QCD & High Energy Interactions

Theory Summary

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University at Buffalo

54th Recontres de Moriond, La Thuile, Italy
30 March 2019
Theory -> Prediction -> Measurement -> Discovery
Predicting flavor observables BSM

\[ \mathcal{L}_{BSM} \]

**BSM dynamics**

\[ \mathcal{L}_{SM} + \sum_{d > 4} \frac{Q_i^{(d)}}{\Lambda^{d-4}} \]

**Weak scale operators**

\[ \mathcal{L}_{eff}^{weak} \sim G_F \sum_c c_i Q_i + \mathcal{L}_{QCD+QED} \]

**Non-perturbative matching**

(or quark-hadron duality)

\[ \mathcal{L}_{eff}(\pi, N, K, D, B, \ldots) \]

\[ M_{12}^{SM} = \frac{G_F m_i^2}{16\pi^2} (V_{ti} V_{tj})^2 \langle M | (\bar{d_L} \gamma_\mu d_R) | M \rangle F \left( \frac{m_i^2}{m_W^2} \right) + \ldots, \]

CKM & loop suppression

LD Lattice QCD input

SD systematically calculable in perturbation theory
**New method:** $V_{cb}$ from $\Gamma_{\text{tot}}$, $\Delta Br(q_{\text{cut}}^2)$ and $\langle (q^2)^n \rangle_{\text{cut}}$ up to $1/m_b^4$, completely data driven.

\[
2 \text{Im} \frac{C_{ij}(\mu, \alpha_s)}{m_b^i} \langle B | O_{j=3+i}^d | B \rangle \mu
\]

**Problem:** number of HQE parameters at higher orders
- 4 up to $1/m_b^3$
- 13 up to $1/m_b^4$
- 31 up to $1/m_b^5$

**$1/m_b^2$**

Kinetic energy: \[2m_B\mu_\pi^2 = -\langle B | \bar{b}_\nu(iD)^2b_\nu | B \rangle\]

Chromomagnetic moment: \[2m_B\mu_C^2 = \langle B | \bar{b}_\nu(iD_\mu)(iD_\nu)(-i\sigma^{\mu\nu})b_\nu | B \rangle\]

**$1/m_b^3$**

Darwin term: \[2m_B\rho_D^3 = \langle B | \bar{b}_\nu(iD_\mu)(ivD)(iD^\mu)b_\nu | B \rangle\]

Spin-orbit: \[2m_B\rho_{LS}^3 = \langle B | \bar{b}_\nu(iD_\mu)(ivD)(iD_\nu)(-i\sigma^{\mu\nu})b_\nu | B \rangle\]

**$1/m_b^4$:** 9 parameters (tree level);

**Total rate and $q^2$ moments are RPI:**

3 param. instead of 13 up to $1/m_b^4$. 

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3/30/2019: Theory Summary

54th Rencontres de Moriond: QCD & High Energy Interactions
The trouble with $R_K$: global fits and future directions

$\mathcal{H}(b \to s\gamma(\ast)) \propto G_F V_{ts}^* V_{tb} \sum_i C_i \mathcal{O}_i$

to separate short and long distances ($\mu_b = m_b$)

- $\mathcal{O}_7 = \frac{e}{g^2} m_b \bar{s}\sigma^{\mu\nu}(1 + \gamma_5)F_{\mu\nu} b$ [real or soft photon]
- $\mathcal{O}_9 = \frac{e^2}{g^2} \bar{s}\gamma_\mu(1 - \gamma_5)b \bar{\ell}\gamma^\mu\ell$ [$b \to s\mu\mu$ via $Z$/hard $\gamma$...]
- $\mathcal{O}_{10} = \frac{e^2}{g^2} \bar{s}\gamma_\mu(1 - \gamma_5)b \bar{\ell}\gamma^\mu\gamma_5\ell$ [$b \to s\mu\mu$ via $Z$]

$C_{7}^{SM} = -0.29$, $C_{9}^{SM} = 4.1$, $C_{10}^{SM} = -4.3$

NP changes short-distance $C_i$ or add new operators $\mathcal{O}_i$

- Chirally flipped ($W \to W_R$) $\mathcal{O}_7 \to \mathcal{O}_7' \propto \bar{s}\sigma^{\mu\nu}(1 - \gamma_5)F_{\mu\nu} b$
- (Pseudo)scalar ($W \to H^+$) $\mathcal{O}_9, \mathcal{O}_{10} \to \mathcal{O}_S \propto \bar{s}(1 + \gamma_5)b\bar{\ell}\ell, \mathcal{O}_P$
- Tensor operators ($\gamma \to T$) $\mathcal{O}_9 \to \mathcal{O}_T \propto \bar{s}\sigma_{\mu\nu}(1 - \gamma_5)b \bar{\ell}\sigma_{\mu\nu}\ell$
The trouble with $R_K$: global fits and future directions

- $p$-value: $\chi^2_{min}$ considering $N_{dof}$
  - goodness of fit: does the hypothesis give an overall good fit?
- Pull$_{SM}$: $\chi^2_{min}(C_i = 0) - \chi^2_{min}$
  - metrology: how much does the hyp. solve SM deviations?

