\%}_{-3.2\%} \pm 1.2\%$	1.26
$\sigma_{Qq^{(3,1)},Qq^{(3,1)}}$	$462.25(3)^{+8.4\%}_{-4.1\%} \pm 12.7\%$	$545.50(5)^{+7.4\%}_{-17.4\%} \pm 2.9\%$	1.18
$\sigma_{Qq^{(3,8)}}$	0	$-0.9(3)^{+23.3\%}_{-26.3\%} \pm 19.2\%$	–
$\sigma_{Qq^{(3,8)},Qq^{(3,8)}}$	$102.73(5)^{+8.4\%}_{-4.1\%} \pm 12.7\%$	$111.18(5)^{+9.3\%}_{-18.4\%} \pm 2.8\%$	1.08

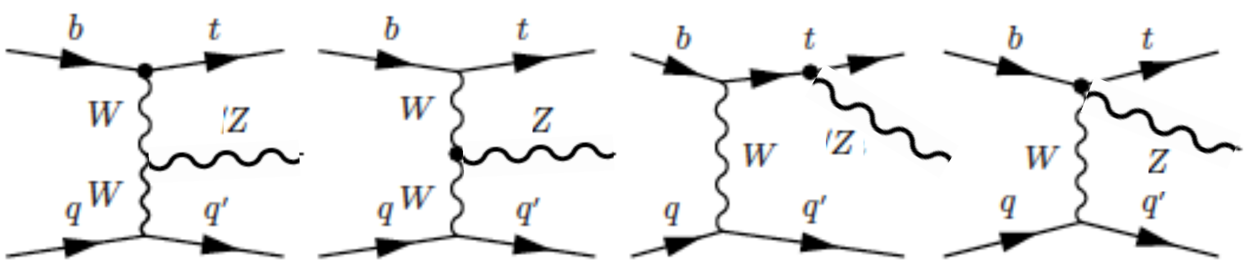
Unique interplay

