QCD Corrections to BSM Signal Processes

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DFG Deutsche Forschungsgemeinschaft

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Small Problem

But there is <u>no</u> BSM physics at the LHC!!

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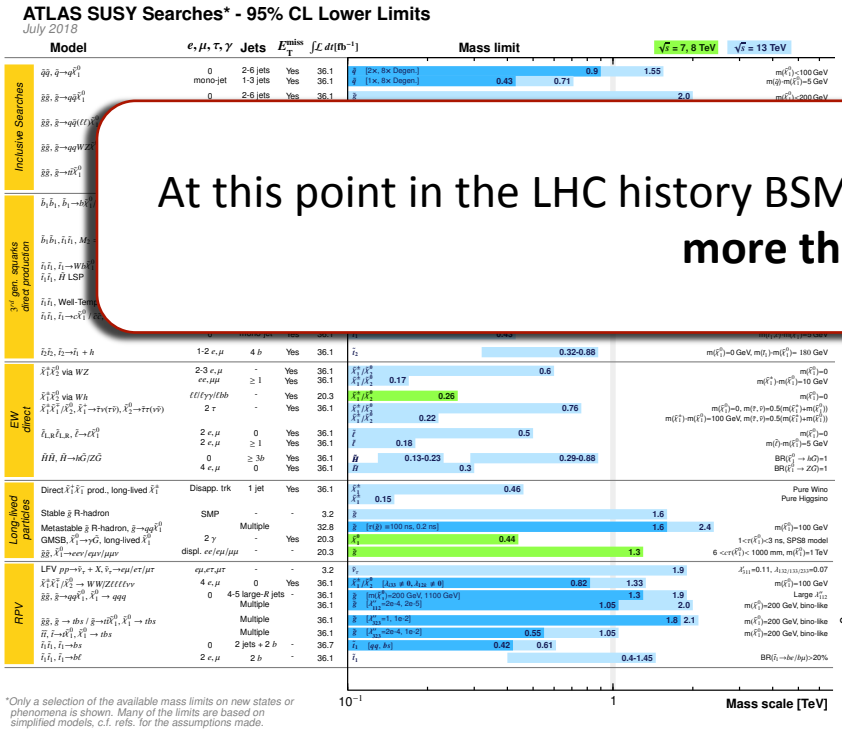
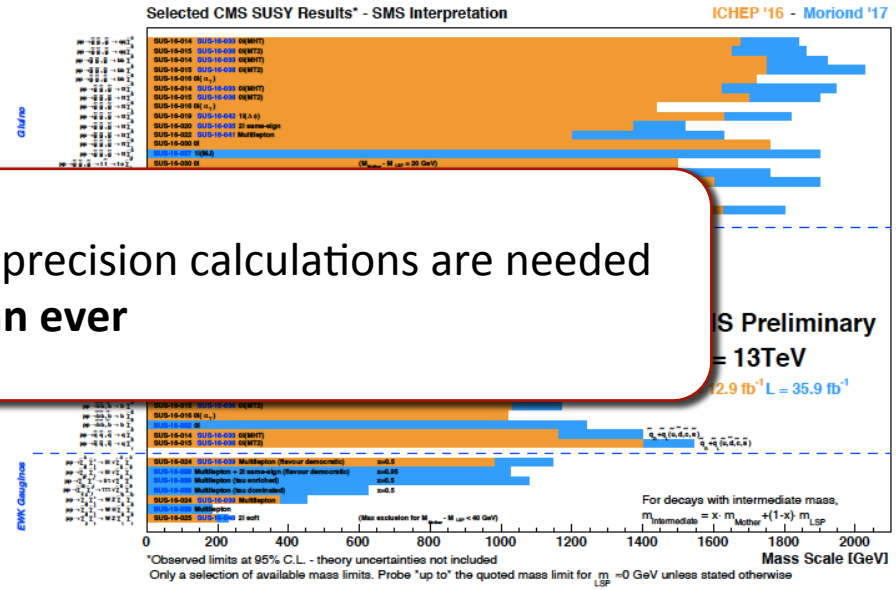
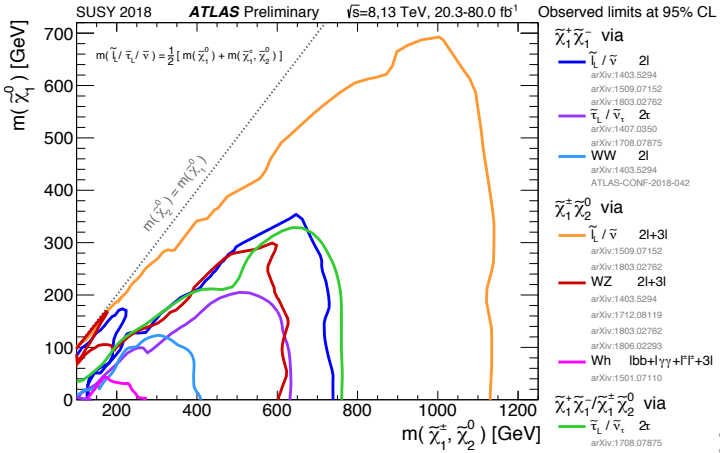
(* shakes head, opens up laptop, checks emails *)





At this point in the LHC history BSM precision calculations are needed **more than ever**



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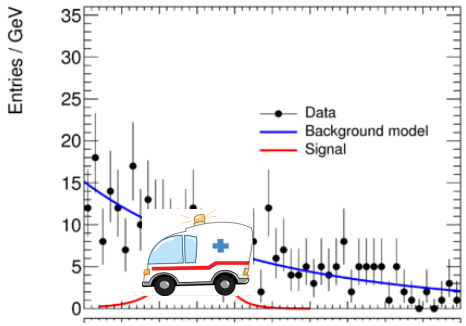
The question is not if BSM exists but if it is at reach at the LHC

Possible Scenarios

As in real life…

- Dumb luck
  - teeny-tiny resonance hiding somewhere in the data



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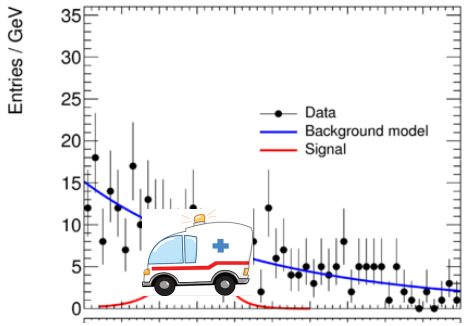

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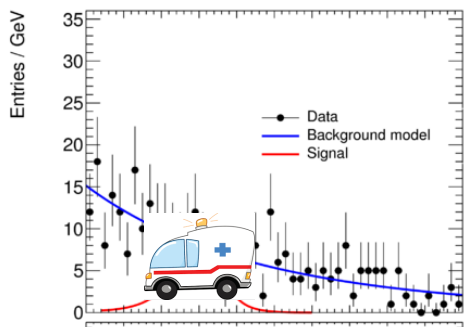

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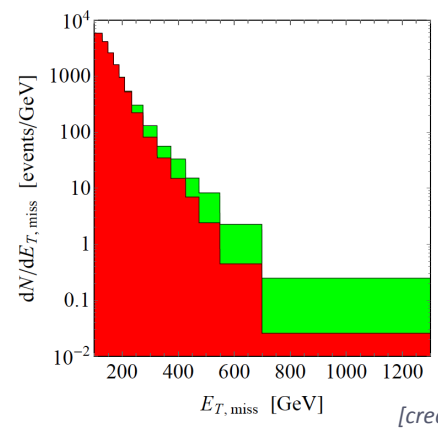
- Hard work
  - need to search for BSM effects in the "boring SM physics"
  - focus on determination of SM couplings and kinematical distributions of SM particles, search for deviations from the SM predictions



[credit: U.Haisch]

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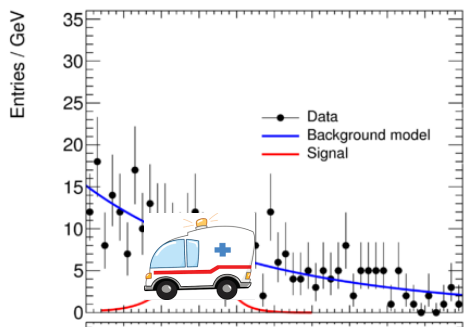

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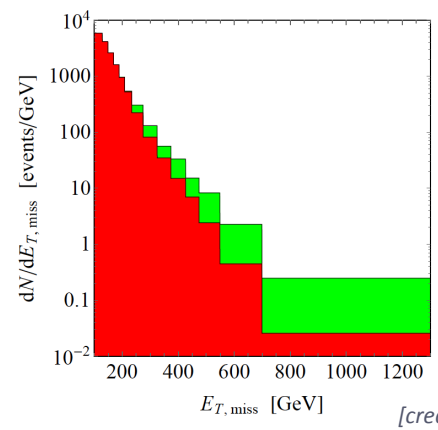

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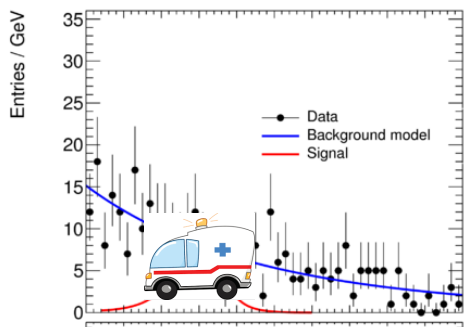

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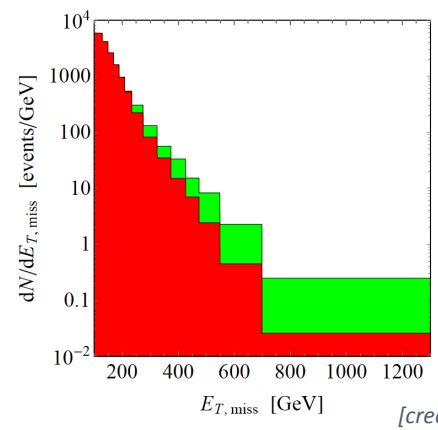

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loops & legs equally important: N^nLO (+NNLL / to a parton shower)

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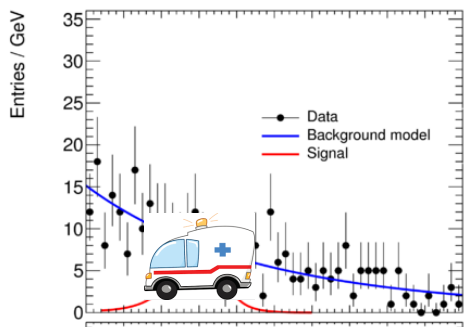

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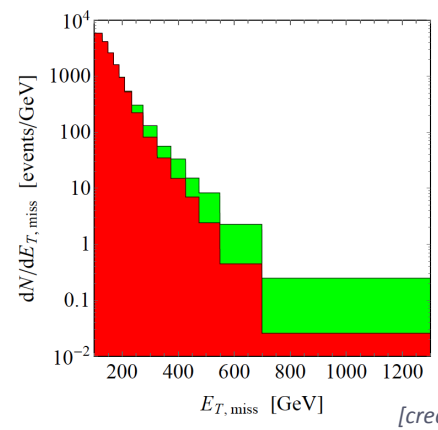

[credit: U.Haisch]

precision

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backgrounds to BSM searches: see previous talk by P. Gunnelini and J. Lindert

Theoretical Approaches

[slide credit: M. Spannowsky]

Connecting Higgs measurements with UV physics

Kappa Framework	EFT	Simplified Models	Full (UV) Model
• NP models simple rescaling of couplings • No new Lorentz -structures or kinematics	• SM degrees of freedom and symmetries • New kinematics/ Lorentz structures	• New low-energy degrees of freedom • Subset of states of full models, reflective at scale of measurement	• Very complex and often high-dimensional parameter space • Allows to correlate high-scale and low-scale physics

Complexity/Flexibility

Theoretical Approaches

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Complexity/Flexibility

Ignorance/Generality

Theoretical Approaches

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Complexity/F

Ignorance/G

- In what follows a selection of recent activities / progress
- Obviously, the literature is much richer -- apologies if some specific work has not been mentioned!

