QCD@LHC 2023

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Towards automation of inclusive quarkonium production in MadGraph5_aMC@NLO

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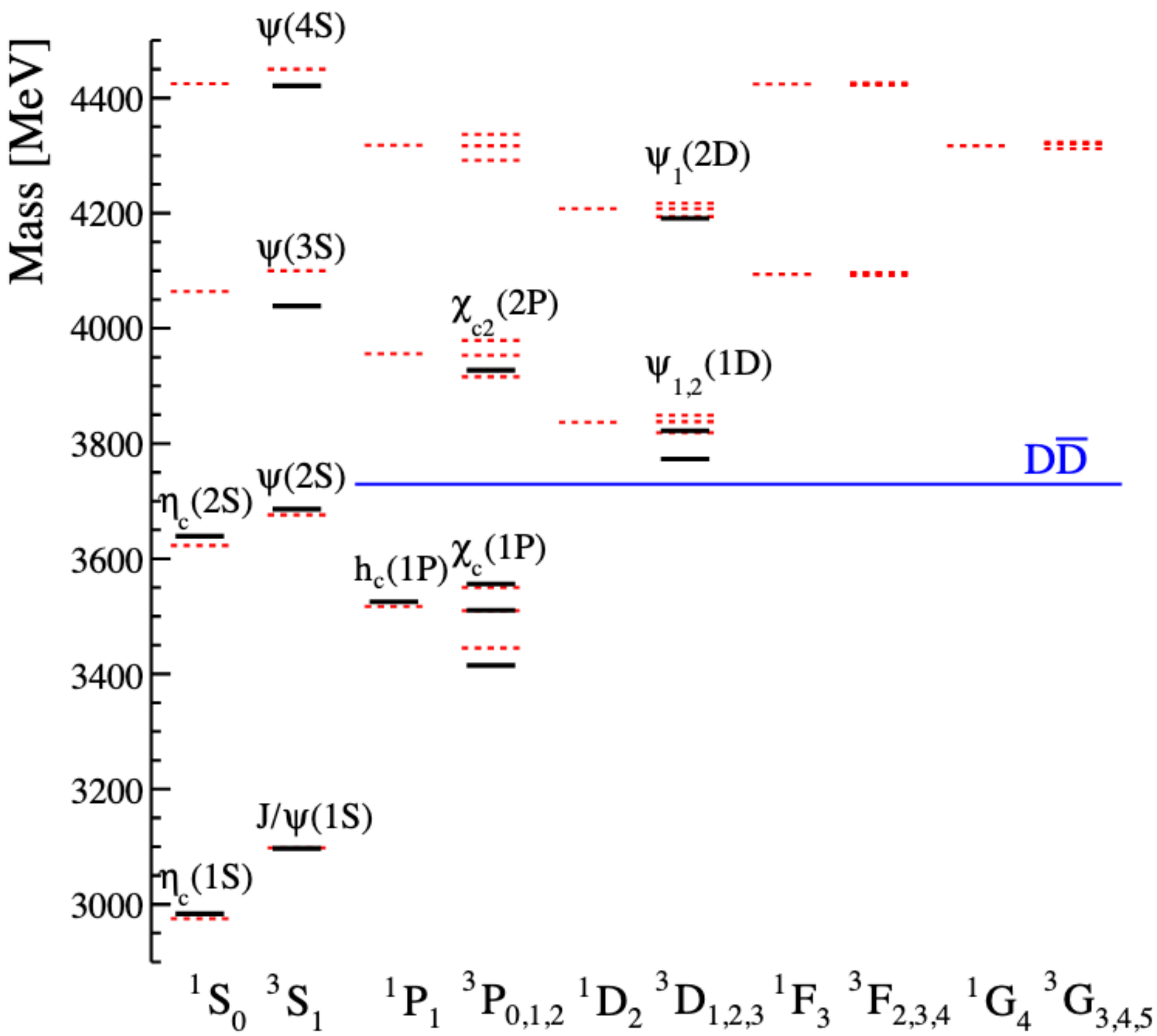
Introduction - why quarkonia?

