DM Pair Production in Simplified Models and the MSSM

Gabriele Coniglio

based on `Eur.Phys.J. C79 (2019) no.5, 428`

[C. Borschensky, GC, B. Jäger]

KIT NEP '19 - Karlsruhe

EBERHARD KARLS
UNIVERSITÄT
TÜBINGEN

09 October 2019

Outline

The dark matter model space

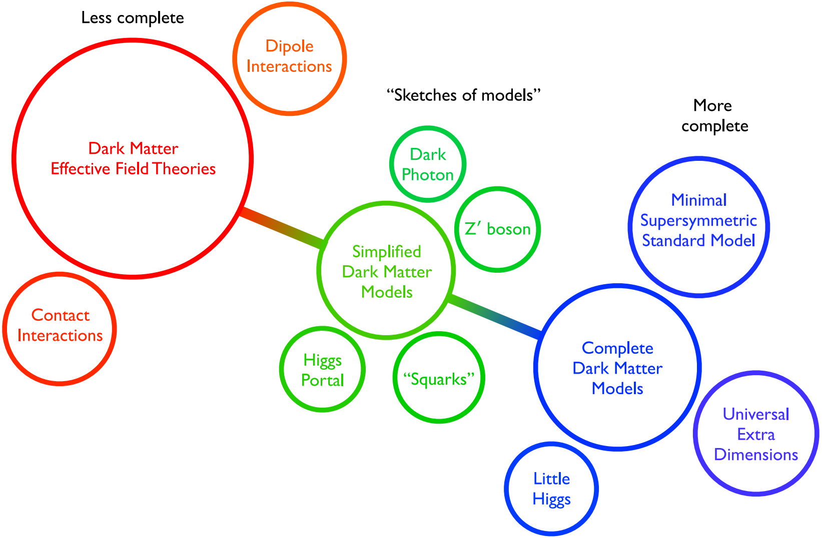


Figure taken from *[1506.03116]*

The dark matter model space

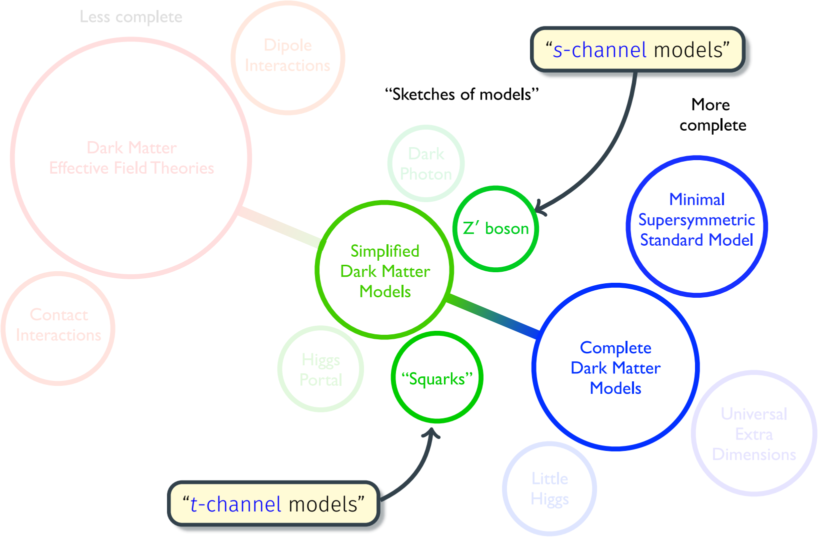
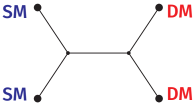


Figure taken from [1506.03116]

s-channel model

Assumption: DM is a singlet under SU(3)×SU(2)×U(1) and ...

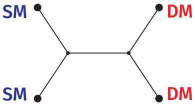
- ... consists of Dirac/Majorana fermions χ
- ... interacts with the SM via the topology:



s-channel model

Assumption: DM is a singlet under SU(3)×SU(2)×U(1) and ...

