Polarization and resummation for slepton-pair hadroproduction

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in collaboration with Giuseppe Bozzi and Michael Klasen


LoopFest V
SLAC (California), June 19-21, 2006
Outline

1. Introduction and Motivations
   - The Minimal Supersymmetric Model
   - Slepton production at hadron colliders
   - Tau slepton identification
   - Importance of transverse-momentum distribution

2. Fixed order calculations
   - Leading order
   - Next-to-leading order
   - Fixed order failure

3. Transverse-momentum resummation
   - Main features
   - The resummed component
   - The finite component
   - Non-perturbative effects
   - $q_T$-resummation for slepton-pair production at the LHC

4. Conclusions
The Minimal Supersymmetric Model

Main features

- High energy extension to Standard Model.
- Symmetry between fermions and bosons.
- One SUSY partner for each SM particle.
- 5 Higgs bosons.
- R-parity conservation.

Advantages

- Gauge couplings unification at Planck scale.
- Possible inclusion of gravity.
- Solution to hierarchy problem.
- Dark matter candidate.
- New CP-violation phases.
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Why study slepton production?

- Due to their purely electroweak couplings, sleptons are among the lightest SUSY particles in many SUSY-breaking scenarios.
  

- Often directly decays into the lightest SUSY particle (LSP) plus the corresponding standard model partner (lepton or neutrino).

- Clean signal with a highly energetic lepton and missing energy.
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Slepton production at hadron colliders

\[ q\bar{q} \rightarrow \tilde{l}_i\tilde{l}_j^* : \]
- slepton-pair production
- neutral current

\[ q\bar{q}' \rightarrow \tilde{l}_i\tilde{\nu}_j^* + \tilde{l}_j^*\tilde{\nu}_i \]
- slepton-sneutrino associated production
- charged current

We focus on tau slepton and sneutrino. Why?
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In general SUSY-breaking models, interaction eigenstates are not identical to mass eigenstates

$\left( \tilde{l}_1 \right) = \left( \begin{array}{cc} \cos \theta_{\tilde{l}} & \sin \theta_{\tilde{l}} \\ -\sin \theta_{\tilde{l}} & \cos \theta_{\tilde{l}} \end{array} \right) \left( \begin{array}{c} \tilde{l}_L \\ \tilde{l}_R \end{array} \right),$

where

$$\tan 2 \theta_{\tilde{l}} = \frac{2 m_1 m_{LR}}{m_{LL}^2 - m_{RR}^2}.\]

[Haber, Kane, Phys. Rept. 117, 75 (1985)]

- Mixing proportional to corresponding lepton mass
  \( \Rightarrow \) only important for third generation.

- Third generation SUSY particles are lighter \( \Rightarrow \) more easily produced.
Third generation slepton and sneutrino properties

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\[
\begin{pmatrix}
\tilde{\ell}_1 \\
\tilde{\ell}_2
\end{pmatrix} = \begin{pmatrix}
\cos \theta_{\tilde{\ell}} & \sin \theta_{\tilde{\ell}} \\
-\sin \theta_{\tilde{\ell}} & \cos \theta_{\tilde{\ell}}
\end{pmatrix} \begin{pmatrix}
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Are tau sleptons detectable?

**Tau slepton often decays in one tau lepton plus one neutralino**

⇒ **tau tagging at hadron colliders?**

- Leptonic decays (35%): isolated muons or electrons plus $q_T$
  ⇒ Limited use (origin of the lepton unknown).

- Hadronic decays (65%): narrow isolated jet with low track multiplicity and invariant mass, plus $q_T$.

- Require significant $q_T$.


**CMS:** [Gennai, Nucl. Phys. Proc. Suppl. 123, 244 (2003)]

**CDF:** [Anastassov et al., Nucl. Instrum. Meth. A 518, 609 (2004)]

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Slepton-pair production signal made of two SM leptons and large missing energy due to two massive unobserved LSPs.

Longitudinal momentum balance unknown in hadronic collision ⇒ importance of a precise knowledge of the $q_T$-balance.

Can be used to distinguish SUSY signals from SM background (lepton-pairs from $WW$ or $t\bar{t}$ decays have a different $q_T$-shape)

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Problem: We have two massive particles carrying missing momentum.