HIGGS & FRIENDS

BSM Higgs

- Higgs sector extensions attract a lot of interest:
  - the least explored sector
  - many BSM models modify or extend the scalar sector of EW breaking
  - can either be constructed as complete models or simplified models

- Typical examples
  - Singlet (under SM gauge symmetry) extension: two CP- even neutral scalars *h,H*
  - Two Higgs Doublet Model (2HDM) / Minimal Supersymmetric Standard Model (MSSM): two CP-even neutral scalars *h,H,* CP-odd neutral scalar *A* and two charged H^+, H^- scalars

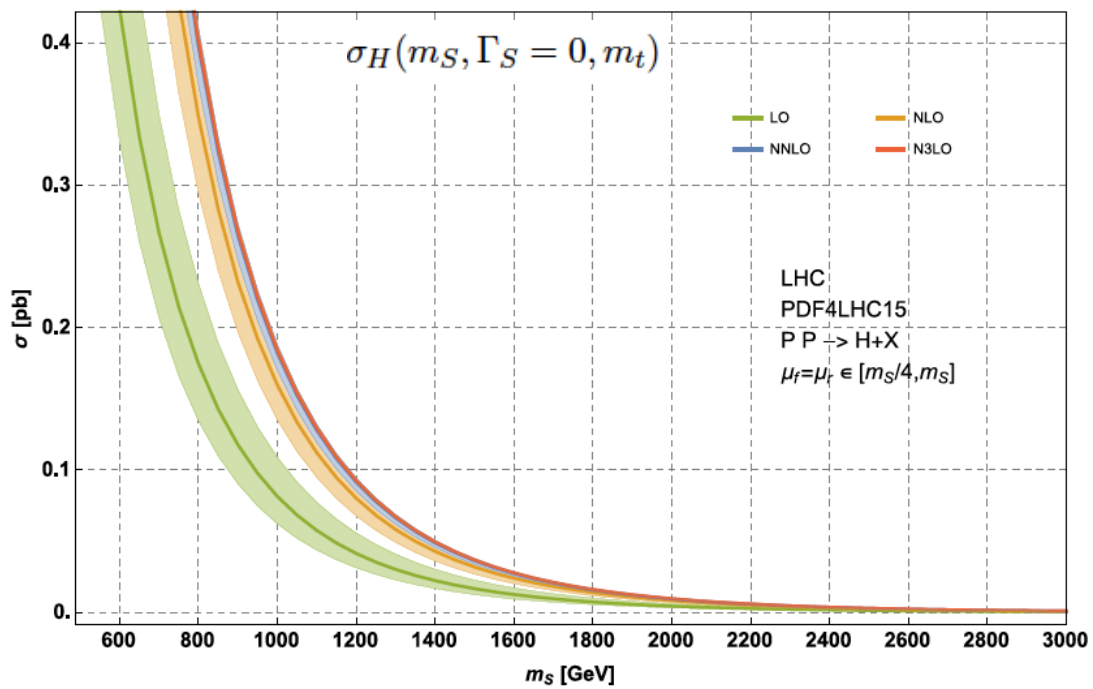
CP-Even Higgs from Gluon Fusion

[Anastasiou et al.'16]

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \mathcal{L}_S - \frac{1}{4v} C_S \, S \, G^a_{\mu\nu} G^{\mu\nu}_a$$

$$\sigma_S(m_S, \Gamma_S, \Lambda_{\text{UV}}) = \left| \frac{C_S(\mu_0, \Lambda_{\text{UV}})}{C(\mu_0, m_t)} \right|^2 \sigma_H(m_S, \Gamma_S, m_t)$$

- Gluon fusion: SM N^{3}LO results can be recast to calculate cross section for a CP-even scalar directly coupling to gluons in an effective theory approach
- Exact N^{3}LO available in `iHixs2` *[Dulat, Lazopoulos, Mistlberger'18]*
- N^{3}LO from threshold expansion implemented also in `SusHi Bento` *[Harlander, Liebler, Mantler'16]*



Pseudoscalar from Gluon Fusion

- For pseudoscalars N^3LO not fully known, N^3LO_A approximation proposed *[Ahmed et al.'16]*

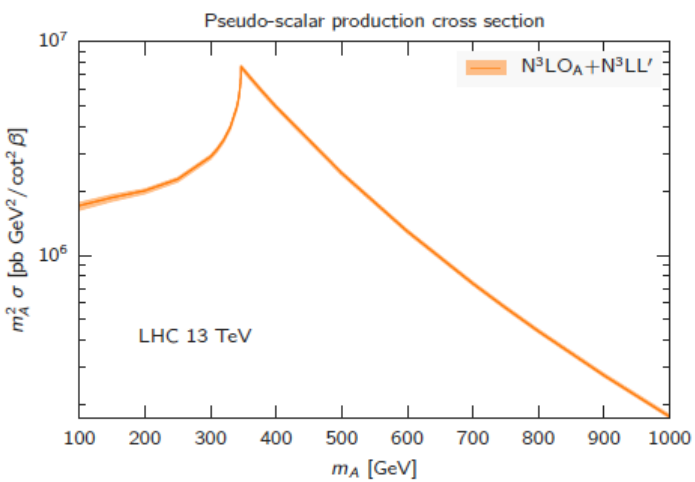
$$\sigma(\tau, m_A^2) = \tau\sigma_0 \sum_{i,j} \int_\tau^1 \frac{dz}{z} \mathscr{L}_{ij}\left(\frac{\tau}{z}, \mu_F^2\right) C_{ij}(z, \alpha_s, \mu_F^2)$$

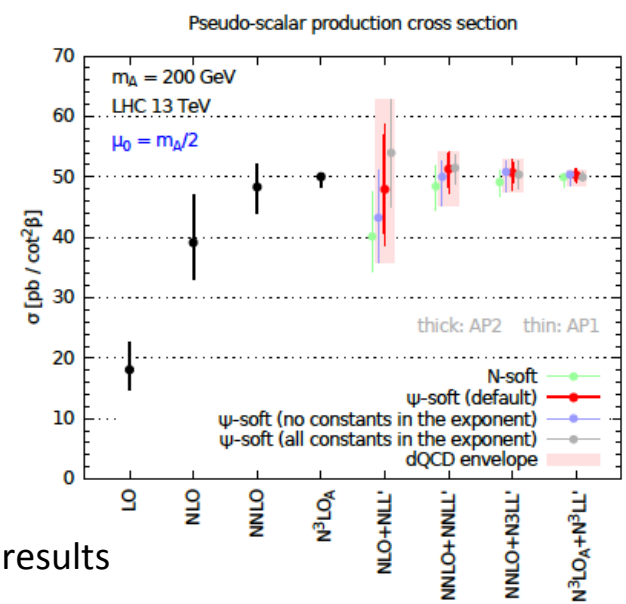
where $$C_{ij}(z,\alpha_s) = \frac{g_0(\alpha_s)}{g_0^H(\alpha_s)}\left[C_{ij}^H(z,\alpha_s) + \delta C_{ij}(z,\alpha_s)\right]$$

each component known up to N^3LO

use NNLO

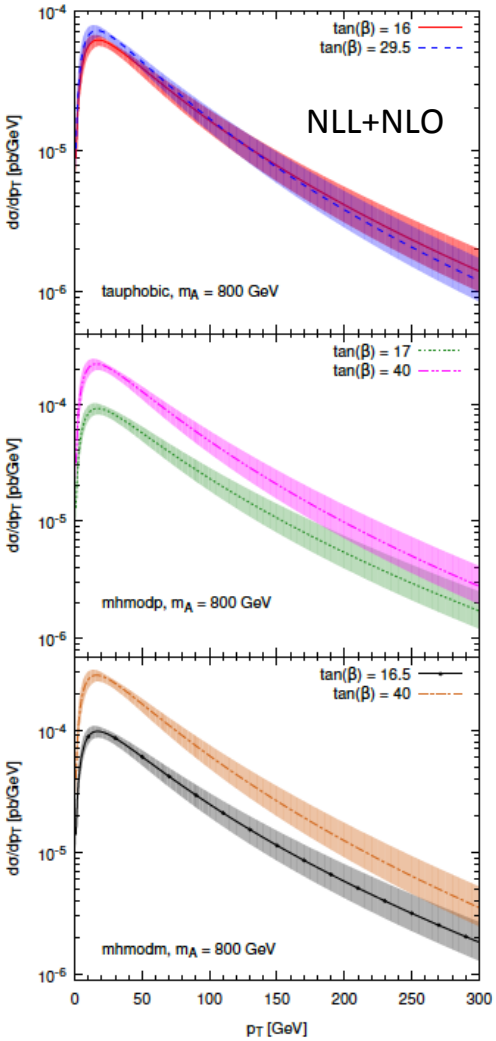
- Resummation added at N^3LL' accuracy (hard function known at three loops *[Ahmed, Gehrmann, Mathews, Rana, Ravindran'15]*)



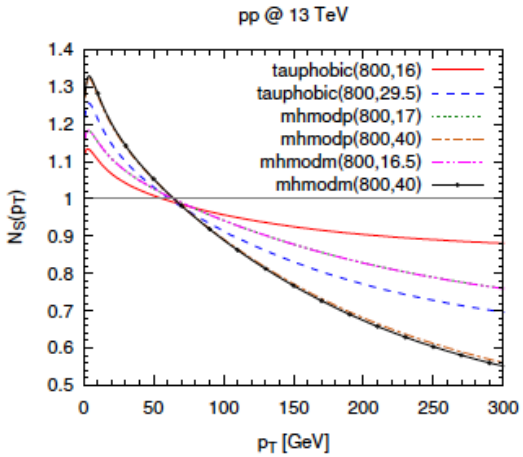


- see also *[Schmidt,Spira'15]* for NNLO+N³LL for *h,H* and *A* results

MSSM Higgs p_T



- p_T spectra available in specific models, e.g. 2HDM/ MSSM *[Bagnaschi,Degrassi, Slavich, Vicini'11] [Mantler, Wiesemann'15]* (NLO +PS) *[Harlander, Mantler, Wiesemann'14]*(NLO+NLL), NMSSM *[Mantler, Wiesemann'16]*
  - Results for the light Higgs very SM-like
  - For heavy or pseudoscalar Higgs exact results dependent on a particular scenario but p_T spectra generally softer than in the SM
  - contributions involving b-quark loops very important



Shape ratios:

$$N_{\mathcal{S}}(p_T) = \frac{\mathrm{d}\bar{\sigma}_{\mathcal{S}}/\mathrm{d}p_T}{\mathrm{d}\bar{\sigma}_{\mathrm{SM}}/\mathrm{d}p_T},$$

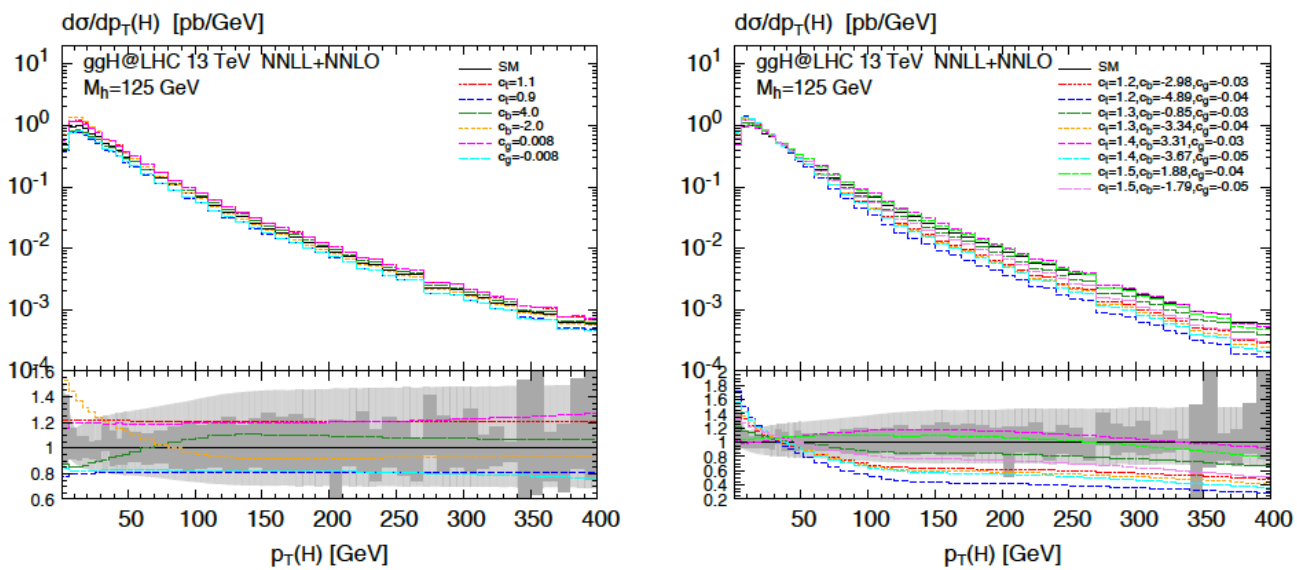
- `MoRe-SusHi` *[Harlander, Mantler, Wiesemann'14]*
- Pseudoscalar p_T distributions at $\mathrm{NNLO_A}$+NNNL recently obtained in *[Agarwal et al.'18]*

Higgs' p_T in the EFT

[Grazzini, Ilnicka, Spira, Wiesemann'16-'17]

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i$$

$$\frac{c_1}{\Lambda^2}\mathcal{O}_1 \to \frac{\alpha_S}{\pi v} c_g h G^a_{\mu\nu} G^{a,\mu\nu}\,, \quad \frac{c_2}{\Lambda^2}\mathcal{O}_2 \to \frac{m_t}{v} c_t h\bar{t}t\,, \quad \frac{c_3}{\Lambda^2}\mathcal{O}_3 \to \frac{m_b}{v} c_b h\bar{b}b$$



- Modifications introduced by different operators affect mostly different p_T regions

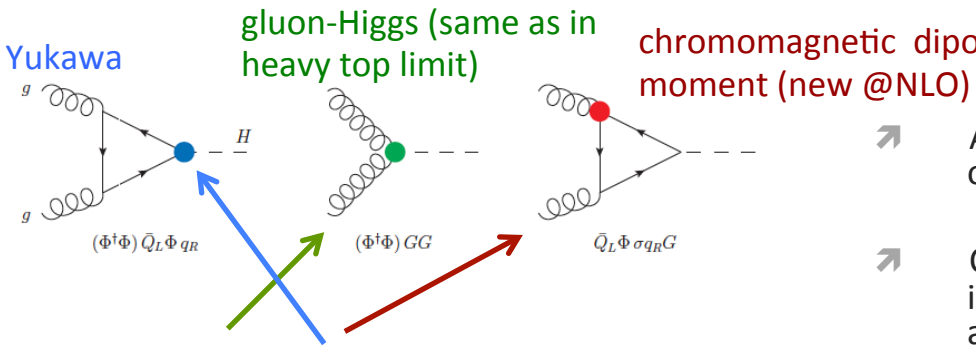
scale uncertainty @NLL+NLO

scale uncertainty @NNLL+NNLO

$$\left(\frac{d\sigma}{dp_t}\right)^{SMEFT}_{NNLL+NNLO}(p_T) = \frac{\left(\frac{d\sigma}{dp_t}\right)^{SMEFT}_{NLL+NLO}(p_T)}{\left(\frac{d\sigma}{dp_t}\right)^{SM}_{NLL+NLO}(p_T)} \cdot \left(\frac{d\sigma}{dp_t}\right)^{SM}_{NNLL+NNLO}(p_T)$$

