The impact of top-quark modelling in tt+DM searches at the LHC

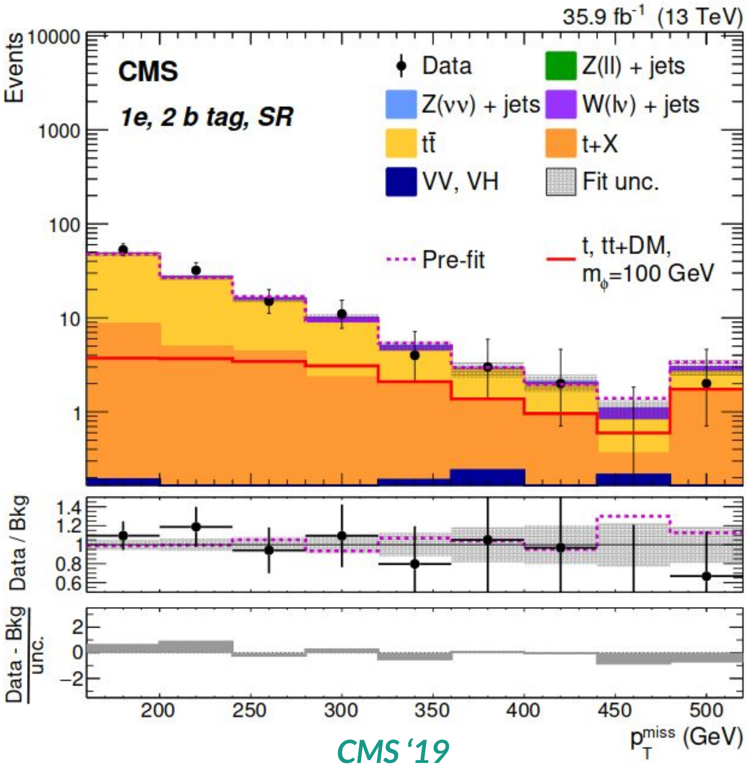
arXiv:2108.01089

Jonathan Hermann • 15.09.2021
In collaboration with: Małgorzata Worek

Introduction

- Ongoing search for DM includes CMS & ATLAS
- Need precise predictions (NLO, off-shell) for a plethora of background processes
- DM signals most prominent in distribution tails
  -> This is the region where NLO and off-shell corrections are generally large
- Problem: calculations very involved

-> Are these corrections actually necessary for DM searches at the LHC?



CMS '19

Setup

⇨ Calculate signal strength exclusion limits to quantify the relevance of these effects

Signal: $pp \to b\bar{b}e^+\mu^-\nu_e\bar{\nu}_\mu\chi\bar{\chi}$ (tt+DM)

-> Spin-0 s-channel mediator model, DMsimp implementation *Backović, Krämer, Maltoni, Martini, Mawatari, Pellen ‘15*

-> generated with MadGraph *Alwall, Frederix, Frixione, Hirschi, Maltoni, Mattelaer, Shao, Stelzer, Torrielli, Zaro ‘14*

-> always kept at NLO with LO decays

Background: $pp \to b\bar{b}e^+\mu^-\nu_e\bar{\nu}_\mu$ (tt) *Bevilacqua, Czakon, van Hameren, Papadopoulos, Worek ‘11*

$pp \to b\bar{b}e^+\mu^-\nu_e\bar{\nu}_\mu\nu_\tau\bar{\nu}_\tau$ (ttZ) *Bevilacqua, Hartanto, Kraus, Weber, Worek ‘19*

-> generated with HELAC-NLO *Bevilacqua, Czakon, Garzelli, van Hameren, Kardos, Papadopoulos, Pittau, Worek ‘11*

-> Compare LO & NLO as well as NWA & full off-shell

Modelling of unstable particles

Full off-shell treatment:

- All diagrams & interferences included
- Breit-Wigner distribution for unstable particles

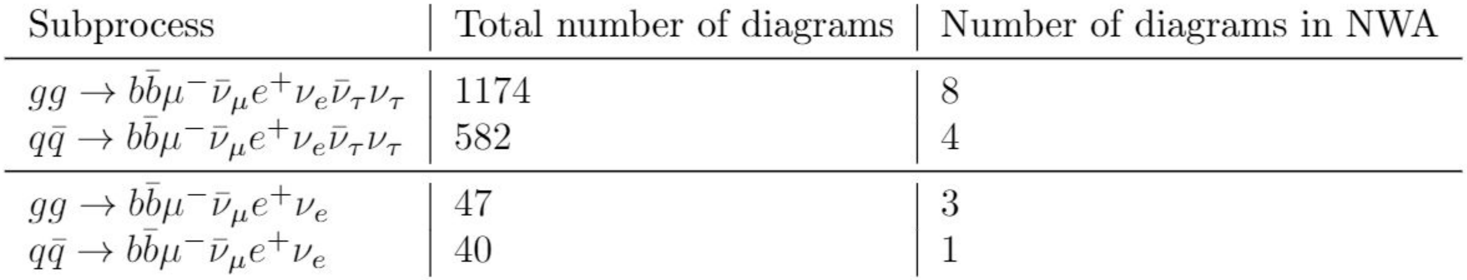
$$\frac{d\sigma}{dp^2} \sim \frac{1}{(p^2-m^2)^2+m^2\Gamma^2}$$

$$\xrightarrow{\frac{\Gamma}{m}\to 0}$$

Narrow-width approximation (NWA):

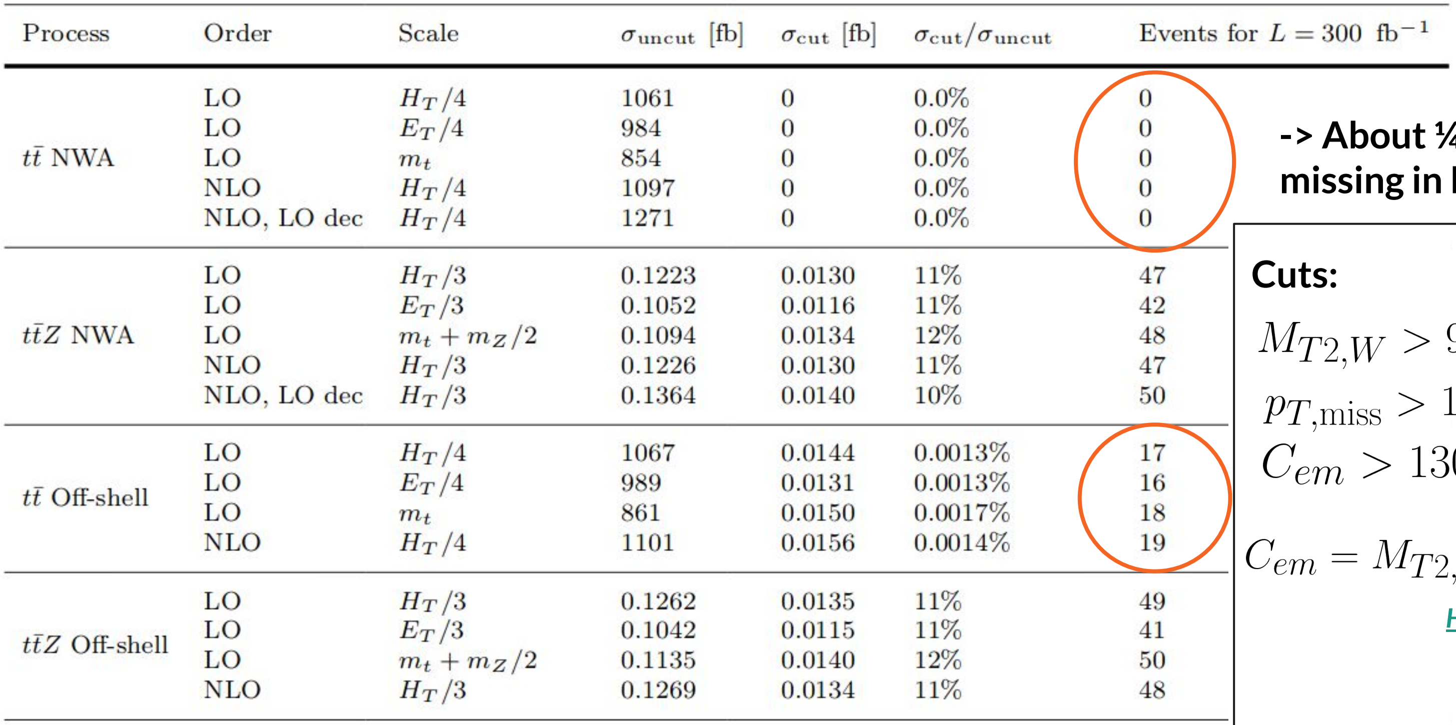
- Only double-resonant diagrams included
- Delta distribution for unstable particles

$$\frac{d\sigma}{dp^2} \sim \frac{\pi}{m\Gamma}\delta\left(p^2-m^2\right)$$



Subprocess	Total number of diagrams	Number of diagrams in NWA
$gg \to b\bar{b}\mu^-\bar{\nu}_\mu e^+\nu_e\bar{\nu}_\tau\nu_\tau$	1174	8
$q\bar{q} \to b\bar{b}\mu^-\bar{\nu}_\mu e^+\nu_e\bar{\nu}_\tau\nu_\tau$	582	4
$gg \to b\bar{b}\mu^-\bar{\nu}_\mu e^+\nu_e$	47	3
$q\bar{q} \to b\bar{b}\mu^-\bar{\nu}_\mu e^+\nu_e$	40	1