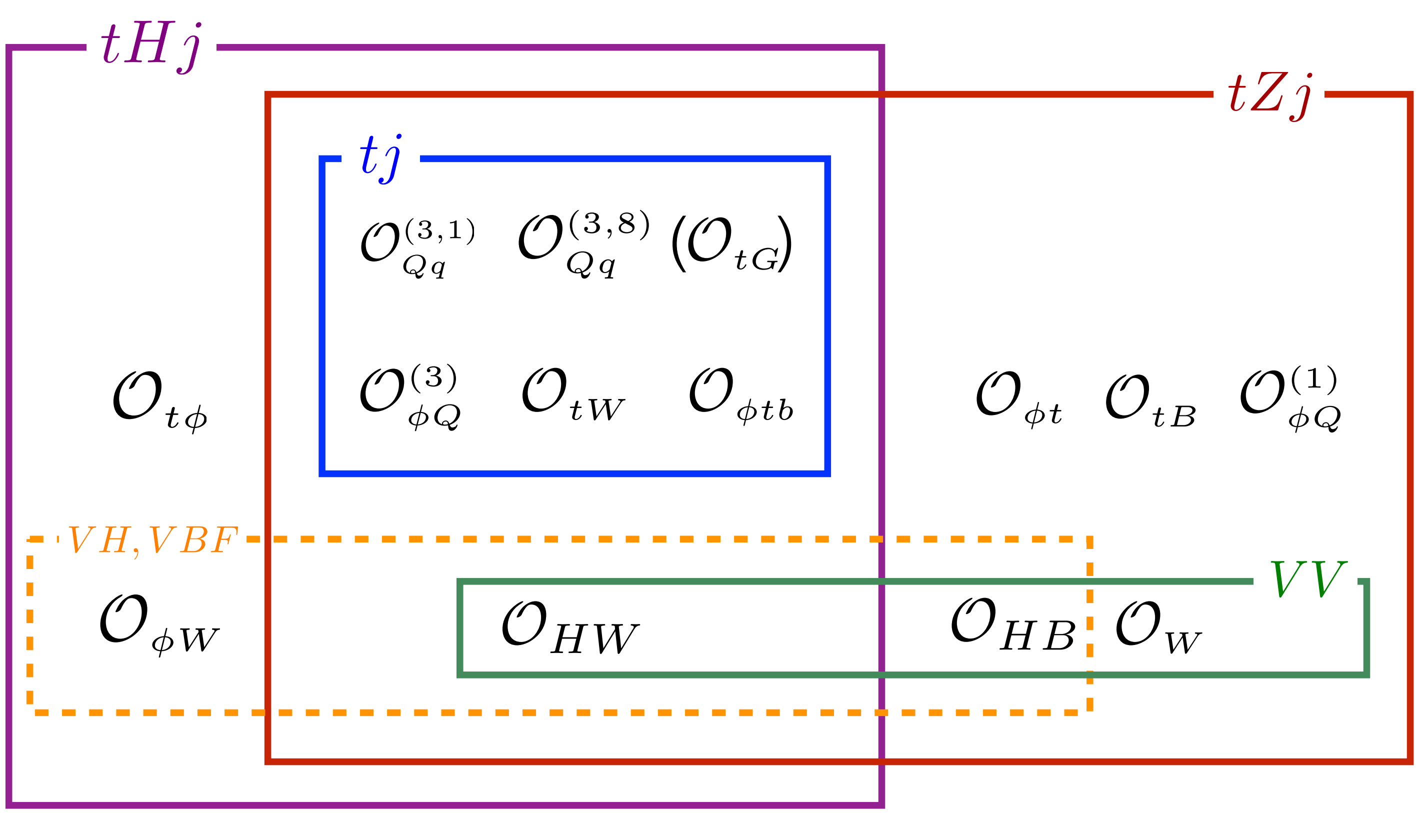
Gauge-Higgs
Top couplings
TGC

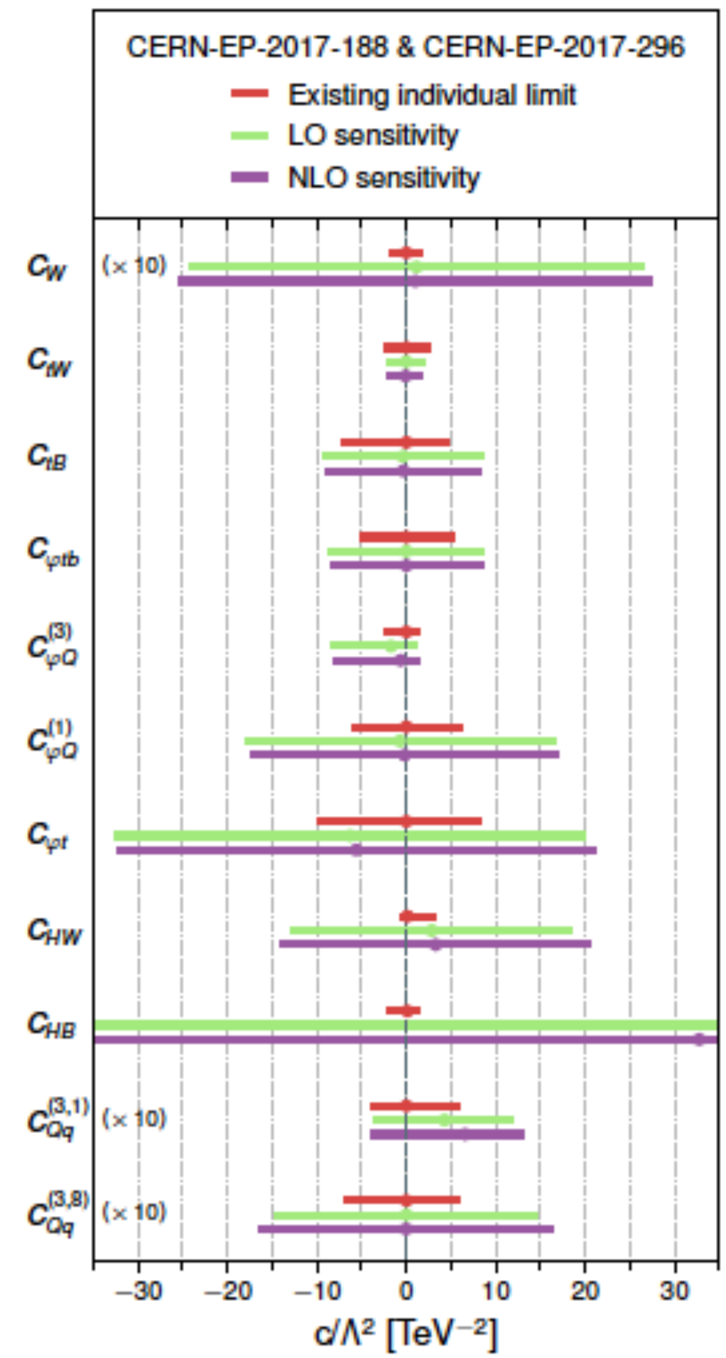
First EFT study, including NLO QCD corrections

arXiv:1804.07773

tZj in the EFT







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tZj measurements:

CMS; PLB 779 (2018) 358-384: 0.75 ± 0.27

ATLAS; CERN-EP-2017-188: 1.31 ± 0.47

arXiv:1804.07773

thanks for your attention