- ... consists of Dirac/Majorana fermions χ
- ... interacts with the SM via the topology:



Possible Lagrangians with a scalar or vector mediator:

$$\mathcal{L}_S = g_\chi^S \bar{\chi}\chi S + \sum_q g_q^S \bar{q} q S$$

$$\mathcal{L}_P = i g_\chi^P \bar{\chi}\gamma_5\chi P + \sum_q g_q^P \bar{q}\gamma_5 q P$$

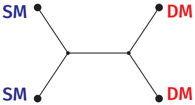
$$\mathcal{L}_V = \bar{\chi}\gamma_\mu \left[g_\chi^V - g_\chi^A \gamma_5 \right] \chi V^\mu + \sum_q \bar{q}\gamma_\mu \left[g_q^V - g_q^A \gamma_5 \right] q V^\mu$$

EBERHARD KARLS UNIVERSITÄT TÜBINGEN

s-channel model

Assumption: DM is a singlet under SU(3)×SU(2)×U(1) and ...

- ... consists of Dirac/Majorana fermions χ
- ... interacts with the SM via the topology:



Possible Lagrangians with a ~~scalar~~ or vector mediator:

$$\mathcal{L}_S = g_\chi^S \bar{\chi}\chi S + \sum_q g_q^S \bar{q} q S$$

$$\mathcal{L}_P = i g_\chi^P \bar{\chi}\gamma_5 \chi P + \sum_q g_q^P \bar{q}\gamma_5 q P$$

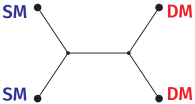
In this talk →

$$\mathcal{L}_V = \bar{\chi}\gamma_\mu \left[g_\chi^V - g_\chi^A \gamma_5 \right] \chi V^\mu + \sum_q \bar{q}\gamma_\mu \left[g_q^V - g_q^A \gamma_5 \right] q V^\mu$$

s-channel model

Assumption: DM is a singlet under SU(3)×SU(2)×U(1) and ...

- ... consists of Dirac/Majorana fermions χ
- ... interacts with the SM via the topology:



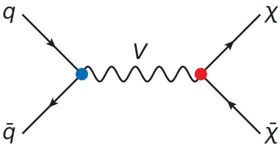
Interaction Lagrangian for a vector mediator [Dudas et al. '09]:

$$\mathcal{L}_V = \bar{\chi}\gamma_\mu \left[g_\chi^V - g_\chi^A \gamma_5\right]\chi V^\mu + \sum_q \bar{q}\gamma_\mu \left[g_q^V - g_q^A \gamma_5\right] q V^\mu$$

with q: quark fields, χ: DM field, V^μ: vector mediator field, g^V, g^A: vector and axialvector couplings

Properties

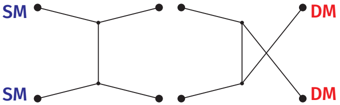
- V is uncoloured and massive (M_V)
- Added to SM by spontanenously broken U(1)' symmetry to generate V mass
- Decays only into SM or DM pairs



t-channel model

Assumption: DM is a singlet under SU(3)×SU(2)×U(1) and ...

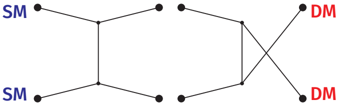
- ... consists of Dirac/Majorana fermions χ
- ... interacts with the SM via the topology:



t-channel model

Assumption: DM is a singlet under SU(3)×SU(2)×U(1) and …

- … consists of Dirac/Majorana fermions χ
- … interacts with the SM via the topology:



Interaction Lagrangian for a coloured scalar mediator:

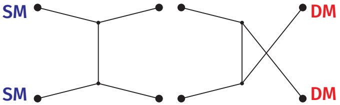
$$\mathcal{L}_{\tilde{Q}} = -\left[\lambda_{Q_L}\bar{\chi}P_L\tilde{Q}_L^\dagger \cdot Q + \lambda_{u_R}\tilde{Q}_{u_R}^*\bar{\chi}P_R u + \lambda_{d_R}\tilde{Q}_{d_R}^*\bar{\chi}P_R d + \text{h.c.}\right]$$

with $\tilde{Q}_L = \begin{pmatrix}\tilde{Q}_{u_L}\\ \tilde{Q}_{d_L}\end{pmatrix}$ an SU(2)×U(1) doublet

t-channel model

Assumption: DM is a singlet under SU(3)×SU(2)×U(1) and ...

