Theory – Collider Phenomenology.

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Deutsches Elektronen-Synchrotron

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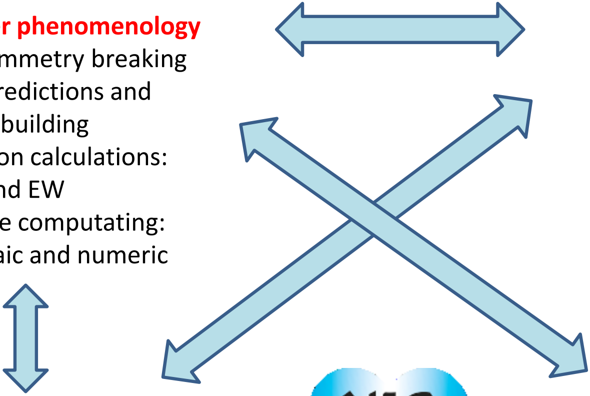
October 19, 2017

Theory Group Overview.



Today:

Collider phenomenology

e.w. symmetry breaking
BSM predictions and
model building
precision calculations:
QCD and EW
massive computating:
algebraic and numeric

Particle cosmology

dark matter
baryogenesis
phase transitions
hidden sectors
inflation
gravitational waves

String theory

dualities
strings on curved spacetimes
integrable systems
conformal field theory

NIC

John von Neumann
Institute for computing
DESY – Jülich - GSI

Lattice QCD

QCD parameters
flavour physics
hadron structure
algorithms

Particle Phenomenology.

Covering a broad spectrum

- Developments
  - Multiloop techniques and computer algebra
  - Factorization and resummation
  - Effective field theories
  - Monte-Carlo generators and algorithms
  - Global fits
- Applications to
  - Precision predictions: QCD, EW, BSM
  - Precision Higgs physics and EW symmetry breaking
  - Standard candles: Drell-Yan, top, jets
  - Dark matter
  - Flavor physics
- Close interactions with experimental groups (ATLAS, CMS, ILC, Belle2)
  - Common studies
  - Developments at experiment-theory interface
  - Tools for wider (exp. and theory) HEP community

⇒ In the following only a selection of recent results

3-Loop Anomalous Dimensions.

J. Blümlein et al.:

$$
\begin{aligned}
\gamma_{qg}^{(2)} = \;& C_A N_F^2 T_F^2 \Bigg\{ -\frac{5N^2+8N+10}{N(N+1)(N+2)} \frac{128}{9} S_{-2} - \frac{64 P_8}{9N(N+1)^2(N+2)^2} S_1^2 \\
& - \frac{64 P_9}{9N(N+1)^2(N+2)^2} S_2 + \frac{64 P_{25}}{27N(N+1)^3(N+2)^3} S_1 + \frac{16 P_{34}}{27(N-1)N^4(N+1)^4(N+2)^4} \\
& + p_{qg}^{(0)}(N) \left(\frac{32}{9} S_1^3 - \frac{32}{3} S_1 S_2 + \frac{64}{9} S_3 + \frac{128}{3} S_{-3} + \frac{128}{3} S_{2,1} \right) \Bigg\} \\
& + C_F N_F^2 T_F^2 \Bigg\{ \frac{5N^2+3N+2}{N^2(N+1)(N+2)} \frac{32}{3} S_2 + \frac{10N^3+13N^2+29N+6}{N^2(N+1)(N+2)} \frac{32}{9} S_1^2 \\
& - \frac{32 P_{12}}{27N^2(N+1)^2(N+2)} S_1 + \frac{4 P_{38}}{27(N-1)N^5(N+1)^5(N+2)^4} \\
& + p_{qg}^{(0)}(N) \left(-\frac{32}{9} S_1^3 - \frac{32}{3} S_1 S_2 + \frac{320}{9} S_3 \right) \Bigg\} \\
& + C_A C_F N_F T_F \Bigg\{ -128 \frac{N^3-7N^2-6N+4}{N^2(N+1)^2(N+2)} S_{-2,1} + \frac{32 P_5}{N^2(N+1)^2(N+2)} S_{-3} \\
& + \frac{16 P_{18}}{9(N-1)N^2(N+1)^2(N+2)^2} S_1^3 - \frac{16 P_{24}}{9(N-1)N^2(N+1)^2(N+2)^2} S_3 \\
& - \frac{8 P_{27}}{9(N-1)N^3(N+1)^3(N+2)^2} S_1^2 + \frac{8 P_{29}}{3(N-1)N^3(N+1)^3(N+2)^3} S_2 \\
& + \frac{P_{37}}{27(N-1)N^5(N+1)^5(N+2)^4} + p_{qg}^{(0)}(N) \Bigg[\left(\frac{640}{3} S_3 - 384 S_{2,1} \right) S_1 + \frac{32}{3} S_1^4 \\
& + 160 S_1^2 S_2 - 64 S_2^2 + \left(192 S_1^2 + 64 S_2 \right) S_{-2} + 96 S_{-2}^2 + 224 S_{-4} - 64 S_{2,-2} + 64 S_{3,1} \\
& + 192 S_{2,1,1} - 256 S_{-2,1,1} - 192 S_1 \zeta_3 \Bigg] - \frac{192 P_{17}}{(N-1)N^2(N+1)^2(N+2)^2} \zeta_3 \\
& + \left(\frac{16 P_{16}}{3(N-1)N^2(N+1)^2(N+2)^2} S_2 + \frac{16 P_{35}}{27(N-1)N^4(N+1)^4(N+2)^4} \right) S_1 \\
& + \left[-\frac{32 P_{15}}{N^3(N+1)^3(N+2)} + \frac{128 \left(N^3 - 13N^2 - 14N - 2 \right)}{N^2(N+1)^2(N+2)} S_1 \right] S_{-2} \\
& + \frac{96 N(N+1) p_{qg}^{(0)}(N)^2}{N-1} S_{2,1} \Bigg\}
\end{aligned}
$$

