28/09/23

Quarkonium quests with inclusive and exclusive productions

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CNRS, IJCLab,
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Background

- Integrated Masters (MPhys) Mathematical Physics

  2011-2016

- Ph.D. '*Exclusive Observables to NLO and low x PDF phenomenology at the LHC*'.

  Thesis advisor: Prof. Thomas Teubner

  2016-2020

- Postdoc #1: QCD Theory group @ The University of Jyväskylä

  2020-2022

- Postdoc #2: Theory Department @ IJCLab, CNRS, Université Paris-Saclay

  2022-present

Research themes

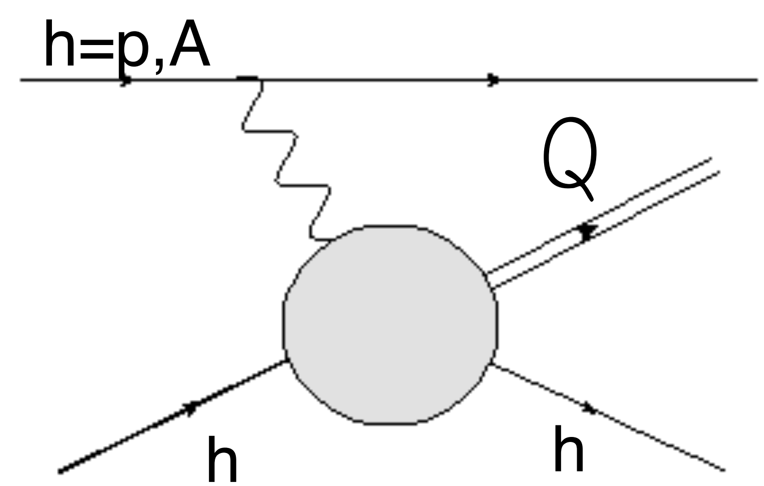
Exclusive heavy vector meson V production $\mathcal{Q}=\mathcal{V}=\ J/\psi, \Upsilon, \psi(2S), \ldots$

