MC4EIC

07/06/24

Extensions of MadGraph5_aMC@NLO for QCD studies

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Work done in collaboration with A. Colpani-Serri, C. Flore, D. Kikola, J.P. Lansberg, L. Manna, O. Mattelaer, H.S. Shao, L. Simon, A. Safronov

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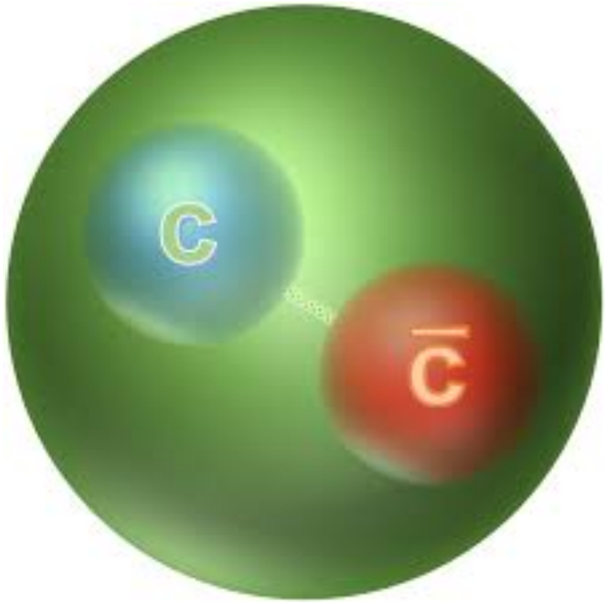
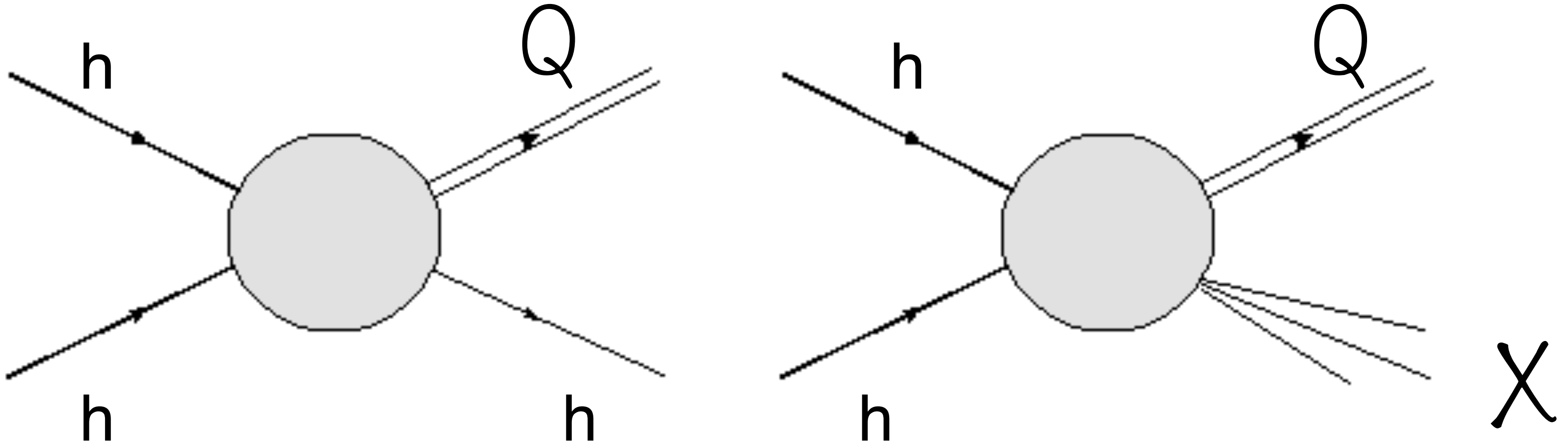
Outline

Extensions fall under the umbrella of automation programs in MadGraph5_aMC@NLO (MG5) and include the two broad categories:

- Quarkonium production
- Asymmetric collisions
    A. Photoproduction induced reactions in electron-hadron
    B. Hadron A + Hadron B induced reactions

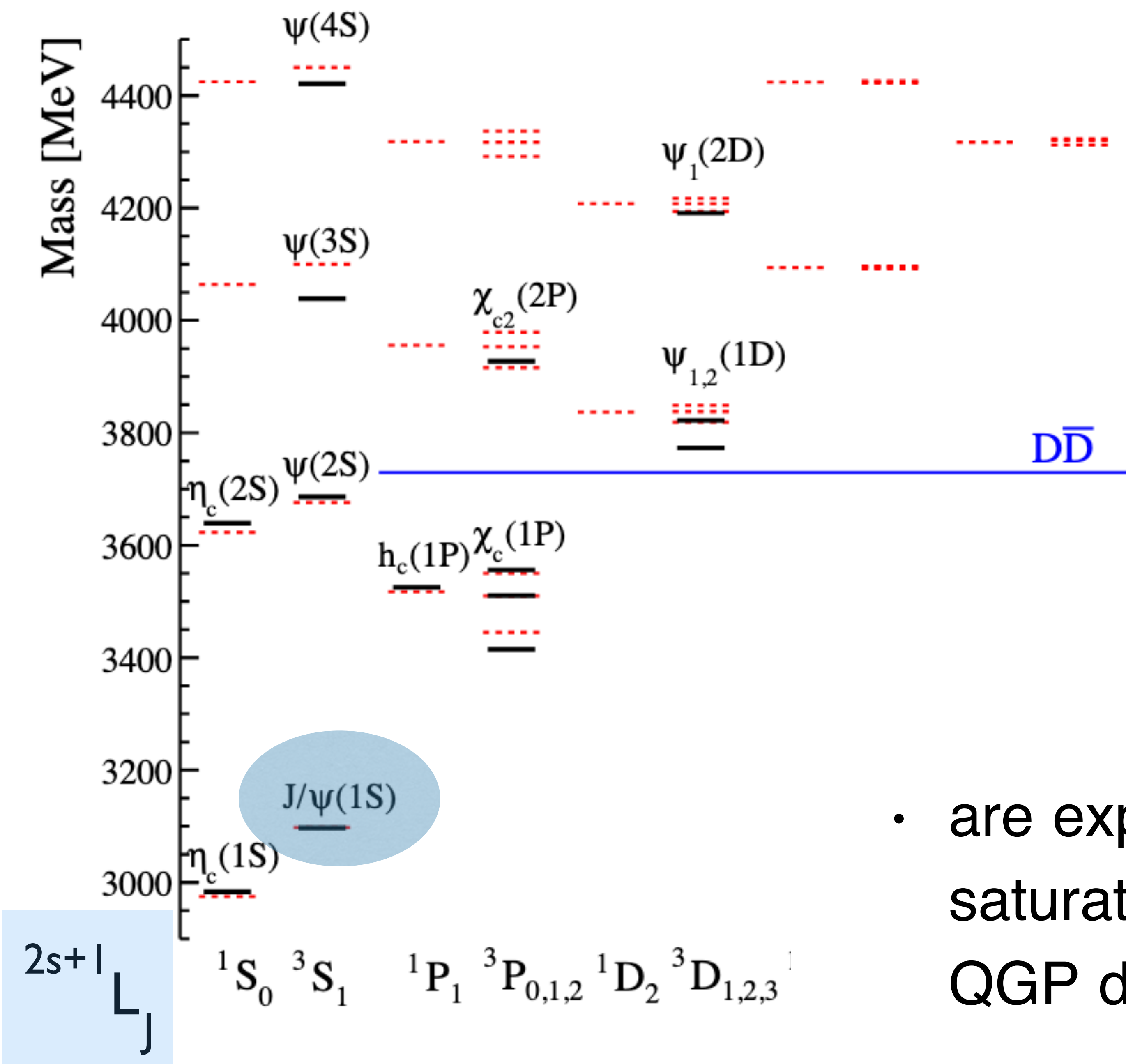


Quarkonium production



Charmonium hierarchy

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



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

50 years since J/ψ discovery

In high-energy facilities, they

- offer complementary information on quarkonium production mechanisms and fundamentals of QCD
- are expected to underpin the search for gluon saturation at the EIC + provide constraints on QGP dynamics.

[1]bound states analogous to those of e^+e^- (positronium)

Quarkonium production à la NRQCD

Factorisation:

$$\sigma(pp \to \mathcal{Q} + X) = \sum_{i,j,n} \int dx_1 dx_2 f_{i/p}(x_1) f_{j/p}(x_2) \times \hat{\sigma}(ij \to Q\bar{Q}[n] + X) \langle \mathcal{O}_n^{\mathcal{Q}} \rangle,$$

$n = {}^{2s+1}L_J^c$

short-distance matrix element (pert.)