Charmonium hierarchy

Rev.Mod.Phys. 90 (2018) 1, 015003



Quarkonia: bound states of heavy c, b, quarks[1]

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[1]bound states analogous to those of positronium

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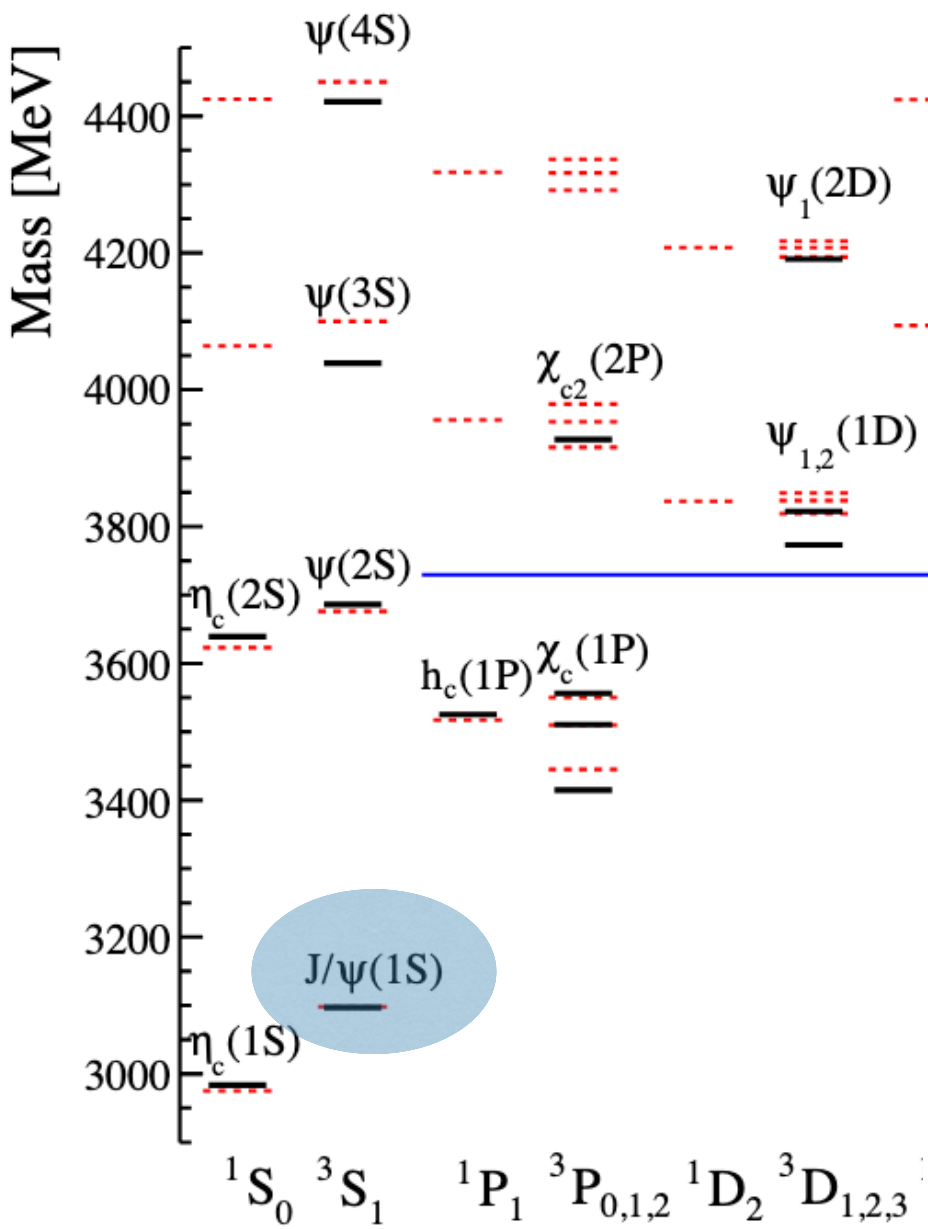
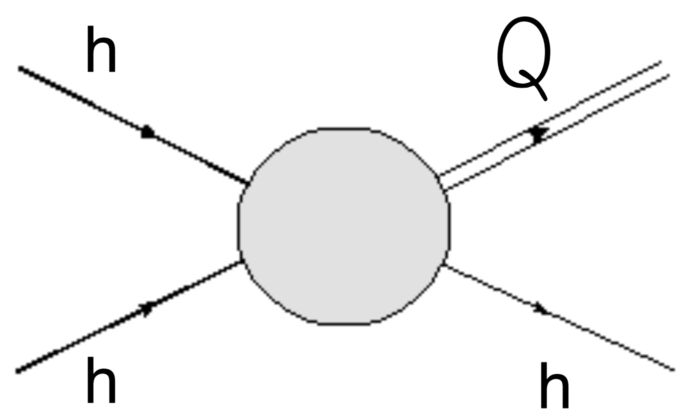