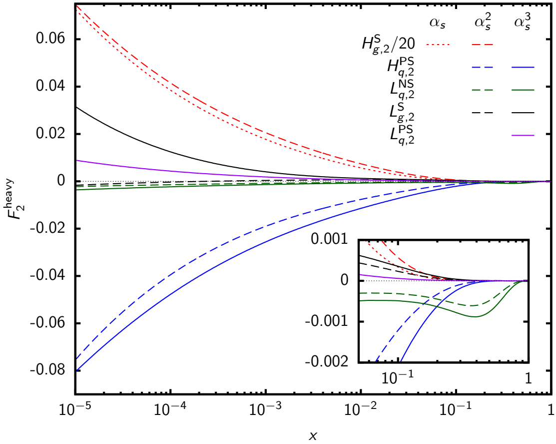
$$
\begin{aligned}
& + C_A^2 N_F T_F \Bigg\{ -\frac{64 P_{11}}{(N-1)N^2(N+1)^2(N+2)^2} S_{-2,1} - \frac{16 P_{20}}{9(N-1)N^2(N+1)^2(N+2)^2} S_3 \\
& - \frac{32 P_{21}}{3(N-1)N^2(N+1)^2(N+2)^2} S_{-3} - \frac{8 P_{22}}{9(N-1)N^2(N+1)^2(N+2)^2} S_1^3 \\
& + \frac{16 P_{32}}{9(N-1)^2 N^3(N+1)^3(N+2)^3} S_1^2 + \frac{16 P_{33}}{9(N-1)^2 N^3(N+1)^3(N+2)^3} S_2 \\
& - \frac{8 P_{39}}{27(N-1)^2 N^5(N+1)^5(N+2)^5} + p_{qg}^{(0)}(N) \Bigg[-\frac{32 P_{10}}{3(N-1)N(N+1)(N+2)} S_{2,1} \\
& + \left(-\frac{704}{3} S_3 + 128 S_{2,1} + 512 S_{-2,1} \right) S_1 - 512 S_{-3} S_1 - \frac{16}{3} S_1^4 - 160 S_1^2 S_2 - 16 S_2^2 - 32 S_4 \\
& + \left(-192 S_1^2 + 320 S_2 \right) S_{-2} - 96 S_{-2}^2 + 96 S_{-4} - 448 S_{2,-2} - 128 S_{3,1} + 512 S_{-3,1} \\
& - 768 S_{-2,1,1} + 192 S_1 \zeta_3 \Bigg] + \frac{96(N-2)(N+3) P_4}{(N-1)N^2(N+1)^2(N+2)^2} \zeta_3 \\
& + \left(\frac{8 P_{19}}{3(N-1)N^2(N+1)^2(N+2)^2} S_2 - \frac{8 P_{36}}{27(N-1)^2 N^4(N+1)^4(N+2)^4} \right) S_1 \\
& + \left(-\frac{64 P_{13}}{(N-1)N^2(N+1)^2(N+2)^2} S_1 + \frac{32 P_{30}}{9(N-1)N^3(N+1)^3(N+2)^3} \right) S_{-2} \Bigg\} \\
& + C_F^2 N_F T_F \Bigg\{ \frac{P_{31}}{N^5(N+1)^5(N+2)} - \frac{8 P_3}{3N^2(N+1)^2(N+2)} S_1^3 - \frac{16 P_6}{3N^2(N+1)^2(N+2)} S_3 \\
& + \frac{64 P_{14}}{N^3(N+1)^2(N+2)} S_{-2} - \frac{8 P_{23}}{N^3(N+1)^3(N+2)} S_1^2 + \frac{8 P_{26}}{N^3(N+1)^3(N+2)} S_2 \\
& + p_{qg}^{(0)}(N) \Bigg[\left(-\frac{704}{3} S_3 + 256 S_{2,1} \right) S_1 - 256 S_{-3} S_1 - \frac{16}{3} S_1^4 - 48 S_2^2 - 160 S_4 - 64 S_{-2}^2 \\
& - 192 S_{-4} - \frac{128}{N(N+1)} S_{2,1} - 128 S_{2,-2} + 64 S_{3,1} + 256 S_{-3,1} - 192 S_{2,1,1} \Bigg] \\
& + \frac{96(N-1)\left(3N^2+3N-2\right)}{N^2(N+1)^2} \zeta_3 - 256 \frac{2-N+N^2}{N^2(N+1)(N+2)} \left[S_{-2} S_1 - S_{-2,1} \right] \\
& + \left(-\frac{8 P_{28}}{N^4(N+1)^4(N+2)} - \frac{8 P_7}{N^2(N+1)^2(N+2)} S_2 \right) S_1 - \frac{128(N-1)}{(N+1)^2(N+2)} S_{-3} \Bigg\},
\end{aligned}
$$

Completed the calculation of all contributing 3-loop anomalous dimensions. Here, $\gamma_{qq}^{(2),\mathrm{PS}}$ and $\gamma_{qg}^{(2)}$ are complete; the others are $\propto T_F$.