Quarkonium production à la NRQCD

Factorisation:

Parton Distribution Functions (PDFs, non-pert.)

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NRQCD:

Phys. Rev. D 51 (1995). [Erratum: Phys.Rev.D 55, 5853 (1997)], pp. 1125–1171

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

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Other mechanisms:

- Colour Singlet Model (CSM) [1]
- Colour Evaporation Model (CEM)

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

Automation of quarkonium cross sections

Facilitates:

- Global data/theory comparisons

  -natural injection of new measurements into global framework rather than incrementally

- Physics cases for future experimental facilities

- Global NRQCD fits

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- Global NRQCD fits

  -wide variety of data for single, double quarkonium production with different sensitivity to LDMEs

Automation of quarkonium cross sections cont.

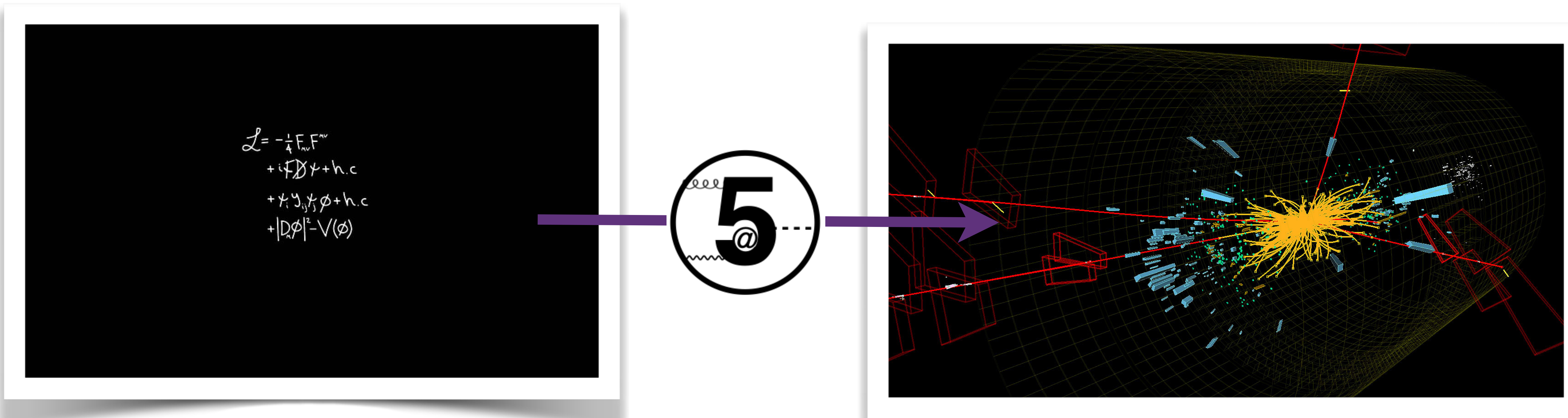
Motivated:

Tool	Features
• MadOnia Artoisenet, Maltoni, Stelzer JHEP 02 (2008) 102	(Deprecated) module within MadGraph4 - was not ported to current version (v5) Single quarkonium production phenomenology
• Helac-Onia Shao Comput.Phys.Commun. 184 (2013) Comput.Phys.Commun. 198 (2016)	One or more S-wave and/or P-wave heavy quarkonia production based on tree-level helicity amplitudes Limited to LO, not immediately extendable to NLO (no NLO matrix element or 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? -- extra complexities arise

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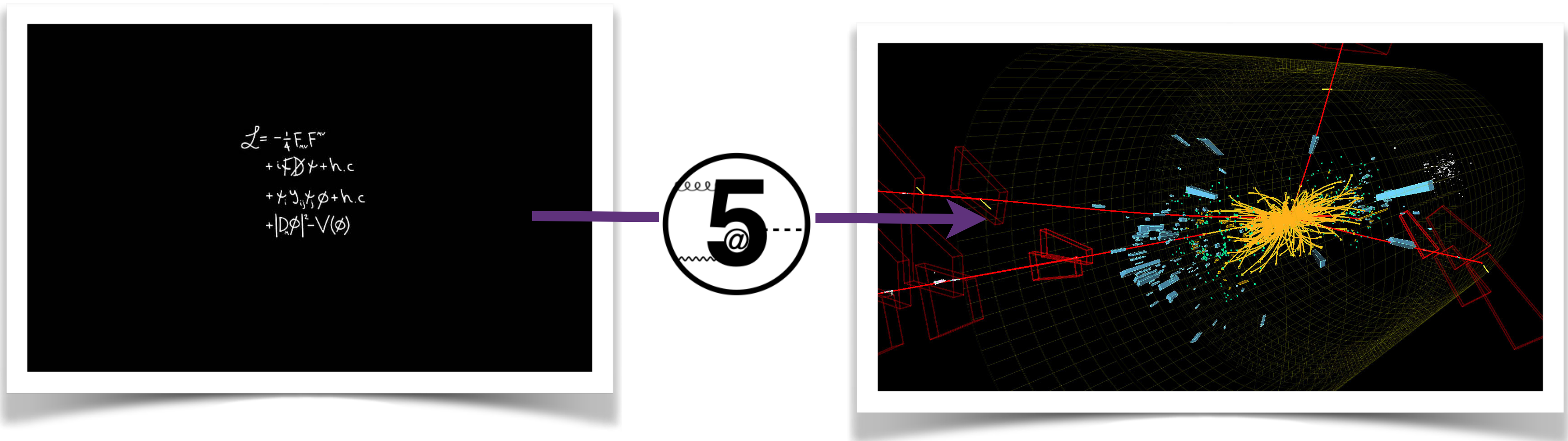

  - But no quarkonia final states -- Why? -- extra complexities arise

Technical: e.g. multi-channeling phase space adaptation needed for quarkonia

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

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

---

*famous resolution of non-cancelling IR divergences through mixing of P wave states with relevant S wave states at $O(v^2)$

MadGraph5_aMC@NLO + quarkonia

Immediate goal:

Produce automation of quarkonium in MG5 at LO

...with NLO in sight

To date:

- Finalising a version of MG5 enabling cross section computations with quarkonium @LO allowing:

LO cross section computations with an arbitrary number of **S-wave** quarkonia and associated particles

- Colour projectors $\mathcal{C}_1 = \delta_{ij}/\sqrt{N_c}$ $\mathcal{C}_8 = \sqrt{2}T^c_{ij}$
- Spin projectors $\bar{v}(p_2, \lambda_2)\Gamma_S \; u(p_1, \lambda_1)$
- Internal and external helicity summations

$$S = 0, \gamma_5; 1, \not{\epsilon}(P)$$
$$P = p_1 + p_2$$
$$M^2 = P^2$$

Metacode: implement new quarkonium formalism via extension of existing .py that produces .f code to perform numerical manipulations

MadGraph5_aMC@NLO + quarkonia cont.

New interface:

E.g. $pp \to J/\psi + \eta_c + c\bar{c}g$

```
MG_aMC>generate p p > J/psi etac c c~ g
```

and

```
MG_aMC>generate p p > c.c~(1|3S11) c.c~(1|1S01) c c~ g
```

Benchmarked our implementation for **matrix element squared** for various processes against `Helac-Onia`

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E.g. `MG_aMC>generate`

- `g g > b.b~(1|1S01)` } single
- `g g > b.b~(1|1S08)` } single
- `g g > b.b~(1|1S01) g` } single + elementary particle
- `g g > b.b~(1|1S01) b.b~(1|1S01)` } multiple
- `g g > b.b~(1|1S01) c.c~(1|1S01)` } multiple

..similarly for spin triplet

MadGraph5_aMC@NLO + quarkonia cont.

New interface:

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To do (short term):

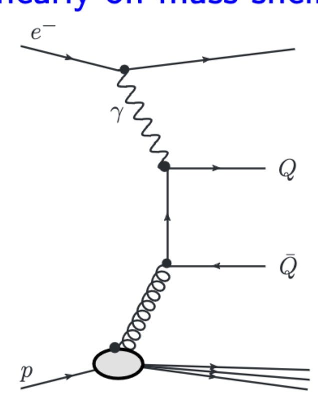
Phase space adaptation & implementation into **`NLOAccess`** (see later)

Plan to release 'onia' branch of MG5 v3.x

Asymmetric collisions

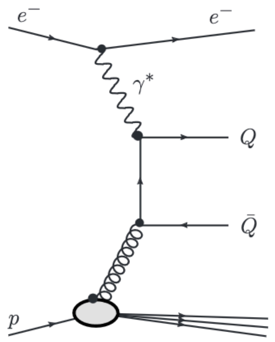
- Photoproduction in eA

I) Photoproduction :
Photon is nearly on mass shell.