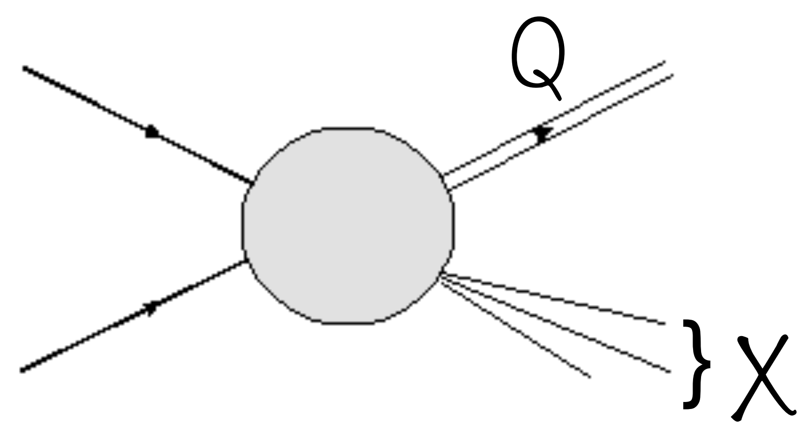
Quarkonia: bound states of heavy c, b, quarks[1]

J/ψ : S=1 (spin triplet), L=0 (S wave), J=1

e.g. gluon PDF constraints at low mom. fractions and res. scales



Exclusive



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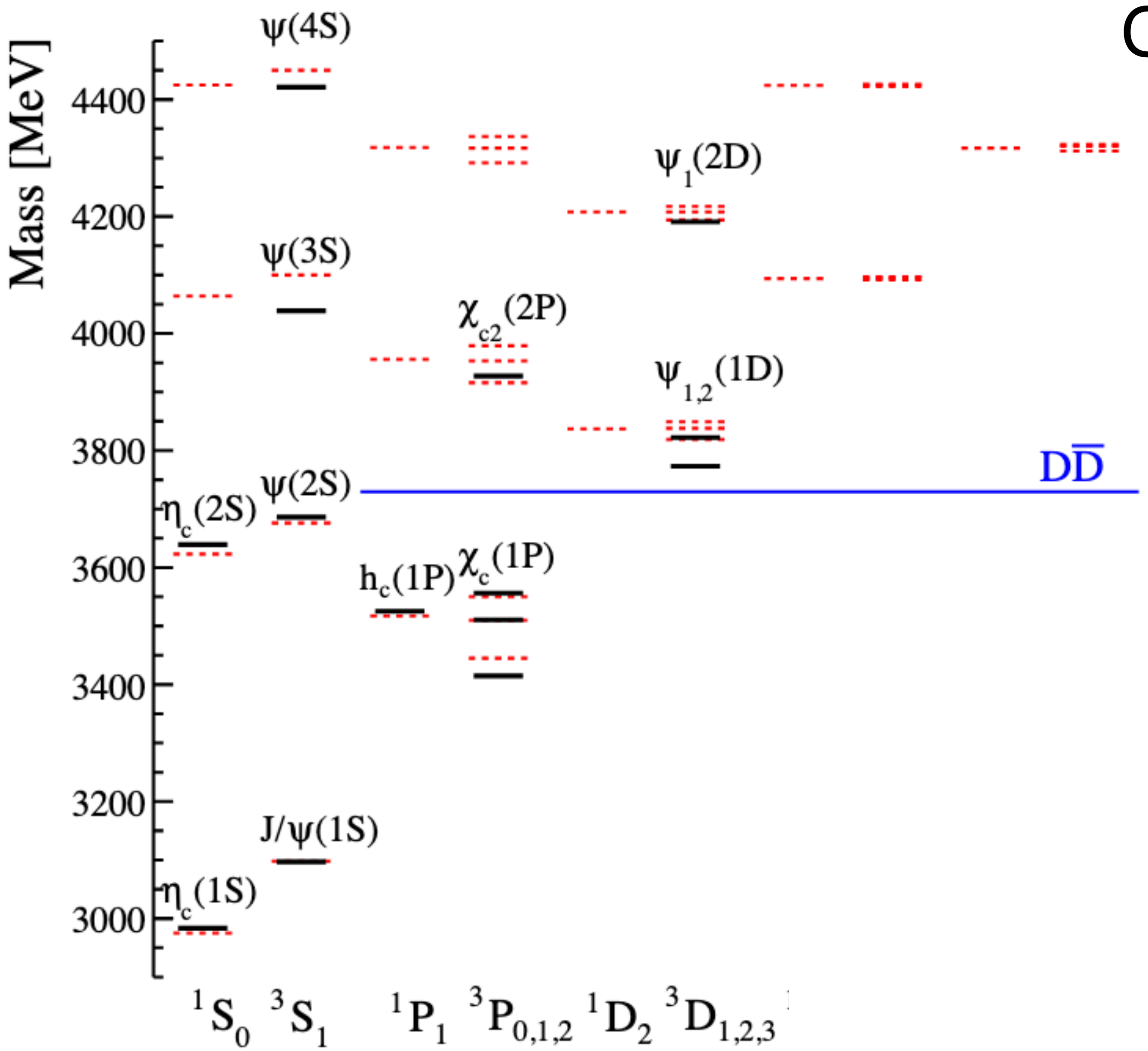

Motivation

Quarkonia:

- offer complementary information on quarkonium production mechanisms and fundamentals of QCD when measured in distinct inclusive and exclusive experimental channels
- are expected to underpin the search for gluon saturation at the upcoming EIC and provide constraints on e.g. the QGP.

Quarkonium production

Factorisation:

proton PDFs (non-pert.)

$$\sigma(pp \to \mathcal{Q} + X) = \sum_{i,j,n} \int \mathrm{d}x_1 \mathrm{d}x_2 f_{i/p}(x_1) f_{j/p}(x_2) \times \hat{\sigma}(ij \to Q\bar{Q}[n] + X) \langle \mathcal{O}_n^{\mathcal{Q}} \rangle,$$

short-distance matrix element (pert.)

long distance matrix element (non-pert.)

Typical quarkonium production mechanisms

- Colour Singlet Model (CSM)[1]
- Colour Evaporation Model (CEM) Phys. Lett. B 390 (1997), pp. 323–328.
- Non-Relativistic QCD (NRQCD) Phys. Rev. D 51 (1995). [Erratum: Phys.Rev.D 55, 5853 (1997)], pp. 1125–1171

[1] coincident with the LO term in the NRQCD expansion for S wave states

Quarkonium production

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NRQCD:

expansion in rel. velocity v of constituent heavy quarks allows one to systematically build up the quarkonium spectrum

e.g. zeroth order term $\mathcal{O}(v^0)$ in expansion for J/ψ (= $^3S_1$ state) couples to $\chi^\dagger(0)\sigma_i\phi(0)$ and the corresponding LDME can be fixed by the QED di-leptonic decay width

Automation of quarkonium cross sections

Facilitates:

- Global data/theory comparisons
- Physics cases for future experimental facilities
- Global NRQCD fits

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In public matrix element generators/event generators:

- Interfacing of e.g. HERWIG or PYTHIA with e.g. MG5_aMC[1]

Facilitates complete computation ⟶

Versatility and enhanced physics simulation capabilities...

...but integration complexity, computational overhead, code compatibility and increased learning requirements.