Exclusion limits - Effects of selection cuts



Process	Order	Scale	$\sigma_{\rm uncut}$ [fb]	$\sigma_{\rm cut}$ [fb]	$\sigma_{\rm cut}/\sigma_{\rm uncut}$	Events for $L = 300$ fb^{-1}
$t\bar{t}$ NWA	LO	$H_T/4$	1061	0	0.0%	0
	LO	$E_T/4$	984	0	0.0%	0
	LO	m_t	854	0	0.0%	0
	NLO	$H_T/4$	1097	0	0.0%	0
	NLO, LO dec	$H_T/4$	1271	0	0.0%	0
$t\bar{t}Z$ NWA	LO	$H_T/3$	0.1223	0.0130	11%	47
	LO	$E_T/3$	0.1052	0.0116	11%	42
	LO	$m_t + m_Z/2$	0.1094	0.0134	12%	48
	NLO	$H_T/3$	0.1226	0.0130	11%	47
	NLO, LO dec	$H_T/3$	0.1364	0.0140	10%	50
$t\bar{t}$ Off-shell	LO	$H_T/4$	1067	0.0144	0.0013%	17
	LO	$E_T/4$	989	0.0131	0.0013%	16
	LO	m_t	861	0.0150	0.0017%	18
	NLO	$H_T/4$	1101	0.0156	0.0014%	19
$t\bar{t}Z$ Off-shell	LO	$H_T/3$	0.1262	0.0135	11%	49
	LO	$E_T/3$	0.1042	0.0115	11%	41
	LO	$m_t + m_Z/2$	0.1135	0.0140	12%	50
	NLO	$H_T/3$	0.1269	0.0134	11%	48

-> About ¼ of events missing in NWA

Cuts:

$$M_{T2,W} > 90\,\text{GeV}$$

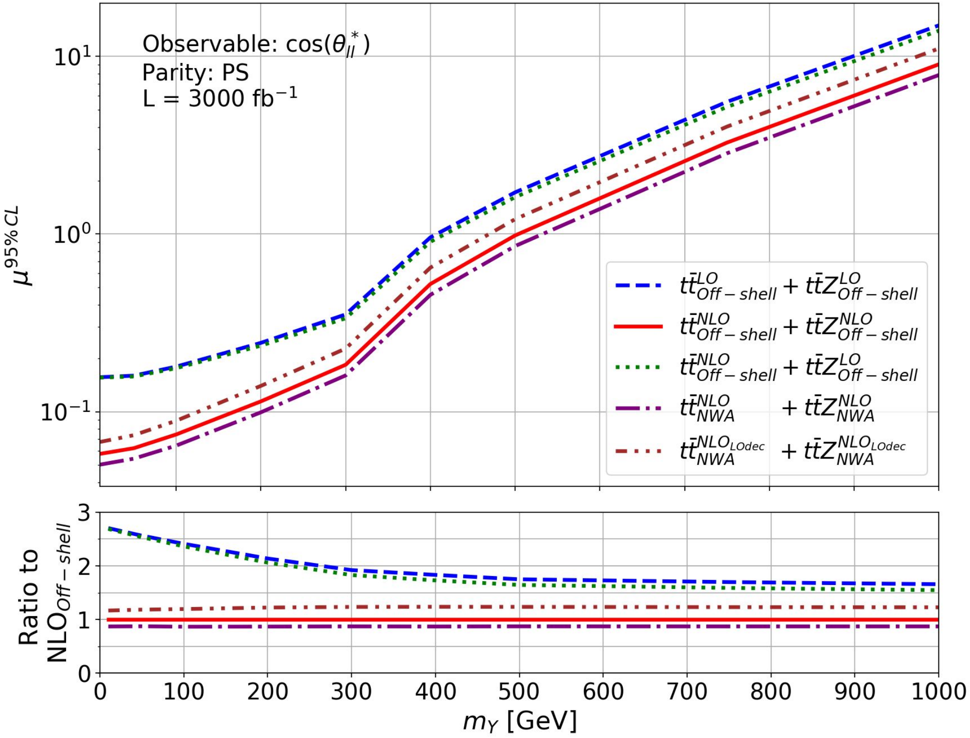
$$p_{T,\text{miss}} > 150\,\text{GeV}$$

$$C_{em} > 130\,\text{GeV}$$

$$C_{em} = M_{T2,W} + 0.2 \cdot (p_{T,\text{miss}} - 200\,\text{GeV})$$

Haisch, Pani, Polesello '17

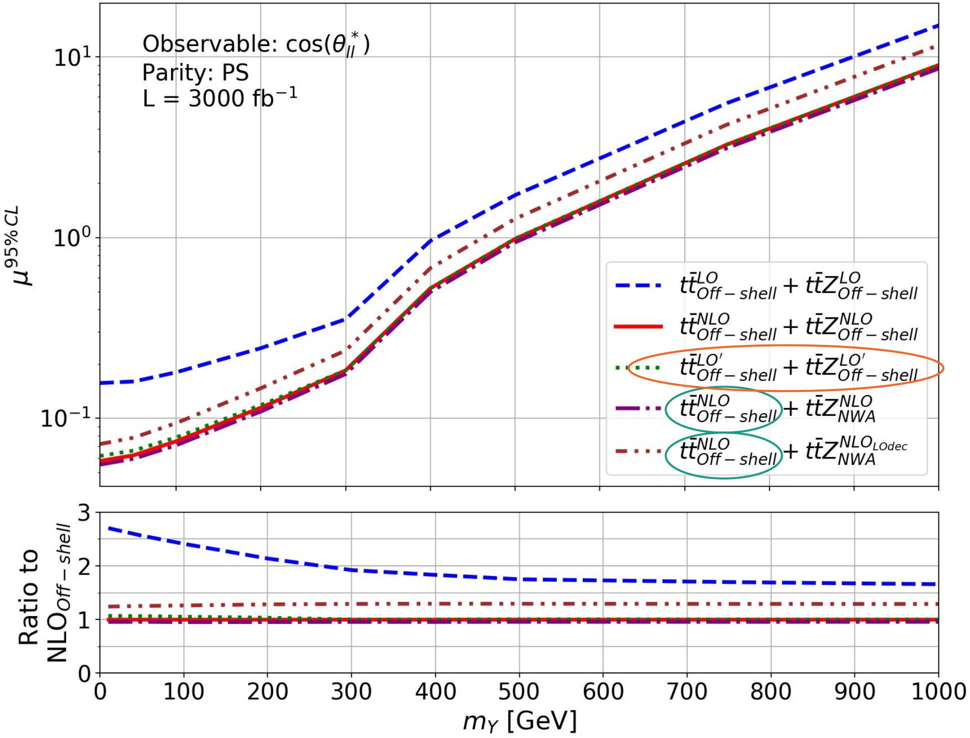
Exclusion limits - Modelling



- LO inadequate due to large uncertainties, even if only using it for ttZ
- NLO with LO decays still too large due to large uncertainties and overestimated normalization
- In NWA, tt contribution is zero
- Full NWA results are too good due to missing off-shell tt contribution

JH, Worek, arXiv:2108.01089

Exclusion limits - Modelling (2)



- Include off-shell tt in all cases
  -> differences almost vanish
  -> off-shell effects not that relevant for ttZ

- LO’ = LO with NLO uncertainties
  -> only smaller uncertainties relevant, not shape distortion

JH, Worek, arXiv:2108.01089

Exclusion limits - Additional analyses

- Choice of observable:
    - Compared five different observables
    - Pseudoscalar mediator: $\cos(\theta^*_{ll}) = \tanh(|\eta_{l_1} - \eta_{l_2}|/2)$ provides most stringent limits
    - Scalar mediator: $M_{T2,t}$ for light mediators, $\cos(\theta^*_{ll})$ for heavier ones

- Scale choice:
    - Important, even at NLO
    - Fixed scale leads to less stringent limits -> use dynamical scale

- Luminosity:
    - Increasing the luminosity improves the limits
    - Modelling effects larger for large luminosity but general behavior is the same

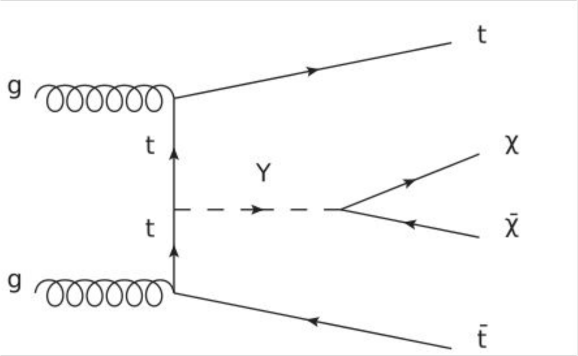
Conclusions

- Use full(!) NLO for tt and ttZ (NLO for production and decays)
- Include off-shell effects for tt, otherwise the contribution vanishes
- For ttZ using the NWA is enough in most cases
- $\cos(\theta^*_{ll})$ provides the most stringent limits for most considered model configurations
- Choose a dynamical scale
- Larger Luminosity always helps

Thank you for your attention!