<table>
<thead>
<tr>
<th></th>
<th>2019</th>
<th>Best fit</th>
<th>1 $\sigma$ CL</th>
<th>Pull$_{SM}$</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C^\text{NP}_{9\mu}$</td>
<td>$L_q \otimes V_\ell$</td>
<td>-1.02</td>
<td>$[-1.18, -0.85]$</td>
<td>5.8</td>
<td>65%</td>
</tr>
<tr>
<td>$C^\text{NP}<em>{9\mu} = -C^\text{NP}</em>{10\mu}$</td>
<td>$L_q \otimes L_\ell$</td>
<td>-0.49</td>
<td>$[-0.59, -0.40]$</td>
<td>5.4</td>
<td>55%</td>
</tr>
<tr>
<td>$C^\text{NP}<em>{9\mu} = -C^\text{NP}</em>{9\mu}$</td>
<td>$A_q \otimes V_\ell$</td>
<td>-1.02</td>
<td>$[-1.18, -0.85]$</td>
<td>5.7</td>
<td>61%</td>
</tr>
<tr>
<td>$C^\text{NP}_{10\mu}$</td>
<td>$L_q \otimes A_\ell$</td>
<td>0.55</td>
<td>[0.41, 0.70]</td>
<td>4.0</td>
<td>29%</td>
</tr>
</tbody>
</table>

- LFUV: 20 obs (LFUV, $b \rightarrow s_\gamma, B_s \rightarrow \mu\mu, B \rightarrow X_s\mu\mu$) (SM p-val 5%)

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<th>1 $\sigma$ CL</th>
<th>Pull$_{SM}$</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C^\text{NP}_{9\mu}$</td>
<td>$L_q \otimes V_\ell$</td>
<td>-1.02</td>
<td>$[-1.38, -0.69]$</td>
<td>3.5</td>
<td>51%</td>
</tr>
<tr>
<td>$C^\text{NP}<em>{9\mu} = -C^\text{NP}</em>{10\mu}$</td>
<td>$L_q \otimes L_\ell$</td>
<td>-0.44</td>
<td>$[-0.55, -0.32]$</td>
<td>4.0</td>
<td>74%</td>
</tr>
<tr>
<td>$C^\text{NP}<em>{9\mu} = -C^\text{NP}</em>{9\mu}$</td>
<td>$A_q \otimes V_\ell$</td>
<td>-1.66</td>
<td>$[-2.15, -1.05]$</td>
<td>3.1</td>
<td>35%</td>
</tr>
<tr>
<td>$C^\text{NP}_{10\mu}$</td>
<td>$L_q \otimes A_\ell$</td>
<td>0.69</td>
<td>[0.50, 0.89]</td>
<td>3.9</td>
<td>72%</td>
</tr>
</tbody>
</table>

Ongoing activity from several groups
- Assess hadronic uncertainties
- Update experimental inputs
- Interpret the data in terms of SM and NP scenarios
- With various statistical approaches, theoretical prejudices...

Still many competing scenarios improving wrt SM
More observables needed soon to disentangle them!
Global EFT fit of flavor data?

- Difficulties (flavor vs EWPO):
  - Nonperturbative QCD input (form factors);
  - CKM parameters (no hierarchy of observables)

The SMEFT is an **efficient** framework to interpret / combine / compare flavor data.

- Traditional approach: [Kamenik's talk]
  - no NP in tree-level extraction of CKM from CC processes
    - [see e.g. recent SMEFT fit: Aebischer, Kumar, Stangl & Straub, 1810.07698]
    - Makes sense ($\Lambda_{NP} >> \text{TeV}$ in other processes), but...
      - It's unnecessary
      - Inconsistent with the EFT counting / philosophy;
      - BSM ~ SM-like?
      - Hints in $R(D), R(D^*)$ [only 0.3 "suppression"]
      - Tree-level CC processes can be very suppressed
        (CKM, chiral suppression, ...)
CKM parameters in the SMEFT

Four "optimal" observables:

\[ \frac{\Gamma(K \to \mu \nu_\mu)}{\Gamma(\pi \to \mu \nu_\mu)} \]  \quad \Gamma(B \to \tau \nu_\tau) \quad \Delta M_d \quad \Delta M_s. \]

\[ \left( \begin{array}{c}
\bar{\lambda} = \lambda + \delta \lambda \\
\bar{A} = A + \delta A \\
\bar{\rho} = \rho + \delta \rho \\
\bar{\eta} = \eta + \delta \eta 
\end{array} \right) = \begin{pmatrix}
0.22537 \pm 0.00046 \\
0.828 \pm 0.021 \\
0.194 \pm 0.024 \\
0.391 \pm 0.048
\end{pmatrix}, \quad \rho = \begin{pmatrix}
1 & -0.16 & 0.05 & -0.03 \\
0 & 1 & 1 -0.25 & -0.24 \\
0 & 0 & 1 & 0.83 \\
0 & 0 & 0 & 1
\end{pmatrix}. \]

NP effects in them calculated: \[ \delta \lambda = f(\varepsilon_i) \]

Any other flavor observable becomes a NP probe:

\[ O_\alpha = O_{\alpha,SM}(W_j) + \delta O_{\alpha,SM}^{\text{direct}} = O_{\alpha,SM}(\bar{W}_j) + \delta O_{\alpha,SM}^{\text{indirect}} + \delta O_{\alpha,SM}^{\text{direct}} \]

\[ W_i = (\lambda, \bar{A}, \rho, \bar{\eta}) \]
Spontaneously broken, flavor dependent gauge $U(1)_F$ extensions of SM:

- Categorised and listed the sets of fermionic charges $F$ that solve the gauge anomaly constraints.
- Probes NP which could explain pattern of fermion masses and mixing.
- Example: Third Family Hypercharge Model

In weak eigenbasis, $Z'$ couples only to third family:

\[
L_{X}\psi = g_F \left( \frac{1}{6} Q'_3 \gamma^\rho Q'_{3L} - \frac{1}{3} L'_3 \gamma^\rho L'_{3L} - e'_3 \gamma^\rho e'_{3L} + \frac{2}{3} u'_3 \gamma^\rho u'_{3R} - \frac{1}{3} d'_3 \gamma^\rho d'_{3R} \right) X_\rho
\]