[1] e.g. cross sections with jets with identified hadrons

JHEP 06 (2016) 121

Automation of quarkonium cross sections cont.

Motivated:

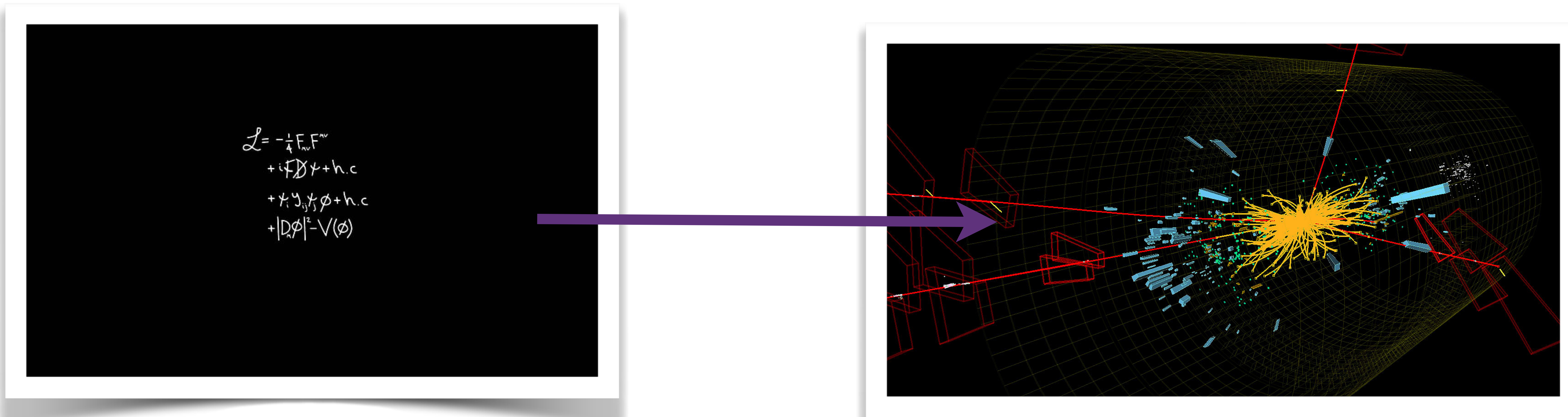
Tool	Features
• MadOnia Artoisenet, Maltoni, Stelzer	(Deprecated) module within MadGraph4 - was not ported to current version (v5) Phenomenology limited to single particle production
• Helac-Onia Shao	One or more S-wave and/or P-wave heavy quarkonia production based on tree-level helicity amplitudes

Limited to LO but not easily extendable to NLO (no NLO matrix element, no phase space integrator for NLO,...)

MadGraph5_aMC@NLO

- Only **automated** matrix element generator at LO and NLO + parton showering
  JHEP 07 (2014) 079

- Flexibility to support SM, BSM and large number of particle physics models



- But no quarkonia final states -- Why?

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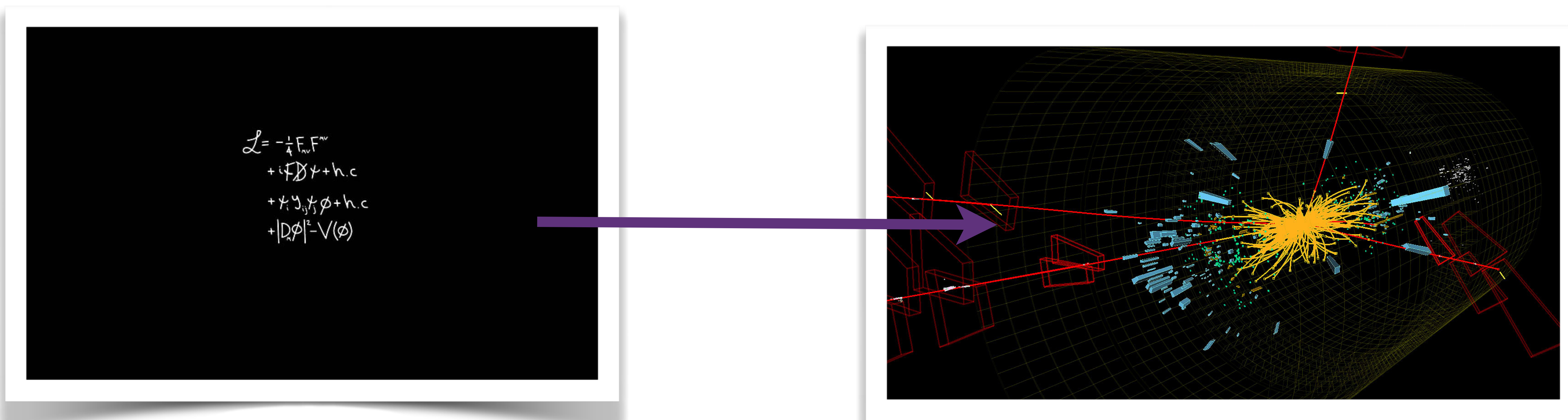