Gluon Fusion @ NLO in SMEFT

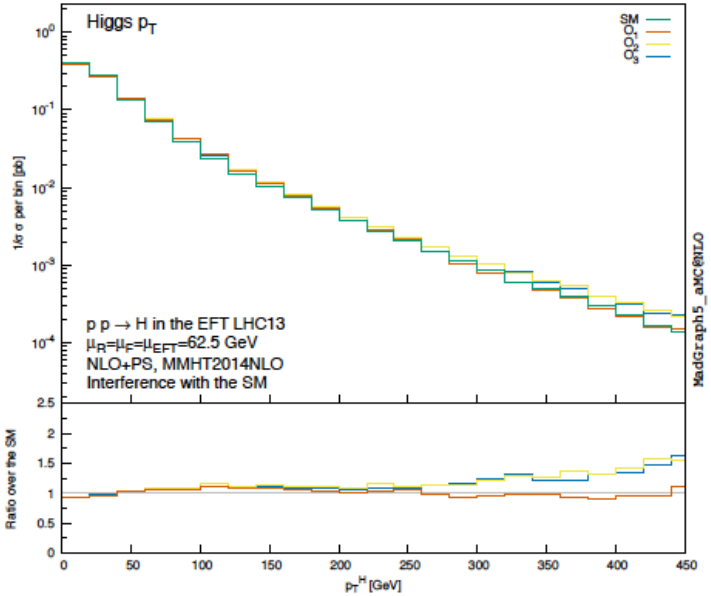
[Deutschmann, Duhr, Maltoni, Vrynidou'17]



at NLO 1- and 2-loop corrections

- At the inclusive level, contributions from effective operators have K-factors similar to the SM one
- Chromomagnetic and gluon-Higgs contact interaction operators modify high p_T tails, see also *[Grazzini, Ilnicka, Spira'18]*

13 TeV	σ LO	σ/σ_{SM} LO	σ NLO	σ/σ_{SM} NLO	K
σ_{SM}	$21.3^{+34.0+1.5\%}_{-25.0-1.5\%}$	1.0	$36.6^{+26.4+1.9\%}_{-20.0-1.6\%}$	1.0	1.71
σ_1	$-2.93^{+34.0+1.5\%}_{-25.0-1.5\%}$	-0.138	$-4.70^{+24.8+1.9\%}_{-20.0-1.6\%}$	-0.127	1.61
σ_2	$2660^{+34.0+1.5\%}_{-25.0-1.5\%}$	125	$4130^{+23.9+1.9\%}_{-19.6-1.6\%}$	114	1.55
σ_3	$50.5^{+34.0+1.5\%}_{-25.0-1.5\%}$	2.38	$83.5^{+26.0+1.9\%}_{-20.6-1.6\%}$	2.28	1.65



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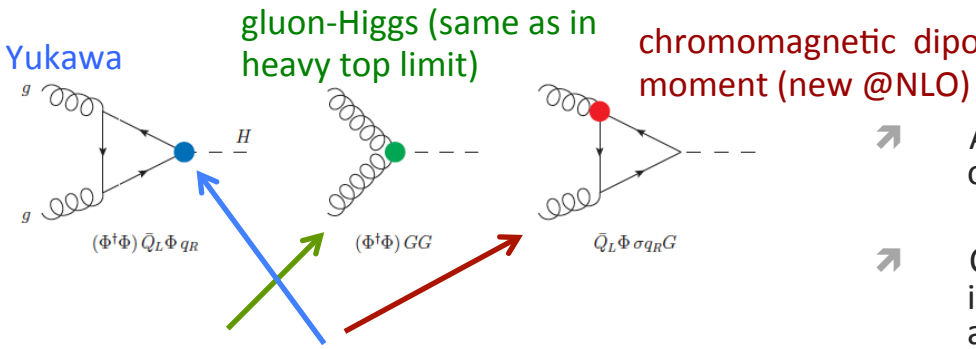

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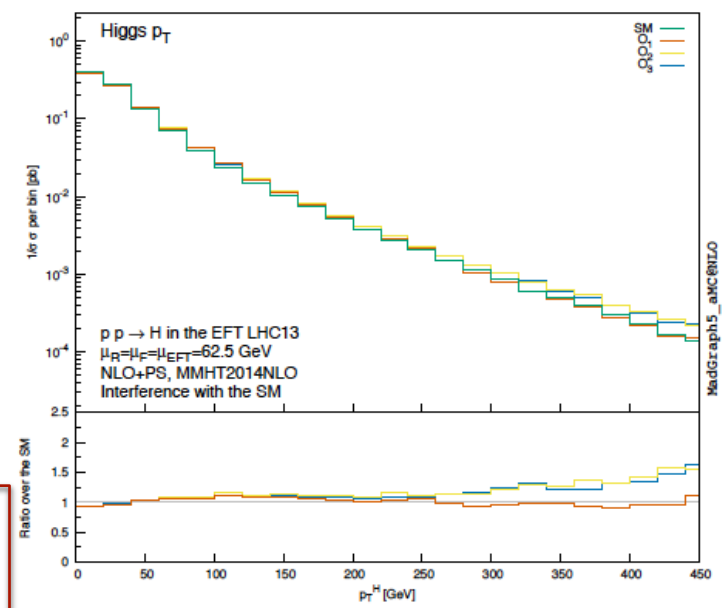
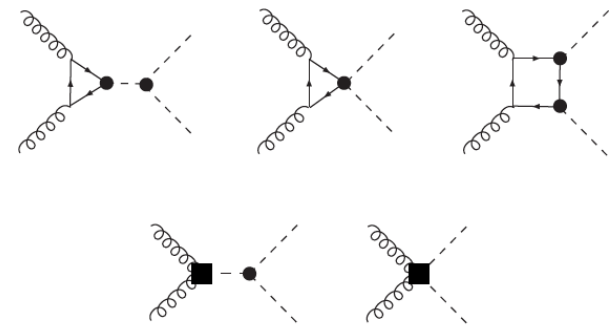


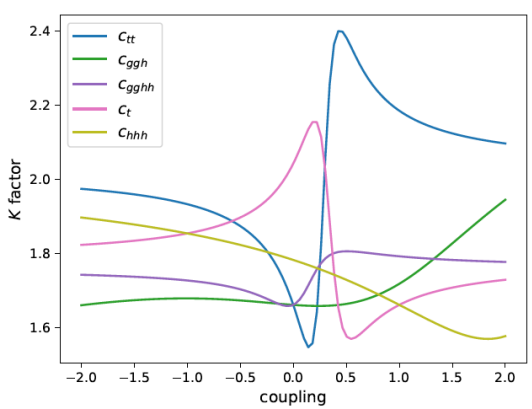
see also a talk on Higgs @ large p_T by K. Kudashkin (Monday afternoon)

Higgs-Pair with Full m_T Dependence @NLO QCD

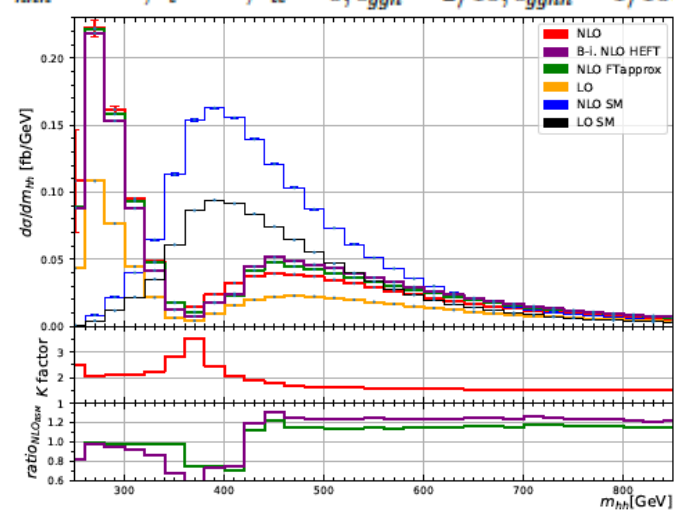
$$\mathcal{L} \supset -m_t\left(c_t\frac{h}{v}+c_{tt}\frac{h^2}{v^2}\right)\bar{t}\,t - c_{hhh}\frac{m_h^2}{2v}h^3 + \frac{\alpha_s}{8\pi}\left(c_{ggh}\frac{h}{v}+c_{gghh}\frac{h^2}{v^2}\right)G^a_{\mu\nu}G^{a,\mu\nu}$$

- NLO *[Gröber, Mühlleitner, Spira, Streicher'15] [Gröber, Mühlleitner, Spira'17]* and NNLO *[de Florian, Fabre, Mazzitelli'17]* calculations in the EFT framework in the $m_t \to \infty$ limit show rather flat K-factors w.r.t. variation of the coupling
- K-factors calculated with full mass dependence can be large and non-uniform as couplings varied *[Buchalla et al.'18]*
- m_{hh} and p_T distributions highly discriminative





$c_{hhh} = 2.4, c_t = 1, c_{tt} = 0, c_{ggh} = 2/15, c_{gghh} = 1/15$



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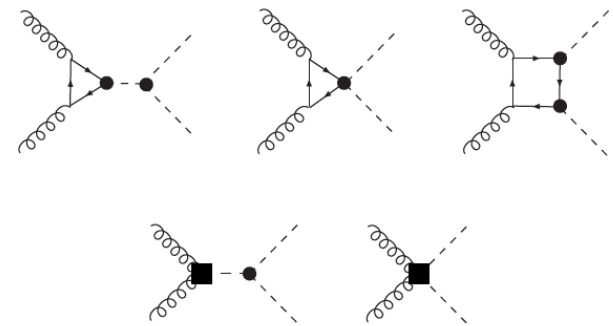

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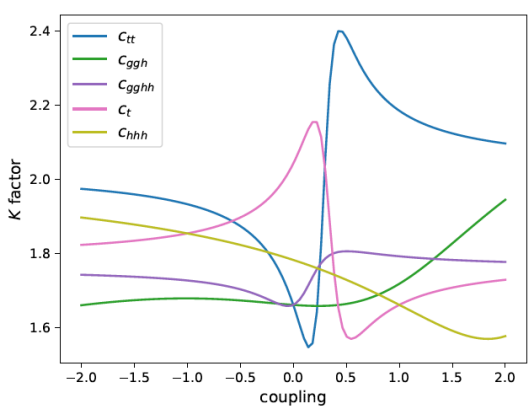
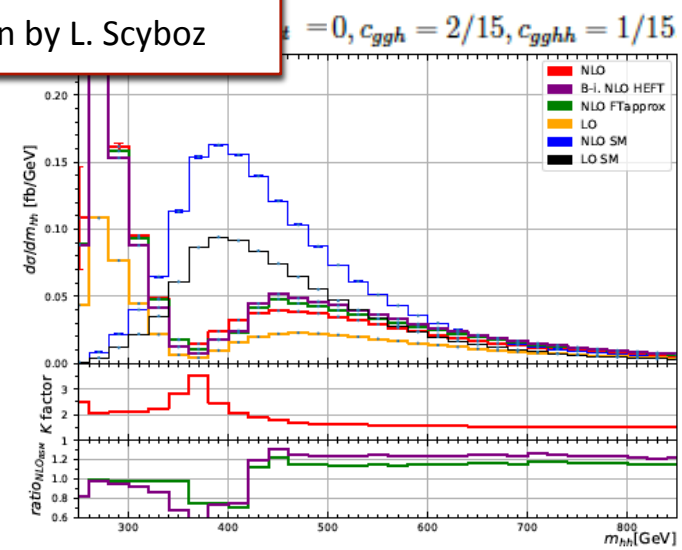
talk today afternoon by L. Scyboz

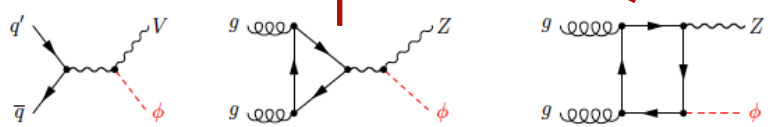




Higgs Strahlung for BSM

$$\sigma^{VH} = \sigma^{VH}_{\text{DY}} + \sigma^{VH}_{\text{non-DY}}$$

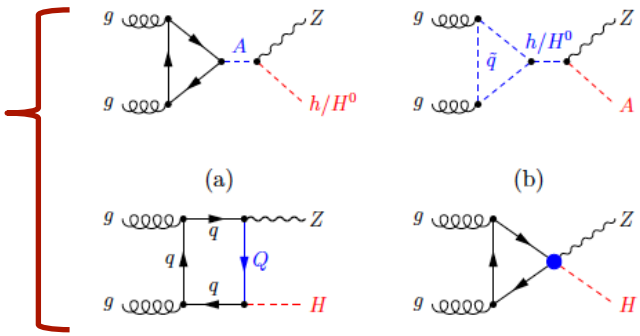
SM:



BSM:

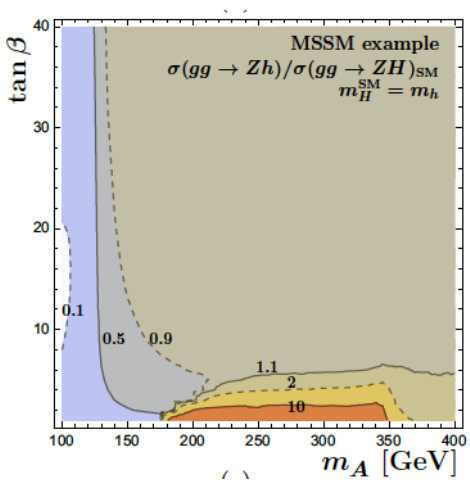
2HDM/MSSM

MSSM



vector-like quarks

dim.-6 operators



- implemented in `vh@nnlo-v2` *[Harlander, Klappert, Liebler, Simon'18]*
- Ratio $R_R^{ZW} = \frac{\sigma^{ZH}/\sigma^{WH}}{\sigma^{ZH}_{\text{DY}}/\sigma^{WH}}$ sensitive to non-DY component -> probe of BSM *[Harlander, Klappert, Pandini, Papaefstathiou'18]*