Exclusive

$$p + p \to p + V + p$$

$$p + A \to p + V + A$$

$$A + A \to A + V + A$$



automation

NLO

global fits

resummation

Quarkonia Q

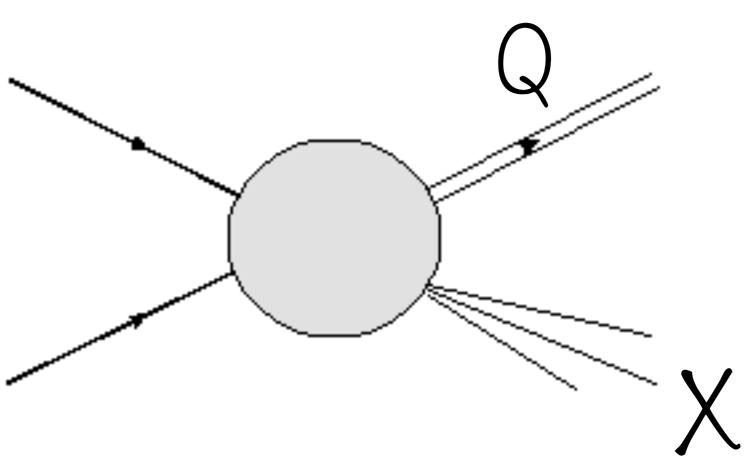
factorisation

NRQCD

stability

Inclusive quarkonium production

e.g. $p + p \to \mathcal{Q} + X$



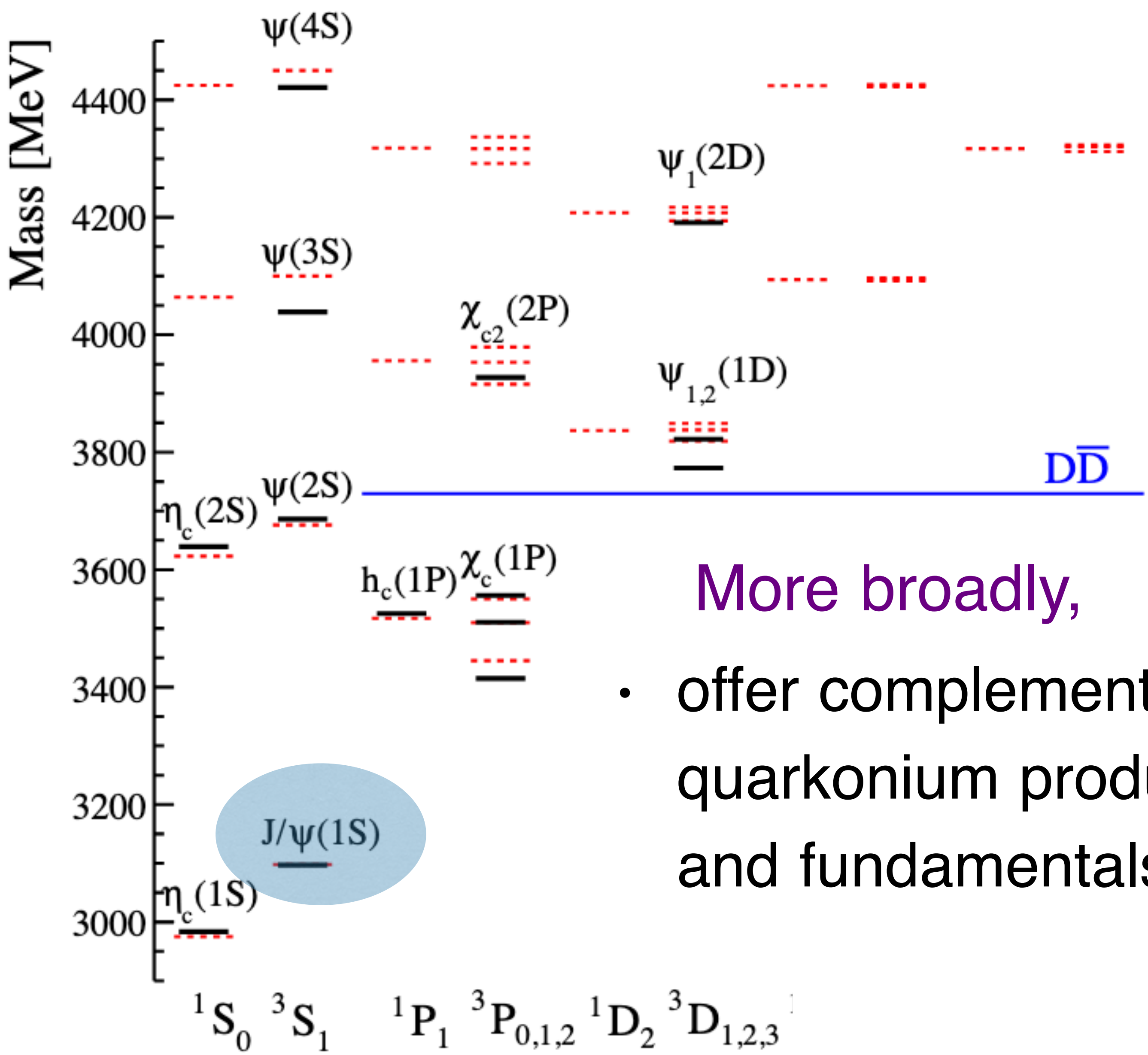
-Madgraph5_aMC@NLO

Inclusive

Introduction - why quarkonia?

Charmonium hierarchy

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



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

More broadly,

- offer complementary information on quarkonium production mechanisms and fundamentals of QCD

underpin the search

on saturation at the upcoming

EIC and provide constraints on e.g.

the QGP.