In mass basis:

\[
L_{X}\psi = g_F \left( \frac{1}{6} u_L \Lambda^{(u_L)} \gamma^\rho u_L + \frac{1}{6} d_L \Lambda^{(d_L)} \gamma^\rho d_L - \frac{1}{2} n_L \Lambda^{(n_L)} \gamma^\rho n_L - \frac{1}{2} e_L \Lambda^{(e_L)} \gamma^\rho e_L + \frac{2}{3} u_R \Lambda^{(u_R)} \gamma^\rho u_R - \frac{2}{3} d_R \Lambda^{(d_R)} \gamma^\rho d_R - e_R \Lambda^{(e_R)} \gamma^\rho e_R \right) Z'_\rho,
\]

\[
\Lambda^{(I)} \equiv V_I^\dagger \xi V_I,
\]

\[
\xi = \begin{pmatrix}
0 & 0 & 0 \\
0 & 0 & 0 \\
0 & 0 & 1
\end{pmatrix}
\]
Explaining the flavor anomalies with the Pati-Salam Leptoquark

Andreas Crivellin

- b→ctν
  - Tree-level effects in semi-leptonic decays
- b→smμ
  - Loop-suppressed effects in other flavour observables like b→sγ and ΔF=2 processes which agree with the SM predictions.

Leptoquarks are tailor-made to explain the flavour anomalies

Good solution but challenging UV completion.

Perfect agreement with data

Pati-Salam LQ can explain the flavour anomalies
Confronting B anomalies with low-energy parity-violation experiments

Let's look at the extreme possibility with electrons only!!

The effective Lagrangian with $Z'$

$$\mathcal{L} = \frac{Z'\mu}{2\cos\theta_w} \left[ g_e(g'_e)\bar{\psi}\gamma_\mu P_L(R)e + g_\mu(g'_\mu)\bar{\mu}\gamma_\mu P_L(R)\mu \\
+ \sum_q (g_q\bar{q}\gamma_\mu P_L q + g'_q\bar{q}\gamma_\mu P_R q) \\
+ (g_t - g_q)\bar{V}_{ts}V_{tb}\bar{\psi}\gamma_\mu P_L(R)b + \ldots \right]$$

$$\mathcal{L}_{QW,Q_P} = \frac{\bar{\psi}\gamma_\mu\gamma_5 e}{2v^2} \sum_{q=u,d} C_{1q}\bar{q}\gamma_\mu q$$

$$C_{LL} = \frac{\sqrt{2}\pi g_e(g_t - g_q)}{4\cos^2\theta_W m_Z^2 G_F \alpha}$$

$$C_{1q}^{\text{eff}} = C_{1q}^{\text{SM}} + \frac{2v^2 g_e g_q}{8\cos^2\theta_W m_Z^2}$$
New Physics Search in the Doubly Weak Decay \( B^0 \rightarrow K^+ \pi^- \)

The doubly weak decays of B meson is highly suppressed in the SM, which can serve as an ideal place for searching of new physics signals.

\[
\mathcal{B}(\overline{B}^0 \rightarrow K^+ \pi^-)_{\text{SM}} = 9.8 \times 10^{-20}
\]

Branching ratio of \( B^0 \rightarrow K^+ \pi^- \) decay in the RS\(_C\) model

\( \Delta M_K, \epsilon_K \) and \( \Delta M_{B_d} \) constraints

KK gluons dominant
Impact of polarization observables an $B_c \rightarrow \tau \nu$ on NP explanations of the $b \rightarrow c\tau \nu$ anomaly

- In this talk focus on two-parameter scenarios. Consider combinations of Wilson coefficients that result from exchange of a single heavy intermediate state:

Compare the two scenarios $C_V^L, C_S^L = -4C_T$ (from leptoquark $S_1$) and $C_S^{L,R}$ (from charged Higgs)

<table>
<thead>
<tr>
<th>2D hyp.</th>
<th>best-fit</th>
<th>$p$-value percent</th>
<th>pull_{SM}</th>
<th>$R(D)$</th>
<th>$R(D^*)$</th>
<th>$F_L(D^*)$</th>
<th>$F_T(D^*)$</th>
<th>$P_T(D)$</th>
<th>$R(\Lambda_c)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$(C_V^L, C_S^L = -4C_T)$</td>
<td>$(0.11, -0.05)$</td>
<td><strong>33.0</strong></td>
<td>3.4</td>
<td>0.327 $-0.2 \sigma$</td>
<td>0.299 $+0.2 \sigma$</td>
<td>0.47 $-1.5 \sigma$</td>
<td>$-0.48 \sigma$</td>
<td>0.22</td>
<td>0.38</td>
</tr>
<tr>
<td>$(C_S^L, C_S^L)</td>
<td>_{60%}$</td>
<td>$(-0.15, -0.7)$</td>
<td>80.0</td>
<td>3.6</td>
<td>0.330 $-0.1 \sigma$</td>
<td>0.299 $+0.1 \sigma$</td>
<td>0.54 $-0.6 \sigma$</td>
<td>$-0.26 \sigma$</td>
<td>0.38</td>
</tr>
<tr>
<td>$(C_S^L, C_S^L)</td>
<td>_{30%}$</td>
<td>$(-0.26, -0.61)$</td>
<td>31.0</td>
<td>3.4</td>
<td>0.347 $+0.4 \sigma$</td>
<td>0.280 $-1.2 \sigma$</td>
<td>0.51 $-1.0 \sigma$</td>
<td>$-0.35 \sigma$</td>
<td>0.41</td>
</tr>
<tr>
<td>$(C_S^L, C_S^L)</td>
<td>_{10%}$</td>
<td>$(0.00, 0.06)$</td>
<td>2.9</td>
<td>2.7</td>
<td>0.360 $+0.9 \sigma$</td>
<td>0.264 $-2.3 \sigma$</td>
<td>0.48 $-1.3 \sigma$</td>
<td>$-0.43 \sigma$</td>
<td>0.43</td>
</tr>
</tbody>
</table>

- Charged-Higgs scenario (with non-zero $C_S^{L,R}$) not ruled out yet
- Scalar leptoquark $S_1$ and vector LQ $U_1$ provide good fits.
- Measurements of polarization observables could differentiate between scenarios.
LHC constraints on extended SUSY

- Non-minimal realisations of SUSY can have quite distinct phenomenological features; may even escape current searches.
- The MSSM has Majorana gauginos; a theoretically very appealing extension is to introduce instead Dirac gauginos.