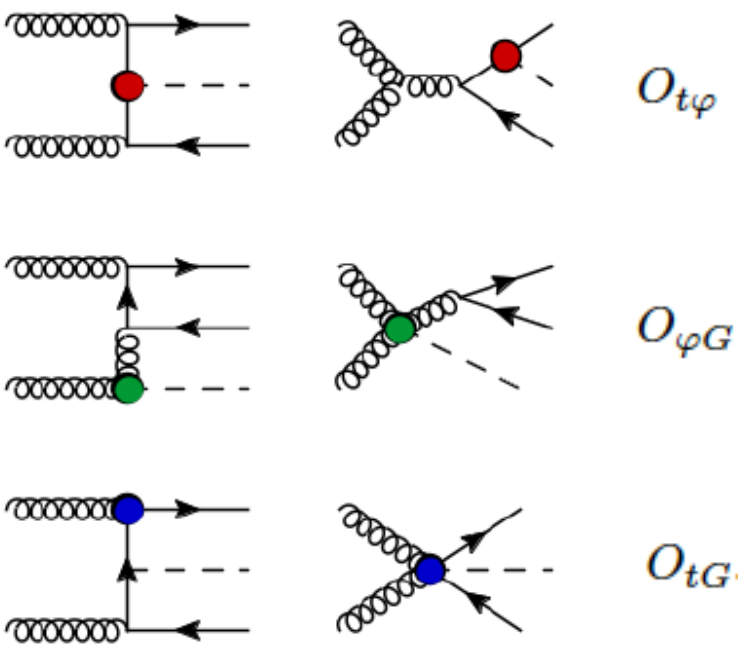
NLO QCD to TTH in the EFT

[Maltoni, Vrynidou, Zhang'16]

- Looking for possible deviations from the SM
  - model-independent theoretical framework of effective field theories
  - SMEFT: Standard Model with higher dimensional operators

$$\mathcal{L}_{\rm EFT} = \mathcal{L}_{\rm SM} + \sum_i \frac{C_i}{\Lambda^2} O_i + \mathcal{O}(\Lambda^{-4}) + h.c.,$$

Tree level contributions from



same operators also probed in *H, Hj* and *HH* production ⟷ cross-talk

NLO QCD to TTH in the EFT

[Maltoni, Vrynidou, Zhang'16]

$$\sigma = \sigma_{SM} + \sum_i \frac{1\text{TeV}^2}{\Lambda^2} C_i \sigma_i + \sum_{i \leq j} \frac{1\text{TeV}^4}{\Lambda^4} C_i C_j \sigma_{ij}.$$

MG5_aMC

MMHT2014 LO/NLO PDFs

$\mu_0^{R,F} = m_t + m_H/2$

$\mu_0^{EFT} = m_t$

Total cross sections:

13 TeV	σ LO	σ NLO	K
σ_{SM}	$0.464^{+0.161+0.000+0.005}_{-0.111-0.000-0.004}$	$0.507^{+0.030+0.000+0.007}_{-0.048-0.000-0.008}$	1.09
$\sigma_{t\phi}$	$-0.055^{+0.013+0.002+0.000}_{-0.019-0.003-0.001}$	$-0.062^{+0.006+0.001+0.001}_{-0.004-0.001-0.001}$	1.13
$\sigma_{\phi G}$	$0.627^{+0.225+0.081+0.007}_{-0.153-0.067-0.005}$	$0.872^{+0.131+0.037+0.013}_{-0.123-0.035-0.016}$	1.39
σ_{tG}	$0.470^{+0.167+0.000+0.005}_{-0.114-0.002-0.004}$	$0.503^{+0.025+0.001+0.007}_{-0.046-0.003-0.008}$	1.07
$\sigma_{t\phi,t\phi}$	$0.0016^{+0.0005+0.0002+0.0000}_{-0.0004-0.0001-0.0000}$	$0.0019^{+0.0001+0.0001+0.0000}_{-0.0002-0.0000-0.0000}$	1.17
$\sigma_{\phi G,\phi G}$	$0.646^{+0.274+0.141+0.018}_{-0.178-0.107-0.010}$	$1.021^{+0.204+0.096+0.024}_{-0.178-0.085-0.029}$	1.58
$\sigma_{tG,tG}$	$0.645^{+0.276+0.011+0.020}_{-0.178-0.015-0.010}$	$0.674^{+0.036+0.004+0.016}_{-0.067-0.007-0.019}$	1.04
$\sigma_{t\phi,\phi G}$	$-0.037^{+0.009+0.006+0.000}_{-0.013-0.007-0.000}$	$-0.053^{+0.008+0.003+0.001}_{-0.008-0.004-0.001}$	1.42
$\sigma_{t\phi,tG}$	$-0.028^{+0.007+0.001+0.000}_{-0.010-0.001-0.000}$	$-0.031^{+0.003+0.000+0.000}_{-0.002-0.000-0.000}$	1.10
$\sigma_{\phi G,tG}$	$0.627^{+0.252+0.053+0.014}_{-0.166-0.047-0.008}$	$0.859^{+0.127+0.021+0.017}_{-0.126-0.020-0.022}$	1.37

- K-factors depend on the eff. operator, corrections up to 60%
- Renormalization and factorization scale variation dominant uncertainty, substantially reduced @NLO

$\mu_0^{R,F}/2 < \mu_F = \mu_R < 2\,\mu_0^{R,F}$

$\mu_0^{EFT}/2 < \mu^{EFT} < 2\,\mu_0^{EFT}$

pdf uncertainty

NLO QCD to TTH in the EFT

[Maltoni, Vrynidou, Zhang'16]

$$\sigma = \sigma_{SM} + \sum_i \frac{1\text{TeV}^2}{\Lambda^2} C_i \sigma_i + \sum_{i \le j} \frac{1\text{TeV}^4}{\Lambda^4} C_i C_j \sigma_{ij}.$$

MG5_aMC

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$\sigma_{t\phi,t\phi}$	$0.0016^{+0.0005+0.}_{-0.0004-0.}$
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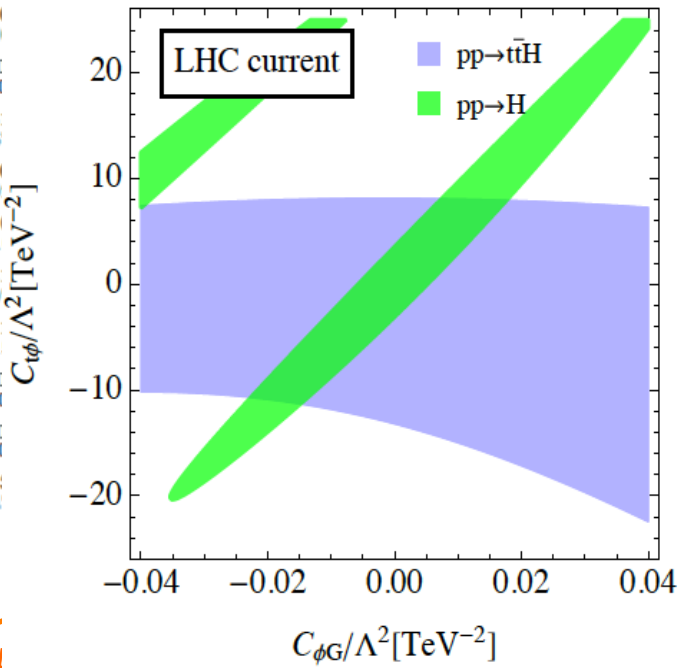
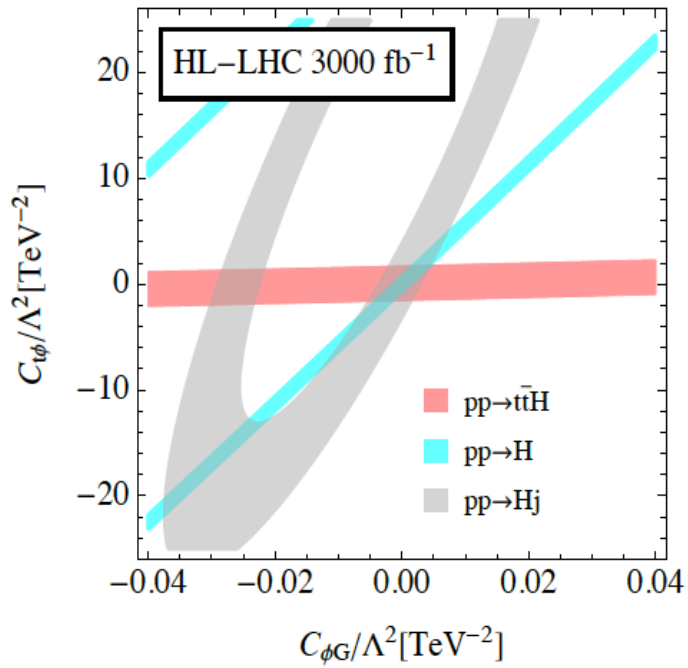
$\sigma_{t\phi,tG}$	$-0.028^{+0.007+0.}_{-0.010-0.}$
$\sigma_{\phi G,tG}$	$0.627^{+0.252+0.05}_{-0.166-0.04}$

$\mu_0^{R,F}/2 < \mu_F = \mu$





COLOURED SECTOR

SUSY @THE LHC

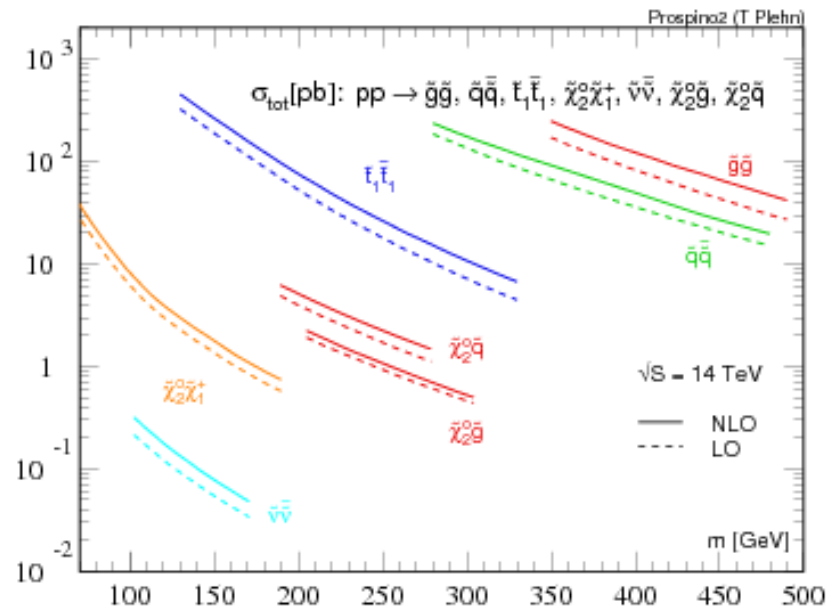
MSSM:
minimal content of SUSY particles + R-parity

Hadron colliders:
coloured sparticles most copiously produced

High rates for pair-production of squarks and gluinos

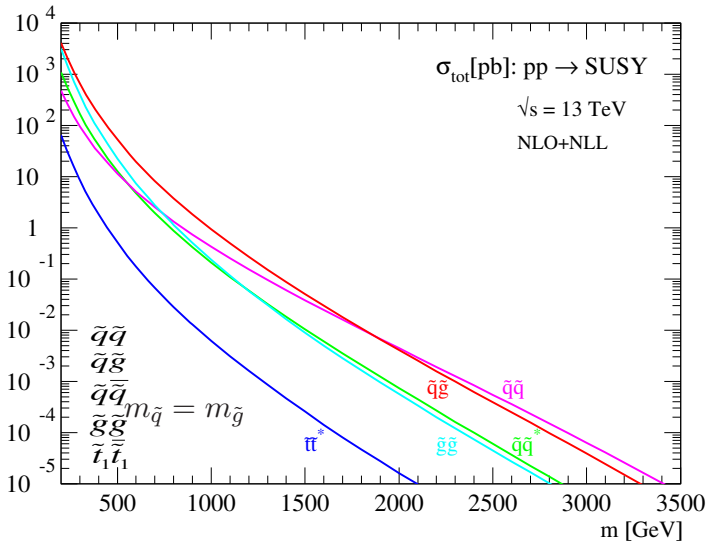
$$p\overset{(-)}{p} \to \tilde{t}_k\bar{\tilde{t}}_k,\ \tilde{q}\bar{\tilde{q}},\ \tilde{q}\tilde{q},\ \tilde{q}\tilde{g},\ \tilde{g}\tilde{g}$$