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

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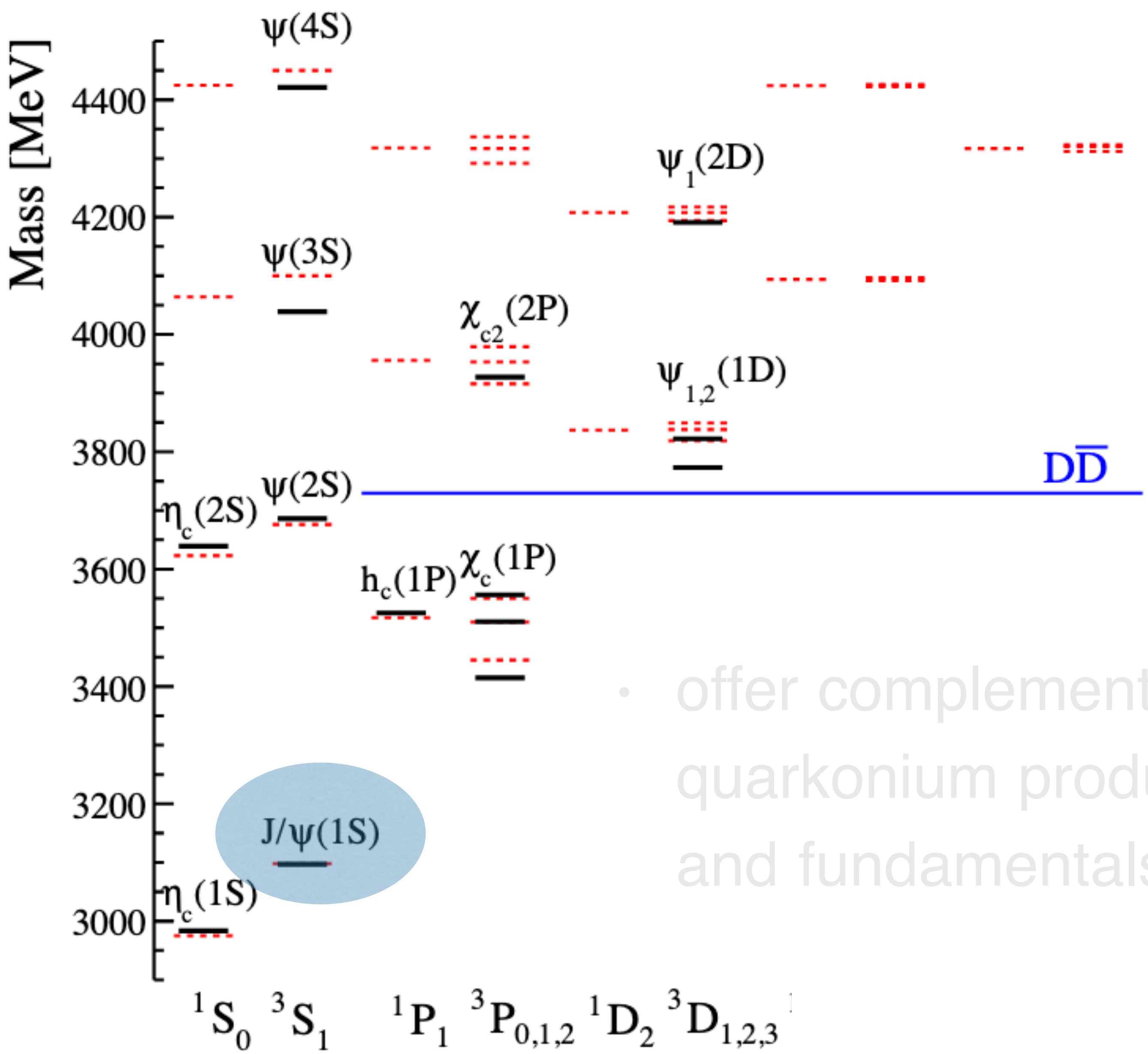

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e.g. gluon PDF constraints at low mom. fractions and res. scales

• offer complementary information on quarkonium produc... and fundamentals of QCD

• are expected to underpin the search for gluon saturation at the upcoming EIC and provide constraints on e.g. the QGP.

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

'Inclusive' quests

Quarkonium production

Factorisation:

proton PDFs (non-pert.)

$$\sigma(pp \to \mathcal{Q} + X) = \sum_{i,j,n} \int dx_1 dx_2 f_{i/p}(x_1) f_{j/p}(x_2)$$

$$\times \hat{\sigma}(ij \to Q\bar{Q}[n] + X) \langle \mathcal{O}_n^{\mathcal{Q}} \rangle,$$

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

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

short-distance matrix element (pert.)

long distance matrix element (non-pert.)