- ... consists of Dirac/Majorana fermions χ
- ... interacts with the SM via the topology:



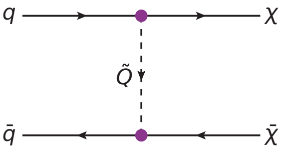
Interaction Lagrangian for a coloured scalar mediator *[An et al. '14]*:

$$\mathcal{L}_{\tilde{Q}} = -\Big[\lambda_{Q_L}\left(\tilde{Q}^*_{u_L}\bar{\chi}P_L u + \tilde{Q}^*_{d_L}\bar{\chi}P_L d\right) + \lambda_{u_R}\tilde{Q}^*_{u_R}\bar{\chi}P_R u + \lambda_{d_R}\tilde{Q}^*_{d_R}\bar{\chi}P_R d + \text{h.c.}\Big]$$

with u, d: up- and down-type quark fields, χ: DM field, $\tilde{Q}_{q_{L/R}}$: coloured scalar mediator fields, λ: DM-quark-squark Yukawa couplings, $P_{L/R}$: left- and right-handed chirality projectors

Properties

- $\tilde{Q}$ are coloured and flavoured (#12)
- Heavier than χ so that the decay $\tilde{Q} \to q\chi$ is possible ($M_{\tilde{Q}} > m_\chi$)



Tools and numerical setup

Roadmap of the calculation:

- *Generate points in MSSM parameter space*
  Spectrum generator: `SPheno 4.0.3` *[Porod '03; Porod, Staub '12]*

CMSSM *[Adeel Ajaib, Gogoladze '17]*	**pMSSM10** *[de Vries et al. '15]*	
$M_0 \in [0, 10]$ TeV	$M_1 \in [-1, 1]$ TeV	$M_2 \in [0, 4]$ TeV
$m_{1/2} \in [0, 10]$ TeV	$M_3 \in [-4, 4]$ TeV	$m_{\tilde{q}_{1/2}} \in [0, 4]$ TeV
$A_0 \in [-3, 3] \times M_0$	$m_{\tilde{q}_3} \in [0, 4]$ TeV	$m_{\tilde{l}} \in [0, 2]$ TeV
$\tan\beta \in [2, 60]$	$M_A \in [0, 4]$ TeV	$A \in [-5, 5]$ TeV
$\text{sign}\,\mu > 0$	$\mu \in [-5, 5]$ TeV	$\tan\beta \in [1, 60]$

  5000 points where $\tilde{\chi}_1^0$ is the LSP and the lightest Higgs mass satisfies 124 GeV $\leq m_h \leq$ 126 GeV

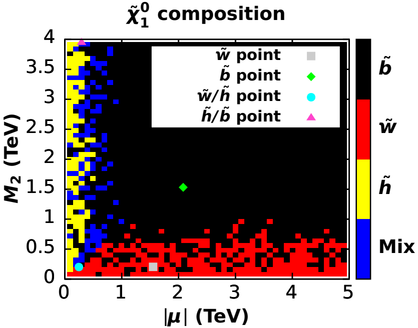
- *Fix parameters of s- and t-channel models*
  Choose: $m_\chi = m_{\tilde{\chi}_1^0}$, M_V = 1 TeV and 10 TeV, $M_{\tilde{Q}}$ = average of $\tilde{u}_{L/R}$, $\tilde{d}_{L/R}$, $\tilde{c}_{L/R}$, $\tilde{s}_{L/R}$, $\tilde{b}_{1/2}$ masses,
  $g_\chi^{V/A} = g_q^{V/A} = g = 0.5$, $\lambda_{Q_L} = \lambda_{u_R} = \lambda_{d_R} = \lambda = 1$

- *Calculate $pp \to \tilde{\chi}_1^0\tilde{\chi}_1^0$ cross section in MSSM for each point*
  `POWHEG-BOX` *[Alioli, Nason, Oleari, Re '10]* with weakino code *[Baglio, Jäger, Kesenheimer '16]*

- *Calculate $pp \to \chi\bar{\chi}$ cross section in SDMMs for each point*
  `POWHEG-BOX` and for the t-channel model `COLLIER-1.2` *[Denner, Dittmaier, Hofer '17]*

LHC at $\sqrt{S}$ = 13 TeV, PDFs used: PDF4LHC15 NLO MC PDFs *[Butterworth et al. '16]*