$Q^2 \leq m_H$

II) Deep-Inelastic-scattering (DIS):
Photon is off mass shell.



$Q^2 >> m_H$

- Hadron-Hadron induced reactions

Asymmetric collisions in MG5

Motivation:

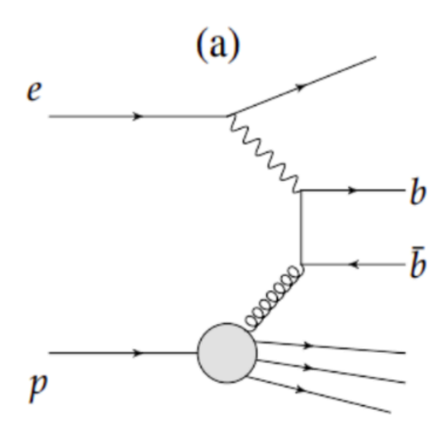
- Need for reliable simulation tool for upcoming eA studies at the EIC to facilitate strategy and accomplishment of future measurements
- Single-usage codes such as FMNR not automated and possible adaptations of Helac-Onia would limit analyses to LO in short term
- NLO invaluable at the EIC --> make extensions within MG5

Currrently in MG5 (symmetric AA collisions):

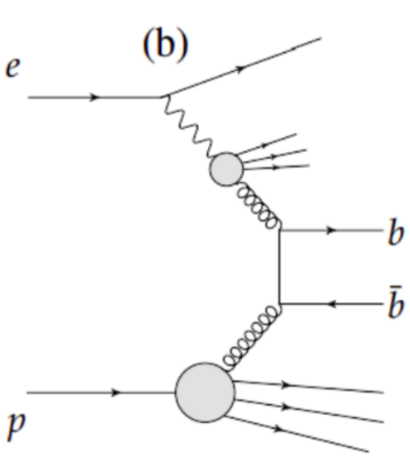
$$\sigma_{AA\to X} = \sum_{i,j} \int dx_i dx_j f_i^A(x_i, \mu_F; \mathrm{LHAID}) f_j^A(x_j, \mu_F; \mathrm{LHAID}) \hat{\sigma}_{ab\to X}(x_i, x_j, \mu_F, \mu_R)$$

Two classes of extension:

- Photoproduction in eA
- Hadron-Hadron induced reactions



a) Direct photoproduction



b) Resolved photoproduction

Photoproduction in MG5

[work by L. Manna]

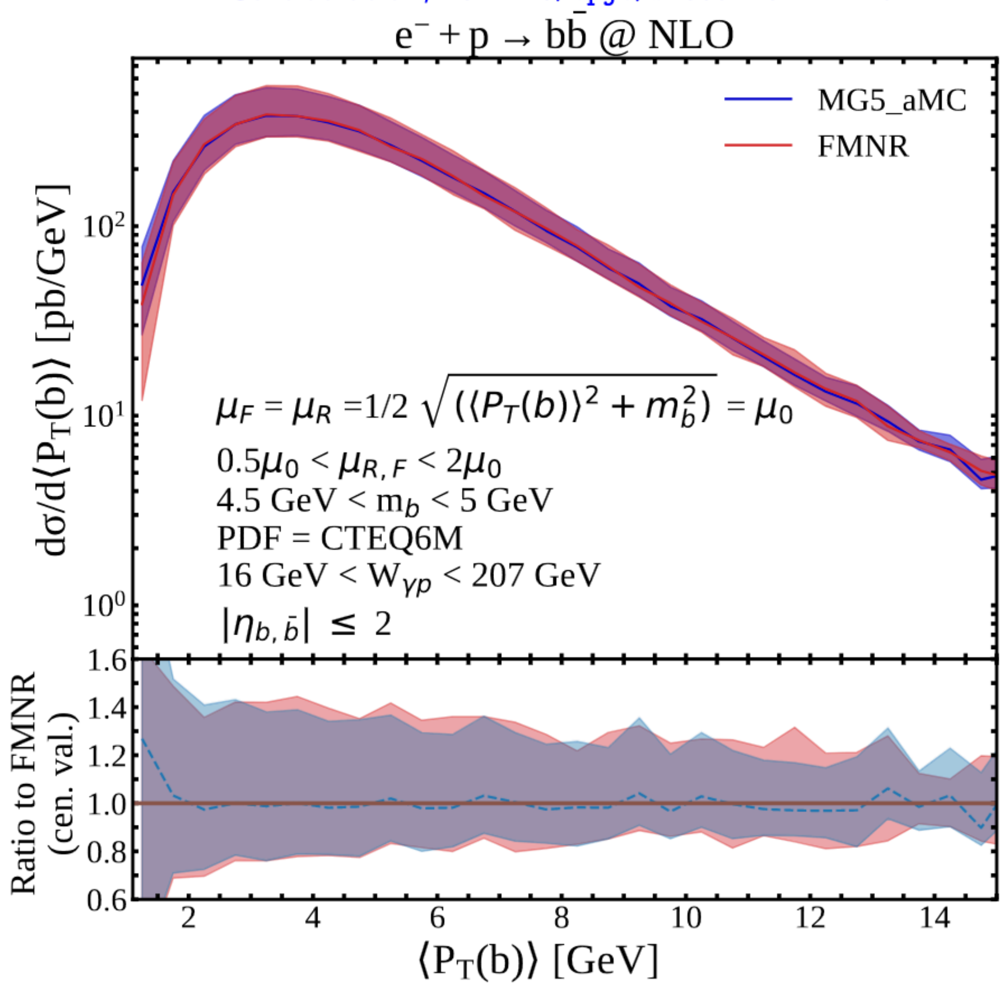
Considered direct + resolved photoproduction

$$\sigma_{eh\to X} = \sum_j \int dx_\gamma dx_j f_\gamma^e(x_\gamma, Q^2_{\max}) f_j^h(x_j, \mu_F; \texttt{LHAID}) \hat{\sigma}_{\gamma j\to X}(x_\gamma, x_j, \mu_F, \mu_R)$$

Bottom production validation

FMNR: Nucl.Phys.B 412 (1994) 225-259

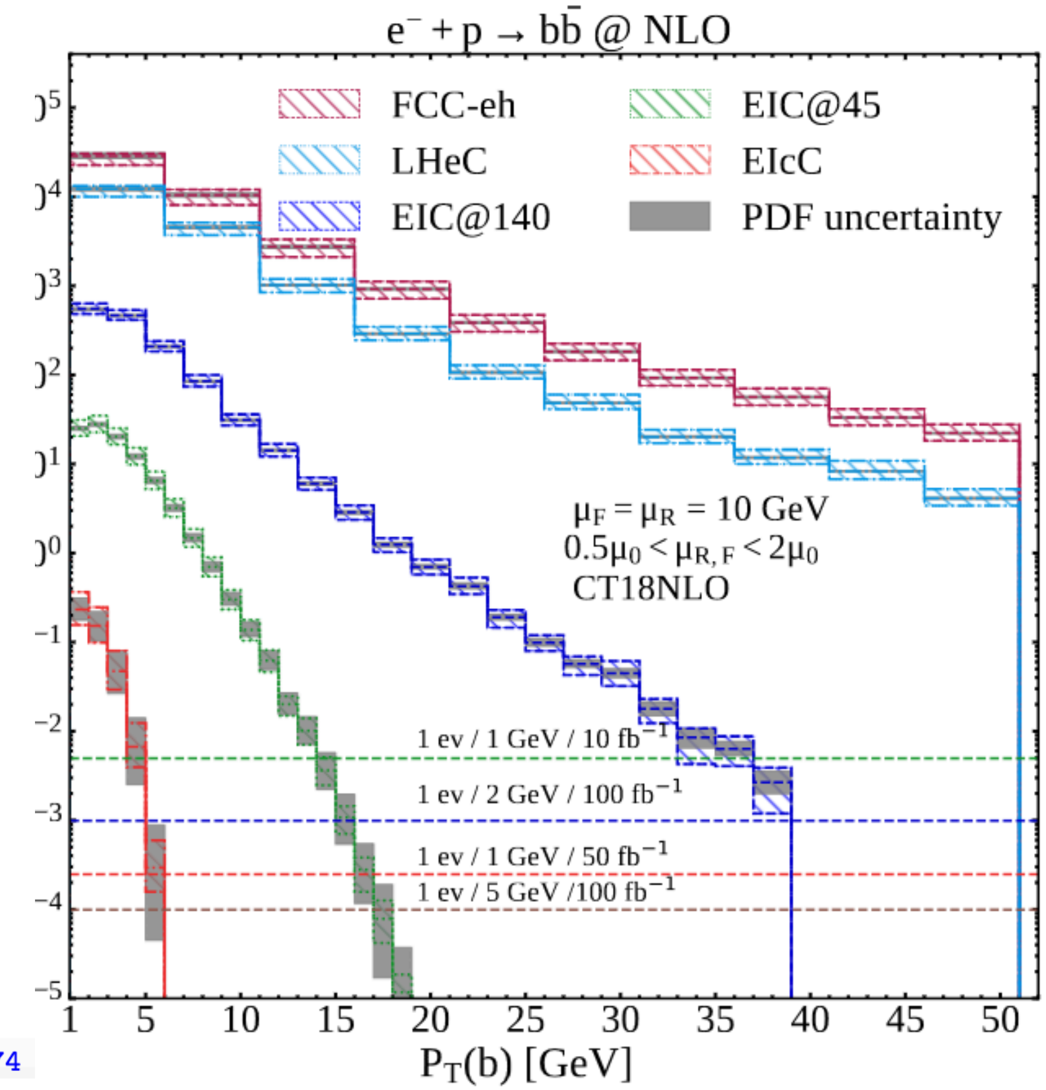
H1 Collaboration, 10.1140/epjc/s10052-012-2148-1