DG model contains a complex color-octet scalar; splits into two non-degenerate real components (a scalar and a pseudoscalar) after SUSY breaking.

Recast of CMS 4-top analysis for 36 fb$^{-1}$ at 13 TeV (CMS-TOP-17-009) allows to exclude pseudoscalar sgluons < 1 TeV
Exploring light SUSY with GAMBIT

GAMBIT: A general framework for BSM global fits

What are the 13 TeV collider constraints on the
chargino/neutralino sector of the MSSM?
(MSSM ≠ simplified model)

- Scan 4D MSSM parameter space
- At every point: Run MC simulations of 13 TeV searches
- Calculate joint likelihood function for all searches

Light SUSY is alive (and kicking?)

- Only LO+LL cross-sections
  - Why? Speed

- For most analyses: can only use one SR per point
  - Why? Missing covariance information

- «Too weak» constraints from CMS multilepton search
  - Why? Too many SRs — had to use the aggregated SRs
  - CMS have recently provided the covariance info — thanks!
Sneutrino dark matter: status and prospectives

- Dark matter candidate

$\text{SM + three heavy neutrinos}$

$M_1, M_2, M_3, m_L, m_R, m_N, m_Q, m_H, A_l, A_{\tilde{b}}, A_q, \tan \beta, \text{sgn}\mu$

- Supersymmetric realisation
  (Right handed sneutrino fields)

Supersymmetrise
($\text{MSSM+RN}$)

Parameters defined at GUT scale, non-universality assumed

Heavy sneutrino, needs off shell Higgs

Heavy Z' needs larger $\sqrt{s}$ to probe
The NNLO revolution

Leandro Cieri
Fully differential VBF $d$-Higgs production at NNLO

Projection-to-Born (P2B)

Schematically we express the "projection-to-Born" (P2B) method as

$$d\sigma = \int d\Phi_B(B + V) + \int d\Phi_R R$$

$$= \int d\Phi_B(B + V) + \int d\Phi_R R_{P2B} + \int d\Phi_R R - \int d\Phi_R R_{P2B}$$

"inclusive" contribution

"exclusive" contribution

HH distributions

Inclusive: from structure function method
Exclusive: VBF $H+3$ jets
Available in the MC program proVBFHH
The **MATRIX framework** for automated NNLO+NNLL calculations

**Amplitudes**

<table>
<thead>
<tr>
<th>OpenLoops</th>
<th>Dedicated 2-loop codes</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Collier, CutTOols, ...)</td>
<td>(VVAMP, GiNaC, TDHPL, ...)</td>
</tr>
</tbody>
</table>

**Munich**

MUlti-chanNel Integrator at Swiss (CH) precision

- $q_T$ subtraction $\Leftrightarrow$ $q_T$ resummation

**MATRIX**

Munich Automates $q_T$ subtraction and Resummation to Integrate X-sections.
Processes available at NNLO QCD within the MATRIX framework

- **Single-boson production (essentially for validation)**
  - $pp \rightarrow Z/W^\pm (\rightarrow ll/\ell\nu) + X$
    - agreement with ZWPROD (on-shell Z) [Hamberg, van Neerven, Matsuura (1991 & 2002)]
    - agreement with DYNNLO [Catani, Grazzini (2007); Catani, Cieri, Ferrera, de Florian, Grazzini (2009)]
    - agreement with NNLOJET [Gehrmann–De Ridder, Gehrmann, Glover, Huss, Morgan]
  - $pp \rightarrow H + X \ (m_t \rightarrow \infty)$
    - agreement with HNNLO [Catani, Grazzini (2007); Grazzini (2008); Grazzini, Sargsyan (2013)]
    - agreement with SusHi [Harlander, Liebler, Mantler (2012)]

- **Boson-pair production (unknown before, apart from $\gamma\gamma$)**
  - $pp \rightarrow \gamma\gamma + X$
    - agreement with 2GAMMA NNLO [Catani, Cieri, Ferrera, de Florian, Grazzini (2011 & 2016 & 2018)]
    - agreement with MCFM [Campbell, Ellis, Li, Williams (2016)]
  - $pp \rightarrow Z\gamma/W^\pm\gamma (\rightarrow ll\gamma/\ell\nu\gamma/\nu\nu\gamma) + X$
    - confirmation ($Z\gamma$) by MCFM [Campbell, Neumann, Williams (2017)]
  - $pp \rightarrow ZZ/W^+W^- /W^\pm Z (\rightarrow 4l/2\ell2\nu/3\ell\nu) + X \ (DF + SF channels)$
    - confirmation (on-shell ZZ) by [Heinrich, Jahn, Jones, Kerner, Pires (2017)]
  - $pp \rightarrow HH + X \ (m_t \rightarrow \infty)$ [de Florian, Grazzini, Hanga, SK, Lindert, Maierhöfer, Mazzitelli, Rathlev (2016)]
    - agreement with inclusive result ($m_t \rightarrow \infty$) of [de Florian, Mazzitelli (2013 & 2015)]