- But no quarkonia final states -- Why?

-For colour octet configurations, very many more diagrams

-Final state IR divergence cancellation issues (different NRQCD Fock states contribute)

-Feynman integral reduction to master integral basis using standard tools fails

MadGraph5_aMC@NLO + quarkonium

Aim:

Produce automation of LO quarkonium in MG5_aMC with NLO in sight

To date:

Towards single and multiple S-wave **inclusive** quarkonium (and associated) production at LO

- Colour projectors $\mathcal{C}_1 = \delta_{ij}/\sqrt{N_c}$ $\mathcal{C}_8 = \sqrt{2}T^c_{ij}$
- Spin projectors
- Interface
- Phase space adaptation

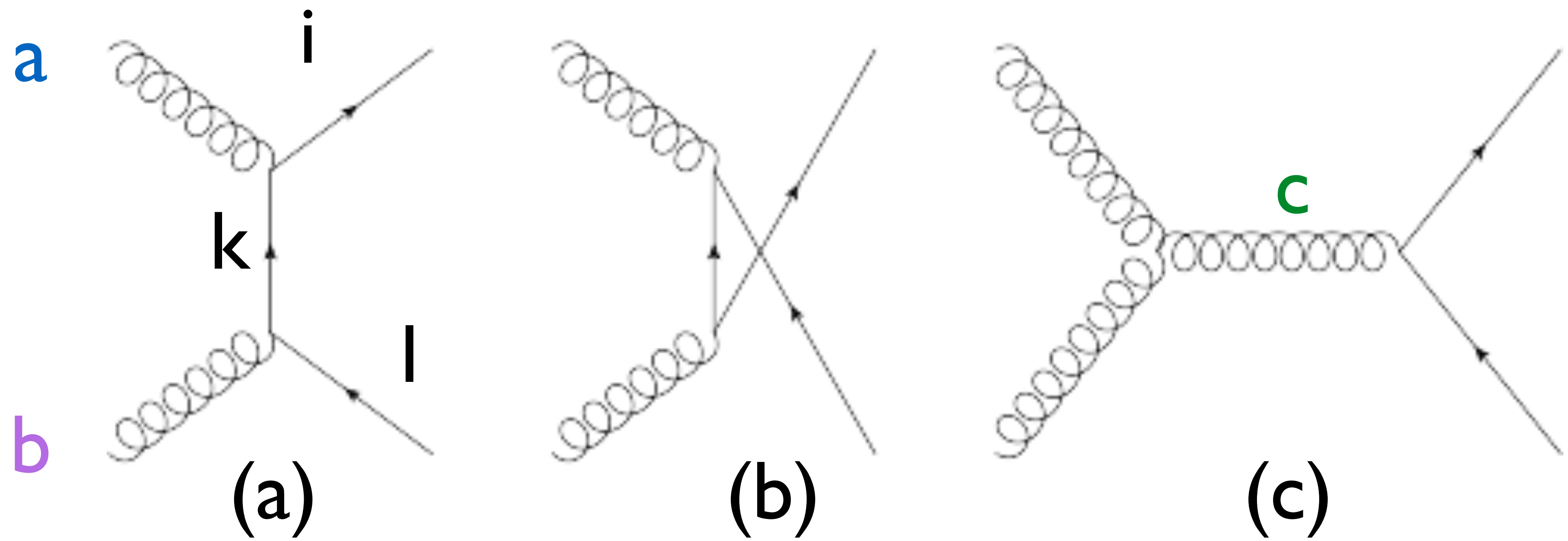
Metacode: implement formalism in .py that produces .f code to perform numerical manipulations