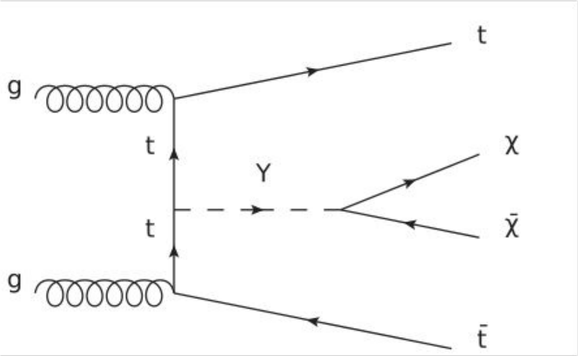
Backup

Spin-0 s-channel simplified DM model



- Two new particles:
    - Fermionic DM particle
    - Scalar or Pseudoscalar mediator
      → couples SM to dark sector
- Minimal flavor violation:
    - Flavor symmetry only broken by masses
      → mediator-quark couplings proportional to Yukawa coupling
- No mixing between SM Higgs and scalar mediator

Spin-0 s-channel simplified DM model



$$\mathcal{L}_\mathrm{S} \supset -g_\chi Y_\mathrm{S} \bar{\chi}\chi - \frac{1}{\sqrt{2}} Y_\mathrm{S} \sum_q g_q y_q \bar{q} q$$

Mediator couplings

$$g_\chi = g_q = 1$$

Yukawa-coupling

$$y_q = \sqrt{2}\frac{m_q}{v}$$

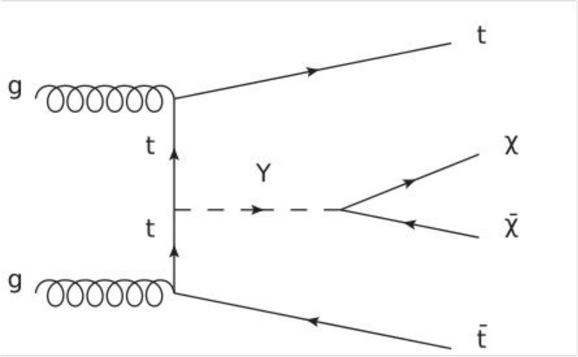
- Four new parameters:
  $$\{g_q, g_\chi, m_\chi, m_Y\}$$
  → use $m_\chi = 1\,\mathrm{GeV}$
- Implementation:
  - DMsimp *[Backović et al., 2015]*

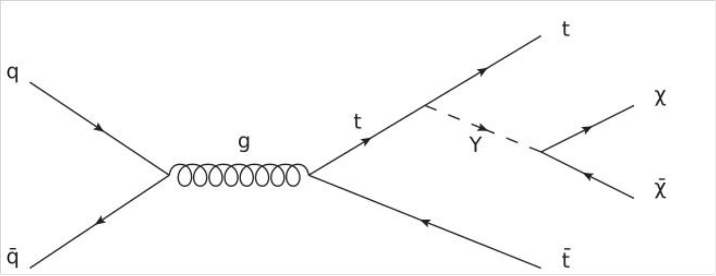
Spin-0 s-channel simplified DM model

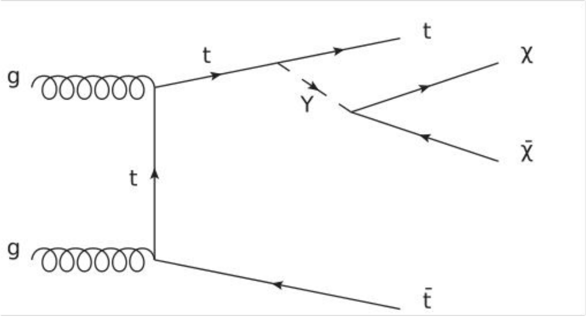
Yukawa-coupling

$$y_q = \sqrt{2}\frac{m_q}{v}$$

Mediator produced in association with top pair





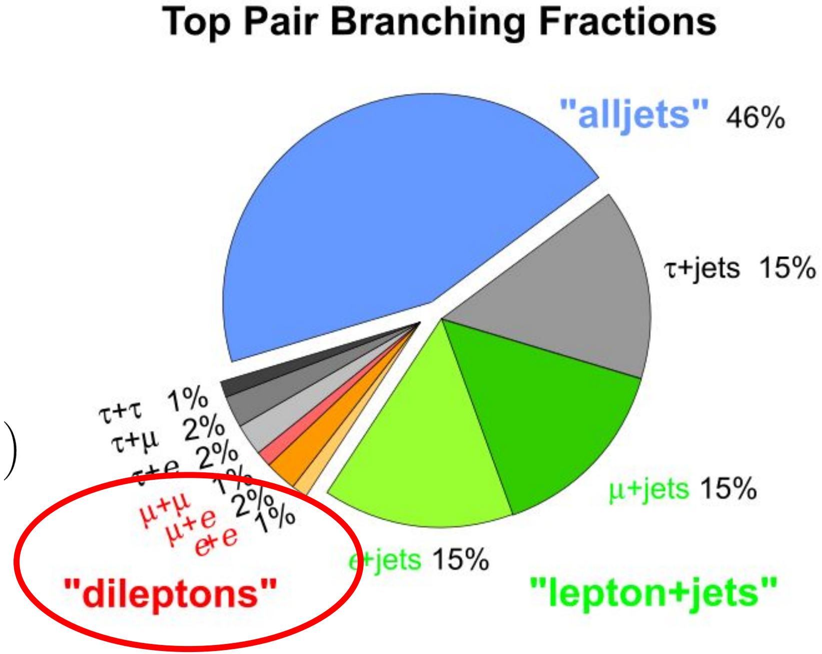


Spin-0 s-channel simplified DM model

Yukawa-coupling

$$y_q = \sqrt{2}\frac{m_q}{v}$$

Mediator produced in association with top pair



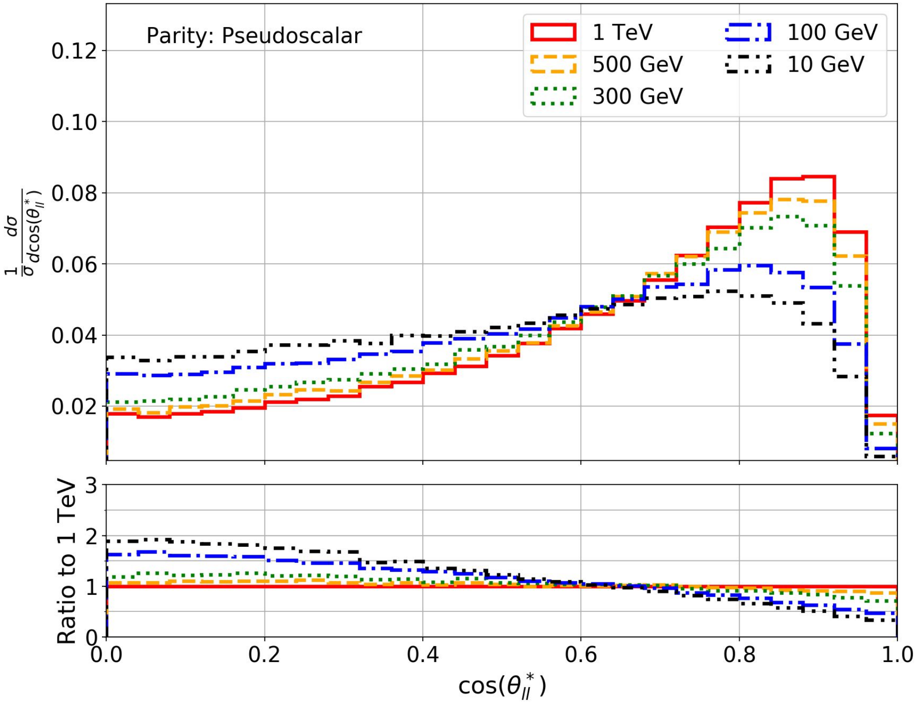
Why di-lepton channel?

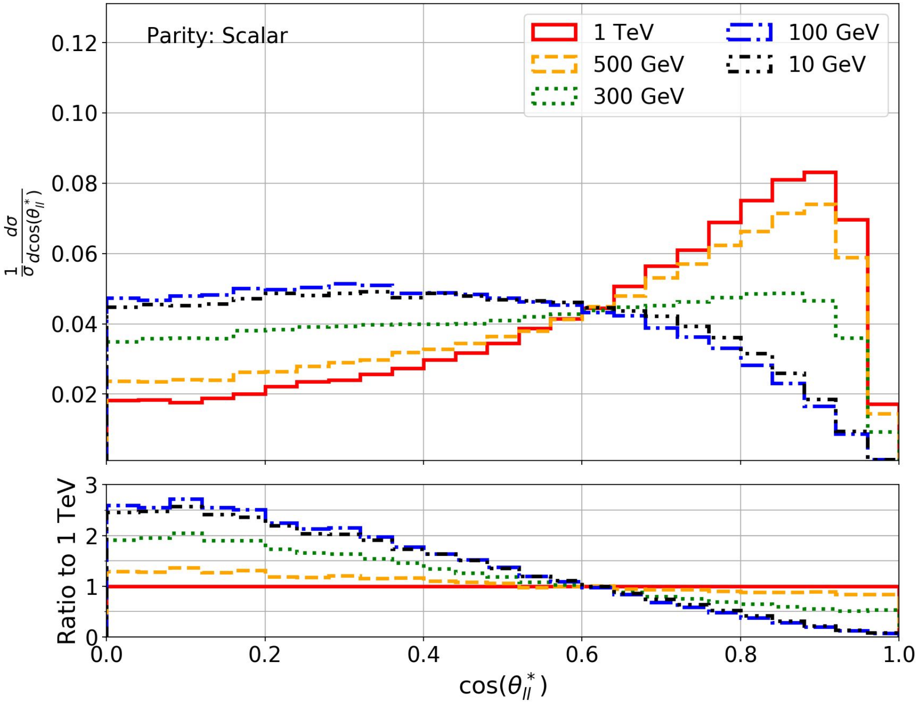
- Experimentally clean
- Access to leptonic variables $\Delta\phi_{ll}$ and $\cos(\theta_{ll})$
  → CP discriminant