- **Heavy-quark pair production**
  - $pp \rightarrow t\bar{t} + X$ [Catani, Devoto, Grazzini, SK, Mazzitelli, Sargsyan (2019)]
    - agreement with TOP++ [Czakon, Mitov (2011)]
Combination of NNLO QCD and NLO EW predictions for VV production

Stefan Kallweit
ZZ production at the LHC: NLO QCD corrections to the loop-induced gluon fusion channel

MATRIX: combine the NNLO contribution with NLO corrections to the gg channel in a single generator M. Grazzini, S. Kallweit, M. Wiesemann and J. Y. Yook (2018)

- Approximate N3LO calculation (nNNLO)
- Quark-gluon (qg) initial channel is included for the first time

Including the NLOgg contribution increases the previous NNLO prediction by 5% at 8 TeV and 6% at 13 TeV.
Isolated photon and photon+jet production at NNLO QCD accuracy

- small dynamical cone to eliminate fragmentation dependence
- fixed cone with $R^2 \gg R_0^2$ mimicking experimental isolation
- correctly describes dependence on $R$ (up to potential $R$-indep. shift)

hybrid [F. Siegert, 1611.07226]

Marius Hoefer
Analytic form of planar 2-loop five-parton scattering amplitudes in QCD

Cross-section for 3jet production at NNLO

\[ A = \sum c_i(\vec{x}, \epsilon) m_i(\vec{x}, \epsilon) \]

Two-loop numerical unitarity:

- generic approach, scales well with the number of variables 😊
- possible numerical instabilities over phase space, longer calculation times 😞

Use exact two-loop numerical unitarity results to determine the analytic expressions

New approach to amplitude evaluation: two-loop numerical unitarity & analytic reconstruction

**GOAL:** reconstruct the simplest objects you can think of

Finite reminder in terms pentagon functions:

\[ R^{(2)} = \sum c_i(\vec{x}) h_i(\vec{x}) \]

Opens the door to phenomenology of 3-jet production at the LHC
Pentagon functions for 3-jet production at NNLO

progress in calculations thanks to nice mathematics!

All master integrals for massless 2-loop 5-parton scattering are known! Pentagon functions are the basic building blocks of 2-loop 5-point master integrals: analytic expressions in terms of Goncharov polylogarithms.

Iterated integrals along path $\gamma$

$$\int_{\gamma} d \log W_{i_1} \cdots d \log W_{i_n}$$

31 integration kernels $W$ related to branch cuts

<table>
<thead>
<tr>
<th>Letter</th>
<th>$s$ notation</th>
<th>momentum notation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W_1$</td>
<td>$s_{12}$</td>
<td>$2p_1 \cdot p_2$</td>
</tr>
<tr>
<td>$W_6$</td>
<td>$s_{34} + s_{45}$</td>
<td>$2p_4 \cdot (p_3 + p_5)$</td>
</tr>
<tr>
<td>$W_{11}$</td>
<td>$s_{12} - s_{45}$</td>
<td>$2p_3 \cdot (p_4 + p_5)$</td>
</tr>
<tr>
<td>$W_{16}$</td>
<td>$s_{45} - s_{12} - s_{23}$</td>
<td>$2p_1 \cdot p_3$</td>
</tr>
<tr>
<td>$W_{17}$</td>
<td>$s_{45} - s_{12} - s_{23}$</td>
<td>$2p_3 \cdot (p_1 + p_4)$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\sqrt{\Delta}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\text{tr} \left( \gamma \sigma \right)$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\text{tr} \left( (1 - \gamma) \sigma \right)$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\text{tr} \left( (1 + \gamma) \sigma \right)$</td>
</tr>
</tbody>
</table>

Soft/collinear limits

Vanishing Gram determinant

Phases
Analytic result for 2-loop five particle amplitude

Simone Zoia

\[ N = 4 \text{ super Yang-Mills} \]

\[ N = 8 \text{ supergravity} \]

**Amplitude assembly – Real world**

- Integrand
- Master integrals
- IBP reduction
- Numerical routine
- Rational reconstruction
- Rational basis
- Lower loop amplitudes
- Amplitude

**Leading singularities**

- [Cachazo '08]
- [Chicherin, Gehrmann, Henn, Wasser, Zhang, Zoia '18]
- [Abreu, Dixon, Herrmann, Page, Zeng '19]

**Extremely elegant hard functions**

- \[ N = 4 \text{ super Yang-Mills (double-trace part)} \]
  \[
  \sum_{S_5} \text{Tr}[12](\text{Tr}[345] - \text{Tr}[543]) \frac{\delta^{(8)}(Q)}{(12)(23)(34)(45)(51)} f^{(4)}
  \]

**IR structure ✓**

**Collinear limits ✓**

**Soft limits ✓**
Elliptic polylogarithms and why they are useful for collider physics

Multiple polylogarithms: integrals over rational functions only
Elliptic multiple polylogs: 2-loop with internal masses, higher final-state multiplicity
Higgs production using the $qT$ subtraction formalism at N3LO

N$^3$LO HADRON-COLLIDER CALCULATIONS VS. TIME

First calculations

2014  2015  2016  2017  2018

This Talk

Andrea Pelloni's Talk

Leandro Cieri
Small $q_T$ behaviour is known from $q_T$ resummation (Collins, Soper, Sterman)

In agreement with Dulat, Misteberger and Peloni (2018) [Higgs production in TH expansion approximation]
Which is far from a trivial test!!
Higgs rapidity distribution in ggF at N3LO (using an expansion about the production threshold)

\[ \bar{Z} = 1 - Z = 1 - \frac{m_H^2}{s} \sim 0 \]