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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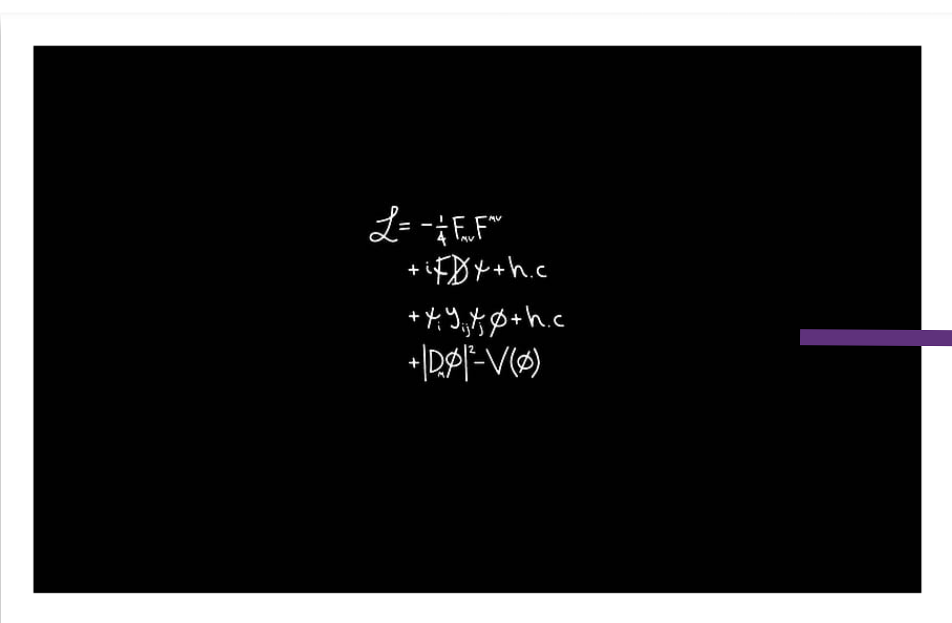
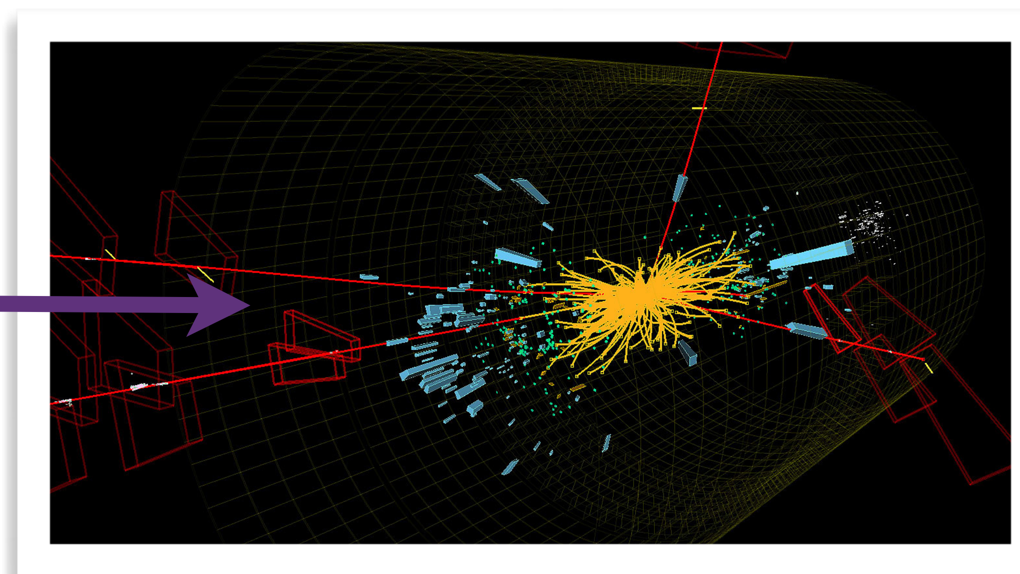
MadGraph5_aMC@NLO

- 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..