Key discovery processes in SUSY searches



Soft Gluon resummation at NLL+NLO

Problem: at higher orders in QCD, large corrections of the form $\alpha_s^n \log^m(1-4m^2/\hat{s})$ $\quad m \le 2n$



resummation

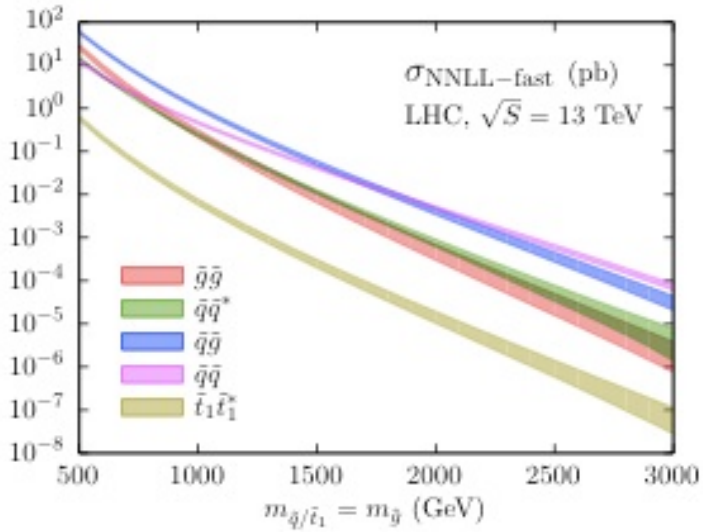
better control over theoretical error

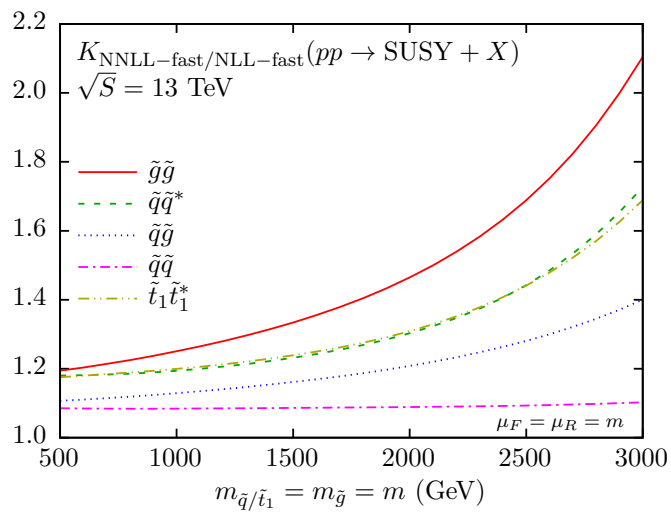
Numerical tool: **NLL-fast**

- standard tool to evaluate total cross section in SUSY, used in 100+ experimental analysis of Run 1 and Run 2

[AK and L. Motyka, Phys. Rev. Lett. 102, 111802 (2009)][AK and L. Motyka, Phys. Rev. D 80 (2009) 095004][W. Beenakker, S. Brensing, M. Krämer, AK, E. Laenen and I. Niessen, JHEP 12 (2009) 041][W. Beenakker, S. Brensing, M. Krämer, AK, E. Laenen and I. Niessen, JHEP 08 (2010) 098][W. Beenakker, S. Brensing, M. Krämer, AK, E. Laenen, L.Motyka and I. Niessen, IJMP A26 (2011) 2637] [M. Krämer, AK, R. van der Leeuw, M. Mangano, S. Padhi, T.Plehn, X.Portell'12][C.Borschensky, M. Krämer, AK, M. Mangano, S. Padhi, T.Plehn, X.Portell'14]

Squarks and Gluinos at NNLL



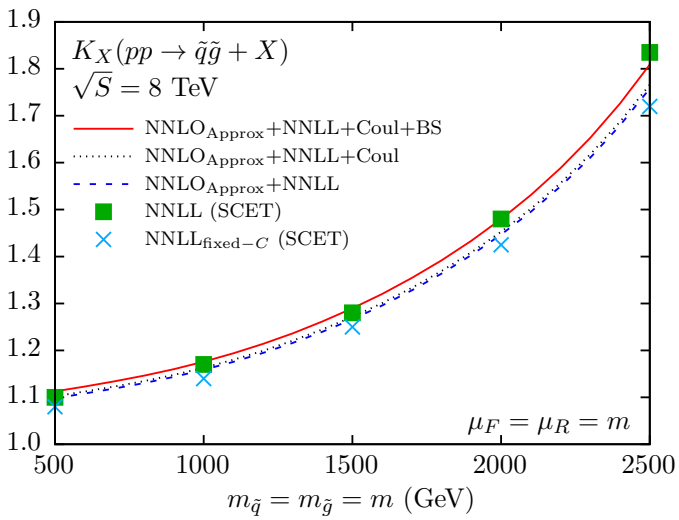


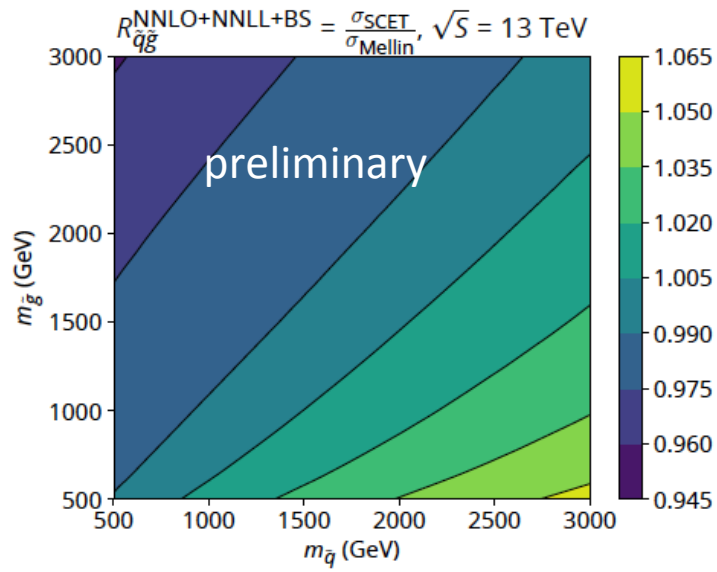
- NNLL resummation of soft gluon corrections combined with Coulomb resummation (NRQCD approach with NLO potential) and LO bound states corrections below threshold
- Significant increase of the total cross section for almost all processes of squark and gluino production
- Scale variation error decreases due to including NNLL terms down to 5-10%
- Public tool to calculate NNLL+NNLO$_{\text{approx}}$ cross sections at 13 TeV: **NNLL-fast**

[W. Beenakker, S. Brensing, M. Krämer, AK, E. Laenen, L.Motyka and I. Niessen'11] [Beenakker, Borschensky, Krämer, AK, Laenen, Thewes, Theeuwes'14]] [Beenakker, Borschensky, Heger, Krämer, AK, Laenen'16][Beenakker, Borschensky, Krämer, AK, Laenen'16]

The Ultimate NNLL

- NNLO $_{\text{Approx}}$+NNLL calculations also performed in the SCET framework *[Beneke, Piclum, Schwinn, Wever'16]*



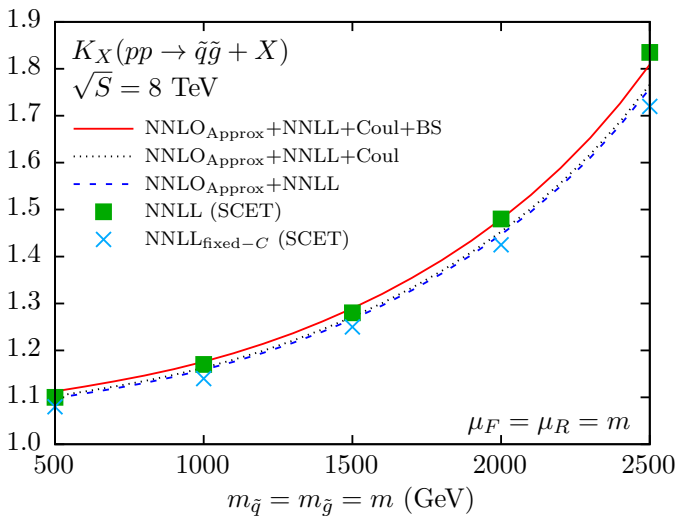


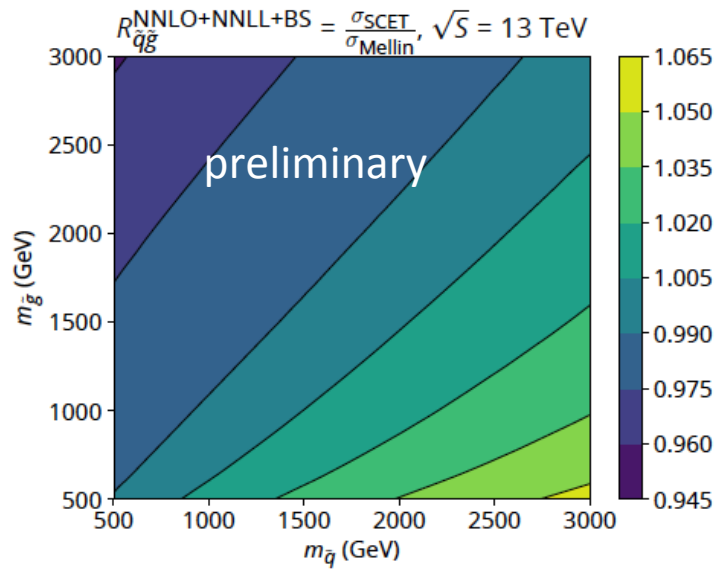
[Beneke, Borschensky, Krämer, AK, Piclum, Schwinn, Wever, in prep.]

- Work in progress: comparison of the results with the predictions obtained in the SCET framework

The Ultimate NNLL

- NNLO $_{\text{Approx}}$+NNLL calculations also performed in the SCET framework *[Beneke, Piclum, Schwinn, Wever'16]*





[Beneke, Borschensky, Krämer, AK, Piclum, Schwinn, Wever, in prep.]

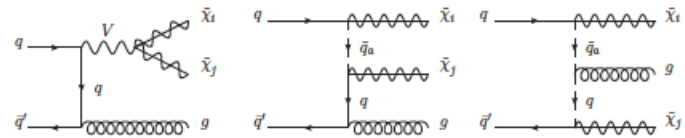
- Work in progress: comparison of the results with the predictions obtained in the SCET framework

Gluino-gaugino production known at NLO+NLL *[Fuks, Klasen, Rothering'16]*, squark-gaugino only at NLO *[Plehn'04]*

In search of DM @the LHC

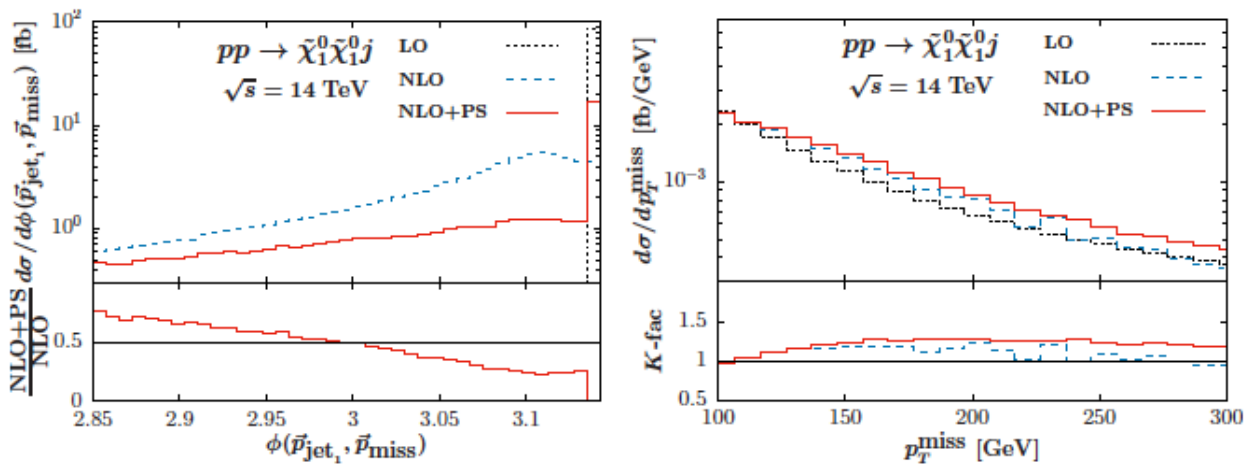
- In MSSM with R-parity, neutralino (mixture od superpartners of Higgs and Z bosons) is a DM candidate

- Direct pair production difficult to observe → need a visible particle to recoil against → "mono-X" searches (X= jet, Z, photon,…)



- NLO SUSY-QCD corrections to $pp \to \tilde{\chi}_1^0 \tilde{\chi}_1^0 j$ first considered in *[Cullen, Greiner, Heinrich'13]*

- NLO SUSY QCD matched to PS (in POWHEG-BOX) $pp \to \tilde{\chi}_i \tilde{\chi}_j j$. result including a scheme to remove on-shell single and double resonances in *[Baglio, Jäger, Kesenheimer'17]*



$$m_{\tilde{\chi}_1^0} = 111.9 \text{ GeV}, \quad m_{\tilde{\chi}_2^0} = 129.3 \text{ GeV}, \quad m_{\tilde{\chi}_3^0} = 211.7 \text{ GeV}, \quad m_{\tilde{\chi}_4^0} = 245.6 \text{ GeV}$$
$$m_{\tilde{d}_L/\tilde{s}_L} = m_{\tilde{u}_L/\tilde{c}_L} = 1.836 \text{ TeV}, \quad m_{\tilde{d}_R/\tilde{s}_R} = m_{\tilde{u}_R/\tilde{c}_R} = 1.833 \text{ TeV},$$
$$m_{\tilde{b}_1} = 1.330 \text{ TeV}, \quad m_{\tilde{b}_2} = 1.346 \text{ TeV}, \quad m_{\tilde{t}_1} = 1.229 \text{ TeV}, \quad m_{\tilde{t}_2} = 1.423 \text{ TeV}$$

Non-minimal SUSY

- MRSSM model *[Kribs, Poppitz, Werner'07]* : unbroken, continous R-symmetry (additional symmetry allowed by SUSY algebra)
  - solves the SUSY flavour problem, consistent with EW precision observables, Higgs mass and and LHC EW searches *[Diessner, Kalinowski, Kotlarski, Stöckinger'15-16]*, provides a candidate for a DM particle, viable parameter space
  - MRSSM phenomenology different from MSSM: R-charge conservation imposes constraints on the allowed chiralities of SUSY final states

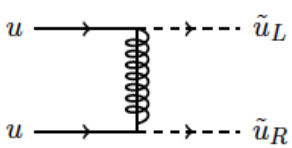
R-charge

superfield		boson		fermion	
left-handed (s)quark	$\widehat{Q}_L$	$\tilde{q}_L$	1	q_L	0
right-handed (s)quark	$\widehat{Q}_R$	$\tilde{q}_R^\dagger$	1	$\bar{q}_R$	0
gluon vector superfield	$\widehat{V}$	g	0	$\tilde{g}_L$	+1
adjoint chiral superfield	$\widehat{O}$	O	0	$\tilde{g}_R$	−1