- We have 6 terms in the threshold expansion
- Impose conditions to the missing orders in \( \bar{Z} \) such that it matches the inclusive at all orders!

\[ \eta_{ij}^{(3), \text{matched}}(x_1, x_2) = \eta_{ij}^{(3), \text{app.}}(x_1, x_2) + \frac{x_1 + x_2}{2(1 - x_1 x_2)} \times \left[ \eta_{ij}^{(3), \text{inc.}}(x_1 x_2) - \eta_{ij}^{(3), \text{inc.,app.}}(x_1 x_2) \right] \]

- The **N3LO** correction is well within the scale variation of NNLO!
- Significant reduction of scale uncertainty [-3.4%, +0.9%]
- Agreement with another approximation

[Cieri, Chen, Gehrmann, Glover, Huss]
In processes involving disparate scales $Q \gg Q_0$, higher-order corrections are enhanced by large logarithms

$$\alpha_s^n \ln^m \frac{Q}{Q_0}$$

which can spoil perturbative expansion. Maximum power of logarithms depends on problem

- **Single logarithmic**: $m \leq n$
- **Sudakov** (soft + collinear): $m \leq 2n$

Resum enhanced contributions to all orders.

- Count $\ln(Q/Q_0) \sim 1/\alpha_s$
- Systematic expansion: LL, NLL, NNLL, …
Associated top-pair production with a heavy boson through NNLL+NLO

Extending accuracy of the perturbative prediction beyond fixed-order by adding a systematic treatment of logarithmic contributions due to soft gluon emission is a common standard in precision phenomenology.

\[
\frac{d\tilde{\sigma}_{ij \rightarrow klB}^{(res)}}{dQ^2} (N, Q^2, \{m^2\}, \mu_F^2, \mu_R^2) =
\]

\[
= \text{Tr} \left[ H_{ij \rightarrow klB}(Q^2, \{m^2\}, \mu_F^2, \mu_R^2) S_{ij \rightarrow klB}(N+1, Q^2, \{m^2\}, \mu_R^2) \right] \Delta_i^j (N+1, Q^2, \mu_F^2, \mu_R^2) \Delta^j (N+1, Q^2, \mu_F^2, \mu_R^2)
\]

Hard off-shell \hspace{2cm} Soft wide-angle

Collinear

Universal, known

\[ pp \rightarrow t\bar{t}H \]

\( \sqrt{S} = 13 \text{ TeV} \)
Resummations up to $N^3\text{LL}$ for hadronically inclusive cross sections and event shapes, but jet observables exhibit a much more complicated pattern of non-global logarithms.

Effective field theory for (non-global) jet observables:

$$\sigma(Q, Q_0) = \sum_{m=2}^{\infty} \langle \mathcal{H}_m(\{n\}, Q, \mu) \otimes S_m(\{n\}, Q_0, \mu) \rangle$$

Wilson coefficients fulfill renormalization group (RG) equations

$$\frac{d}{d \ln \mu} \mathcal{H}_m(Q, \mu) = -\sum_{l=2}^{m} \mathcal{H}_l(Q, \mu) \Gamma_{lm}^H(Q, \mu)$$

equivalent to parton shower equation

$$\mathcal{H}_m(t) = \mathcal{H}_m(t_1)e^{(t-t_1)V_n} + \int_{t_1}^{t} dt' \mathcal{H}_{m-1}(t') R_{m-1}e^{(t-t')V_n}$$
Constraining the MSSM Higgs sector using precise Higgs mass predictions

Precise for low SUSY scales, but for high scales large logarithms appear, $\ln(M_{\text{SUSY}}/M_t)$, spoiling convergence of perturbative expansion

- Integrate out all SUSY particles $\rightarrow$ SM as EFT
- Higgs self-coupling fixed at matching scale $\lambda(M_{\text{SUSY}}) = \frac{1}{4}(g^2 + g'^2)c^2_{2\beta} + ...$
- Use RGEs to run $\lambda$ down to electroweak scale $\rightarrow$ resummation of large logarithms
- Status: full LL+NLL, $O(\alpha_s, \alpha_t, \alpha_b)$ NNLL, partial $N^3LL$

- EFT approach precise for high SUSY scales
- Hybrid approach merges fixed-order and EFT approaches $\rightarrow$ precise also for intermediary scales
SCET for BSM:
Under the assumption that NP is heavy, the scale separation between NP and SM require the use of EFTs to avoid large logarithms.

Assume a new spin-0, gauge-singlet particle $S$ and build a general framework based on **Soft-Collinear Effective Theory** (SCET) in the SMEFT-spirit:

Write out all possible operators:

$$\mathcal{L}_{\text{eff}} = \sum_i C_i \otimes \left( S \cdot J^{\text{SM}}_i \right)$$

The Lagrangian $\mathcal{L}_{\text{eff}}$ separates the scales $m_S$ and $m_{\text{SM}}$ and the RG running of $C_i$ resums the corresponding (double-) logs!

Radiative corrections introduce **large (Sudakov) logarithms**, arising from soft-collinear divergences.

```
\[ \mathcal{M}_{\text{LO}} \left\{ 1 + \frac{\alpha_s(\mu)}{\pi} \frac{C_F}{\mu} \ln \frac{\mu^2}{m_q^2} \right\} \]
```

**Resummation** proceeds, as usual, via **renormalization** of the effective Lagrangian.
Goal: observables carrying quality physics messages.

The Higgs boson’s parity is imprinted in M.E.

- $H/A$ parity information can be extracted from the correlations between $\tau^+$ and $\tau^-$ spin components which are further reflected in correlations between the $\tau$ decay products in the plane transverse to the $\tau^+\tau^-$ axes.