Parameter scan in the pMSSM10

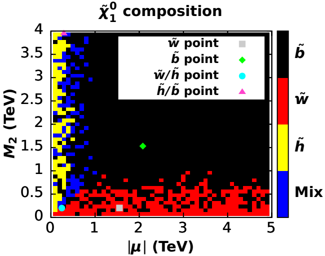


[C. Borschensky, GC, B. Jäger; Eur.Phys.J. C79 (2019) no.5, 428]

$\tilde{\chi}_1^0$ composition

- Distinguish between $\tilde{b}$ino, $\tilde{w}$ino, $\tilde{h}$iggsino
- Pure bino/wino: no Z exchange possible

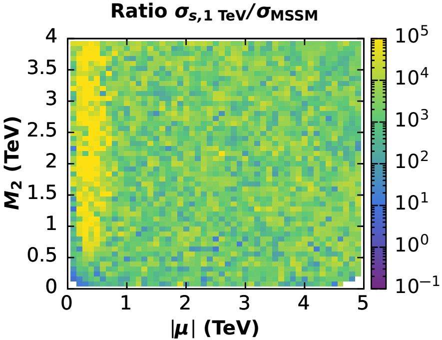
Parameter scan in the pMSSM10

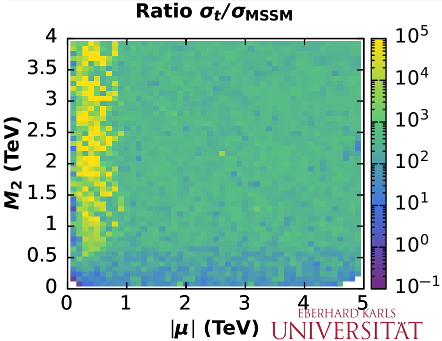


[C. Borschensky, GC, B. Jäger; Eur.Phys.J. C79 (2019) no.5, 428]

$\tilde{\chi}_1^0$ composition

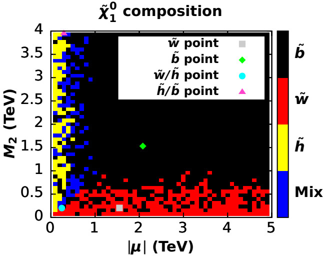
- Distinguish between $\tilde{b}$ino, $\tilde{w}$ino, $\tilde{h}$iggsino
- Pure bino/wino: no Z exchange possible
- Higher s-channel mediator mass M_V smoothens the bino region a bit, difficult to distinguish from t-channel model





EBERHARD KARLS UNIVERSITÄT TÜBINGEN

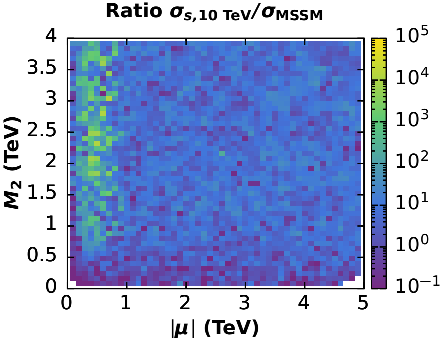
Parameter scan in the pMSSM10

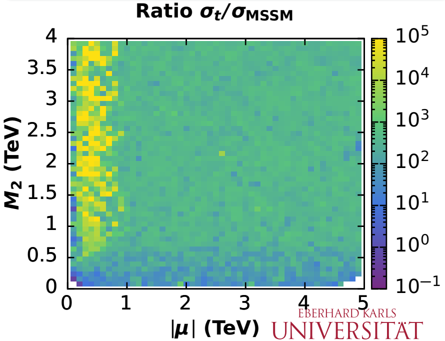


[C. Borschensky, GC, B. Jäger; Eur.Phys.J. C79 (2019) no.5, 428]