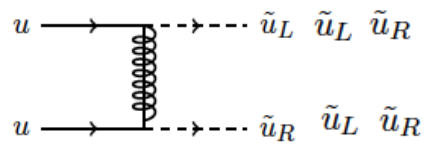
scalar superpartner of gluino (sgluon)

Dirac gluinos

MRSSM:



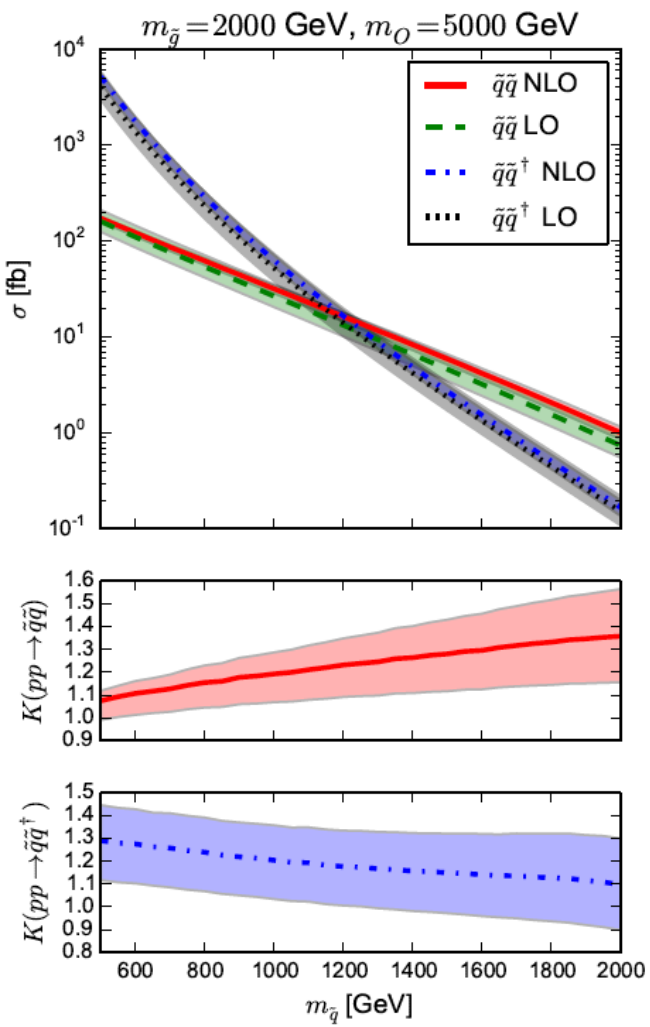
vs MSSM:



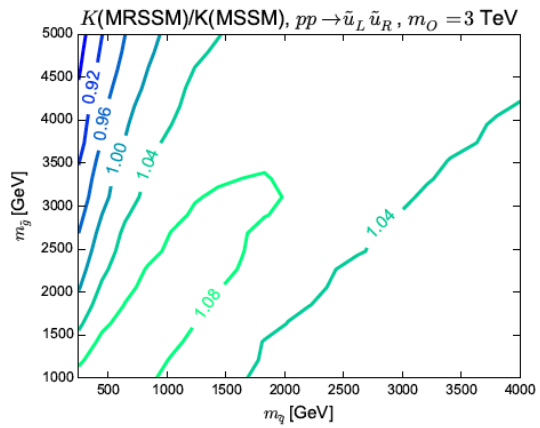
➔ squark production rates lower in MRSSM

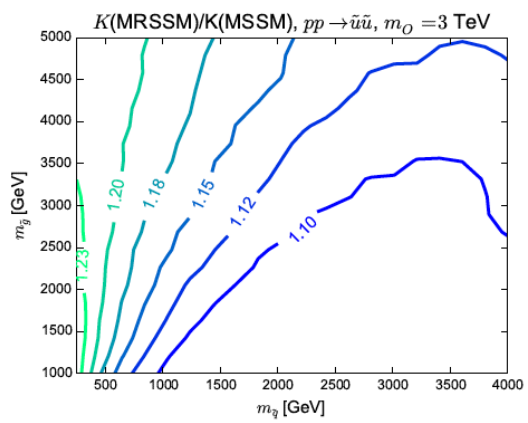
MRSSM K-factors?

NLO QCD in MRSSM



[Diessner, Liebschner, Kotlarski, Stöckinger'17]

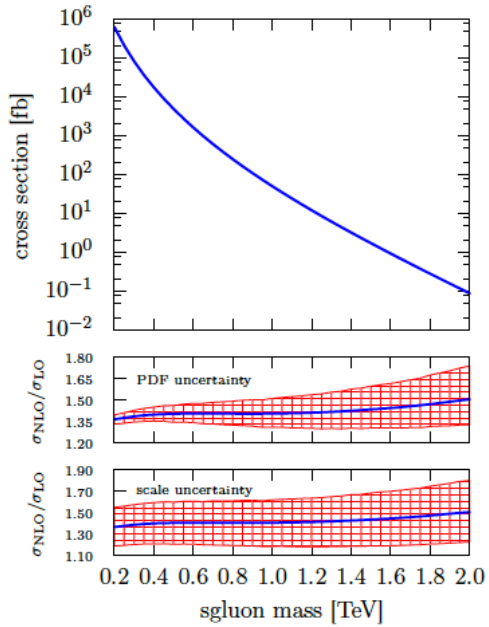


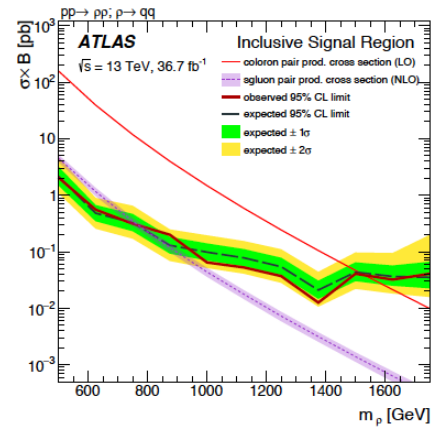


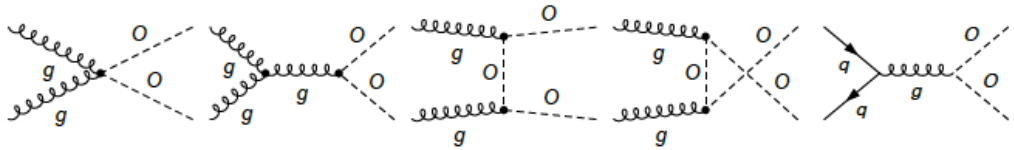
- SUSY QCD corrections to squark-squark and squark-antisquark pair production
- The 10-20% difference in K-factors generally does not compensate the decrease in the LO rates at large squark masses -> avoids detection

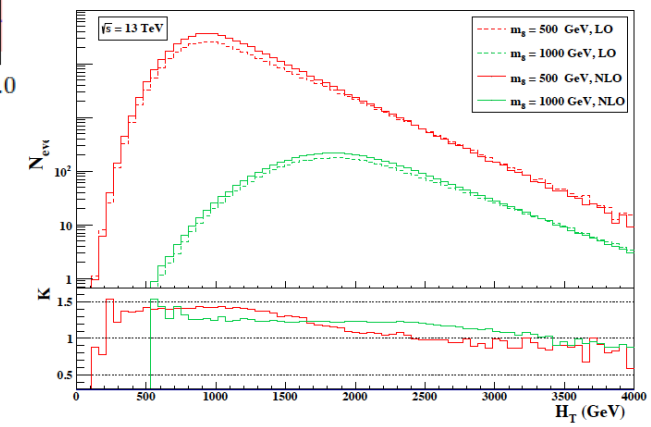
Sgluons

- Sgluons: coloured scalar partners of the gluons in the adjoint representation of the QCD gauge group
- Appear in the non-minimal versions (e.g. hybrid N=1/N=2, R-symmetric) SUSY, extra dimensions, ..
- Ongoing searches at the LHC
- Studies of sgluon pair production @NLO QCD in simplified models *[Goncalves Netto et al.'12] [Degrande et al.'14] [Beck et al.'15][Kotlarski'16][Darme, Fuks, Goodsell'18]*









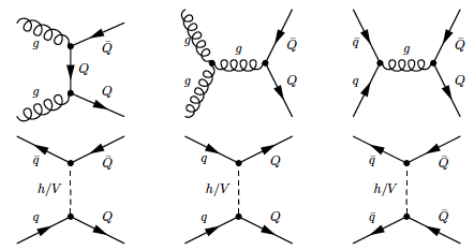
- For NLO results on massive colour octet vector (coloron) production see *[Sekhar Chivukula et al. '11-Freytas, Wieland'17]*

Vector-Like Quarks

- Vector-like quarks: fermions with LH and RH components in the same representation of the EW symmetry group
- Appear e.g. in extra dimension models, composite/ little Higgs models
- Single and pair production modes studied

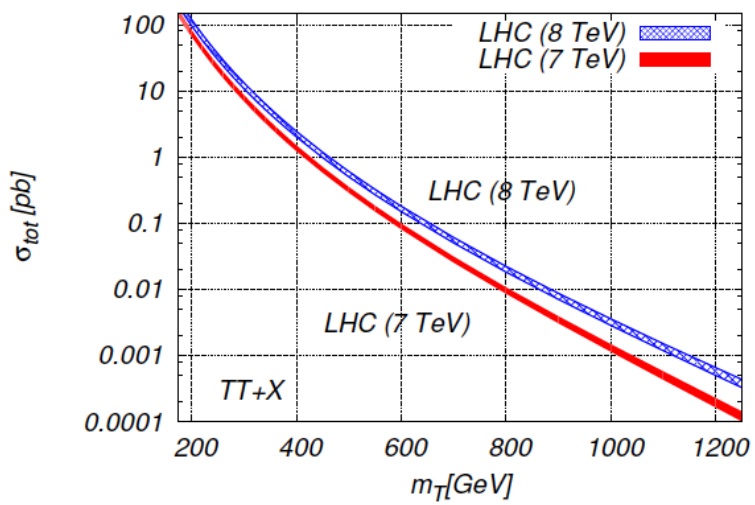
		SM	SU(2) Singlet	SU(2) Doublet	SU(2) Triplet
EM charge	5/3			$\begin{pmatrix} X \\ T \end{pmatrix}$	$\begin{pmatrix} X \\ T \\ B \end{pmatrix}$
	2/3	$\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix}$	(T)	$\begin{pmatrix} T \\ B \end{pmatrix}$	$\begin{pmatrix} T \\ B \\ Y \end{pmatrix}$
	-1/3		(B)	$\begin{pmatrix} B \\ Y \end{pmatrix}$	
	-4/3				

credit: A. Modak



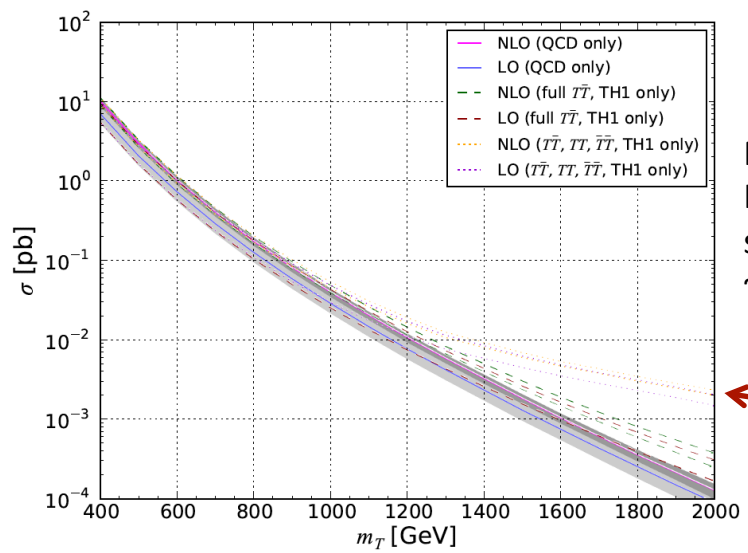
QCD; model independent

EW; model dependent



pure QCD @NNLO+NNLL *[Cacciari et al.'11]*

Total cross section for $pp \to T\bar{T}, TT, \bar{T}\bar{T}$ (TH scenarios)



NLO QCD K-factor ~ 1.5, scale error ~10%

EW mode

[Fuks and Shao'16]

Vector-Like Quarks

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- Appear e.g. in extra dimension models, composite/ little Higgs models

		SM	SU(2) Singlet	SU(2) Doublet	SU(2) Triplet
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	-1/3		(B)	$\begin{pmatrix} B \\ Y \end{pmatrix}$	
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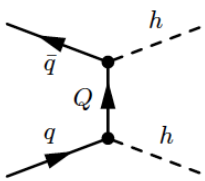
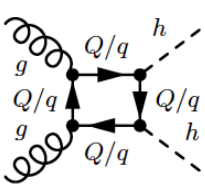
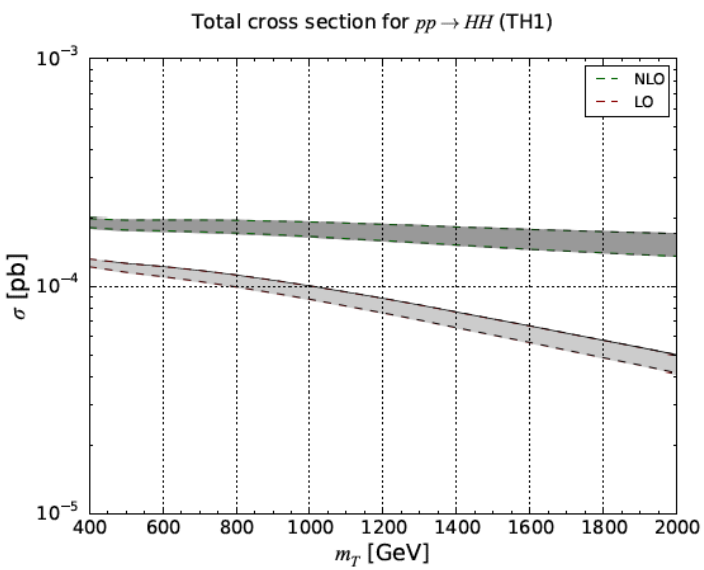
credit: A. Modak