Amplitude generation & spin projectors

- MG5 organises amplitude into colour basis '**JAMPs**'

Efficiency: For given process, may have large # of diagrams but colour basis will be much smaller

E.g. generate LO g g > c c~ colour singlet (CS) and colour octet (CO)



$$\text{CS} : c_1 = \text{Tr}(t^a t^b)$$

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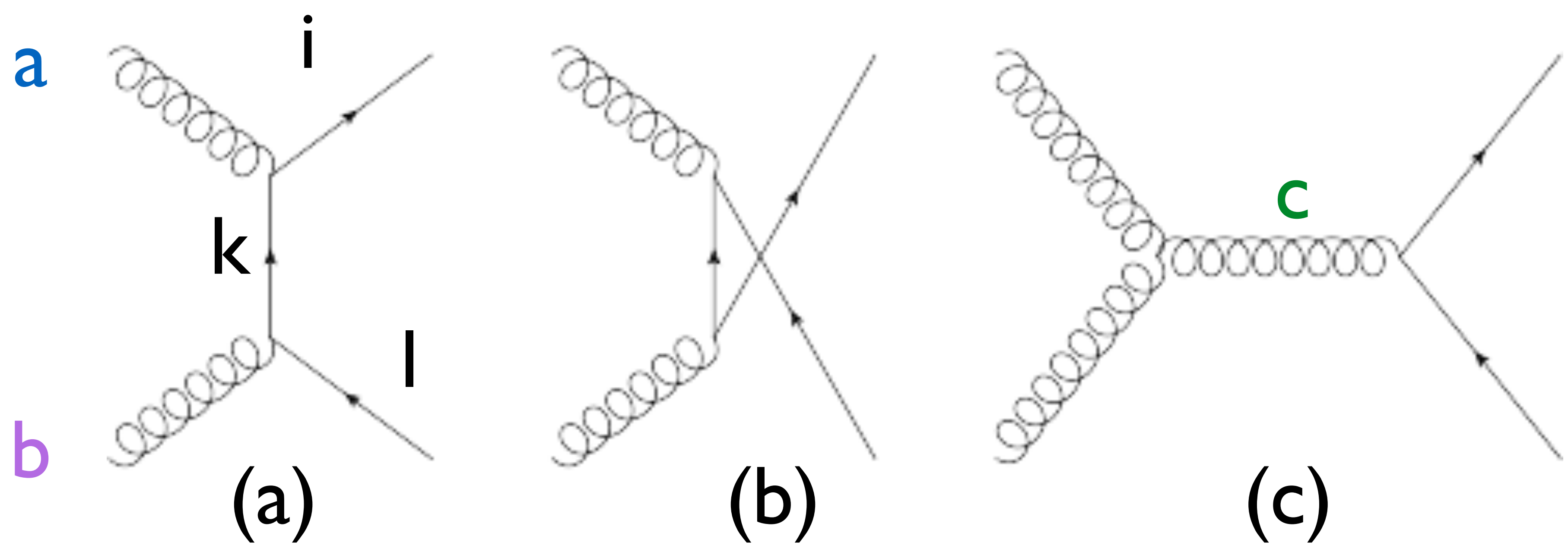


$$\mathcal{A} = A_a + A_b + A_c$$

$$A_a = c_1 A_{11}$$

$$A_b = c_2 A_{22}$$

$$A_c = c_1 A_{31} + c_2 A_{32}$$

$$\text{CO}: c_1 = \text{Tr}(t^a t^b t^c)$$

$$c_2 = \text{Tr}(t^b t^a t^c)$$

$$\text{JAMP}_1 = A_{11} + A_{31} \propto c_1$$

$$\text{JAMP}_2 = A_{22} + A_{32} \propto c_2$$

$$|\mathcal{A}|^2 = \Sigma_{i,j=1,2} \text{JAMP}_\text{i}^* \langle c_i | c_j \rangle \text{JAMP}_\text{j}$$