$\tilde{\chi}_1^0$ composition

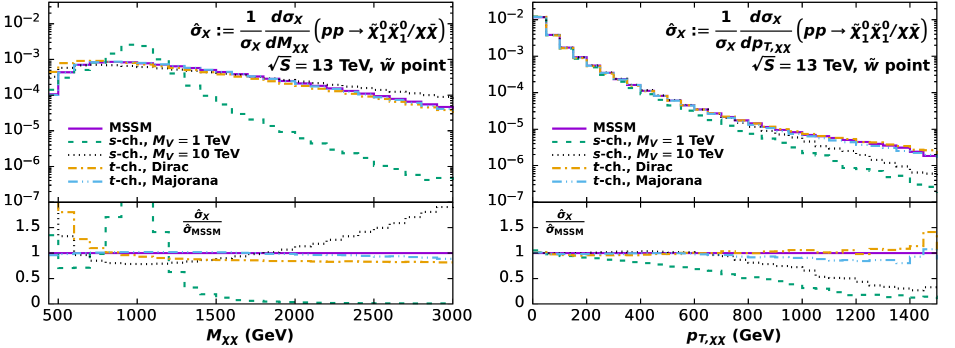
- Distinguish between $\tilde{b}$ino, $\tilde{w}$ino, $\tilde{h}$iggsino
- Pure bino/wino: no Z exchange possible
- Higher s-channel mediator mass M_V smoothens the bino region a bit, difficult to distinguish from t-channel model





Distributions: $\tilde{w}$ point

[C. Borschensky, GC, B. Jäger; Eur.Phys.J. C79 (2019) no.5, 428]

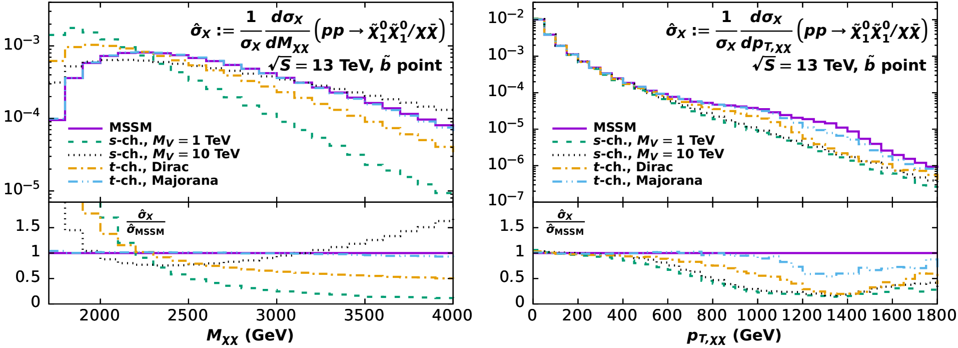


Analysis at NLO + parton shower accuracy

- $\tilde{\chi}_1^0$ mainly $\tilde{w}$ino, DM mass ~ 220 GeV, squark masses ~ 3 TeV
- *t*-channel very close to MSSM, agreement with *s*-channel (M_V = 1 TeV) is worst

Distributions: $\tilde{b}$ point

[C. Borschensky, GC, B. Jäger; Eur.Phys.J. C79 (2019) no.5, 428]

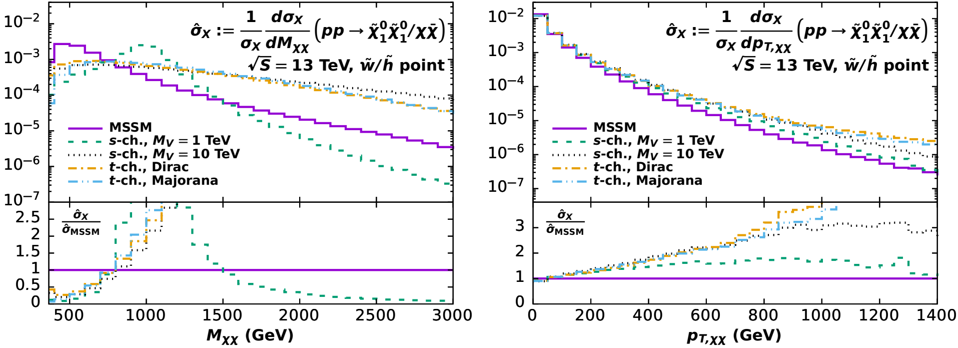


Analysis at NLO + parton shower accuracy

- $\tilde{\chi}_1^0$ mainly $\tilde{b}$ino, DM mass ~ 850 GeV, squark masses ~ 2.5 TeV
- *t*-channel close to MSSM, Majorana case better than Dirac
- Bump around $p_{T,XX} \approx 1.25$ TeV remnant of on-shell subtraction procedure