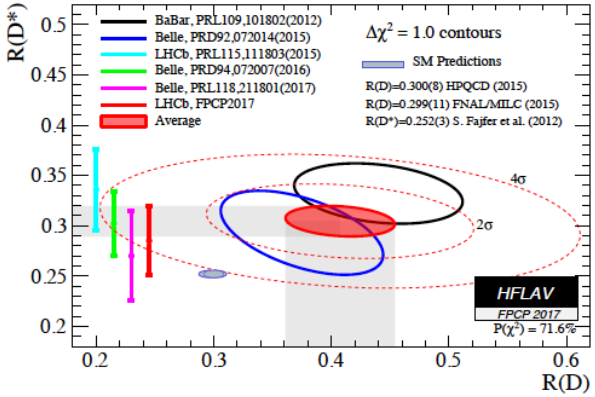


large K-factors, new qg channel opens up

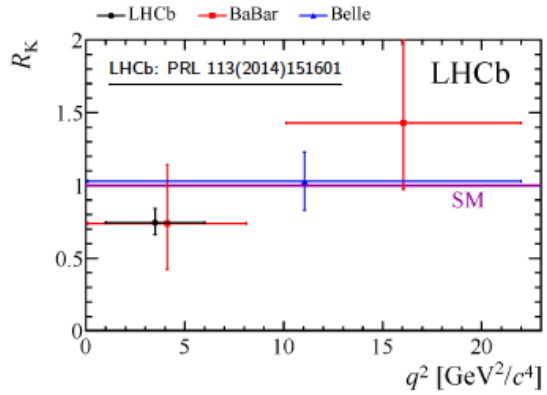
[Fuks and Shao'16]

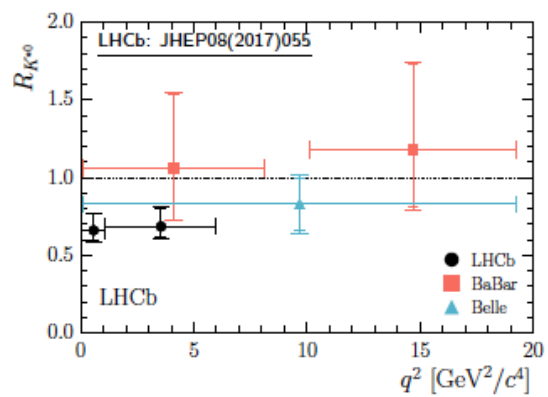
MEANWHILE...

... in the land of flavour...



$$\mathcal{R}(D^*) = \frac{\mathcal{B}(\overline{B} \to D^* \tau^- \overline{\nu}_\tau)}{\mathcal{B}(\overline{B} \to D^* \ell^- \overline{\nu}_\ell)}$$





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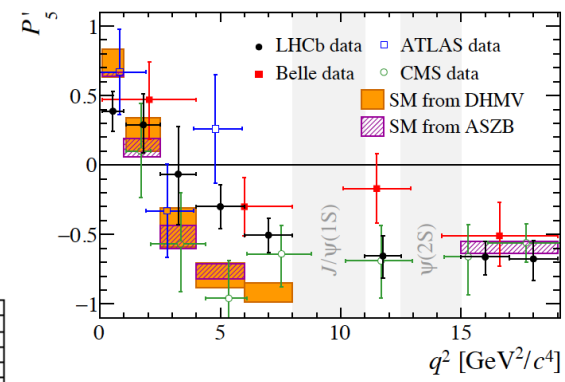

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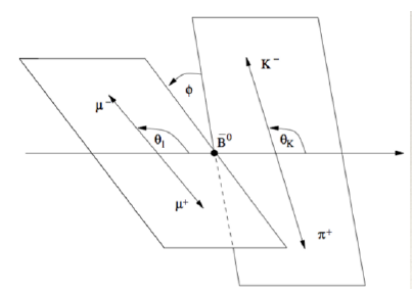

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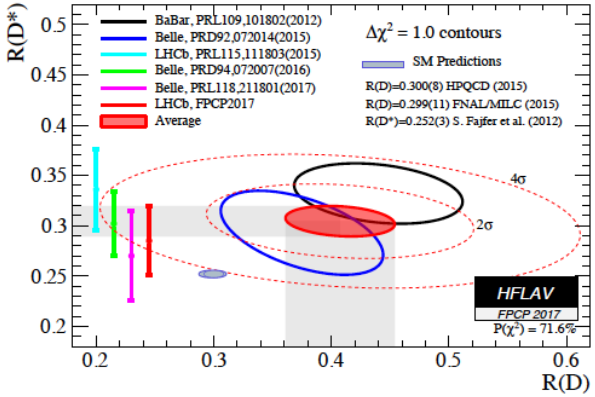

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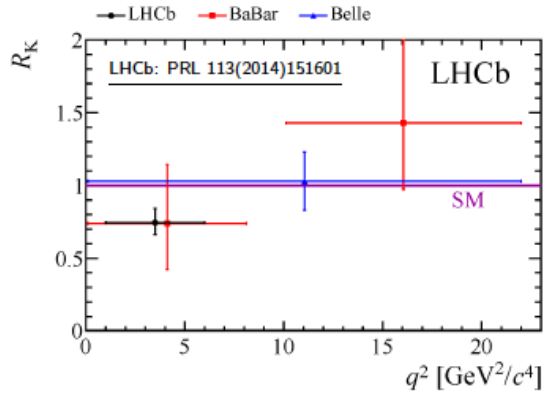

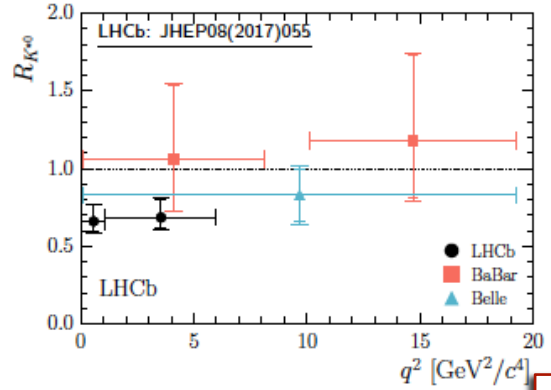

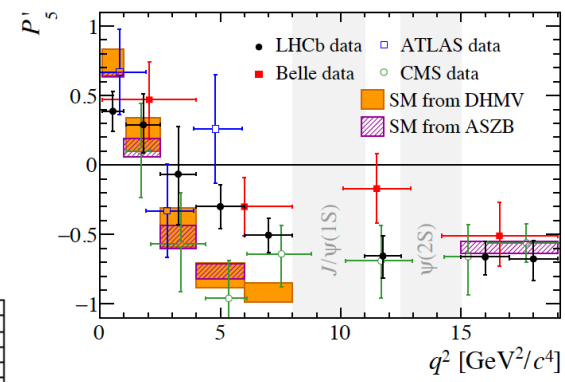

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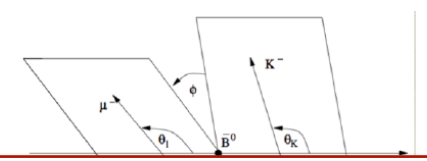

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see talk on Thursday afternoon by Ch. Langenbruch

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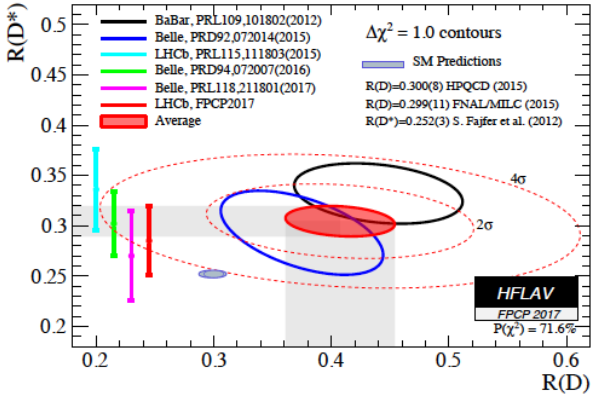

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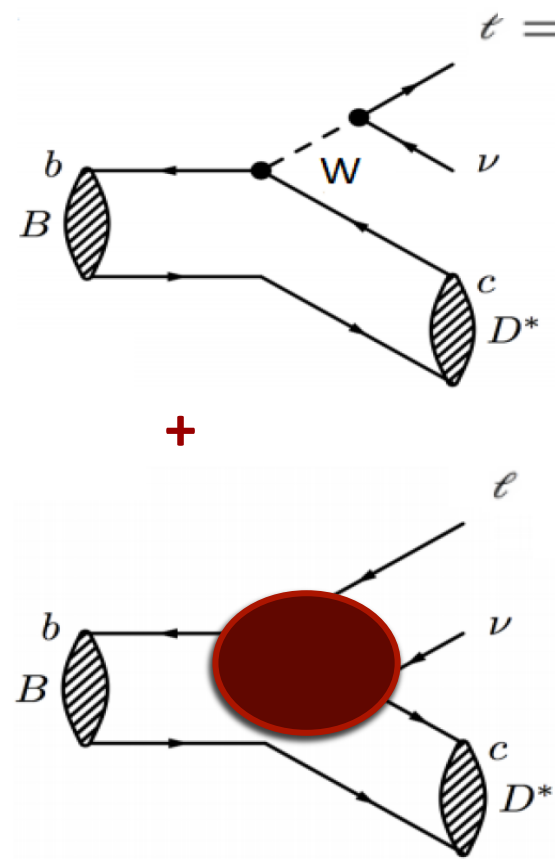

BSM ?

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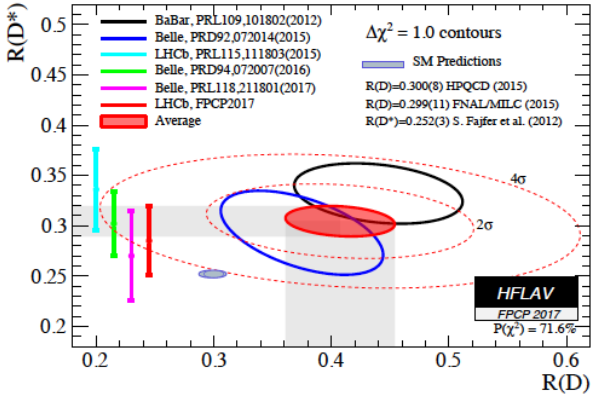

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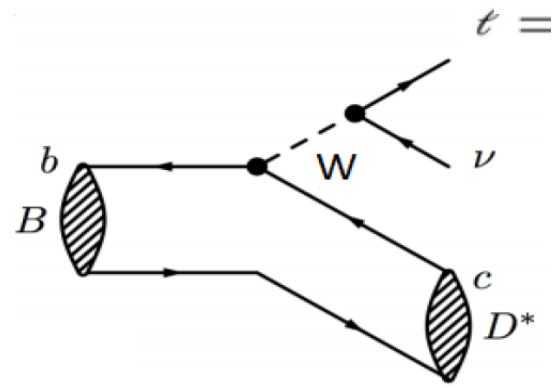

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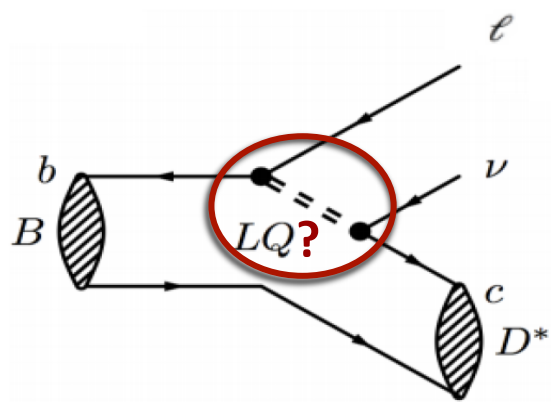
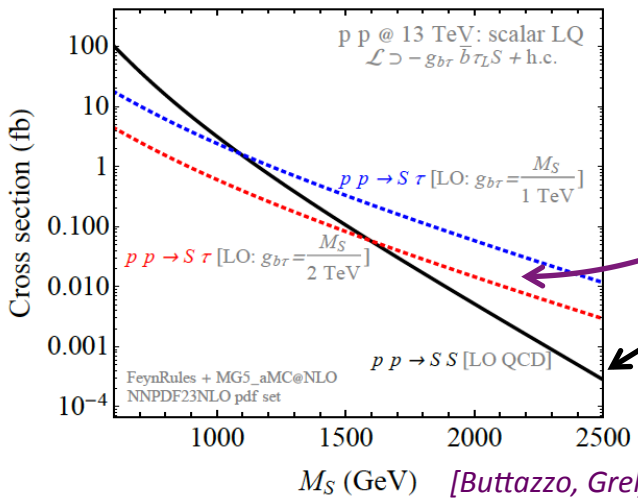


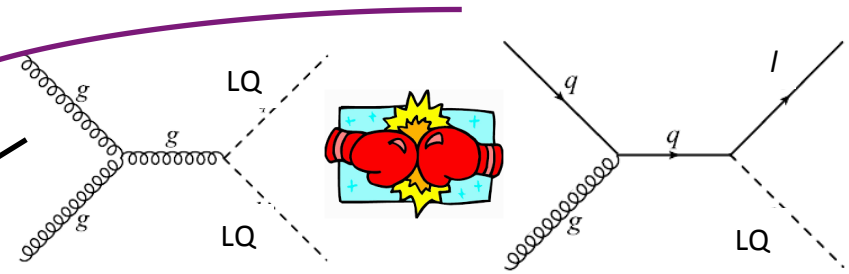
BSM ?