1. We have demonstrated that ML techniques can be useful to distinguish in statistically controllable way between hypotheses of Higgs coupling to tau being CP even, CP-odd or even CP-mix

   *no problem if observables are massively multi-dimensional.*
Which measurements will help the most to constrain PDFs and their uncertainties?

**Setup of xFitter analysis**

Datafiles with pseudo-data generated for many PDF sets with the following setup:

- AFB central values:
  - 120 bins of 1 GeV from 80 GeV to 200 GeV.
- Estimation of statistical uncertainty:
  - at different integrated luminosities (30 fb⁻¹, 300 fb⁻¹ and 3000 fb⁻¹)
  - including detector acceptance and efficiency in the di-electron final state.
- Rapidity cuts:
  - different lower rapidity cuts applied (|Y| > 0, |Y| > 0.8 and |Y| > 1.5)

Profiling exercise performed on 5 NNLO PDF sets:

- ABMP16NNLO, CT14NNLO, HERA2.0NNLO, MMHT2014NNLO,
- NNPDF3.1NNLO (hessian set).

Results will be shown for 2 reference scales $Q^2 = 100 \text{ GeV}^2$ and $Q^2 = M_T^2 \text{ GeV}^2$. 
Determination of pion PDF using xFITTER

To describe $\pi^-$ with a small number of parameters assume at starting scale $Q_0^2 = 1.9\text{GeV}^2$ SU(3)-symmetric sea and neglect electroweak corrections:

$\bar{u} = d$, $\bar{d} = u = s = \bar{s}$

$$v := \frac{(d - \bar{d}) - (u - \bar{u})}{2} = d - u$$
$$xv = A_v x^B_v (1 - x)^C_v$$

$$s := \frac{u + \bar{d}}{2} = u$$
$$xs = A_s x^B_s (1 - x)^C_s$$

$$g := g$$
$$xg = A_g x^B_g (1 - x)^C_g$$

$A_v$ and $A_g$ are fixed by valence and momentum sum rules:

$$\int_0^1 v dx = 1$$
$$\int_0^1 x(2v + 6s + g) dx = 1$$

Other parameters are varied to minimize $\chi^2$.

$C$-parameters determine high-$x$ behavior, $B$-parameters determine low-$x$ behavior.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$P_{\text{lab}}\text{GeV}^2$</th>
<th>Reaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>E615$^1$</td>
<td>252</td>
<td>$\pi^- W \rightarrow \mu^+ \mu^- X$</td>
</tr>
<tr>
<td>NA10$^2$</td>
<td>194, 286</td>
<td>$\pi^\pm p \rightarrow \gamma X$</td>
</tr>
<tr>
<td>WA70$^3$</td>
<td>280</td>
<td>Total:</td>
</tr>
</tbody>
</table>

3/30/2019: Theory Summary 54th Rencontres de Moriond: QCD & High Energy Interactions
Angular ordering effects in TMD parton distribution functions and Drell-Yan qT spectra

Motivation:
We want to develop an approach in which transverse momentum kinematics will be treated without any mismatch between matrix element (ME) and PS

Parton showers in PDFs: (alternative approaches: CSS, SCET, TMD)
Parton branching evolution equation for TMD PDFs: dependence on different orderings, comparison with CSS

\[ \tilde{A}_a(x, k_\perp, \mu^2) = \Delta_a(\mu^2) \tilde{A}_a(x, k_\perp, \mu_0^2) + \sum_b \int_{\mu_0^2}^{\mu^2} \frac{d^2\mu'_2}{\pi\mu'^2} \frac{\Delta_a(\mu'^2)}{\Delta_a(\mu'^2)} \int_{z_M}^{z_M\approx 1} dze^{P_{ab}^R(z, \mu'^2, \alpha_s(1, \mu'^2))} \tilde{A}_b \left( \frac{x}{z}, k_\perp + a(z) \mu_\perp, \mu'^2 \right) \left| \int dk_\perp^2 \right| \]
PS in PDFs in the PB method

Aleksandra Lelek

Comparable in precision to NLO+NNLL (see, e.g., 1805.05916 (up to NNLO+N3LL) )
Power corrections to TMD factorization

A typical factorization formula for production of a particle with a small transverse momentum in hadron-hadron collisions:

$$\frac{d\sigma}{d\eta d^2q_\perp} = \sum_f \int d^2b_\perp e^{i(q,b)_\perp} D_{f/A}(x_A, b_\perp, \eta) D_{f/B}(x_B, b_\perp, \eta) \sigma(ff \rightarrow H)$$

+ power corrections + Y - terms

If $Q^2 \gg k_\perp^2 \gg m_N^2$ we can approximate

$$W_Z(p_A, p_B, q) = -\frac{e^2}{8s_W^2c_W^2N_c} \int d^2k_\perp$$

$$\times \left\{(1 + a_u^2) \left[1 - 2\frac{(k, q - k)_\perp}{Q^2}\right] f_{1u}(\alpha_z, k_\perp) \bar{f}_{1u}(\beta_z, q_\perp - k_\perp) \right. 
+ 2(a_u^2 - 1) \frac{k_\perp^2}{m_N^2Q^2} \left. h_{1u}^+(\alpha_z, k_\perp) \bar{h}_{1u}^+(\beta_z, q_\perp - k_\perp) + (\alpha_z \leftrightarrow \beta_z)\right\} 
+ \{u \leftrightarrow c\} + \{u \leftrightarrow d\} + \{u \leftrightarrow s\} \left(1 + O\left(\frac{1}{N_c}\right)\right).$$

Higher-twist power corrections for H and Z production at LO.
Next: NLO and match to evolution of TMDs.