Amplitude generation & spin projectors

Generic quarkonium spin projector:

$$\Sigma_{\lambda_1,\lambda_2=-1/2}^{1/2}\,\bar{v}(p_2,\lambda_2)\Gamma_S\,\frac{\not{P}+M}{2M}\,u(p_1,\lambda_1) \qquad *$$

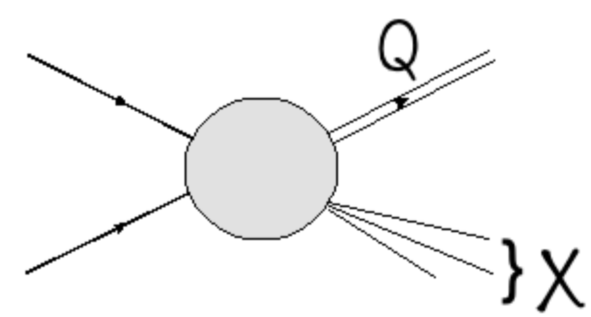
$$S = 0,\gamma_5;\, 1,\, \not{\epsilon}(P)$$

$$P = p_1 + p_2$$

$$M^2 = P^2$$

Generic fermion line:

$$\bar{u}(p_1,\lambda_1)\;\Gamma_1\ldots\Gamma_2\;\nu(p_2,\lambda_2) \qquad **$$



Contract fermion lines (**) with projector (*) :

$$\Sigma_{\lambda_2=-1/2}^{1/2}\,\bar{v}(p_2,\lambda_2)\Gamma_S\,\frac{\not{P}+M}{2M}(\not{p}_1 - m_1)\;\Gamma_1\ldots\Gamma_2\;\nu(p_2,\lambda_2)$$

$$\sim\;\Sigma_{\lambda=-1/2}^{1/2}\,\Gamma_2\,(\not{p}_2 - m_2)\,\frac{\Gamma_S}{2M}\,u(P,\lambda)\;\bar{u}(P,\lambda)\,(\not{p}_1 - m_1)\;\Gamma_1$$

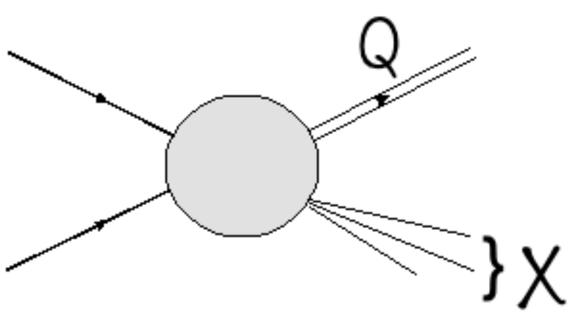
$\bar{\nu}_{\rm eff}(P,\lambda)$ $\qquad$ $u_{\rm eff}(P,\lambda)$

Amplitude generation & spin projectors

$$\sim \ \Sigma_{\lambda=-1/2}^{1/2} \Gamma_2 \left(\not{p}_2 - m_2 \right) \frac{\Gamma_S}{2M} u(P,\lambda) \ \bar{u}(P,\lambda) \left(\not{p}_1 - m_1 \right) \Gamma_1$$

$\bar{\nu}_{\text{eff}}(P,\lambda)$ $u_{\text{eff}}(P,\lambda)$

Motivation: MG5 recursively generates diagrams by carefully merging legs to avoid a double counting
-- leads to problem after spin projector applied because it 'glues' the two external quarkonium wfs.



Counteract: we introduce new effective wavefunctions

Summary & Outlook

Summary

- Implementation of LO inclusive quarkonium + associated production for **S wave** Fock states in MG5. Finalise user interface and incorporation into EU virtual access project **NLOAccess**

Outlook

- Extension to states with leading **P wave** Fock states --> global NRQCD picture and/or BSM

- Ultimately NLO in mind with few caveats.