Solution: use of the Cambridge *stransverse mass* $M_{T2}^2$

\[
m^2_T(q^l_T, q^\tilde{\chi}_T) = m^2_l + m^2_{\tilde{\chi}} + 2 \left( E^l_T E^\tilde{\chi}_T - q^l_T \cdot q^\tilde{\chi}_T \right)
\]

\[
m_{T2}^2 = \min_{q_1 + q_2 = q_T} \left[ \max \left\{ m^2_T(q^l_T, q^1_T), m^2_T(q^l_T, q^2_T) \right\} \right]
\]

\[
m_{T2}^2 \leq m^2_l
\]

- Optimistic: $\tilde{\chi}_1^0$ mass is known, slepton mass can be deduced.
- More realistic: relationship between neutralino and slepton masses.


- Bonus: can be used for spin determination.

[Barr, JHEP 0602, 042 (2006)]
Transverse mass variables

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Slepton production at hadron colliders
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Fixed order calculations

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Next-to-leading order
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Transverse-momentum resummation

Main features
The resummed component
The finite component
Non-perturbative effects
$q_T$-resummation for slepton-pair production at the LHC

Conclusions
LO cross section and mixing effects for $h_1 \, h_2 \rightarrow \tilde{l}_i \, \tilde{l}_j^*$

\[
\frac{d\hat{\sigma}_{h_a,h_b}}{dt} = \frac{4\pi\alpha^2}{3s^2} \left[ \frac{u \, t - m_i^2 m_j^2}{s^2} \right] \left[ e_q^2 \, e_f^2 (1 - h_a h_b) \frac{\delta_{ij}}{2} \right.
+ \frac{e_q \, e_f \, \text{Re}(L_I + R_I) \left[ (1 - h_a) (1 + h_b) L_q + (1 + h_a) (1 - h_b) R_q \right]}{8 \, x_W (1 - x_W) (1 - m_Z^2 / s)} \delta_{ij}
+ \frac{|L_I + R_I|^2 \left[ (1 - h_a) (1 + h_b) L_q^2 + (1 + h_a) (1 - h_b) R_q^2 \right]}{64 \, x_W^2 (1 - x_W)^2 (1 - m_Z^2 / s)^2} \left. \right],
\]

with

\[ L_I = (2 \, T_f^3 - 2 \, e_f \, x_W) \, S_{i1} \, S_{j1}^* \quad \text{and} \quad R_I = (-2 \, e_f \, x_W) \, S_{i2} \, S_{j2}^*. \]

- No mixing matrix $S$ for sneutrino ($S_{11} = 1$, and all others $S_{ij} = 0$).
- For charged current, all right couplings and electric charges are set to zero, and $L_I$ is set to $\sqrt{2} \, \cos \theta_W \, S_{i1}$. 

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$$+ \frac{|L_l + R_l|^2 \left[ (1 - h_a) (1 + h_b) L_q^2 + (1 + h_a) (1 - h_b) R_q^2 \right]}{64 x_W^2 (1 - x_W)^2 (1 - m_Z^2/s)^2},$$

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Leading order: Single-spin asymmetry and mixing effects

- Sensitive to the mixing angle (7% – 8%).
- PDF uncertainties are still large (5% – 6%).
- Lepton-pair production: $A_L \approx -0.09$ ⇒ discrimination SUSY/SM.
- Missing: an upgraded Tevatron with one polarized beam. [SPIN collaboration, 10th Topical Workshop on Proton-Antiproton Collider Physics (1995)]

\[ p \bar{p} \rightarrow \tilde{\tau}_j \tilde{\tau}_j^*, \text{Tevatron}, \sqrt{s}=1.96 \text{ TeV} \]

Graph showing single-spin asymmetry as a function of \( \cos \theta_{\tilde{\tau}} \).

mSUGRA parameters, based on SPS 1a:
- \( m_0 = 70 \text{ GeV} \)
- \( m_{\tilde{g}} = 250 \text{ GeV} \)
- \( -200 \text{ GeV} \leq A_0 \leq 525 \text{ GeV} \)
- \( \tan \beta = 10 \)
- \( \mu > 0 \)

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\[
\begin{array}{c}
\text{GRSV-STD/GRV98} \\
\text{GRSV-VAL/GRV98}
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\]

\[ A_L, \cos \theta_{\tilde{\tau}} \]