Distributions: $\tilde{w}/\tilde{h}$ point

[C. Borschensky, GC, B. Jäger; Eur.Phys.J. C79 (2019) no.5, 428]



> **Analysis at NLO + parton shower accuracy**
> - $\tilde{\chi}_1^0$ mainly $\tilde{w}$ino-$\tilde{h}$iggsino, DM mass ~ 180 GeV, squark masses ~ 3.4 TeV
> - No agreement between simplified models and MSSM for M_{XX} and $p_{T,XX}$ distributions

Eberhard Karls Universität Tübingen

Summary and conclusions

Simplified models: studying DM with a minimal set of parameters

Summary and conclusions

Simplified models: studying DM with a minimal set of parameters

Two specific models studied:

- *s*-channel model with a vector mediator, and *t*-channel model with coloured scalar mediators
- NLO QCD corrections including PS (PYTHIA 6) calculated for DM pair production at the LHC and implemented in the POWHEG-BOX framework

Summary and conclusions

Simplified models: studying DM with a minimal set of parameters

Two specific models studied:

- *s*-channel model with a vector mediator, and *t*-channel model with coloured scalar mediators
- NLO QCD corrections including PS (`PYTHIA 6`) calculated for DM pair production at the LHC and implemented in the `POWHEG-BOX` framework

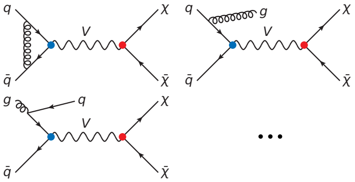
Comparison with $\tilde{\chi}_1^0$ pair-production in the MSSM:

- Simplified models can reproduce some MSSM features, in particular the *t*-channel model with only three parameters (m_χ, $M_{\tilde{Q}}$, λ)
- However, poor agreement for our studied models in other regions
- Require more complex models, or simplified models better suited for description of some other non-SUSY theory?

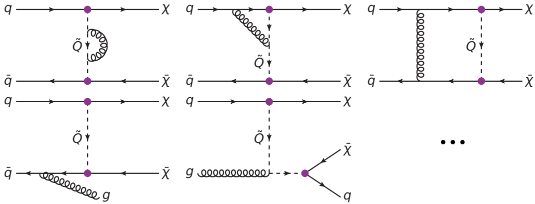
EBERHARD KARLS UNIVERSITÄT TÜBINGEN

Backup :NLO QCD corrections

s-channel



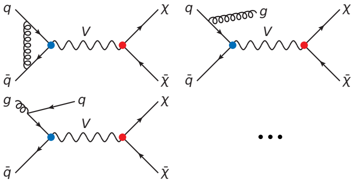
t-channel



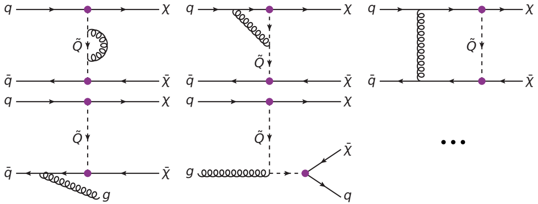
$$|\mathcal{M}_{\text{NLO}}|^2 = |\mathcal{M}_{\text{Born}}|^2 + 2\,\text{Re}\left(\mathcal{M}_{\text{Born}}\mathcal{M}^*_{\text{virt}}\right) + |\mathcal{M}_{\text{real}}|^2 + \mathcal{O}(\alpha_s^2)$$

Backup :NLO QCD corrections

s-channel



t-channel

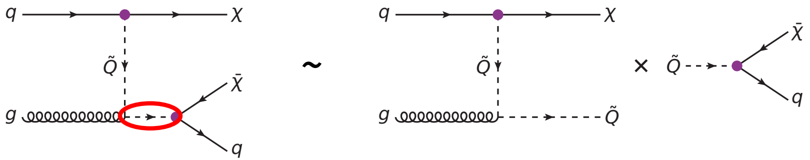


$$|\mathcal{M}_{\rm NLO}|^2 = |\mathcal{M}_{\rm Born}|^2 + 2\,{\rm Re}\left(\mathcal{M}_{\rm Born}\mathcal{M}^*_{\rm virt}\right) + |\mathcal{M}_{\rm real}|^2 + \mathcal{O}(\alpha_s^2)$$