For the LHC @ 13 TeV:

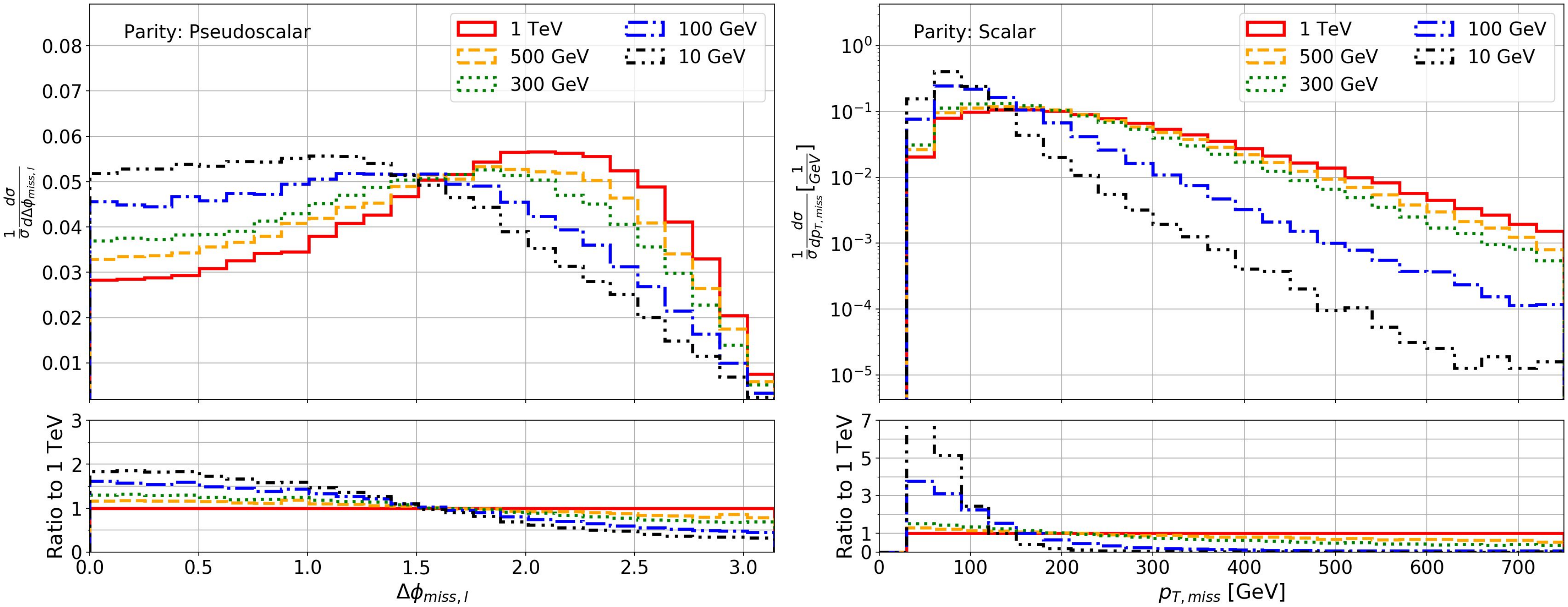
$$\boxed{pp \to b\bar{b}e^{+}\mu^{-}\nu_e\bar{\nu}_\mu\chi\bar{\chi}}$$

DM distributions





DM distributions



Signal strength exclusion limits - Likelihood

Poisson distributions
→ relative statistical uncertainty $\sim 1/\sqrt{\lambda_i}$

Log-normal distributions
→ PDF and scale uncertainty

Likelihood:

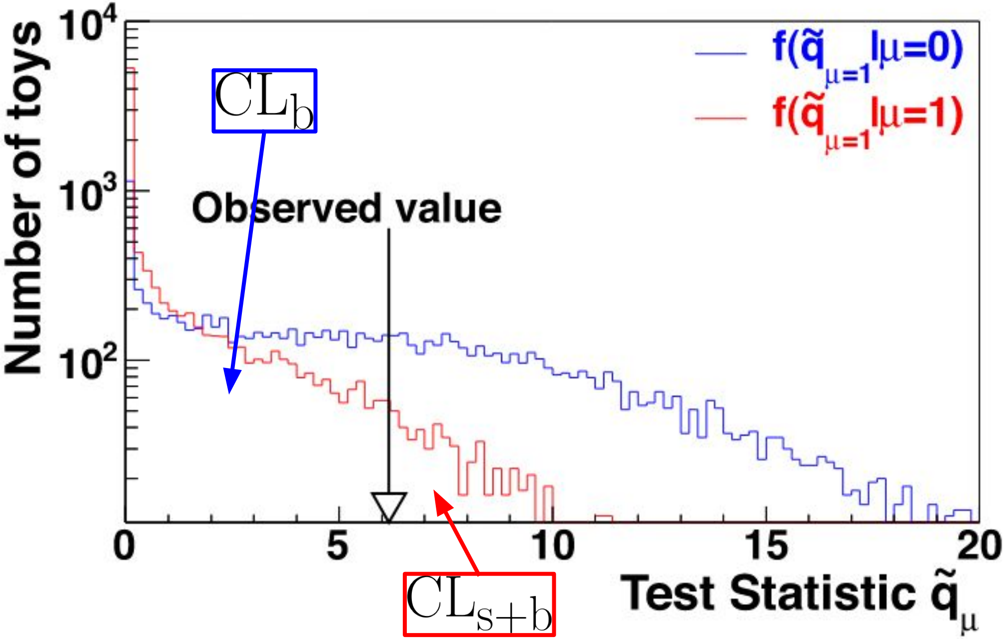
$$L(X|\lambda(\mu,\nu)) = \prod_i P_i(X_i|\lambda_i)\cdot\pi_i^{\mathrm{PDF}}(\tilde{\nu}_i^{\mathrm{PDF}},\nu_i^{\mathrm{PDF}})\cdot\pi_i^{\mathrm{scale}}(\tilde{\nu}_i^{\mathrm{scale}},\nu_i^{\mathrm{scale}})$$

Prediction: $\lambda = \{\lambda_i\}$

Data: $X = \{X_i\}$

Signal strength exclusion limits - PDF

$$\tilde{q}_\mu = -2\log\left(\frac{L(X|\lambda(\mu,\hat{\nu}_\mu))}{L(X|\lambda(\mu',\hat{\nu}_{\mu'}))}\right)$$



$$\mathrm{CL_s} = \frac{\mathrm{CL_{s+b}}}{1-\mathrm{CL_b}}$$

Setup - Input

Parameters:

$$\Gamma_W = 2.0988\,\text{GeV}, \quad \Gamma_Z = 2.50782\,\text{GeV}$$

$$G_\mu = 1.166378 \times 10^{-5}\,\text{GeV}^{-2}, \quad m_W = 80.385\,\text{GeV}, \quad m_Z = 91.1876\,\text{GeV}$$

$$\Gamma_t^{\text{LO,NWA}} = 1.50174\,\text{GeV}, \quad \Gamma_t^{\text{LO,FW}} = 1.47848\,\text{GeV}, \quad m_t = 173.2\,\text{GeV}$$

Scales:

$$H_T = p_{T,b} + p_{T,\bar{b}} + p_{T,e^+} + p_{T,\mu^-} + p_{T,\text{miss}}$$

$$\mu_0^{t\bar{t}} = H_T/4, \quad \mu_0^{t\bar{t}Z} = H_T/3, \quad \mu_0^{\text{DM}} = H_T/3$$

PDFs:

$$\text{CT14}, \quad \text{MMHT14}, \quad \text{NNPDF3.0}$$

Setup - Inclusive cuts

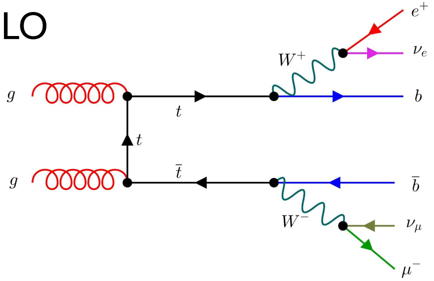
$$p_{T,b} > 40\,\mathrm{GeV}, \qquad |\eta_b| < 2.5, \qquad \Delta R_{b\bar{b}} > 0.4$$

$$p_{T,l} > 30\,\mathrm{GeV}, \qquad |\eta_l| < 2.5, \qquad \Delta R_{lb} > 0.4, \qquad \Delta R_{ll} > 0.4$$

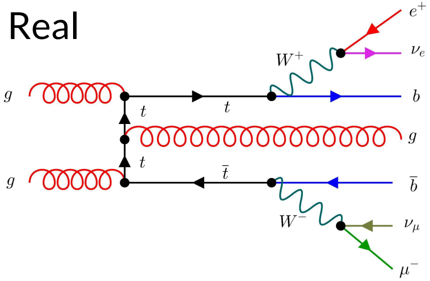
$$p_{T,\mathrm{miss}} > 50\,\mathrm{GeV}$$