First confirmation of the results of Moch, Vermaseren, Vogt, 2004.

Charm NC Corrections to $F_2(x, Q^2)$ to 3 Loops.

J. Blümlein et al.:



$Q^2 = 100\mathrm{GeV}^2$ [$H_{g,2}^S$ scaled down by a factor 20.] We have calculated 18 of 28 color and ζ-factors of $A_{Qg}^{(3)}$, as well as 2000 moments analytically. (MATAD, 2009: $N \leq 10$).

Iterative Non-Iterative Integrals.

J. Blümlein et al.:

A New Class of Integrals in QFT:

$$\begin{aligned}
\mathbb{H}_{a_1,\ldots,a_{m-1};\{a_m;F_m(r(y_m))\},a_{m+1},\ldots,a_q}(x) &= \int_0^x dy_1 f_{a_1}(y_1) \int_0^{y_1} dy_2 \ldots \int_0^{y_{m-1}} dy_m f_{a_m}(y_m) \\
&\quad \times F_m[r(y_m)] H_{a_{m+1},\ldots,a_q}(y_{m+1}), \\
F[r(y)] &= \int_0^1 dz g(z, r(y)), \quad r(y) \in \mathbb{Q}[y],
\end{aligned}$$

In general, this spans all solutions and the story would end here.
May be, most of the practical physicists, would led it end here anyway.
This type of solution applies to many more cases beyond ${}_2F_1$-solutions (if being properly generalized).
Elliptic Integrals form the simplest representants. The above structure is the general one in massive analytic calculations.

Muon Anomalous Magnetic Moment.

P. Marquard et al.:

Completed the calculation of all pure QED contributions to the muon magnetic moment at four loops ⇒ full agreement

Comparing [Kurz,PM,Steinhauser,Smirnov,Smirnov,Wellmann '15-'17] with [Kinoshita] and [Laporta]

$$\begin{array}{lllll} & \text{universal} & e^{-} & \tau & e^{-}+\tau \\ a_\mu^{(8)} = & -1.87(12) & +132.86(48) & +0.0424941(53) & +0.062722(10) \\ a_\mu^{(8)} = & -1.912\,98(84) & +132.6852(60) & +0.04234(12) & +0.06272(4) \\ a_\mu^{(8)} = & -1.9122457649264\ldots & & & \end{array}$$

After multiplication with $(\alpha/\pi)^4$ we obtain $(\times 10^{-11})$

$$\begin{array}{lllll} (-5.44(35) & +386.77(1.40) & +0.12371(15) & +0.182592(29)) \\ (-5.56894(245) & +386.264(17) & +0.12326(35) & +0.18259(12)) \\ (-5.56679893738506\ldots+\ldots) & & & \end{array}$$

On-shell Renormalization of QCD at 4 Loops.

P. Marquard et al.:

Completed the on-shell renormalization of QCD at four loops

$$
\begin{aligned}
z_m^{(4)} &= -3654.15 \pm 1.64 + (756.942 \pm 0.040) n_l \\
&\quad -43.4824 n_l^2 + 0.678141 n_l^3 \,.
\end{aligned}
$$

for the top quark the results in

$$
\begin{aligned}
m_t(m_t) &= M_t \left(1 - 0.4244\,\alpha_s - 0.9246\,\alpha_s^2 - 2.593\,\alpha_s^3 - (8.949 \pm 0.018)\,\alpha_s^4\right) \\
&= 173.34 - 7.924 - 1.859 - 0.562 - (0.209 \pm 0.0004)\ \text{GeV}
\end{aligned}
$$

[PM,Smirnov,Smirnov,Steinhauser,Wellmann '16-'17]

The publication for Z_2^{OS} @ four loops is in preparation.
For the 5+ loop loop contribution we find including light quark mass effects

$$
\begin{aligned}
\delta^{(5+)} &= 0.304^{+0.012}_{-0.063}\,(N) \pm 0.030\,(m_{b,c}) \\
&\quad \pm 0.009\,(\alpha_s) \pm 0.108\ (\text{ambiguity})\ \text{GeV}\,,
\end{aligned}
$$

[Beneke,PM,Nason,Steinhauser '16-'17]

5-Loop $\overline{\mathrm{MS}}$ Renormalization of QCD.