- Born, spin-/colour-correlated Born, and real amplitudes calculated with `MadGraph 4` *[Murayama et al., Stelzer et al., Alwall et al. '92-'07]*
- Virtual amplitudes calculated with `FeynArts 3.9/FormCalc 9.4` *[Hahn et al. '98-'16]*

Backup: On-shell subtraction for the t-channel model

Subtlety in real corrections: intermediate $\tilde{Q}$ becomes on-shell

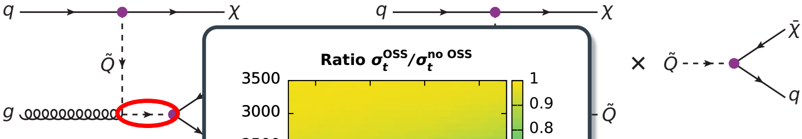


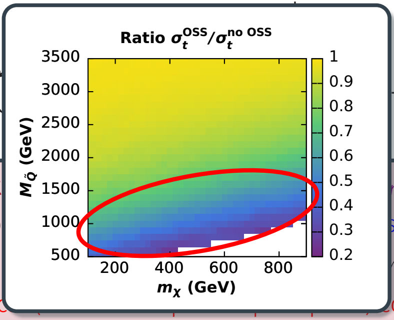
On-shell subtraction (follow mainly [Baglio, Jäger, Kesenheimer '16-'17])

- Split up amplitude into non-resonant (nr) and possibly resonant (r) diagrams:
$$|\mathcal{M}_{\text{real}}|^2 = |\mathcal{M}_{\text{nr}}|^2 + 2\,\text{Re}\left(\mathcal{M}_{\text{nr}}\mathcal{M}_{\text{r}}^*\right) + |\mathcal{M}_{\text{r}}|^2$$
- Construct local (i.e. for each phase space point) counterterm
$$\text{CT} \propto \text{BW} \times |\mathcal{M}_{\text{r}}^{\text{OS}}|^2$$
with $\mathcal{M}_{\text{r}}^{\text{OS}}$ mapped to on-shell kinematics $p^2 = M_{\tilde{Q}}^2$, and where BW is a Breit-Wigner factor shaping the resonant propagator

Backup: On-shell subtraction for the t-channel model

Subtlety in real corrections: intermediate $\tilde{Q}$ becomes on-shell





On-shell subt ... nheimer '16-'17])

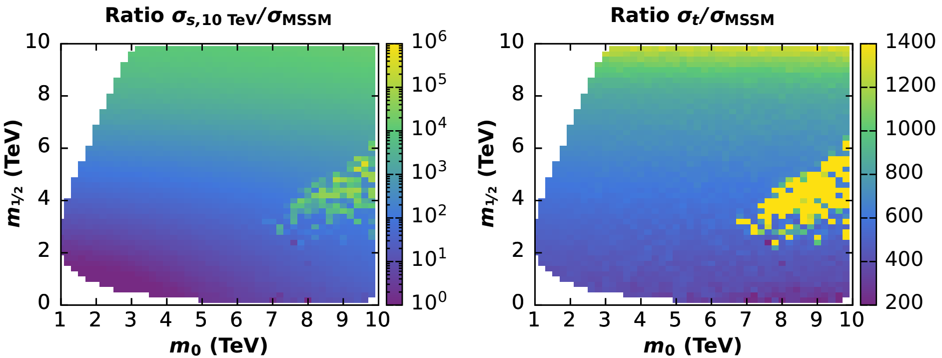
- Split up amp ... ssibly resonant (r) diagrams: ... $\mathcal{M}_r|^2$
- Construct loc ... counterterm

$$\text{CT} \quad \propto \quad \text{BW} \times |\mathcal{M}_r^{\text{OS}}|^2$$

with $\mathcal{M}_r^{\text{OS}}$ mapped to on-shell kinematics $p^2 = M_{\tilde{Q}}^2$, and where BW is a Breit-Wigner factor shaping the resonant propagator