Importance of correct modelling - NLO corrections

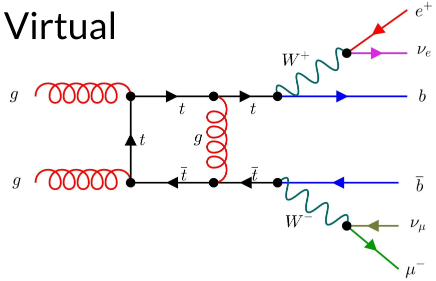
LO



Real



Virtual

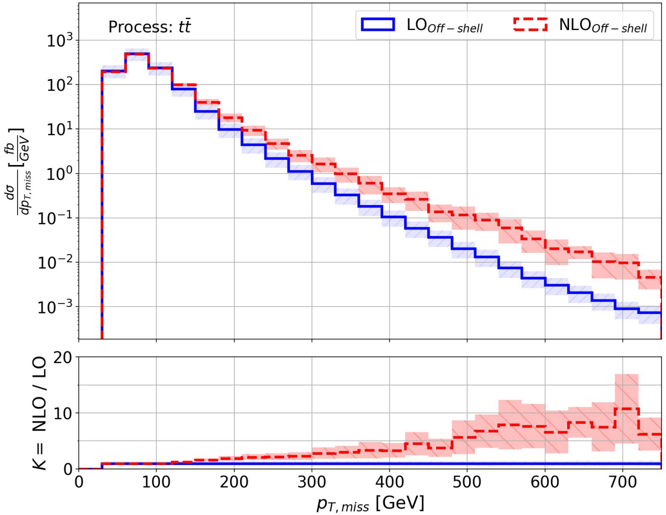


Diagrams created with FeynGame

Harlander, Klein, Lipp ‘20

NLO effects:

- Reduced scale uncertainties
- Modified distribution shapes and normalization
- Largest effects in distribution tails!

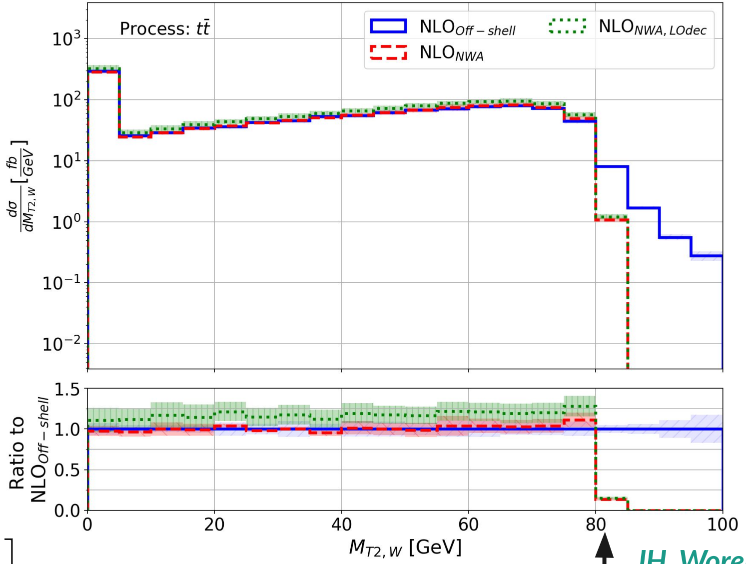


JH, Worek, arXiv:2108.01089

Importance of correct modelling - Off-shell effects

Off-shell effects:

- Only small effects on normalization and angular distributions
- Modified distribution shapes for some dimensionful observables
- Largest effects in distribution tails and around kinematic edges



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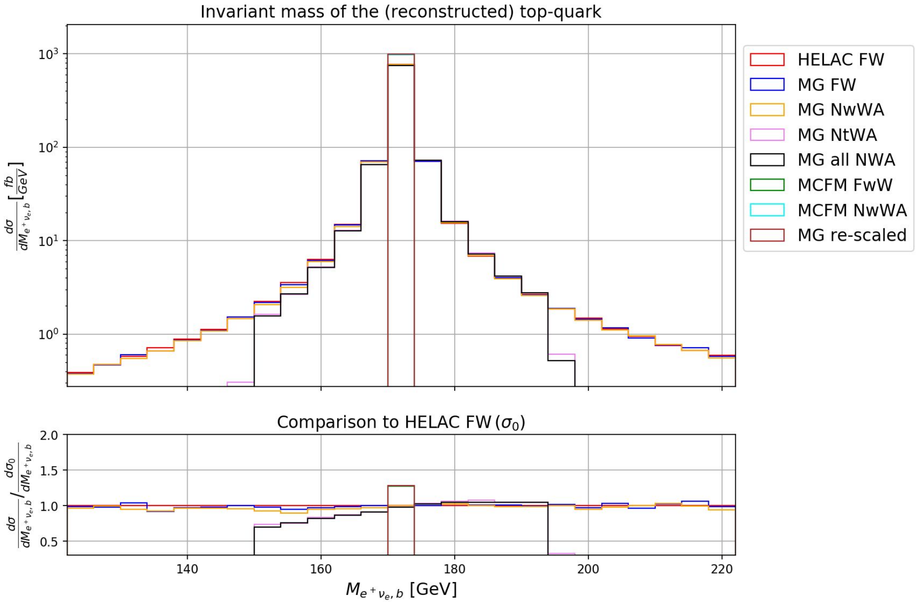
$$M^2_{T2,W} = \min_{\mathbf{p}_T^{\nu_1}+\mathbf{p}_T^{\nu_2}=\mathbf{p}_{T,\text{miss}}} \left[\max\left\{M_T^2\left(\mathbf{p}_T^{l_1},\mathbf{p}_T^{\nu_1}\right), M_T^2\left(\mathbf{p}_T^{l_2},\mathbf{p}_T^{\nu_2}\right)\right\}\right]$$

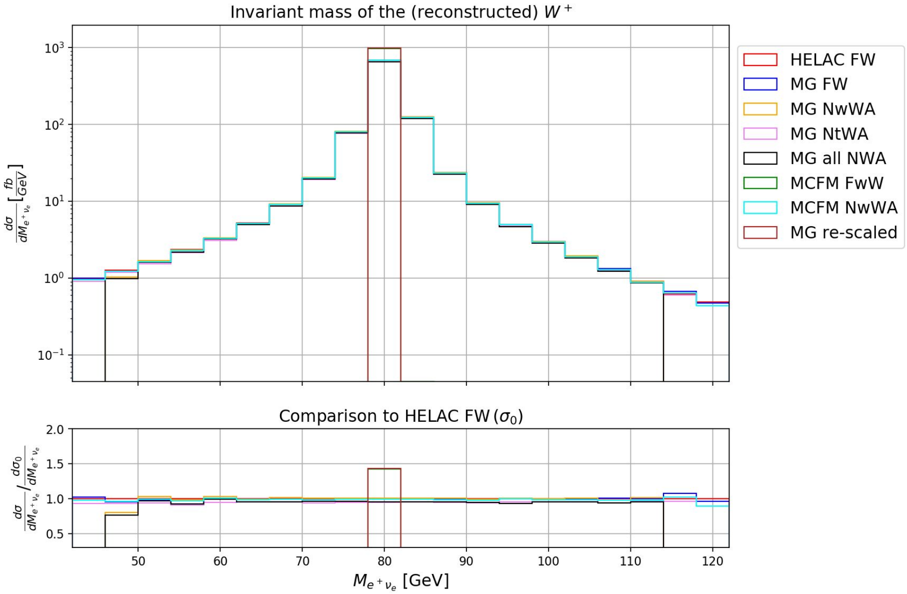
Lester, Summers ‘99; Barr, Lester, Stephens ‘03