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\[ \cos \theta_{\tilde{\tau}} = 0.22, 0.24, 0.26, 0.28, 0.30 \]

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\[ [\text{Bozzi, BF, Klasen, Phys. Lett. B609, 339 (2005)}] \]
**Next-to-leading order $K$ factor**

**QCD:** [Baer, Harris, Reno, Phys. Rev. D 57, 5871 (1998)]


- $K$ factors for slepton-pair in NLO SUSY-QCD not too different from QCD only.
- NLO contributions not negligible ($\sim 35\%$ for the LHC and $\sim 25\%$ for Tevatron)

Importance of higher order calculations.
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Fixed order failure at low $q_T$

$q_T$-distribution features.

- **Soft** and **collinear** radiation enhance the cross section by powers of logarithmic terms $\propto \frac{\alpha_s^n}{q_T^2} \log^m \frac{Q^2}{q_T^2} (m \leq 2n - 1)$.

- Cross section diverges as $q_T \to 0$.

- Higher order contributions increase the divergence.

- Fixed order theory convergence definitely spoiled.

Why?

- Real and virtual contributions highly unbalanced.

- Cancellation does not occur order by order.

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Main features

Reorganization of the cross section

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\frac{d\sigma}{dq_T^2} = \left[ \frac{d\sigma}{dq_T^2} \right]_{\text{res}} + \left[ \frac{d\sigma}{dq_T^2} \right]_{\text{fin}} .
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- \( \left[ \frac{d\sigma}{dq_T^2} \right]_{\text{res}} \)
  - Contains all the logarithmic terms.
  - Contains all the terms proportional to \( \delta(q_T) \).
  - Resummation to all orders in \( \alpha_s \).
  - Exponentiation \( \Rightarrow \) finite term.

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Universal resummation formalism developed by Bozzi, Catani, de Florian, Grazzini. [Catani, de Florian, Grazzini, Nucl. Phys. B 596, 299 (2001)]

- **process-independent** coefficient functions $C_{ac}$ (collinear radiation at very low $q_T$),
- **process-independent** Sudakov form factor $S_c$ (soft radiation, and collinear radiation at intermediate $q_T$),
- **process-dependent** factor $H^F_c$ (hard contributions at $q_T \sim Q$).
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The resummed component

\[
\left[ \frac{d\sigma}{dq_T^2} \right]_{\text{res}} (q_T, Q, s) = \sum_{a,b} \int_0^1 dx_1 \int_0^1 dx_2 f_{a/h_1}(x_1, \mu_F) f_{b/h_2}(x_2, \mu_F) \times \left[ \frac{d\sigma_{ab}}{dq_T^2} \right]_{\text{res}} (q_T, Q, \hat{s}; \mu_R, \mu_F)
\]

\[
\left[ \frac{d^2\sigma_{ab}}{dq_T^2} \right]_{\text{res}} (q_T, Q, \hat{s}; \mu_R, \mu_F) = \frac{Q^2}{\hat{s}} \int \frac{b}{2} db J_0(b q_T) \mathcal{W}_{ab}^F(b, Q, \hat{s}; \mu_R, \mu_F).
\]

\( \mathcal{W}_{ab}^F \) contains all previously cited contributions, plus PDFs evolution.

- In the original impact-parameter space formula, the PDFs are evaluated at the scale \( b_0/b \).
- \( \Rightarrow \) involves an extrapolation of the PDFs in the non-perturbative region.
- PDFs will be evaluated at factorization scale, and evolution will be included in \( \mathcal{W}_{ab}^F \).
The resummed component:

\[
\frac{d\sigma}{d q_T^2} \left( q_T, Q, s \right)_{\text{res}} = \sum_{a,b} \int_0^1 dx_1 \int_0^1 dx_2 f_{a/h_1}(x_1, \mu_F) f_{b/h_2}(x_2, \mu_F) \\
\times \frac{d\sigma_{ab}}{d q_T^2} \left( q_T, Q, \hat{s}; \mu_R, \mu_F \right)_{\text{res}}
\]

\[
\frac{d^2\sigma_{ab}}{d q_T^2} \left( q_T, Q, \hat{s}; \mu_R, \mu_F \right) = \frac{Q^2}{\hat{s}} \int \frac{db}{2} J_0(b q_T) \mathcal{W}_{ab}^F(b, Q, \hat{s}; \mu_R, \mu_F).
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\]