Approximately $\sim \mathcal{O}(1\%)$ agreement (direct photon contribution)!

L. Manna et. al, PoS EPS-HEP 2023 449 https://doi.org/10.22323/1.449.0274

Future Predictions for **bottom** production



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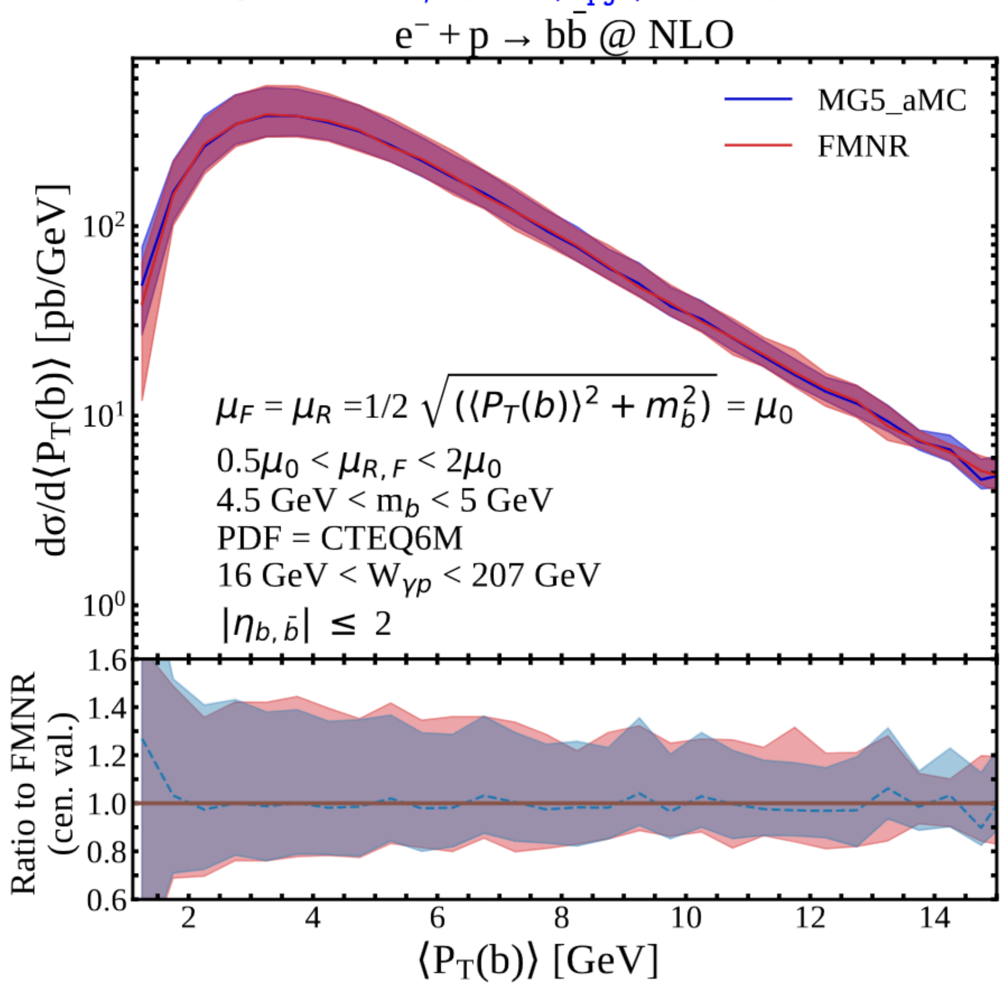

Approximately $\sim \mathcal{O}(1\%)$ agreement (direct photon contribution)!

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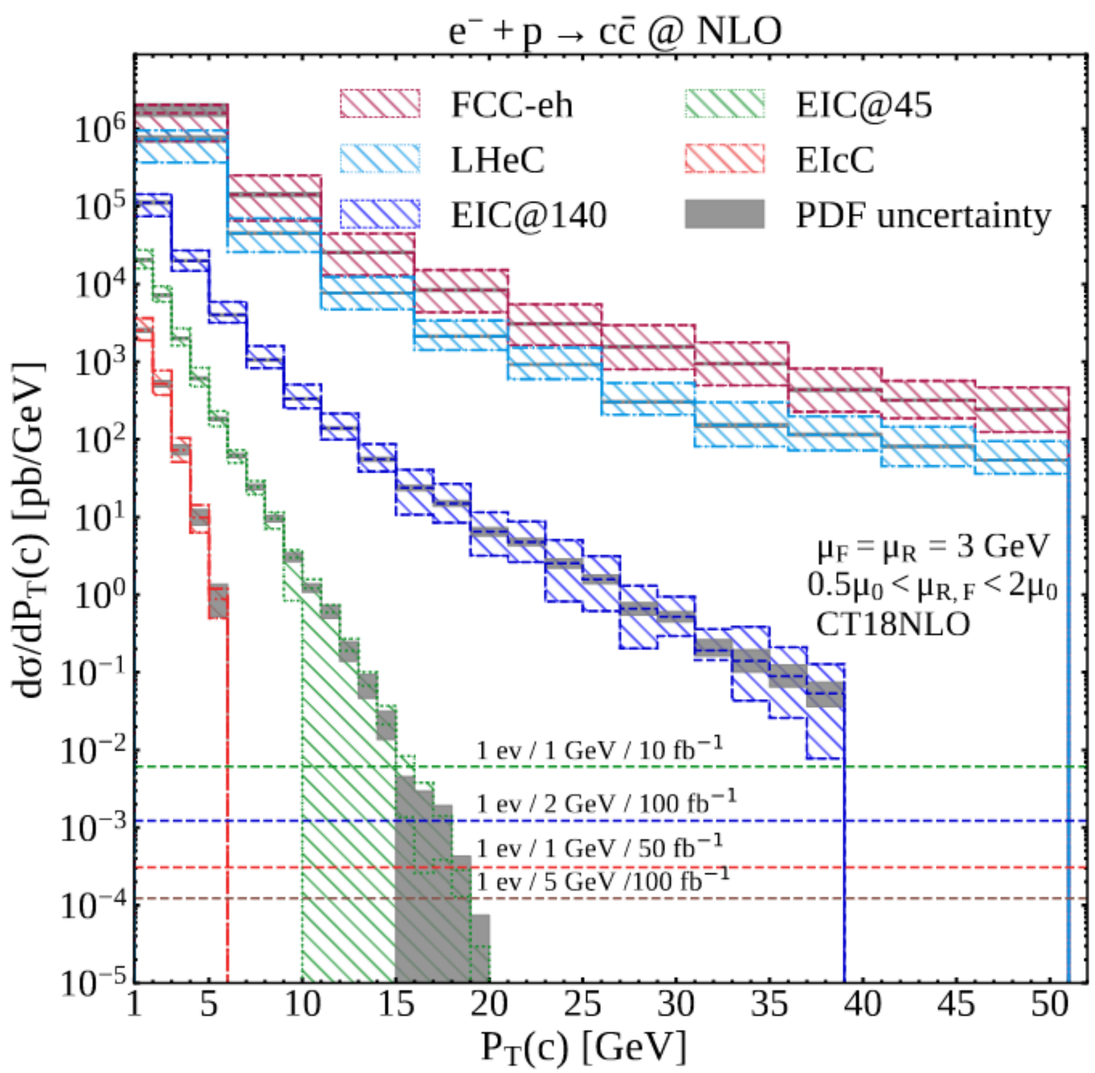
Future Predictions for **charm** production