Cut-off

with $M_{T,W} \leq m_W$ in the NWA

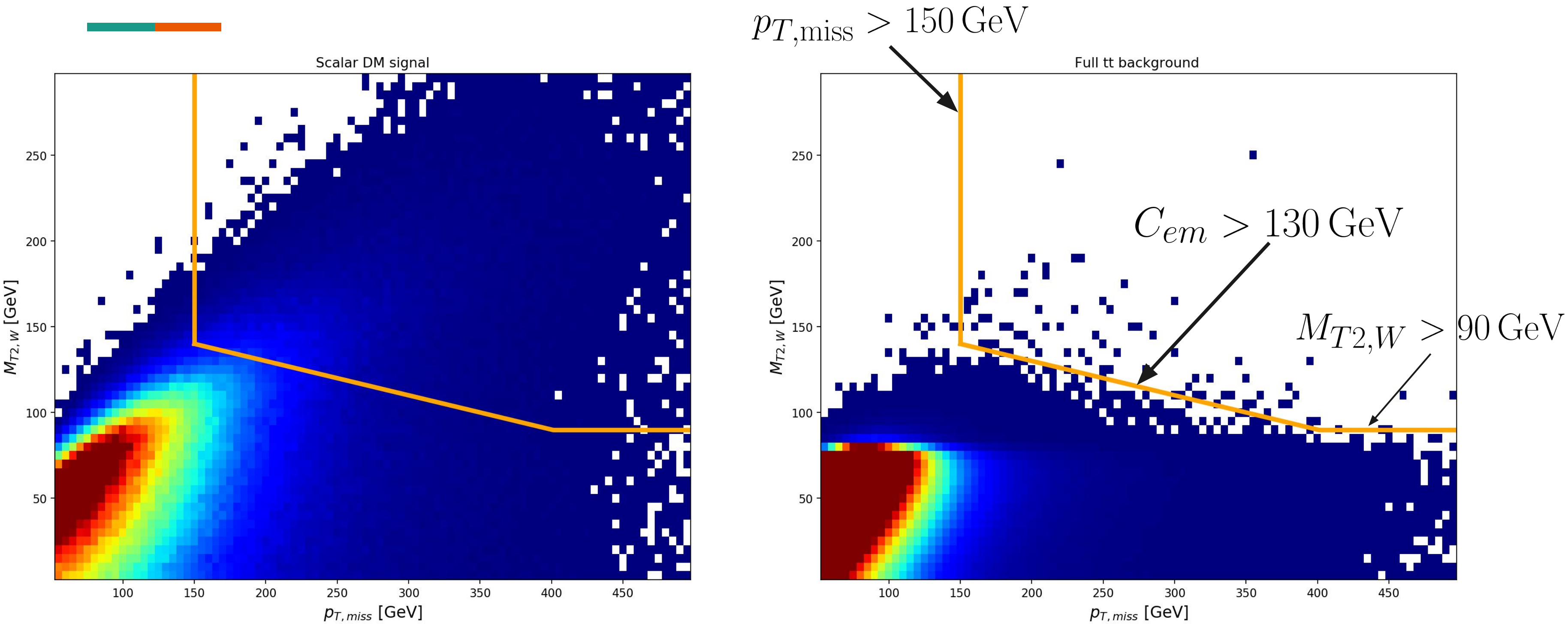
The SM background - unstable particles





Used programs: HELAC-Phegas *[Cafarella et al., 2009]* / HELAC-NLO *[Bevilacqua et al., 2013]*
MCFM *[Campbell and Neumann, 2019]*
MadGraph_aMC@NLO *[Alwall et al., 2014]*

Event selection



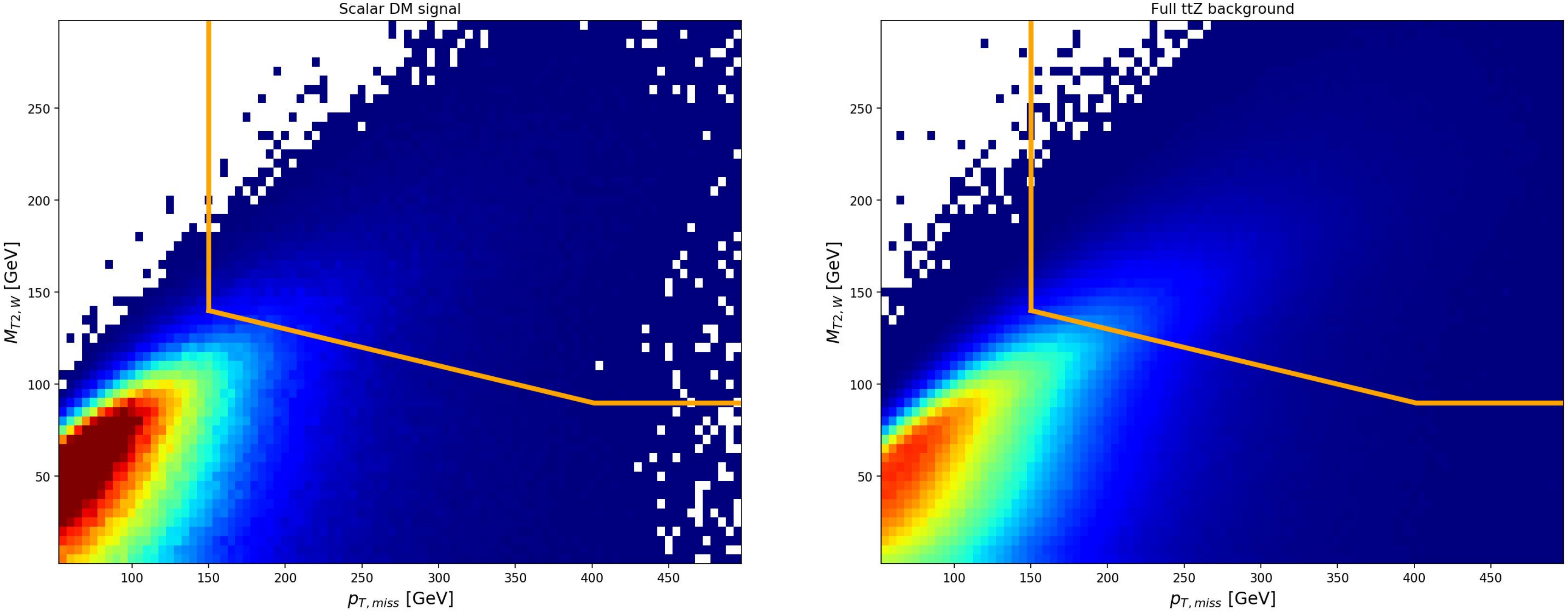
$p_{T,\mathrm{miss}} > 150\ \mathrm{GeV}$

$C_{em} > 130\ \mathrm{GeV}$

$M_{T2,W} > 90\ \mathrm{GeV}$

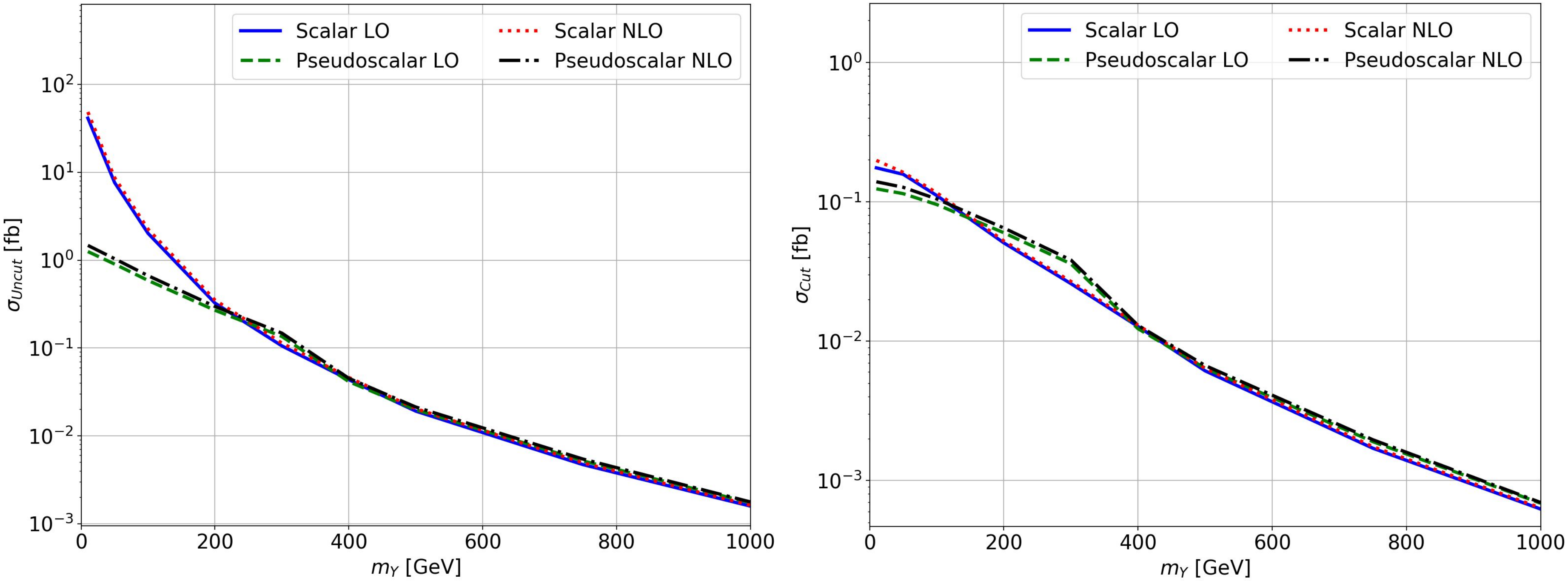
Define linear combination: $C_{em} = M_{T2,W} + 0.2 \cdot (p_{T,\mathrm{miss}} - 200\ \mathrm{GeV})$ *[Haisch et al., 2017]*