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\[ \left[ \frac{d\sigma}{dq_T^2} \right]_{\text{res}} (q_T, Q, s) = \sum_{a,b} \int_0^1 dx_1 \int_0^1 dx_2 f_{a/h_1}(x_1, \mu_F) f_{b/h_2}(x_2, \mu_F) \times \left[ \frac{d\sigma_{ab}}{dq_T^2} \right]_{\text{res}} (q_T, Q, \hat{s}; \mu_R, \mu_F) \]

\[ \left[ \frac{d^2\sigma_{ab}}{dq_T^2} \right]_{\text{res}} (q_T, Q, \hat{s}; \mu_R, \mu_F) = \frac{Q^2}{\hat{s}} \int \frac{b}{2} db J_0(b q_T) \mathcal{W}^F_{ab}(b, Q, \hat{s}; \mu_R, \mu_F) \]

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**N-space and exponentiation**

Computation of $\mathcal{W}_{ab}^F$ in $N$-space $\Rightarrow$ exponentiation.

$$
\mathcal{W}_{ab, N}(b, Q; \mu_R, \mu_F) = \mathcal{H}_{ab, N}(Q; \frac{Q^2}{\mu_R^2}, \frac{Q^2}{\mu_F^2}) \exp[\mathcal{G}_N(L \equiv \log \frac{Q^2 b^2}{b_0^2}; \frac{Q^2}{\mu_R^2})]
$$

$$
\mathcal{G}_N(L; \frac{Q^2}{\mu_R^2}) = L g^{(1)}(\alpha_s L) + \sum_{n=2}^{\infty} \left( \frac{\alpha_s}{\pi} \right)^{n-2} g^{(n)}(\alpha_s L; \frac{Q^2}{\mu_R^2})
$$

$$
\mathcal{H}_{ab, N}(Q; \frac{Q^2}{\mu_R^2}, \frac{Q^2}{\mu_F^2}) = \sigma^{(\text{LO}),F}(Q) \left[ 1 + \sum_{n=1}^{\infty} \left( \frac{\alpha_s}{\pi} \right)^n \mathcal{H}^{(n),F}(\frac{Q^2}{\mu_R^2}, \frac{Q^2}{\mu_F^2}) \right]
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[Bozzi, Catani, de Florian, Grazzini, Nucl. Phys. B 737, 73 (2006)]

- $\mathcal{G}_N$ includes all the $b$-dependence and the logarithmic terms. $L g^{(1)}$ collects the LL contributions, $g^{(2)}$ the NLL ones, ...
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\( N \)-space and exponentiation

Computation of \( \mathcal{W}_{ab}^F \) in \( N \)-space \( \Rightarrow \) exponentiation.

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\mathcal{W}_{ab,\,N}(b, Q; \mu_R, \mu_F) = \mathcal{H}_{ab,\,N}(Q; \frac{Q^2}{\mu_R^2}, \frac{Q^2}{\mu_F^2}) \exp[\mathcal{G}_N(L \equiv \log \frac{Q^2 b^2}{b_0^2}; \frac{Q^2}{\mu_R^2})]
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\]

\[
\mathcal{H}_{ab,\,N}(Q; \frac{Q^2}{\mu_R^2}, \frac{Q^2}{\mu_F^2}) = \sigma^{(LO)}(Q) \left[ 1 + \sum_{n=1}^{\infty} \left( \frac{\alpha_s}{\pi} \right)^{n} \mathcal{H}^{(n)}_{N}(\frac{Q^2}{\mu_R^2}, \frac{Q^2}{\mu_F^2}) \right]
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- Both factors are computed perturbatively. NLL accuracy: need of \( g^{(1)}, g^{(2)}_N \) and \( \mathcal{H}^{(1)}_{N}, \mathcal{H}^{(2)}_{N} \) and \( \mathcal{H}^{(3)}_{N}, \mathcal{H}^{(4)}_{N} \) for higher orders.
\( N \)-space and exponentiation

Computation of \( \mathcal{W}^F_{ab} \) in \( N \)-space \( \Rightarrow \) exponentiation.