$\Rightarrow$ power correction reaches 10% level at $q_\perp \sim \frac{1}{4}Q \sim 20$ GeV
Forward Drell-Yan Process as a Probe of Small x Dynamics

Leszek Motyka

Forward DY structure functions:
Lam-Tung relation violated at NNLO, higher twist effects, \((\text{parton } k_T, \ TDM)\)

Difference in BFKL and GBW: subleading twist effects

Photon* helicity inclusive cross sections

- Clear differences between BFKL and GBW approaches
- For \(M^2 = 20 \text{ GeV}^2\) higher twist corrections are important below \(q_T = 5 \text{ GeV}\)

\[ W_L - 2W_{TT} = 0 \]

DY(l+\bar{l}-) + forward jet production:
Probes high-energy resummation at small x (BFKL)
Hadron production in high-energy collisions in the multi-tube approach

Fragmentation of partons into hadrons: Lund string model (Pythia), cluster model (Herwig, Sherpa)
Flux tube model: (1+1) flux tube=string model

In the multi-flux tube picture:

\[
\frac{dN_h}{d^2 p_T dy} = \sum_{a=1}^{N} \int \frac{d^2 p_{1\perp} d^2 p_{2\perp} dy_1 dy_2}{(2\pi)^6} m_q m_{\overline{q}} \cosh y_1 \cosh y_2 \times 
\left\{ \partial_a(p_T, y; \mathbf{p}_{1\perp} - \mathbf{p}_{2\perp}, y_2 - y_1) \times 
\left\langle \left( \Psi_{q_3}(\mathbf{p}_{1\perp}, y_1) \Psi_{\overline{q}_3}(\mathbf{p}_{1\perp}, y_1) \right) \left( \Psi_{q_3}(\mathbf{p}_{2\perp}, y_2) \Psi_{\overline{q}_3}(\mathbf{p}_{2\perp}, y_2) \right) \right\rangle \right\}
\]

Transverse motion

\[
(p_1 + ip_2)\psi_+(\mathbf{r}_\perp) = (m(\mathbf{r}_\perp) + E_\nu^2)\psi_-(\mathbf{r}_\perp),
\]

\[
(p_1 - ip_2)\psi_-(\mathbf{r}_\perp) = (E_\nu^2 - m(\mathbf{r}_\perp))\psi_+(\mathbf{r}_\perp),
\]

Longitudinal motion

\[
\partial_z^2 \psi(t, z) - \partial_z^2 \psi(t, z) = m_{qT}^2 \psi(t, z),
\]
Hadron production in high-energy collisions in the multi-tube approach

\[
\frac{dN_h}{dy} = \frac{N_f N_c^2 \theta(T_c - T)(1 + (T/m_h))}{256\pi^7 K_1(m_h/T) \exp(m_h/T)}
\]

\[
\sum_{a=1}^{N} \frac{\sum_{a}^{2}}{\sigma^2_a} \left\{ \exp \left( -\frac{2(y - y_a)^2}{\sigma^2_a} \right) + \exp \left( -\frac{2(y + y_a)^2}{\sigma^2_a} \right) \right\}
\]

Comparison with pion production NA61/Shine data (pp collision):
Pre-confined color-singlet clusters can be formed with baryon number $B=0,1,2, \ldots$:

- **Conjecture:** Average of $|B|$ of clusters ($<|B|>$) proportional to # of quarks
- **Experimental evidence:** transverse momentum dependence of production ratio of $B$ hadron

The baryon number (fluctuation) of the clusters has not been studied

Baryon production mechanism related with it

Combination picture for baryon production, modeling (soon to come out)

Baryon production from cluster hadronization:
Radiative quark $p_T$ broadening in QGP beyond soft gluon approximation:

We consider processes $a \rightarrow bc$ in an external vector field $G^\mu$. For $q \rightarrow gq'$ the $S$-matrix element reads

$$\langle gq'|\hat{S}|q \rangle = -ig \int dy \bar{\psi}_{q'}(y)\gamma^\mu A^*_\mu(y)\psi_q(y).$$

The radiative contribution to $p_\perp$ broadening for $a \rightarrow bc$ transition is described by 2 diagrams (for $q \rightarrow qg$ $a = b = q$, $c = g$)

Our results (even for $\hat{q}' = \hat{q}$) differ drastically from Mueller et al.

$$\langle p^2_\perp \rangle_{rad} / \langle p^2_\perp \rangle_0 \approx 0.75$$

For experimentally measured quantity $\langle p^2_\perp \rangle_{tot} = \langle p^2_\perp \rangle_0 + \langle p^2_\perp \rangle_{rad}$ for RHIC(LHC) we obtain

$$\langle p^2_\perp \rangle_{tot} / \langle p^2_\perp \rangle_0 \approx 0.368(0.308), \quad \hat{q}' / \hat{q} = 2.4(2.63).$$
Sound absorption due to interaction of phonons with the soft collective mode of the quark field.
Probing of multi-quark structure in hadron and heavy ion collision

Mikhail Barabanov

FAIR/NICA at JINR:

To look for different charmonium-like states (conventional and exotic) in $pp$ and $pA$ collisions to obtain complementary results to the ones from $e^+e^-$ interactions, $B$-meson decays and $p$ anti-$p$ interactions.

♦ charmonium-like studies are promising for understanding the dynamics of quark interaction at small distances;

♦ charmonium-like spectroscopy represents itself a good testing ground for the theories of strong interactions:
  • QCD in both perturbative and nonperturbative regimes
  • QCD inspired potential models and phenomenological models
Higgs boson production in heavy ion collision

Can we repeat this in p-Pb, PbPb?

What is the fate of the Higgs boson in a QGP?

- Higgs boson final-state interactions in the QGP?
  - ~15% suppression forecasted, BUT virtual corrections kill effect.

David d’Enterria
Thank you!

Images courtesy of Jean Tran Thanh Van.