Leptoquarks

- Leptoquarks (LQ): colour-triplet bosons simultaneously coupling to leptons and quarks at tree level
- Naturally arising in GUT models, also appear in composite Higgs models, R-parity violating SUSY, …
- Under SM gauge group, six scalar and six vector multiplets --singlets, doublets or triplets of SU(2)
- Many analyses attempting to explain flavour anomalies with LQs *[…]* ; not a clear-cut case *[Buttazzo, Greljo, Isidori,Marzocca'17]*
- LQs can be produced directly at the LHC through pair- or single production -> complementarity!

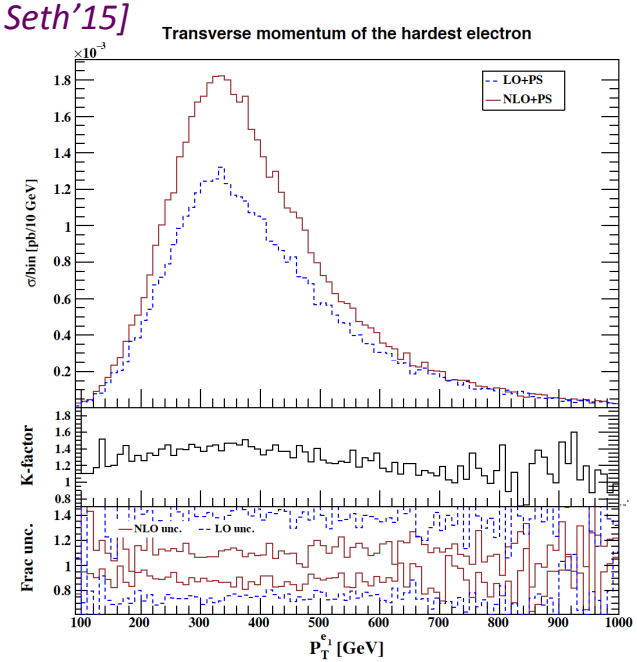


[Buttazzo, Greljo, Isidori,Marzocca'17]

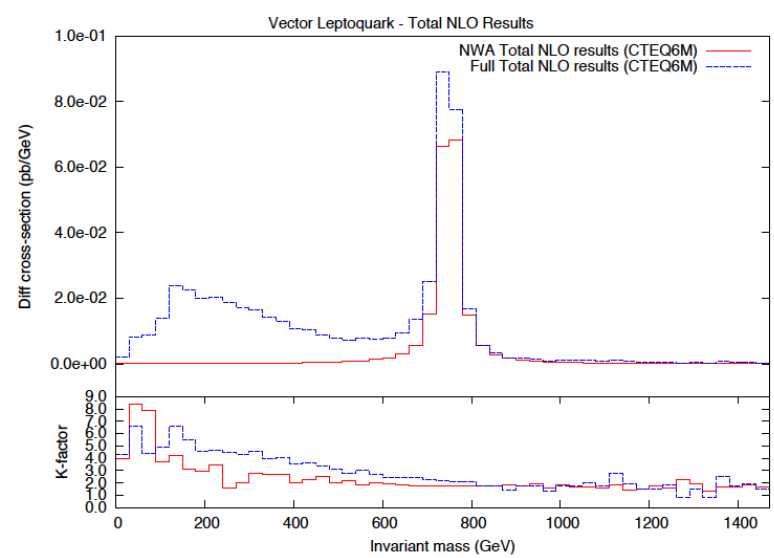


QCD for scalar LQs

- NLO corrections to scalar LQ pair-production *[Krämer, Plehn, Spira, Zerwas'04]* return subtantial K-factors
- K-factors for differential distributions only moderately vary*[Mandal, Mitra, Seth'15]*



- Single scalar production *[Dorsner, Greljo'18]* and single vector production *[Hammett, Ross'15]* known at NLO
- When LQ decay added, important effects from the non-factorizable contribution and qqbar channel opening up, NWA cannot be trusted!



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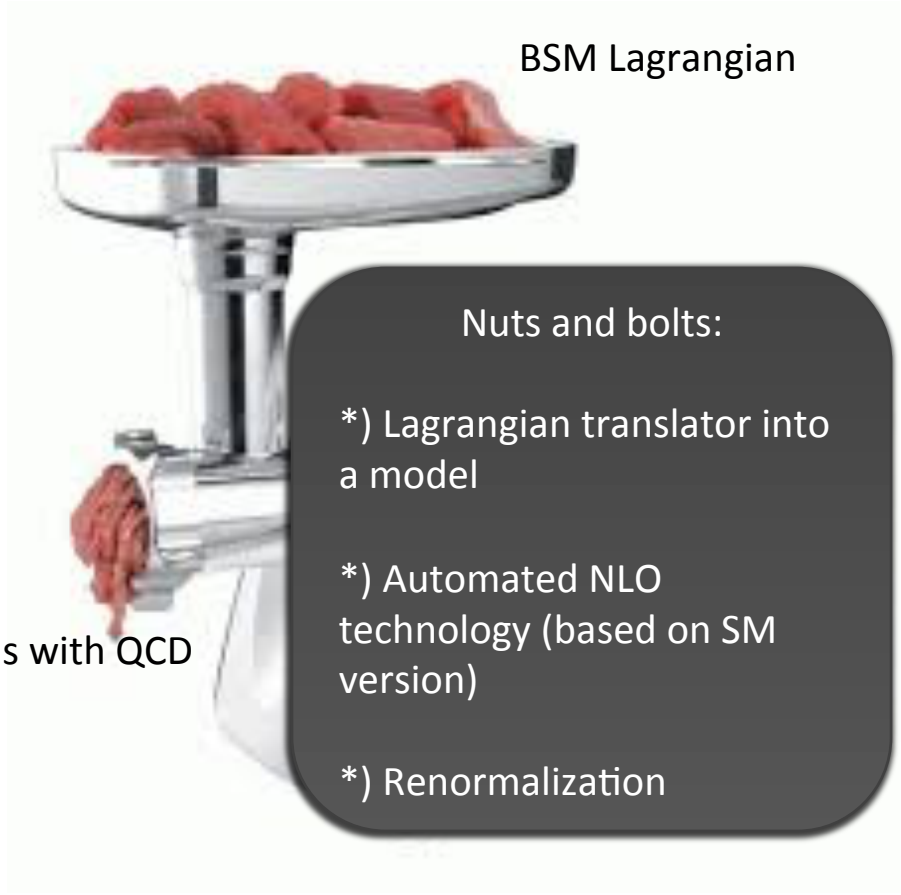

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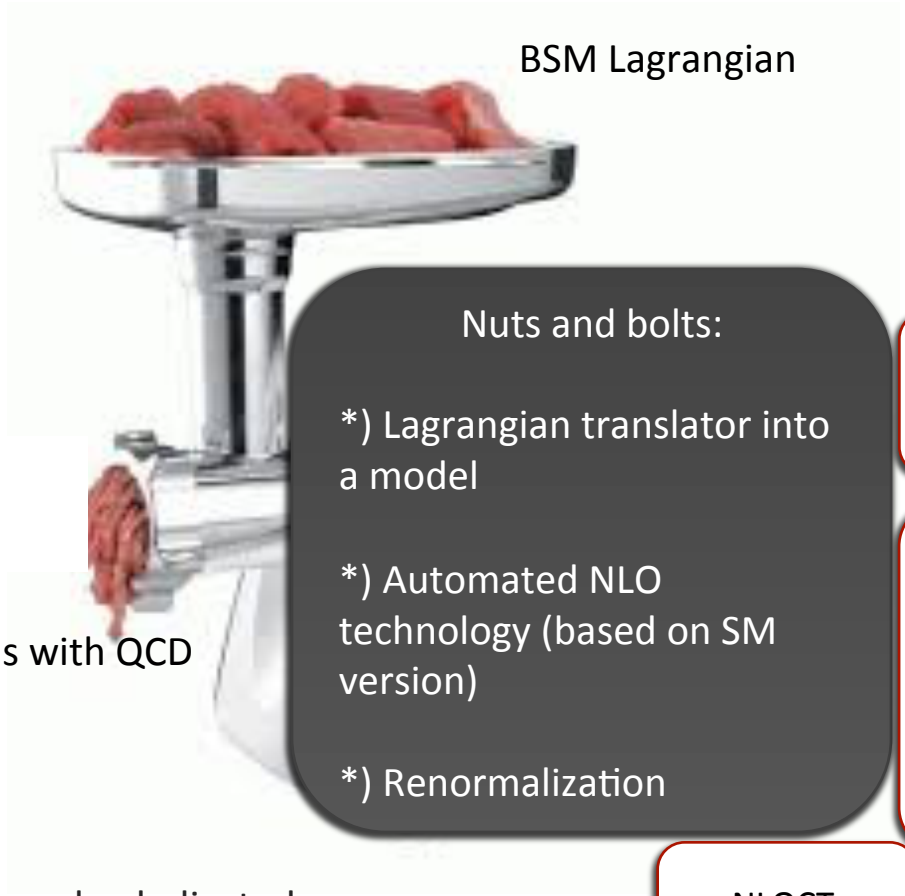
In short: very quick and promising progress!

BSM predictions with QCD corrections



FeynRules, SARAH,..

MadGraph5 _aMC@NLO, Recola2, OpenLoops, Gosam,..

NLOCT, Rept1l,..

*)Beyond NLO and resummation need a dedicated implementation : SusHi, vh@nnlo, NNLL-fast, ..

Summary

- Precision BSM predictions needed more than ever
- QCD corrections a very active field, many new results
- Need for precision in the EFT results very well recognized
- Analyses in EFTs, simplified models and complete-UV models are complementary – all avenues need to be explored
- Trickle down effect: advancements in the SM calculations get transferred to the BSM sector
- Recent progress in the NLO automation will allow to test a large range of BSM models / observables
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BACKUP

Soft gluon resummation

Systematic reorganization of perturbative series (x=1-β)

$$\hat{\sigma} \sim c_{00} + \alpha_s \left(c_{12} \log^2(\beta^2) + c_{11} \log(\beta^2) + c_{10} \right) \leftarrow \text{NLO}$$

$$+ \alpha_s^2 \left(c_{24} \log^4(\beta^2) + c_{23} \log^3(\beta^2) + c_{22} \log^2(\beta^2) + \dots \right) \leftarrow \text{NNLO}$$

$\alpha_s^n \log^{2n}(\beta^2)$ $\alpha_s^n \log^{2n-1}(\beta^2)$

$\log(\beta^2) \leftrightarrow \log(N) \equiv L$

Factorization at threshold: space of Melin moments N ,taken wrt. M^2/S or Q^2/S

$$\hat{\sigma}^{(N)} \sim \mathcal{C}(\alpha_s) \exp\left[L g_1(\alpha_s L) + g_2(\alpha_s L) + \alpha_s g_3(\alpha_s L) + \dots \right]$$

sums up LL: $\alpha_s^n \log^{n+1}(N)$ NLL: $\alpha_s^n \log^n(N)$

Higher Orders at Threshold

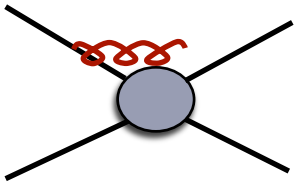
Large masses of SUSY particles ⇒ production close to threshold $\hat{s} \sim 4m^2$

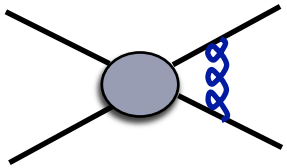
General structure of the NLO correction in the threshold limit $\beta \to 0, \quad \beta^2 = 1 - 4m^2/\hat{s}$

$$\Delta\hat{\sigma}_i^{\mathrm{NLO}} \sim \alpha_s\, \hat{\sigma}_i^{\mathrm{LO}} \left\{ A^{(i)} \log^2(\beta^2) + B^{(i)} \log(\beta^2) + C^{(i)} \frac{1}{\beta} + D^{(i)} \right\}$$

Soft/collinear gluon emission

Coulomb gluons





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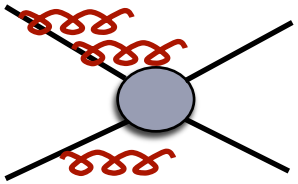

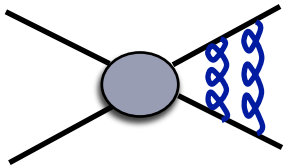

At higher orders:

$$\sim \alpha_s^n \log^{2n}(\beta) \qquad\qquad \sim \alpha_s^n / \beta^n$$

Both types of corrections can be resummed to all orders

Reaching Higher: NNLL

Long-term project, started in 2011…

$$\sigma^{\rm res} \sim \sigma_0 \otimes C(\alpha_s) \otimes \exp\left[L g_1(\alpha_s L) + g_2(\alpha_s L) + \alpha_s g_3(\alpha_s L) + \ldots\right]$$

LL : $\sim \sum_n \alpha_s^n L^{n+1}$

NLL : $\sim \sum_n \alpha_s^n L^n$

NNLL : $\sim \sum_n \alpha_s^n L^{n-1}$

$L = L(\text{threshold variable})$

known at NNLL

$$C(\alpha_s) = C^{\rm Coul}(\alpha_s) \otimes C^{\rm hard}(\alpha_s) = 1 + \alpha_s C^{\rm Coul}_{(1)} + \alpha_s C^{\rm hard}_{(1)} + \ldots$$

- For NNLL, hard matching coefficients $C^{\rm hard}$ need to be known up to $O(\alpha_s)$->
  ✔ *[Beenakker, Janssen, Lepoeter, Krämer, AK, Laenen, Niessen,Thewes, Van Dal'13]*
  [Broggio ,Ferroglia, Neubert, Vernazza, Yang'13]
- Coulomb corrections $C^{\rm Coul}$ at least up to $O(\alpha_s)$, better: $O(\alpha_s^2)$, even better: resummed to all orders