Photoproduction in MG5

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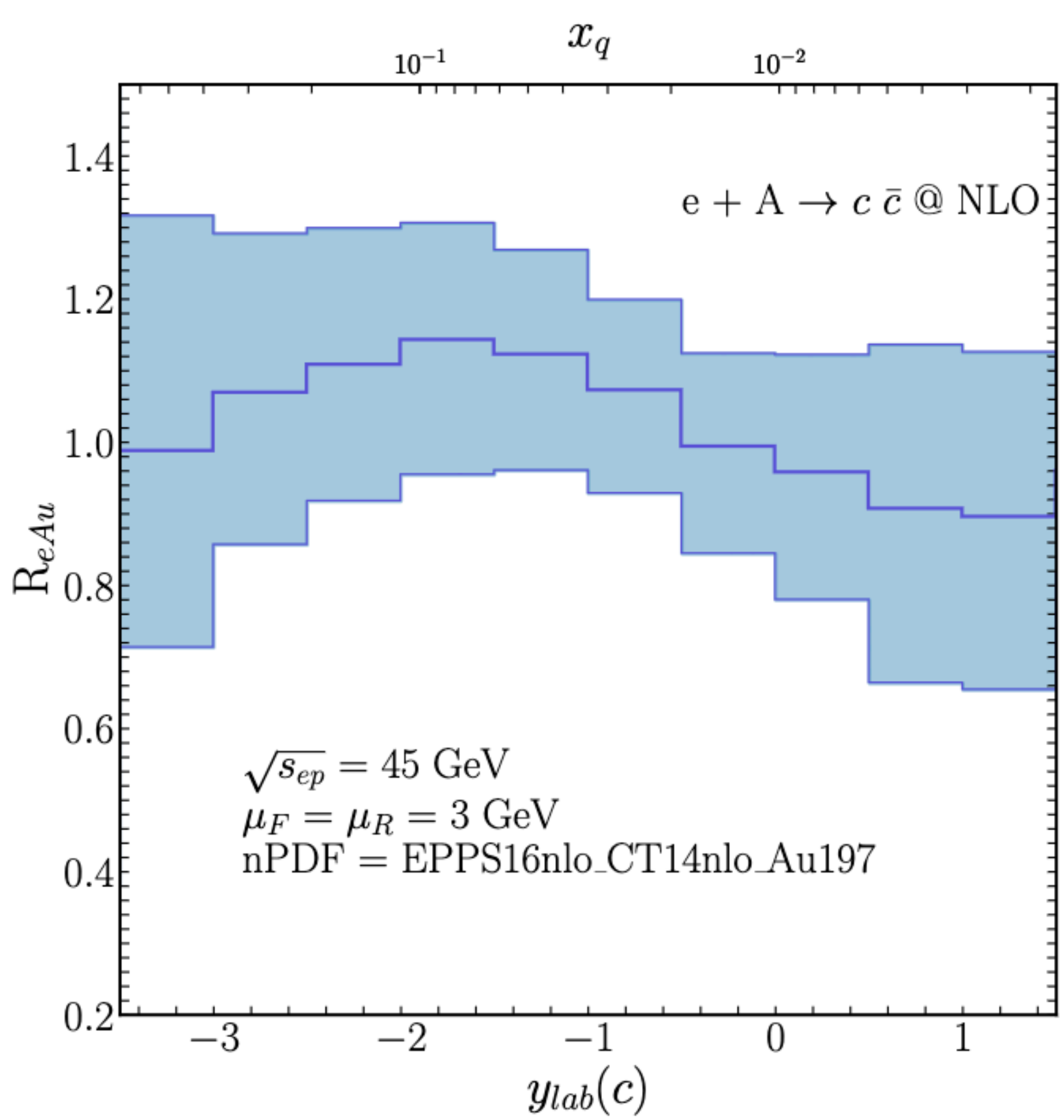
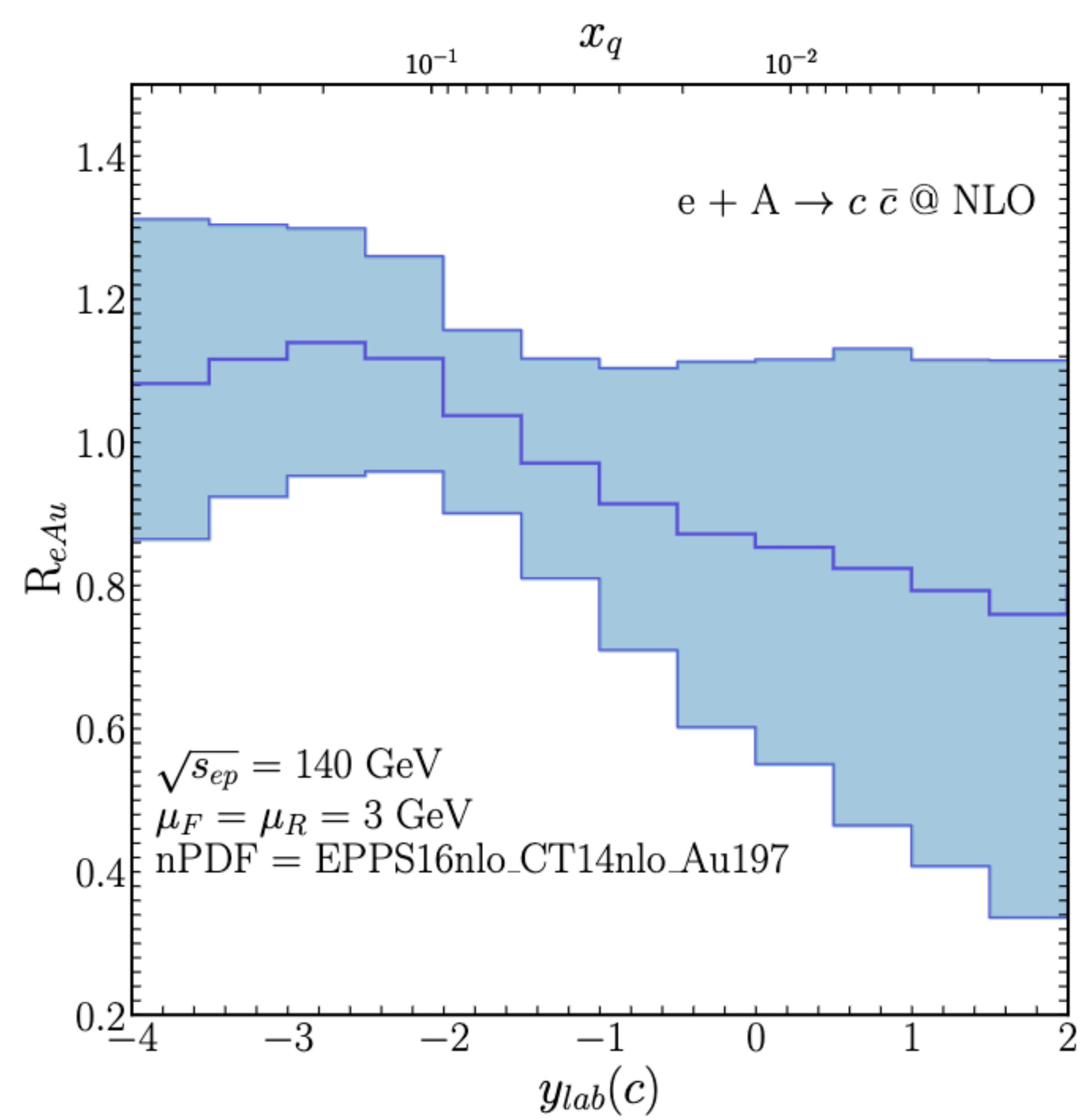
[work by L. Manna]

$$\sigma_{eh\to X} = \sum_j \int dx_\gamma dx_j f_\gamma^e(x_\gamma, Q^2_{\max}) f_j^h(x_j, \mu_F; \texttt{LHAID}) \hat{\sigma}_{\gamma j \to X}(x_\gamma, x_j, \mu_F, \mu_R)$$