P. Marquard et al.:

Completed the calculation of all ren. consts. @ five loops for a general gauge group

[Luthe,Maier,PM,Schröder '16-'17]

- β function, gauge independent, confirmation of the result of [Herzog et al '17] using an independent method
- γ_m, gauge independent
- $\gamma_2, \gamma_{3c}, \gamma_1^{ccg}$, gauge dependent, calculated up to linear term in the gauge parameter

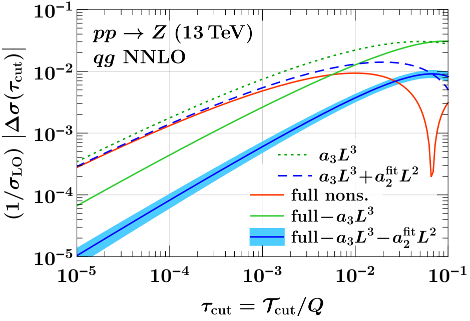
⇒ all 5-loop ren. const. available for a general gauge group and linear gauge parameter dependence.
Full agreement with $N_c = 3$ Feynman gauge results by [Baikov et al '16]

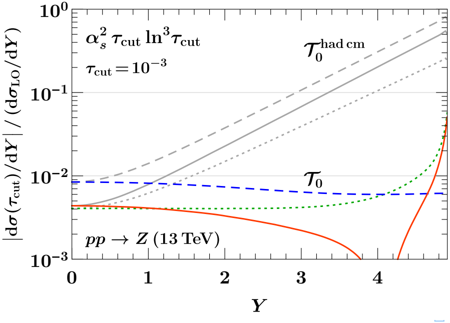
Power Corrections for N-Jettiness Subtractions.

[Moult, Rothen, Stewart, FT, Zhu ’16, ’17]

$$\sigma = \underbrace{\sigma^{\mathrm{sub}}(\tau_{\mathrm{cut}})}_{\text{NNLO}_N} + \underbrace{\int_{\tau_{\mathrm{cut}}} \mathrm{d}\tau_N \frac{\mathrm{d}\sigma}{\mathrm{d}\tau_N}}_{\text{NLO}_{N+1}} + \underbrace{\sigma(\tau_{\mathrm{cut}}) - \sigma^{\mathrm{sub}}(\tau_{\mathrm{cut}})}_{\text{neglect } \mathcal{O}(\tau_{\mathrm{cut}})}$$

- Analytical computation of LL and numerical extraction of NLL power corrections for Drell-Yan-like processes in all partonic channels
  - Improves performance of subtractions by order of magnitude
- Correct definition of τ_N is crucial for stable power expansion across phase space

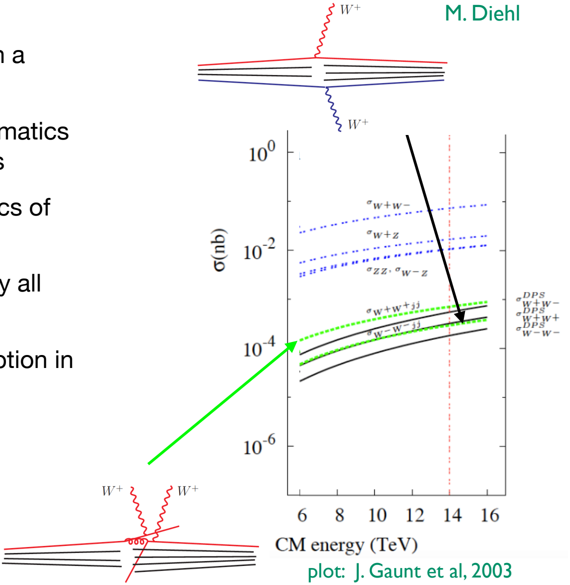




Multiparton Interactions.

- several partons interact in a single pp collision
- important in specific kinematics and/or specific processes
- closely related with physics of underlying event
- relevant measurements by all LHC collaborations
- challenge: reliable description in QCD

example: WW production
both for precision
  ($W^+ W^- \to$ triple gauge couplings)
and as background for searches
  ($W^+ W^+ \to$ same sign leptons)

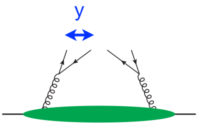


M. Diehl

plot: J. Gaunt et al, 2003

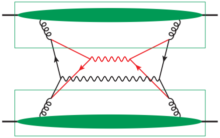
Multiparton Interactions.

- input for theory description: two-parton distributions
- at small transverse distance y between partons: compute from splitting 1 → 2 partons

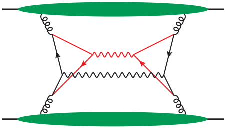


  - ✦ gives singular cross section: $\int d^2y \, / \, y^4$
    - ➡ physics not right

- double counting problem:
  - ✦ double scattering with perturbative splitting



  - ✦ loop correction to single scattering

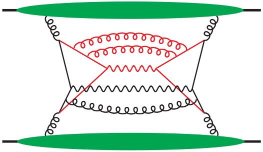


- developed scheme to regularise double parton scattering and to consistently add to single scattering part

Multiparton Interactions: Resummation.

- double scattering part permits all-order resummation of DGLAP type logarithms
  first numerical studies:
  can be important in parts of phase space

  M. Diehl , J. Gaunt, K. Schönwald 2017



Further investigations

- resummation of Sudakov logarithms
  developed theory formalism, numerical studies to follow
  - colour correlations between two partons in one proton
    suppressed at high scales, but may be important for multiple interactions/underlying event kinematics
  - transverse-momentum spectrum

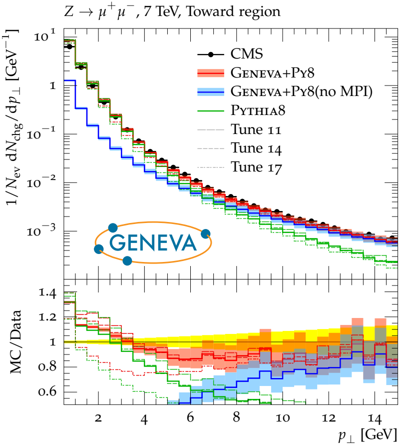
M. Buffing, M. Diehl , T. Kasemets 2017

GENEVA: Drell-Yan at NNLO+NNLL′+PS+MPI.