Event selection

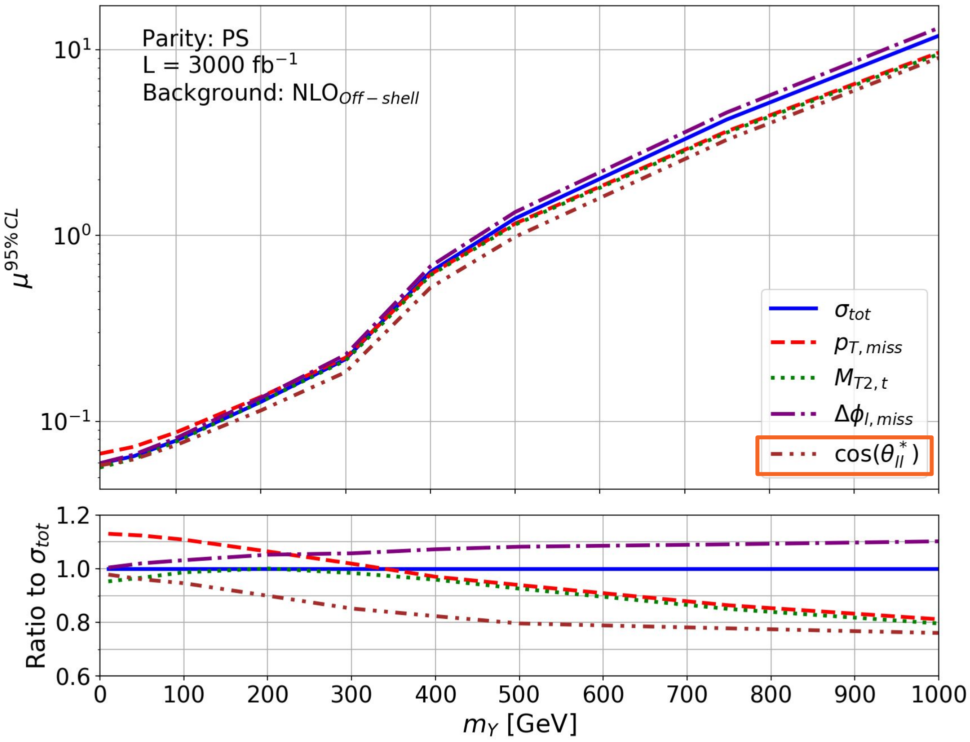


Problem: $t\bar{t}Z$ looks very similar to DM signal

Effects of cut selection



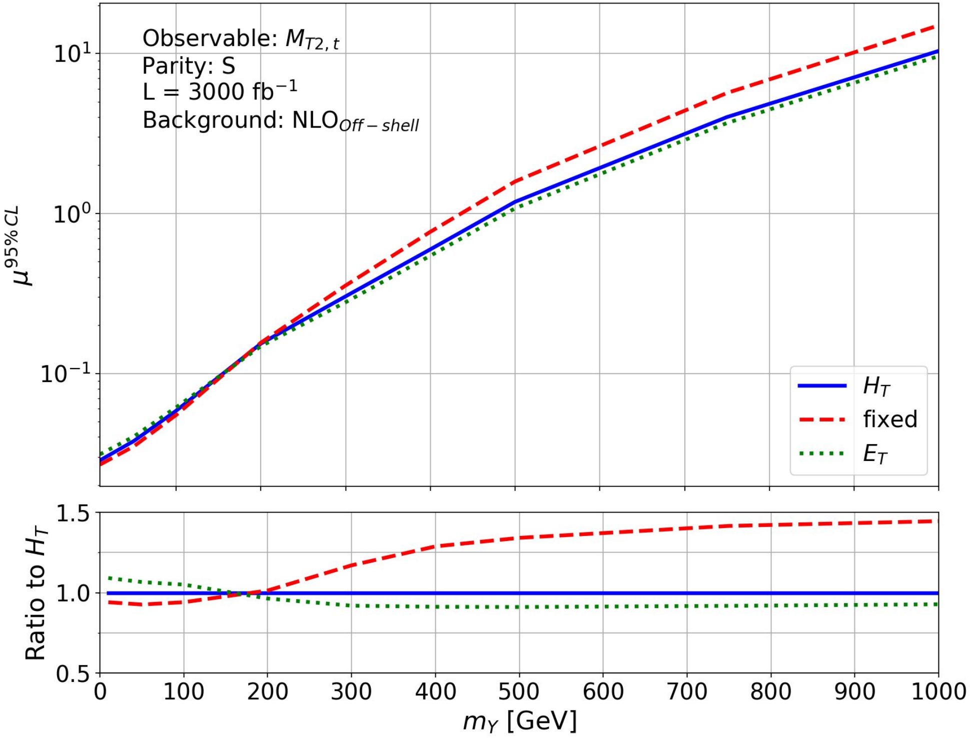
Exclusion limits - Choice of observable



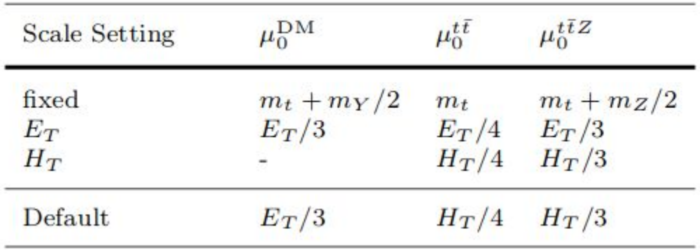
- Five bins for all observables (except integrated fiducial cross section)
- $\cos(\theta^*_{ll}) = \tanh(|\eta_{l_1} - \eta_{l_2}|/2)$ generally best observable, i.e. provides most stringent limits
- For light scalar mediators one should use $M_{T2,t}$ instead
- $\Delta\phi_{l,\mathrm{miss}}$ even worse than the normalization in most cases

JH, Worek, arXiv:2108.01089

Exclusion limits - Scale choice



- Scale choice even important at NLO for some observables
- One should use a dynamical scale
- Reason: large scale uncertainties for the fixed scale



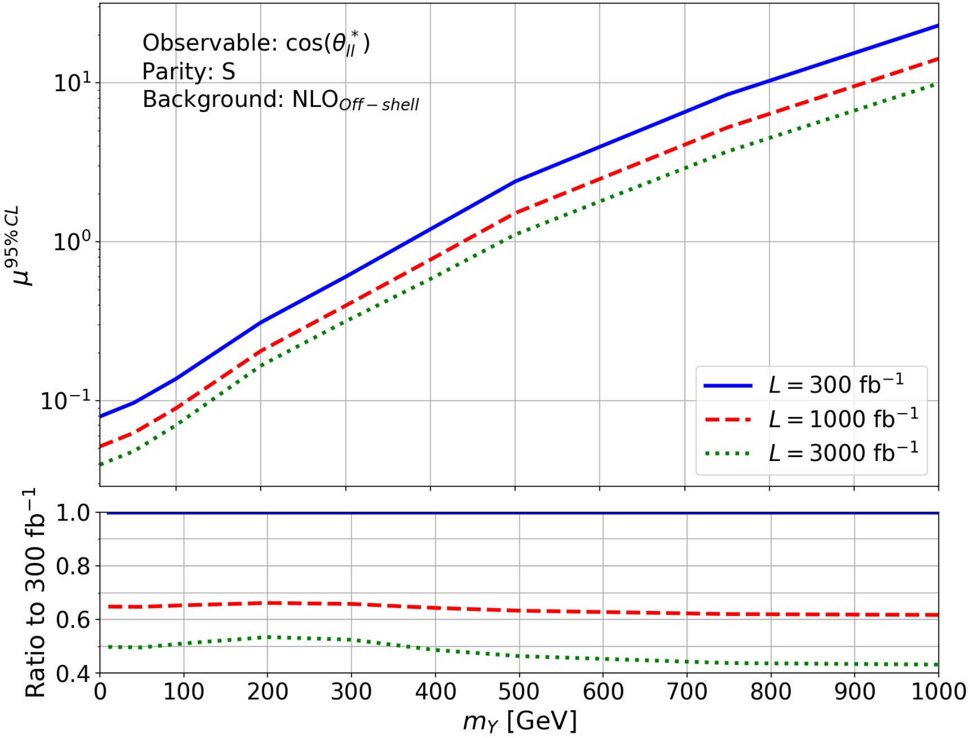
Scale Setting	μ_0^{DM}	$\mu_0^{t\bar{t}}$	$\mu_0^{t\bar{t}Z}$
fixed	$m_t + m_Y/2$	m_t	$m_t + m_Z/2$
E_T	$E_T/3$	$E_T/4$	$E_T/3$
H_T	-	$H_T/4$	$H_T/3$
Default	$E_T/3$	$H_T/4$	$H_T/3$

JH, Worek, arXiv:2108.01089

$$E_T = \sum_{i=t,\bar{t}(,Z,Y)} \sqrt{M_i^2 + p_{T,i}^2} \quad \text{and}$$

$$H_T = p_{T,b} + p_{T,\bar{b}} + p_{T,\mu^-} + p_{T,e^+} + p_{T,\mathrm{miss}}$$

Exclusion limits - Luminosity

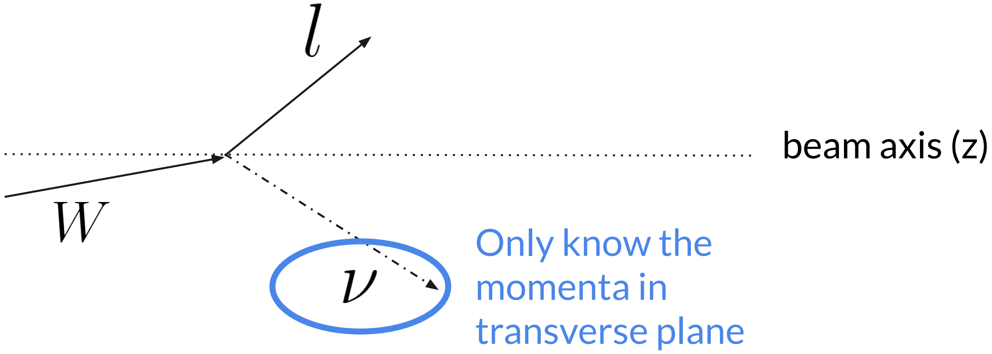


- Larger Luminosity means smaller statistical uncertainties
  -> more stringent limits
- More significant impact for differential distributions
- Previous comparisons with smaller Luminosity: same structure but smaller differences