Nuclear modification factor at the EIC for two energy configurations





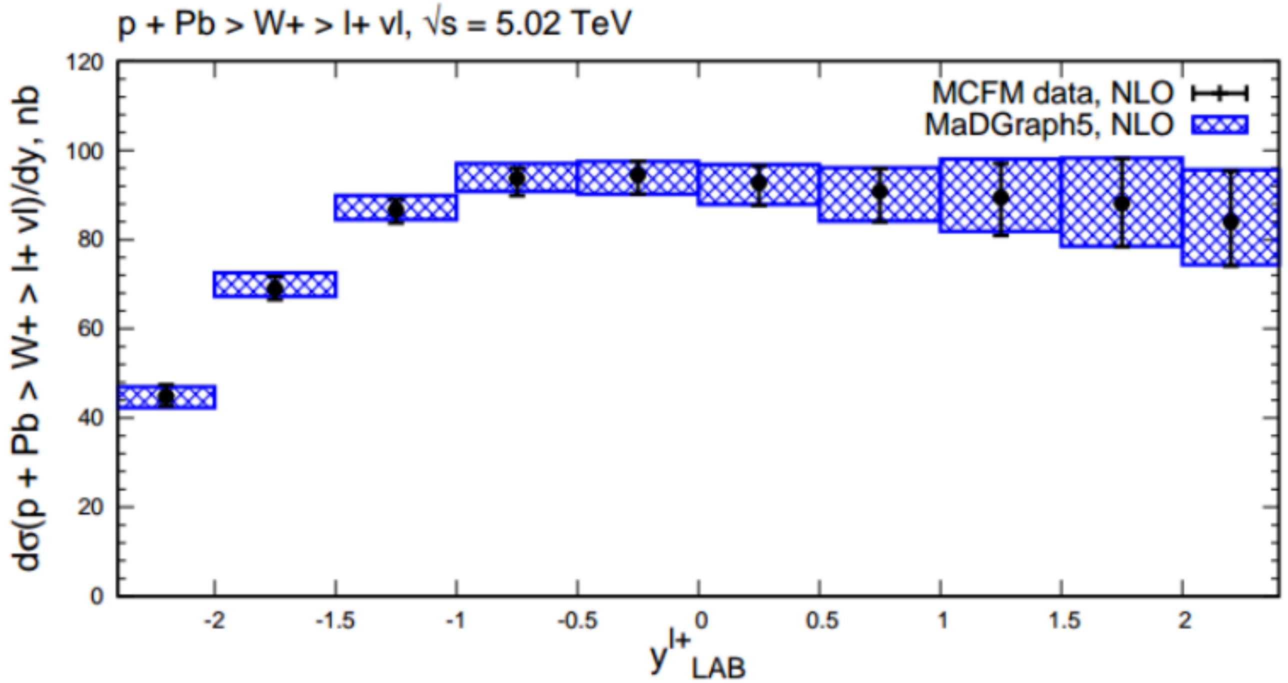
Hadron A + Hadron B in MG5

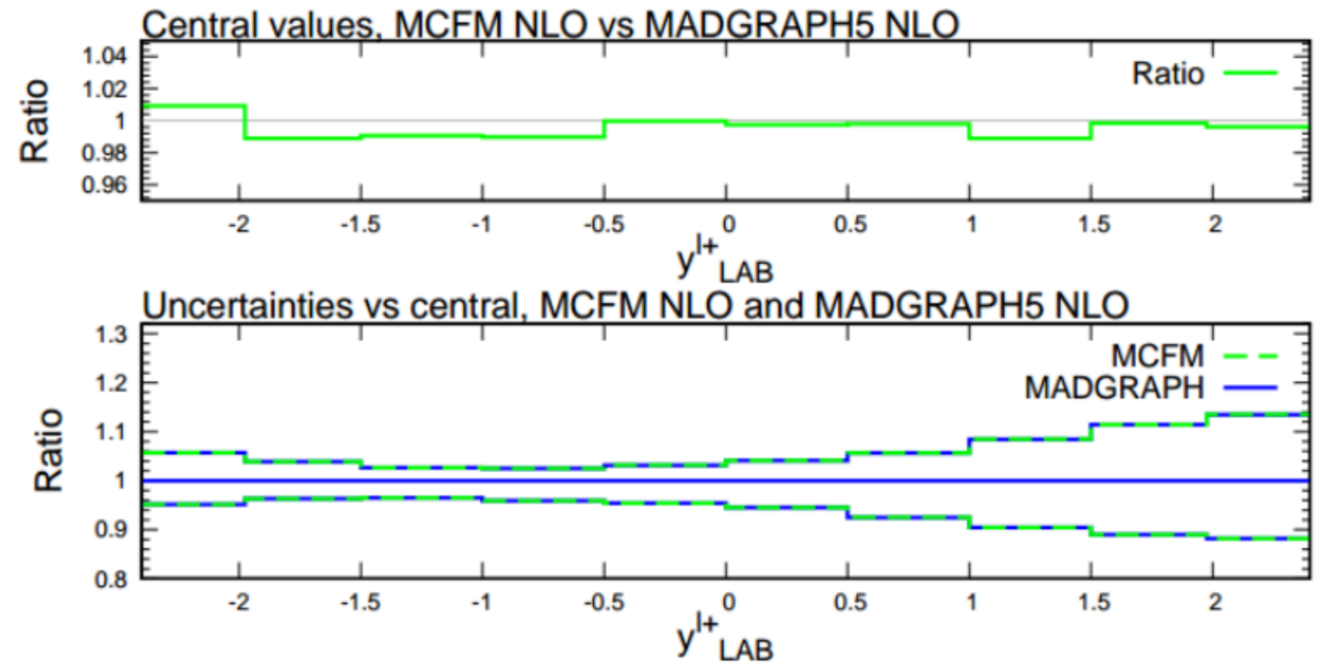
[work by A. Safronov]

$$\sigma_{AB\to X} = \sum_{i,j} \int dx_i dx_j f_i^A(x_i, \mu_F; \texttt{LHAID1}) f_j^B(x_j, \mu_F; \texttt{LHAID2}) \hat{\sigma}_{ab\to X}(x_i, x_j, \mu_F, \mu_R)$$