[Alioli, Bauer, FT, ..., ’15-’17]

First matching of NNLO+NNLL′ with parton shower, hadronization and MPI

- Based on (differential) N-jettiness subtractions and NNLL′ resummation
- 1st public release (1.0-rc1) in May 2017
- ATLAS and CMS are starting to integrate it into their computing frameworks



Development of underlying SCET framework toward higher-order multi-differential (joint/multi-scale) resummation

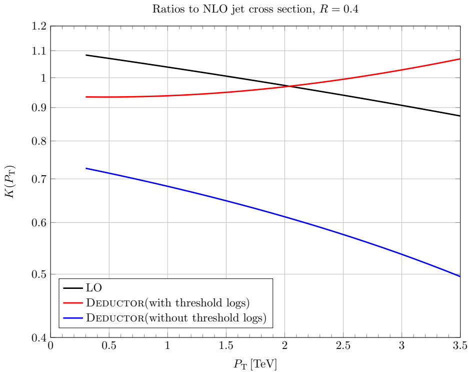
- Finite quark-mass effects [Samitz, Pietrulewicz, FT ’17]
- Rapidity-dependent resummation [Kulesza, Michel, FT ’17]
- Multidifferential resummation [Lustermans, Michel, FT, Waalewijn ’17]

DEDUCTOR: Threshold Resummation in PS.

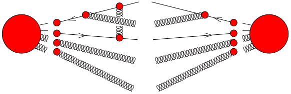
We want to sum up large logarithms in a observable independent way. To do this we have to reorganize the N^{k}LO calculation in such a way that can be interpreted as parton shower cross section.

[Nagy, Soper, '16, '17]

$$\sigma[J] = \big(1\big|\mathcal{O}_J \overbrace{\mathcal{U}(\mu_\mathrm{f}^2,\mu_\mathrm{H}^2)}^{\substack{\text{- Sums up "visible" large logarithms}\\ \text{- Adds new partons}}} \underbrace{\mathcal{U}_{\mathcal{V}}(\mu_\mathrm{f}^2,\mu_\mathrm{H}^2)}_{\substack{\text{- Sums up threshold logarithms}\\ \text{- Doesn't add new partons}}} \overbrace{\mathcal{F}(\mu_\mathrm{H}^2)\mathcal{D}^{-1}(\mu_\mathrm{H}^2)\big|\rho(\mu_\mathrm{H}^2)\big)}^{\text{Hard part, finite in d=4.}} + \mathcal{O}(\alpha_\mathrm{s}^{k+1}) + \mathcal{O}(\mu_\mathrm{f}^2/Q[J]^2)$$



IR sensitive operator describes the IR behaviour of the QCD density operator. It is an universal operator and defined order by order in the perturbation theory.



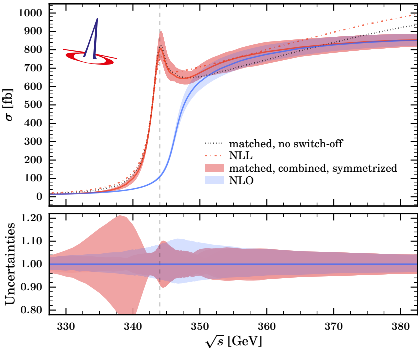
$$\mathcal{D}(\mu^2) = 1 + \sum_{n=1}^{k}\left[\frac{\alpha_\mathrm{s}(\mu^2)}{2\pi}\right]^n \mathcal{D}^{(n)}(\mu^2) + \mathcal{O}(\alpha_\mathrm{s}^{k+1})$$

- Parton shower calculations can be defined systematically from first principles and improved by working to higher order in the perturbation theory.
  - Beyond the leading order the parton shower evolution is much more complex than a DGLAP evolution.
- Matching to exact matrix elements is part of the definition and doesn't requires extra procedure.

WHIZARD: Precision Top Physics at Lepton Colliders.

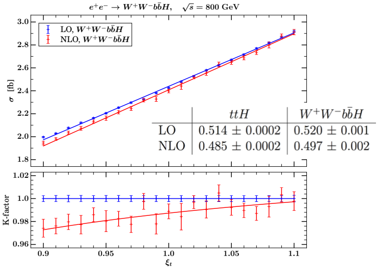
[Chokoufé/Kilian/Lindert/Reuter/Pozzorini/Weiss, 2016]
[Bach/Chokoufe/Hoang/Kilian/Reuter/
Stahlhofen/Teubner/Weiss 2017]

- Completely off-shell leptonic NLO QCD processes:
  $e^+e^- \to l\nu l\nu bb + X$, $e^+e^- \to l\nu l\nu bbH + X$
- WHIZARD framework for automated NLO QCD
- Fully exclusive top threshold description
- Matching of NLO QCD with NLL vNRQCD
  threshold resummation