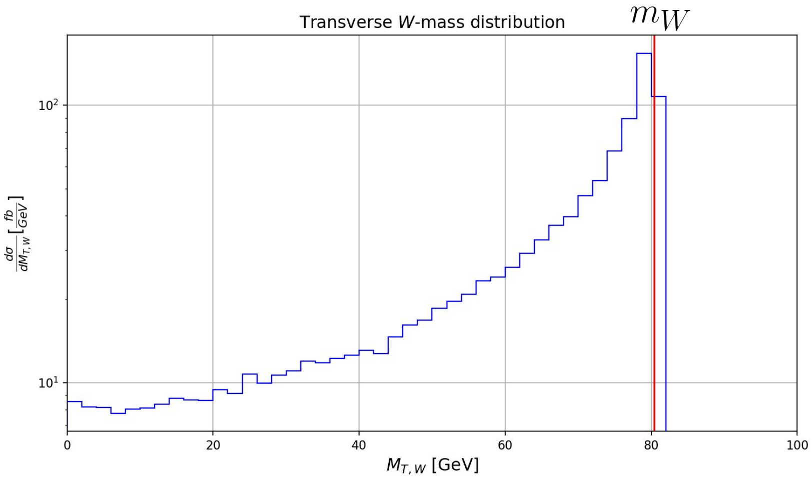
JH, Worek, arXiv:2108.01089

The ‘stransverse’ mass - idea

Transverse mass: reconstruct mass of particle with partly invisible final state



Reconstruct the W mass:



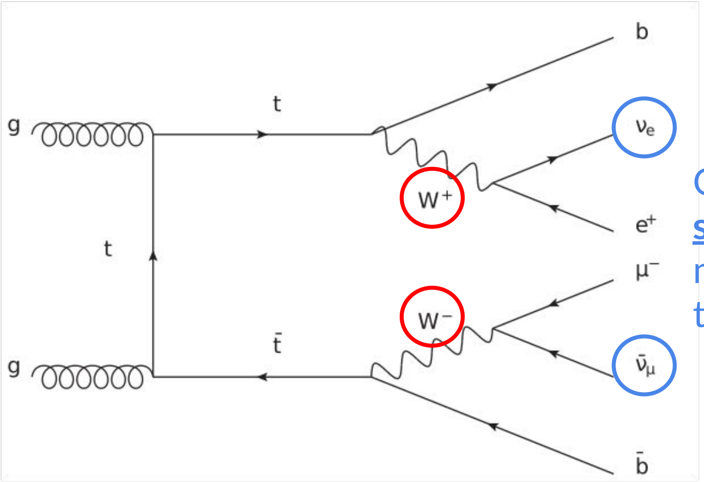
⇨ Define mass & momenta in transverse plane

$$p_T = (E_T, p_x, p_y, 0) \quad \text{where} \quad E_T = \sqrt{p_{T,x}^2 + p_{T,y}^2} \quad \Rightarrow \quad M_T^2 = (p_T^l + p_T^\nu)^2 \leq m_W^2$$

The ‘stransverse’ mass - idea & definition

‘Stransverse’ mass:
generalization for **two** particles with partly invisible final state

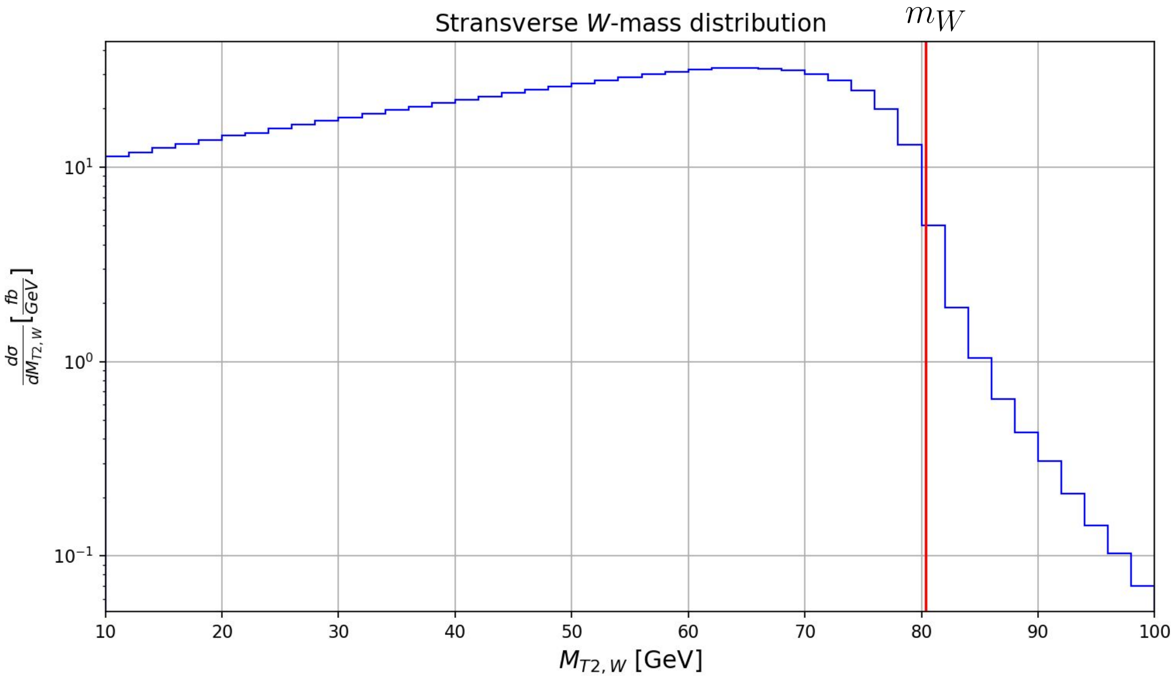
$$M_{T2,W}^2 = \min_{\mathbf{p}_T^{\nu_1}+\mathbf{p}_T^{\nu_2}=\mathbf{p}_{T,\mathrm{miss}}} \left[\max\{ M_T^2\left(\mathbf{p}_T^{l_1}, \mathbf{p}_T^{\nu_1}\right), M_T^2\left(\mathbf{p}_T^{l_2}, \mathbf{p}_T^{\nu_2}\right) \} \right]$$



Only know the sum of the momenta in transverse plane

Minimize over all missing momentum combinations

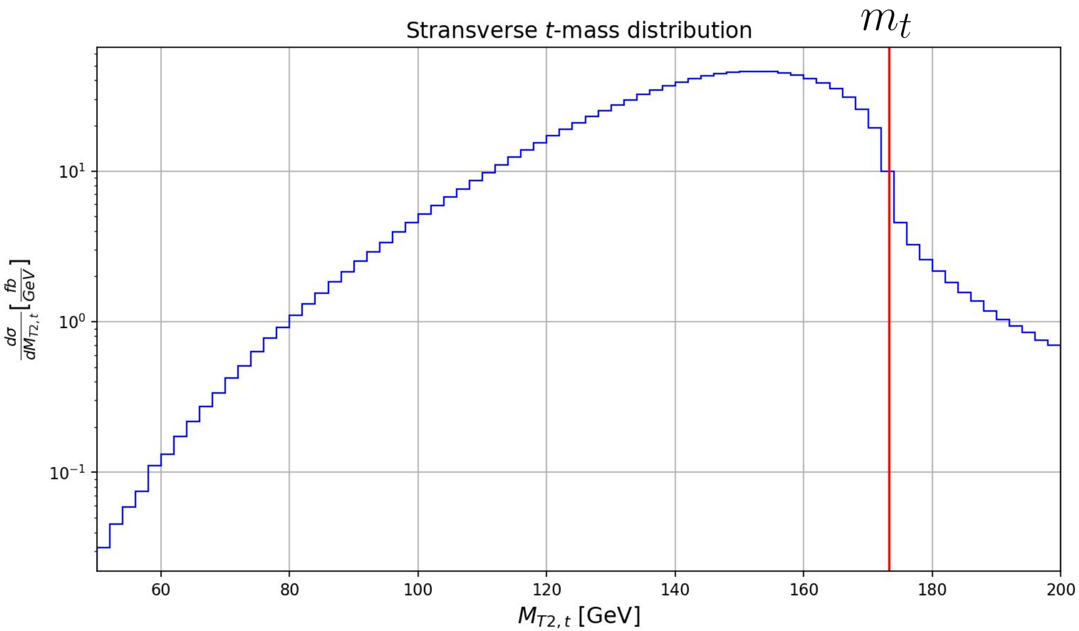
The ‘stransverse’ mass - distribution



Not a ‘hard’ cut-off but drop-off is clearly visible

The ‘stransverse’ mass - distribution

We can do the same for the top quarks:



- Use b-jet + lepton instead of lepton as visible, massive ‘particle’

- Problem: which jet is associated with which lepton?
  - take minimum of invariant b-jet + lepton mass combinations
  - minimize the sum of the two invariant masses to avoid combining one lepton with both b-jets

The ‘stransverse’ mass - definition

$$M_{T2}^2 = \min_{\mathbf{p}_T^{\nu_1} + \mathbf{p}_T^{\nu_2} = \mathbf{p}_{T,\mathrm{miss}}} \left[\max\{ M_T^2 \left(\mathbf{p}_T^{(lb)_1}, \mathbf{p}_T^{\nu_1} \right), M_T^2 \left(\mathbf{p}_T^{(lb)_2}, \mathbf{p}_T^{\nu_2} \right) \} \right]$$

where $$M_T^2 \left(\mathbf{p}_T^{(lb)_i}, \mathbf{p}_T^{\nu_i} \right) = M_{(lb)_i}^2 + 2 \left(E_T^{(lb)_i} E_T^{\nu_i} - \mathbf{p}_T^{(lb)_i} \mathbf{p}_T^{\nu_i} \right)$$

Lepton + b-jet combinations chosen such that $M_{(lb)_1} + M_{(lb)_2}$ is minimal