MadGraph5_aMC@NLO

- 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

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

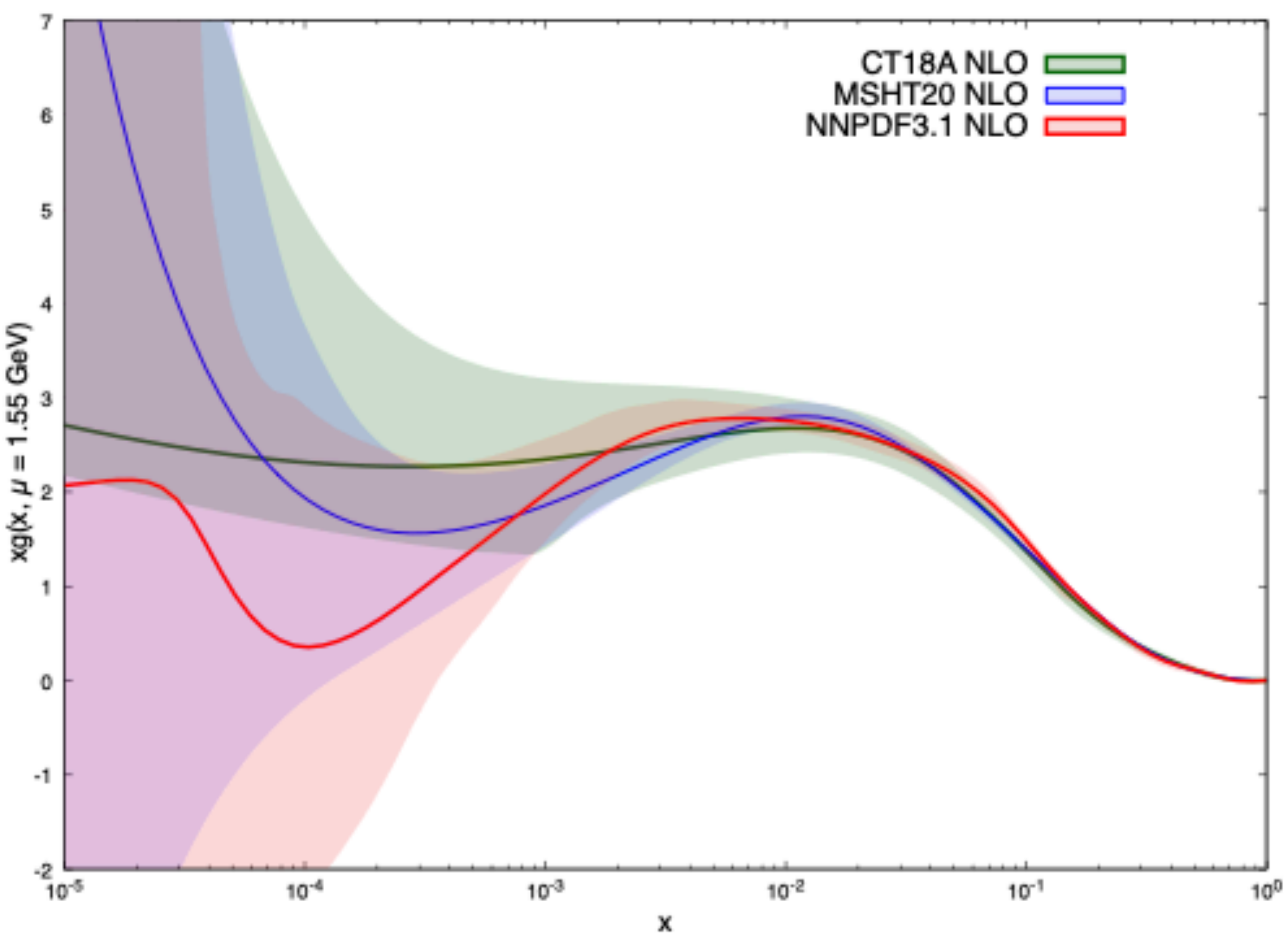