MCFM: 10.1007/JHEP12(2019)034

Validation vs MCFM for CT10 + nCTEQ15 for W production at NLO





A. Safronov et al., PoS ICHEP2022 (2022) 494 (https://doi.org/10.22323/1.414.0494)

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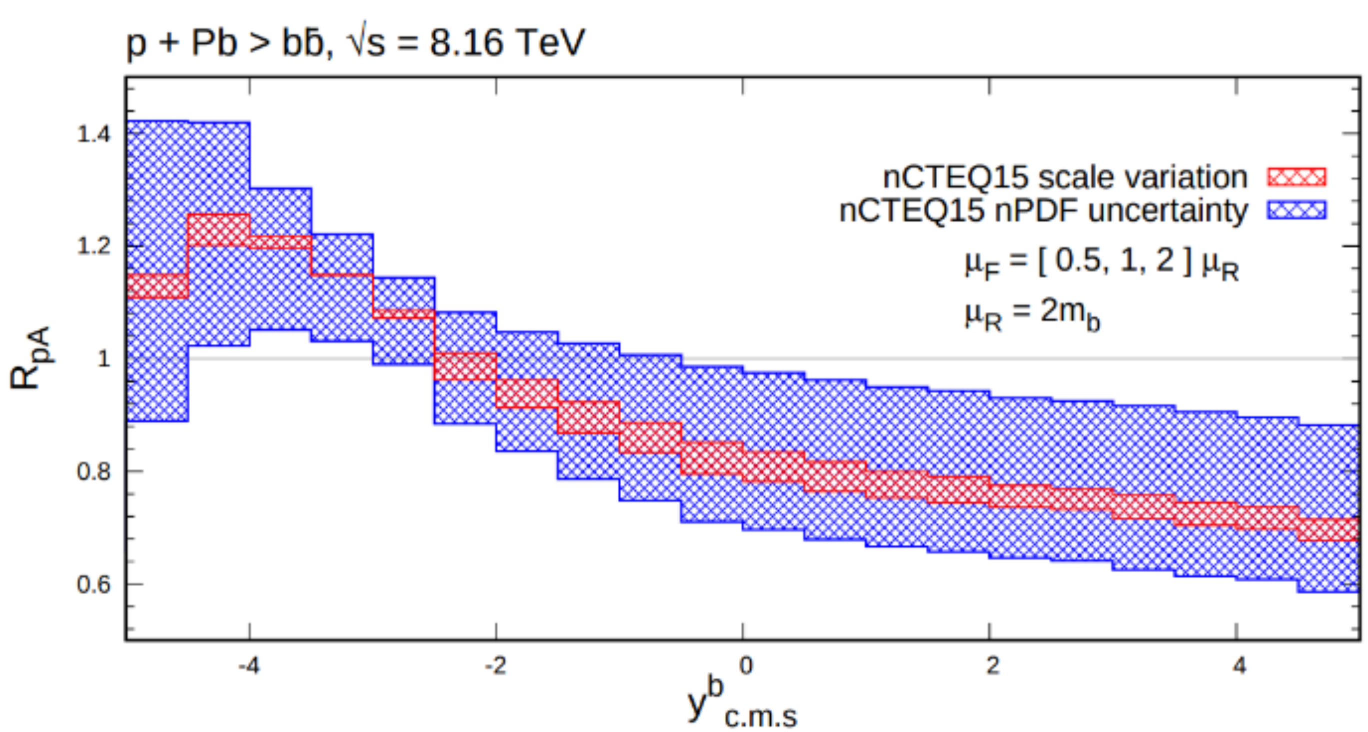
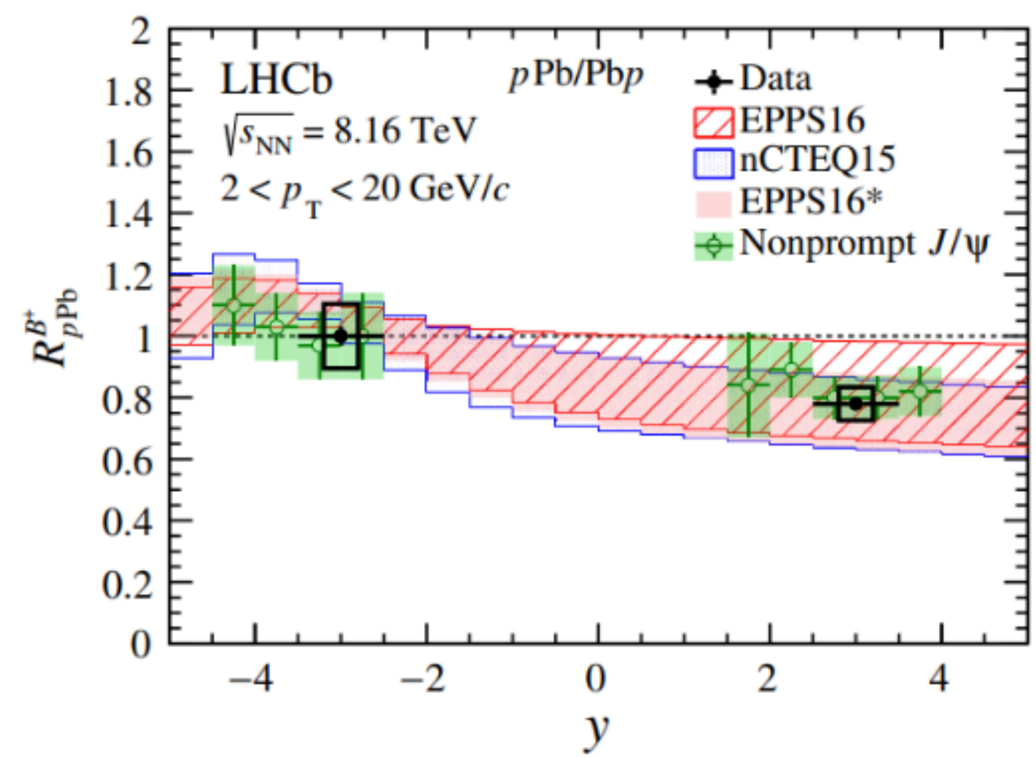
Example: bottom quark production in pPb collision at LHC





Phys. Rev. D99 no. 5, (2019) 052011, arXiv:1902.05599 [hep-ex].

-to generate plot need only the two LHAPDF IDs

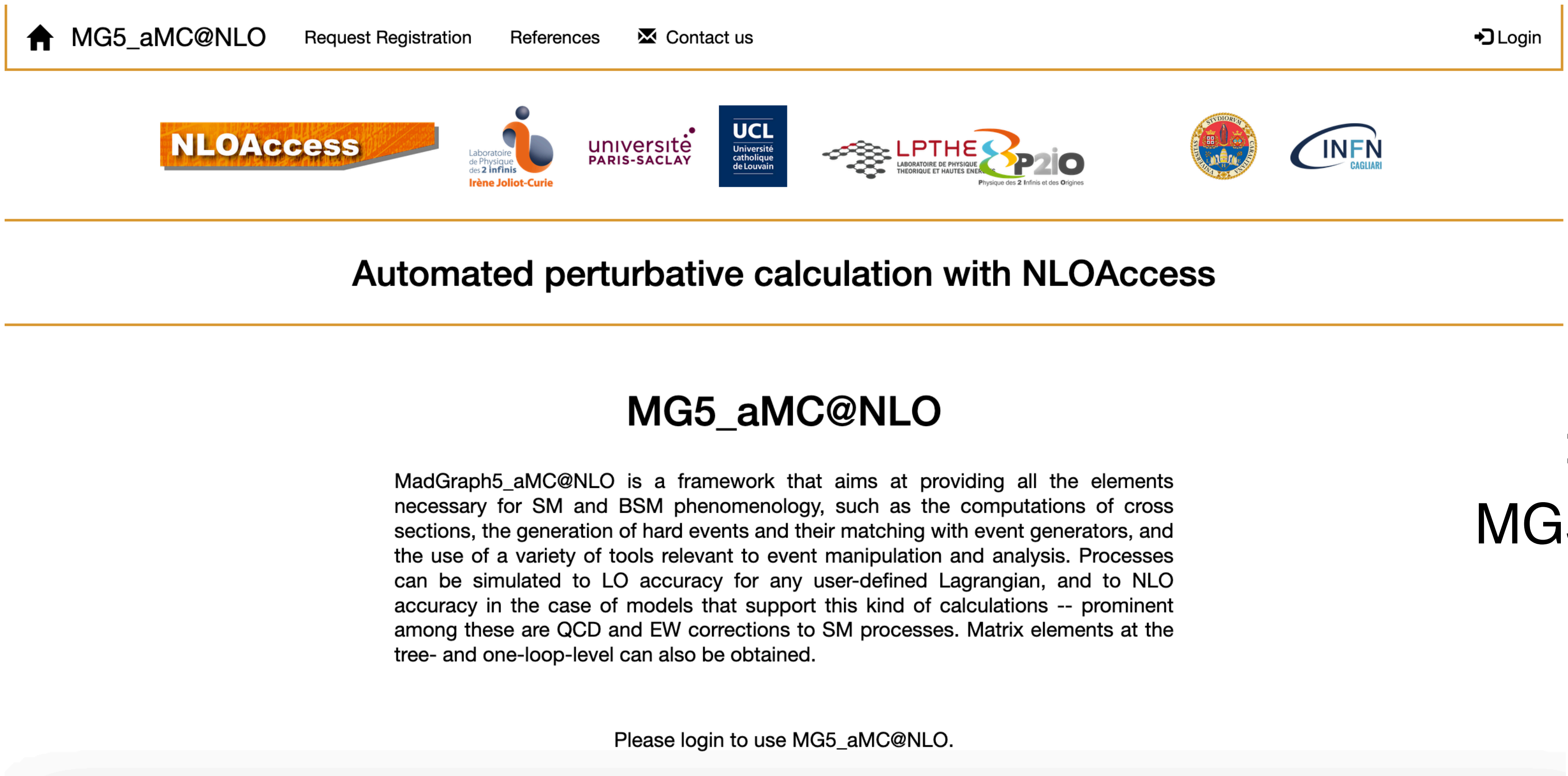
... scale uncertainty automatic

A. Safronov et al., PoS ICHEP2022 (2022) 494 (https://doi.org/10.22323/1.414.0494)

NLOAccess

(https://nloaccess.in2p3.fr/MG5/)

[work by C. Flore]



> HELAC-Onia and MG5_aMC@NLO included

- a **virtual access** for automated perturbative calculations for heavy ions and quarkonia
- any code that could be compiled and launched via bash could be added

- MadGraph5 online version was only limited to LO calculation
- NLOAccess offers access for the first time to full NLO SM online calculation with MG5_aMC@NLO!