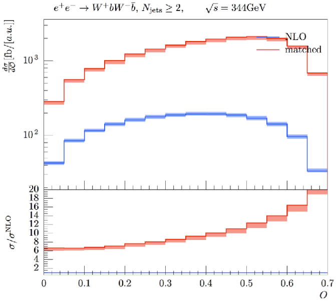


Top threshold matched: $ee \to WbWb$
Energy scan and beam thrust distribution

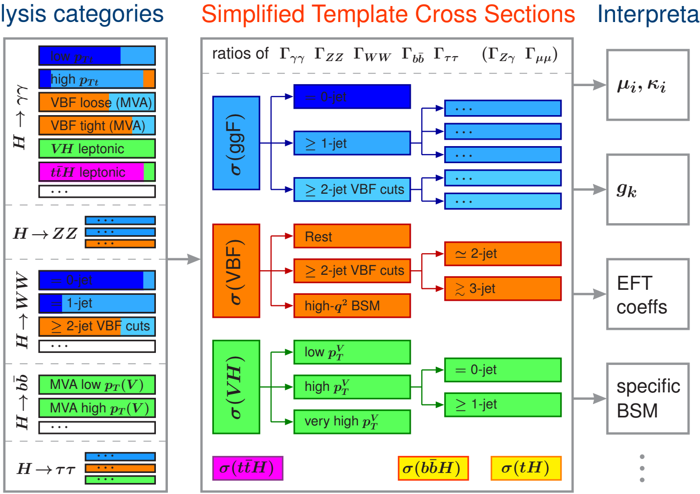
Determination of top Yukawa coupling (*ttH*)



	ttH	$W^+W^-b\bar{b}H$
LO	0.514 ± 0.0002	0.520 ± 0.001
NLO	0.485 ± 0.0002	0.497 ± 0.002



Higgs Simplified Template Cross Section Framework.



Analysis categories

- $H \to \gamma\gamma$
  - low p_{Tt}
  - high p_{Tt}
  - VBF loose (MVA)
  - VBF tight (MVA)
  - VH leptonic
  - $t\bar{t}H$ leptonic
  - $\cdots$
- $H \to ZZ$
  - $\cdots$
  - $\cdots$
  - $\cdots$
- $H \to WW$
  - = 0-jet
  - = 1-jet
  - $\geq$ 2-jet VBF cuts
  - $\cdots$
- $H \to b\bar{b}$
  - MVA low $p_T(V)$
  - MVA high $p_T(V)$
  - $\cdots$
- $H \to \tau\tau$
  - $\cdots$
  - $\cdots$
  - $\cdots$

Simplified Template Cross Sections

ratios of $\Gamma_{\gamma\gamma}$ Γ_{ZZ} Γ_{WW} $\Gamma_{b\bar{b}}$ $\Gamma_{\tau\tau}$ $(\Gamma_{Z\gamma}$ $\Gamma_{\mu\mu})$

- σ(ggF)
  - = 0-jet
  - $\geq$ 1-jet
    - $\cdots$
    - $\cdots$
    - $\cdots$
  - $\geq$ 2-jet VBF cuts
    - $\cdots$
    - $\cdots$
- σ(VBF)
  - Rest
  - $\geq$ 2-jet VBF cuts
    - $\simeq$ 2-jet
    - $\gtrsim$ 3-jet
  - high-q^2 BSM
- $\sigma(VH)$
  - low p_T^V
  - high p_T^V
    - = 0-jet
    - $\geq$ 1-jet
  - very high p_T^V
- $\sigma(t\bar{t}H)$
- $\sigma(b\bar{b}H)$
- $\sigma(tH)$

Interpretation

- μ_i, κ_i
- g_k
- EFT coeffs
- specific BSM
- $\vdots$

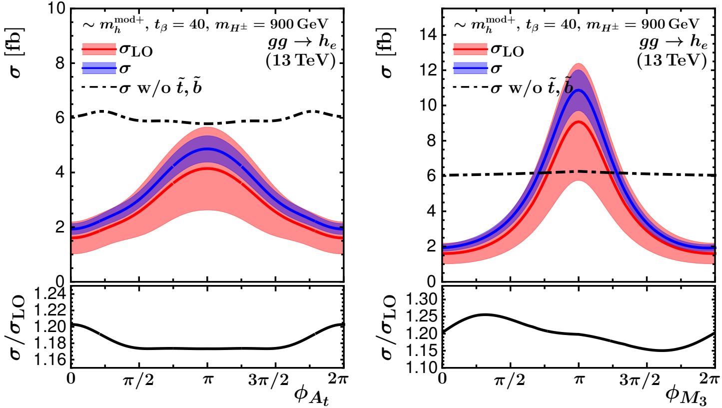
Developed in close collaboration with experiment [FT, K. Tackmann, ...]

- Going to be used for Higgs measurements and combination by ATLAS & CMS
  - Reduce theory dependence folded into measurements
  - Allow flexible reinterpretation in different scenarios (SM, BSM, EFT, ...)

Gluon-Fusion Higgs Production in the MSSM: Incorporation of CP-violating Effects.