EBERHARD KARLS UNIVERSITÄT TÜBINGEN

Backup: Parameter scan in the CMSSM



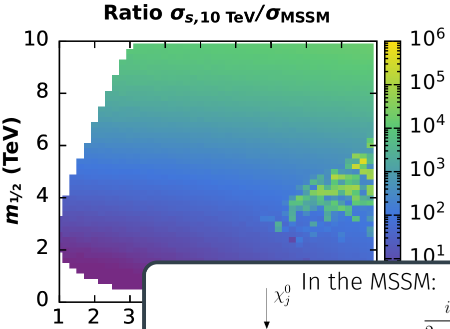
Ratios with respect to MSSM at NLO QCD

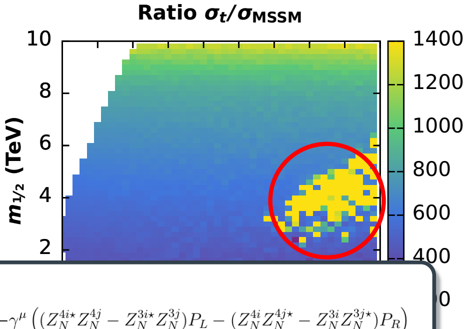
- Ratio involving *s*-channel model varies by several orders of magnitude
- Ratio involving *t*-channel model almost constant (~ factor 3)
- Effect at high M_0 and intermediate $m_{1/2}$ due to "higgsino mixing matrix suppression" in MSSM ⇒ σ_{MSSM} low

[GC, C. Borshensky, B. Jägerr; 1812.08704]

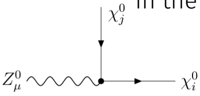
EBERHARD KARLS UNIVERSITÄT TÜBINGEN

Backup: Parameter scan in the CMSSM





In the MSSM:



$$\frac{ie}{2s_W c_W}\gamma^\mu\left((Z_N^{4i\star}Z_N^{4j}-Z_N^{3i\star}Z_N^{3j})P_L-(Z_N^{4i}Z_N^{4j\star}-Z_N^{3i}Z_N^{3j\star})P_R\right)$$

$$\mathcal{M}\propto |N_{14}|^2-|N_{13}|^2$$

[Rosiek '95-'09]

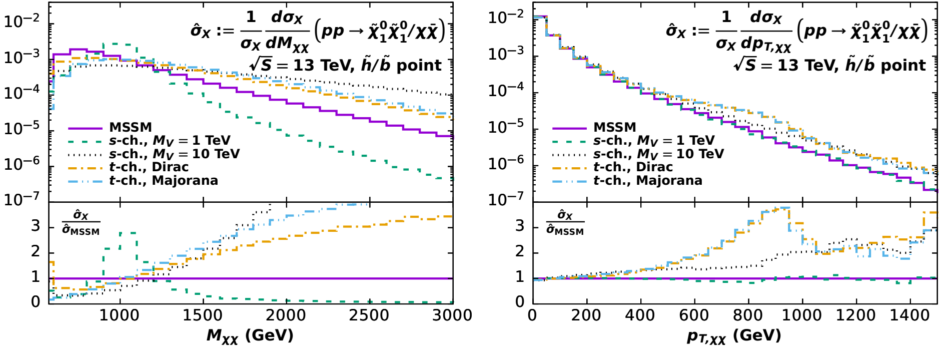
Rati

- Ratio involving *s*-channel model varies by several orders of magnitude
- Ratio involving *t*-channel model almost constant (~ factor 3)
- Effect at high M_0 and intermediate $m_{1/2}$ due to "higgsino mixing matrix suppression" in MSSM ⇒ σ_{MSSM} low

[GC, C. Borshensky, B. Jäger; 1812.08704]

Backup: Distributions: $\tilde{h}/\tilde{b}$ point

[GC, C. Borshensky, B. Jäger; Eur.Phys.J. C79 (2019) no.5, 428]



Analysis at NLO + parton shower accuracy

- $\tilde{\chi}_1^0$ mainly $\tilde{h}$iggsino-mix, DM mass ~ 290 GeV, squark masses ~ 1.8 TeV
- No agreement between simplified models and MSSM for M_{XX} distribution
- Good agreement with s-channel (M_V = 1 TeV) for $p_{T,XX}$ distribution

EBERHARD KARLS UNIVERSITÄT TÜBINGEN