✓

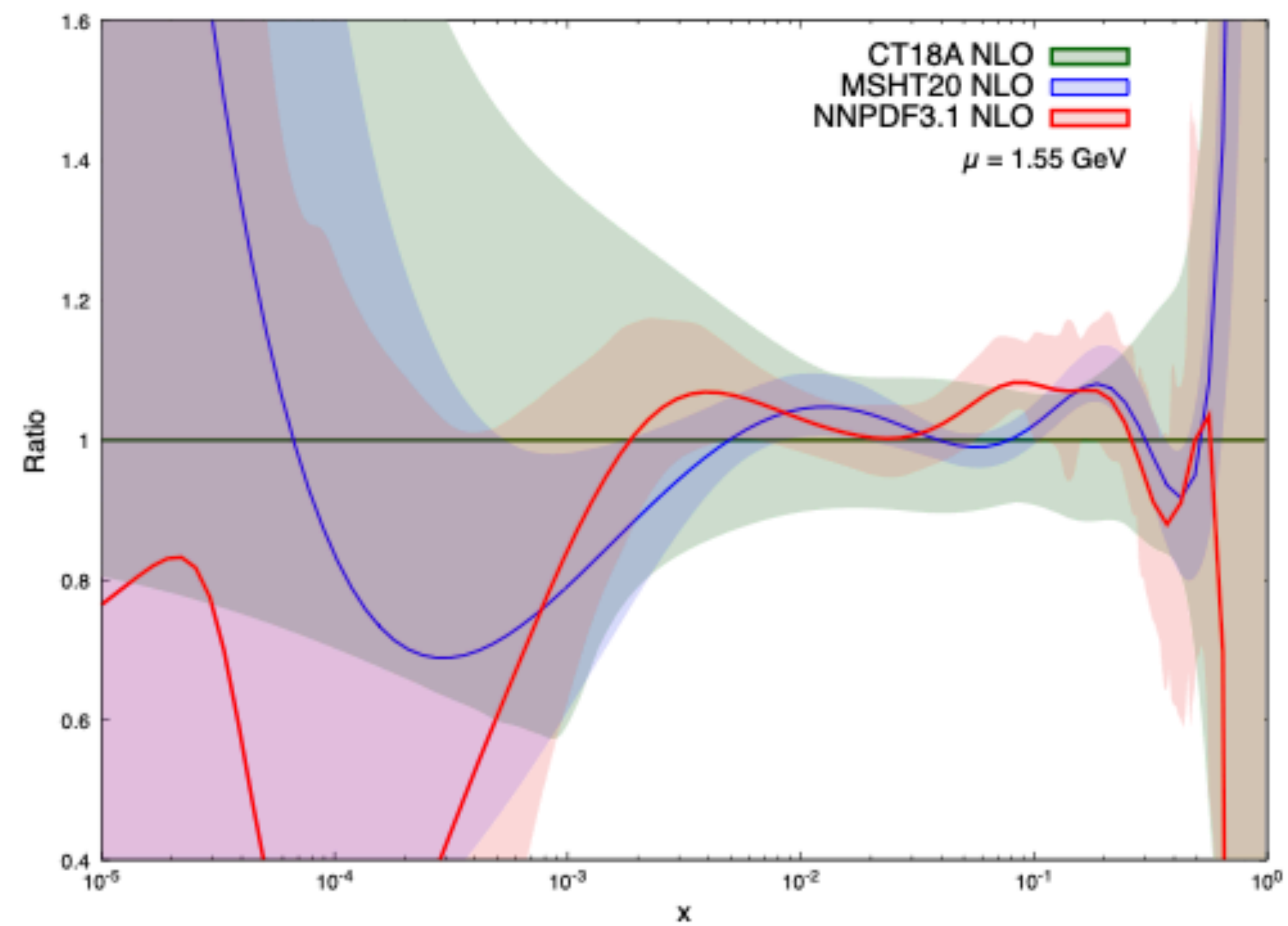
*famous resolution of non-cancelling IR divergences through mixing of P wave states with relevant S wave states at $O(v^2)$