SusHiMi code: *[S. Liebler, S. Patel, G. Weiglein '16]*

gg → h_2 / h_3, phase dependence for dominantly CP-even state "h_e":



Significant reduction of theoretical uncertainty w.r.t. leading-order (LO) result

The interference between the two nearly mass-degenerate heavy Higgs bosons yields an important contribution to the full result for σ x BR

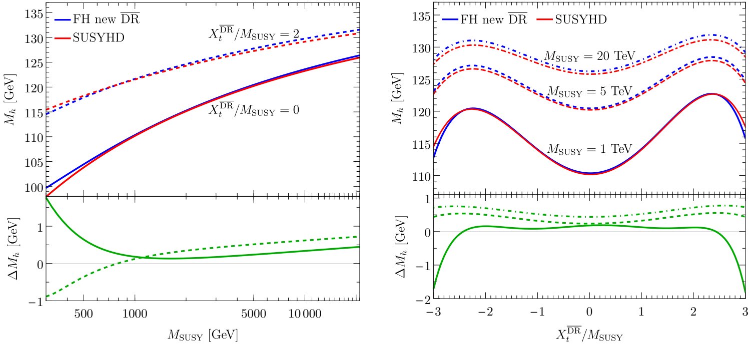
Higgs-mass Predictions in SUSY Models: Effects of Heavy SUSY Particles.

"Hybrid" approach: combination of fixed-order result with resummation of higher-order logarithmic contributions via effective field theory (EFT)

[H. Bahl, S. Heinemeyer, W. Hollik, G. Weiglein'17]

Predictions of hybrid (*FeynHiggs*) and EFT (*SUSYHD*) approach:

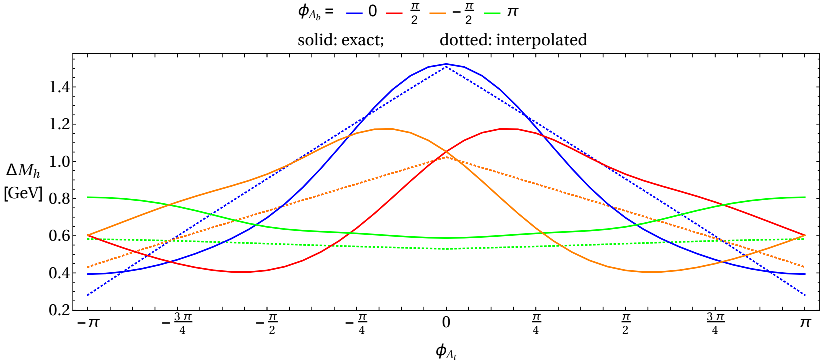
Simplest case: single-scale scenario, where all SUSY mass parameters are equal to each other: $M_{\text{soft}} = \mu = M_A \equiv M_{\text{SUSY}}$



⇒ Good agreement for high SUSY scale; hybrid approach yields precise predictions also at low scale

Two-loop $\mathcal{O}(\alpha_t\alpha_b + \alpha_b^2)$ Corrections for the General Case of Complex Parameters (CP Violation).

Mass shift induced by the new contributions; dependence on the phases of the parameters A_t and A_b in comparison with the previous result based on an interpolation of the phases: *[S. Passehr, G. Weiglein'17]*



⇒ Significant effect of the phase variation at the two-loop level

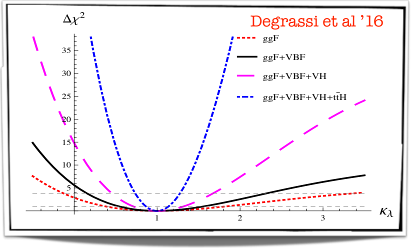
Higgs Self-Interaction Through NLO Effects.

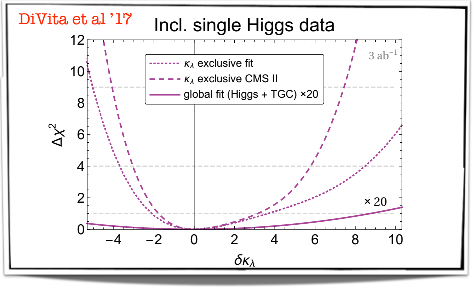
Di Vita, Grojean, Panico, Riembau, Vantalon '17

Higgs self-interactions were thought to be accessed in double Higgs processes only

Following an original proposal from 2015 by McCullough for e^+e^- colliders, two groups last year suggested that h^3 coupling could be constrained at LHC by precise measurements of single Higgs processes through their dependence on h^3 @ NLO

Exclusive fit (h3 coupling only)





$$\kappa_\lambda \in [-0.7, 4.2]$$

No bound from global fit

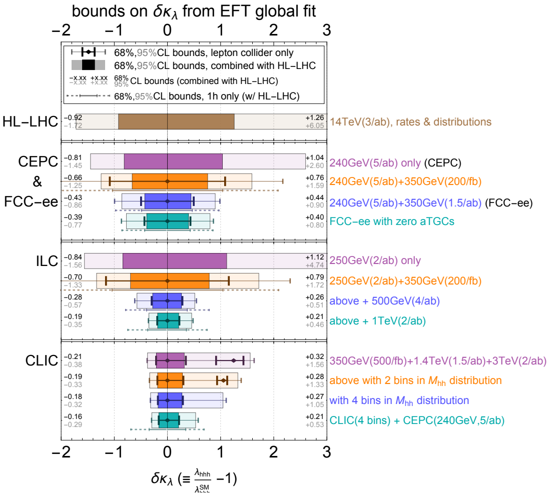
A global fit concludes in an almost flat direction, the h3 coupling cannot be resolved individually through inclusive measurements. Differential data could help lifting this degeneracy.

h^3 at e^+e^- Colliders.