\[
\mathcal{W}^F_{ab, N}(b, Q; \mu_R, \mu_F) = \mathcal{H}^F_{ab, N}(Q; \frac{Q^2}{\mu_R^2}, \frac{Q^2}{\mu_F^2}) \exp[\mathcal{G}_N(L \equiv \log \frac{Q^2 b^2}{b_0^2}; \frac{Q^2}{\mu_R^2})]
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Computation of \( \mathcal{W}_F^{ab} \) in \( N \)-space \( \Rightarrow \) exponentiation.

\[
\mathcal{W}_F^{ab, N}(b, Q; \mu_R, \mu_F) = \mathcal{H}_F^{ab, N}(Q; \frac{Q^2}{\mu_R^2}, \frac{Q^2}{\mu_F^2}) \exp[G_N(L \equiv \log \frac{Q^2 b_2^2}{b_0^2}; \frac{Q^2}{\mu_R^2})]
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Computation of $\mathcal{W}_{ab}^F$ in $N$-space ⇒ exponentiation.

\[
\mathcal{W}_{ab}^F, N(b, Q; \mu_R, \mu_F) = H_{ab, N}^F(Q; \frac{Q^2}{\mu_R^2}, \frac{Q^2}{\mu_F^2}) \exp\left[G_N(L \equiv \log \frac{Q^2 b^2}{b_0^2}; \frac{Q^2}{\mu_R^2})\right]
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\[ \mathcal{W}_{ab, N}(b, Q; \mu_R, \mu_F) = \mathcal{H}_{ab, N}(Q; \frac{Q^2}{\mu_R^2}, \frac{Q^2}{\mu_F^2}) \exp[\mathcal{G}_N(L \equiv \log \left( \frac{Q^2 b^2}{b_0^2} \right); \frac{Q^2}{\mu_R^2})] \]

- At large \( q_T \) (small \( b \)):
  - Usual perturbation theory is valid.
  - Use of the resummation is not justified.

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The finite component

- Logarithmic terms and contributions proportional to $\delta(q_T)$ are included in the resummed component.

$$ \Rightarrow \left[ \frac{d\sigma}{dq_T^2} \right]_{\text{fin}} \text{ can be computed by } $$

$$ \left[ \frac{d\sigma}{dq_T^2} \right]_{\text{fin}} = \left[ \frac{d\sigma}{dq_T^2} \right]_{\text{f.o.}} - \left[ \frac{d\sigma}{dq_T^2} \right]_{\text{res}} \bigg|_{\text{f.o.}}. $$

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Summary

- At small $q_T$, the resummed component dominates, and the finite term is small.
- At intermediate $q_T$, both contributions are consistently matched and double-counting of any term is prevented.
- At large $q_T$, the resummed component becomes negligible (see $\tilde{L}$), and the usual fixed order perturbation theory is recovered.

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- Transverse-momentum distribution is affected by non-perturbative (NP) effects which are important in the large-\(b\) region.
- For Drell-Yan like processes, we multiply the previously cited \(W_{ab}^F\) function by a NP form factor obtained through experiment.

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- Finite result at small $q_T$, enhancement at intermediate $q_T$.
- Improvement of scale dependence (NLL+LO: $\lesssim 5$%; LO: 10%).
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NLL + LO $\mathcal{O}(\alpha_s)$ results for SPS 7

[Bozzi, BF, Klasen, hep-ph/0603074]
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\[ p p \rightarrow \gamma, Z^0 \rightarrow \tilde{\chi}_i \tilde{\chi}_i^* \text{ at the LHC} \]

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NLL + LO \( \mathcal{O}(\alpha_s) \) results for SPS 7

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Outline

1. Introduction and Motivations
   - The Minimal Supersymmetric Model
   - Slepton production at hadron colliders
   - Tau slepton identification
   - Importance of transverse-momentum distribution

2. Fixed order calculations
   - Leading order
   - Next-to-leading order
   - Fixed order failure

3. Transverse-momentum resummation
   - Main features
   - The resummed component
   - The finite component
   - Non-perturbative effects
   - $q_T$-resummation for slepton-pair production at the LHC

4. Conclusions
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- **Slepton-pair hadroproduction**
  - Unpolarized cross sections known at NLO
  - Polarized cross sections known at LO with sfermion mixing.
  - Beam polarization and sfermion mixing correlated.

- **$q_T$-resummation for sleptons**
  - Accurate $q_T$-spectrum needed by experiment
    - Mass determination.
    - Spin determination.
  - Universal formalism implemented.
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