Summary & Outlook

Summary

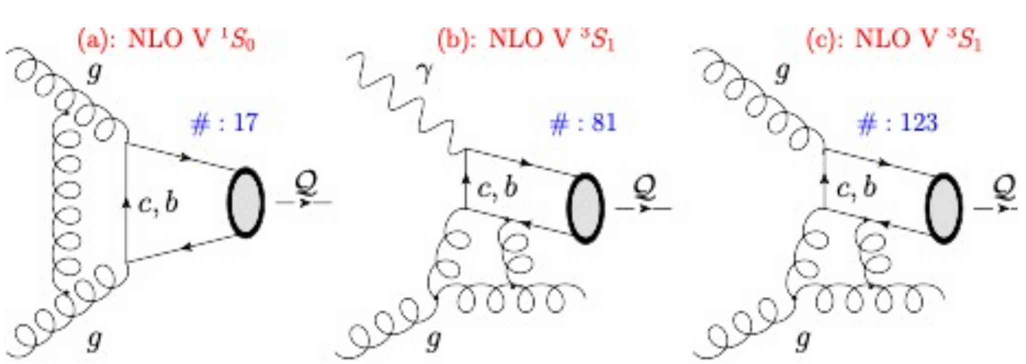
- Towards S-wave quarkonium cross sections @LO in MG5
- Photoproduction in eA collisions in MG5: https://github.com/mg5amcnlo/mg5amcnlo/tree/ep_collision
- Asymmetric hadron-hadron collisions in MG5: https://github.com/mg5amcnlo/mg5amcnlo/tree/RPA

Outlook

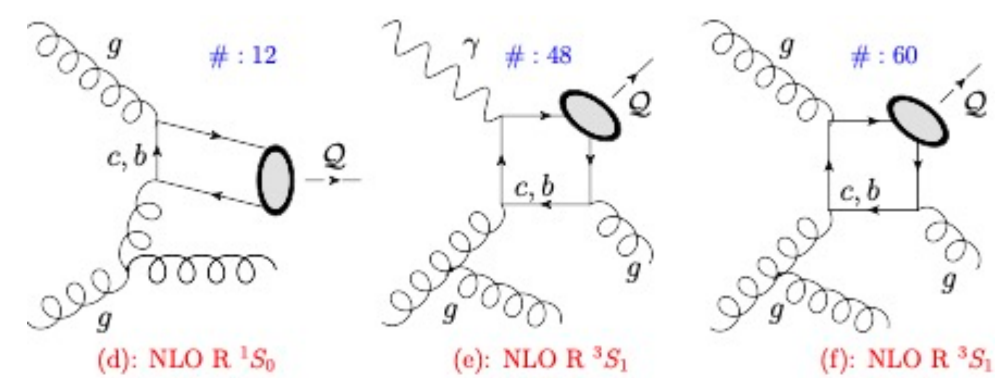
- Extension to states with leading **P wave** Fock states --> global NRQCD picture, and/or BSM. Ultimately **NLO** in mind with few caveats.

H-S. Shao, A. Hamed, L. Simon
arXiv:2402.19221

- Incorporation into EU virtual access project **NLOAccess**



Thank you

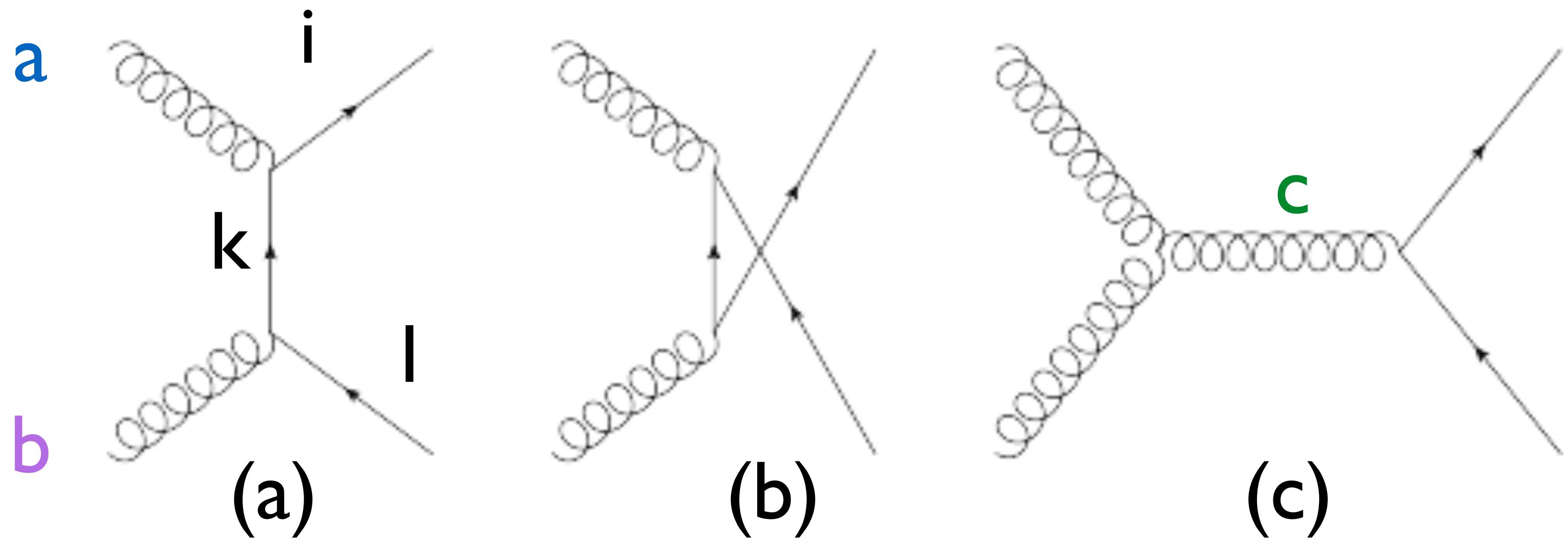


Amplitude generation & spin projectors

- 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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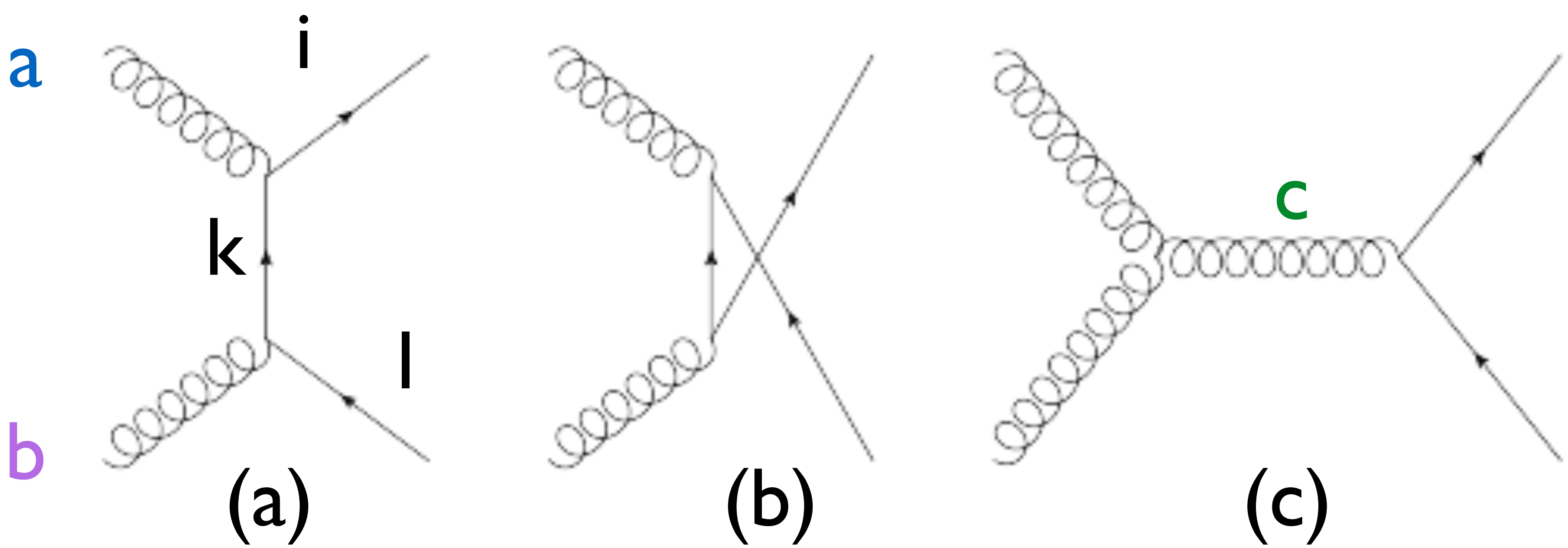

$$\mathcal{A} = A_a + A_b + A_c$$

$$A_a = c_1 A_{11}$$

$$A_b = c_2 A_{22}$$

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

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

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

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

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

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

Automation of quarkonium cross sections

Facilitates:

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- Physics cases for future experimental facilities
- Global NRQCD fits

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.

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[1] e.g. cross sections with quarkonium in jets JHEP 06 (2016) 121