Di Vita, Durieux, Grojean, Gu, Liu, Panico, Riembau, Vantalon '17

More Higgs decay modes can be reconstructed at e^+e^- colliders

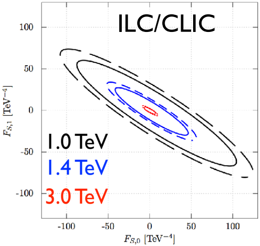
More observables ⇒ no flat direction anymore



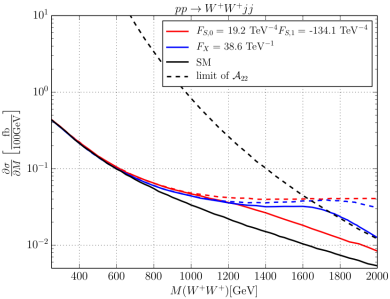
New Physics in Vector-Boson Scattering at the LHC.

[Kilian/Ohl/Reuter/Sekulla, 2015-2016]
[Fleper/Kilian/Reuter/Sekulla, 2016-2017]

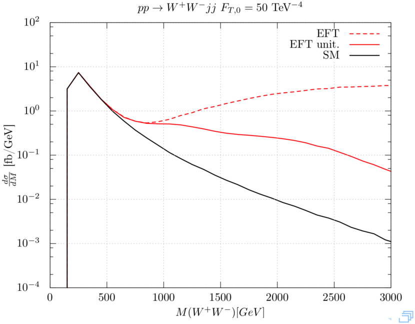
- Assessment of unitarity bounds on dim-6/dim-8 operators
- Simplified models for new electroweak resonances
- Derivation of unitarized limits: used by ATLAS
- Future collides: e.g. high-energy lepton colliders [CLIC]



LHC: Tensor resonances in longitudinal *W*/*Z*



LHC: transversal *W*/*Z* (EFT/dim-8)

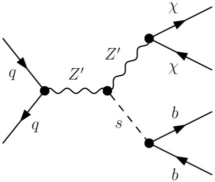


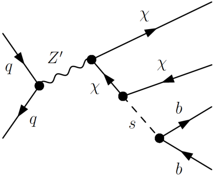
Hunting the Dark Higgs.

[Duerr, Grohsjean, Kahlhoefer, Penning, Schmidt-Hoberg, Schwanenberger ’17]

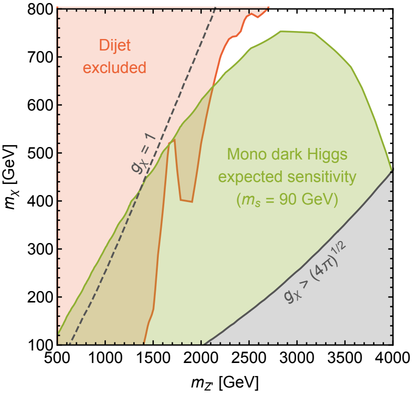
Simplified dark matter models used by LHC experiments for DM studies

- Typically feature one dark matter and one mediator particle
- For vector mediator with axial couplings also requires a “dark Higgs” s





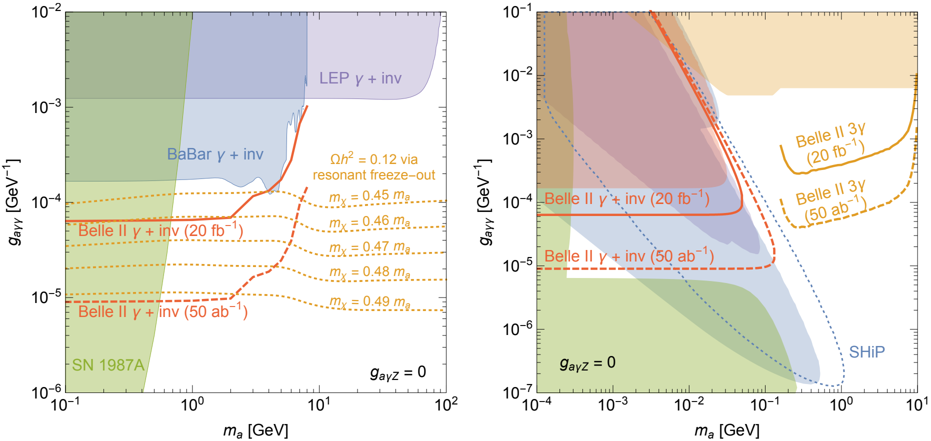
  - Decays via mixing with the SM Higgs primarily to $b\bar{b}$
  - Signal is fat $b\bar{b}$ jet with invariant mass corresponding to the dark Higgs



- Probe large regions of parameter space that are inaccessible to conventional mono-jet or di-jet searches

Belle II Sensitivity for Axion-like Particles (ALP).

[Dolan, Ferber, Hearty, Kahlhoefer, Schmidt-Hoberg ’17]



ALPs coupling only to photons are an interesting possibility

- In the MeV-GeV range could play the role of the mediator to dark matter
- Both visible and invisible decays are possible

⇒ Detailed calculation of the expected sensitivity of Belle II for both cases

Summary and Outlook.

Theory group is very active and visible

- Many new and important results

  (with many more I could not show ...)

Making maximal use of current and coming collider data

- Being able to cover a broad and complementary range of topics is key
- Strong connections with cosmology, string, and lattice
- Direct interactions with experimental groups at DESY are essential

Thanks for your attention!