'Exclusive' quests

Introduction

- Inclusive processes do not well constrain small x/Regge limit domain of PDFs
- Exclusive processes offer sensitive probe of this domain but as of yet not included in global analyses PDF determination – why?
    1. Off forward kinematics imply sensitivity to GPD over conventional PDFs
    2. Scale dependence and stability of theoretical predictions





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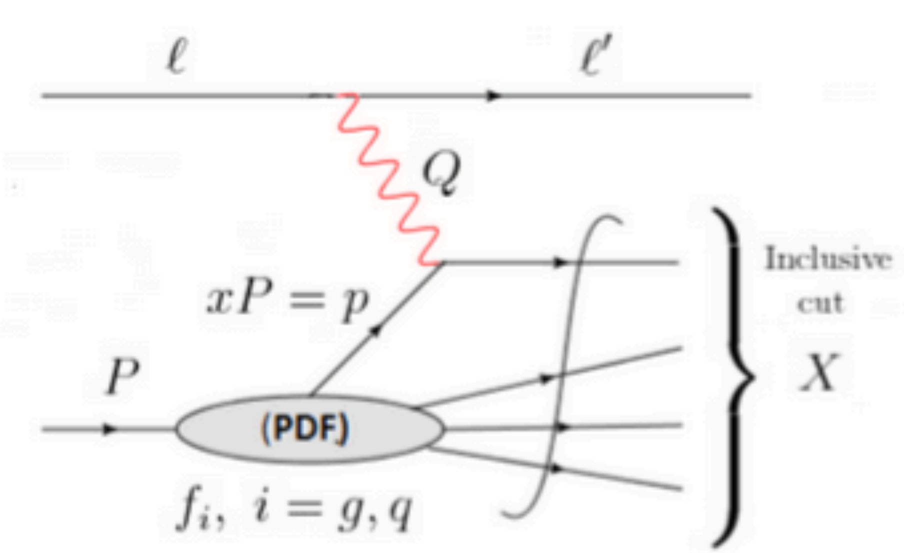
- As higher CM energies are realised at LHC, pushed towards small x domain, W ~ 1/x

LLx exclusive J/psi production:

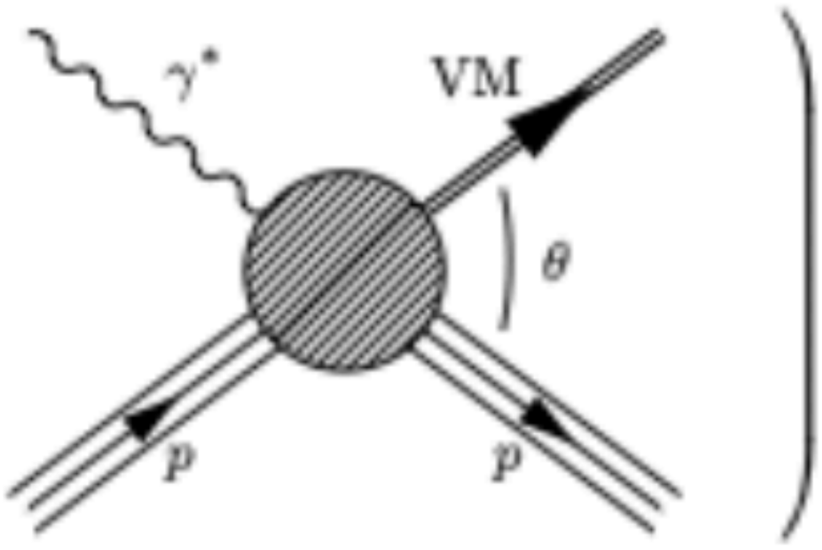
Ryskin 1993

$$\frac{d\sigma}{dt}(\gamma^* p \to J/\psi p)\Big|_{t=0} = \frac{\Gamma_{ee}^{J/\psi} M_{J/\psi}^3 \pi^3}{48\alpha_{\rm em}} \left[\frac{\alpha_s(\bar{Q}^2)}{\bar{Q}^4} \; xg(x,\bar{Q}^2)\right]^2 \left(1 + \frac{Q^2}{M_{J/\psi}^2}\right)$$

Inclusive – e.g. DIS included in global parton analyses



Exclusive – can we use the data?



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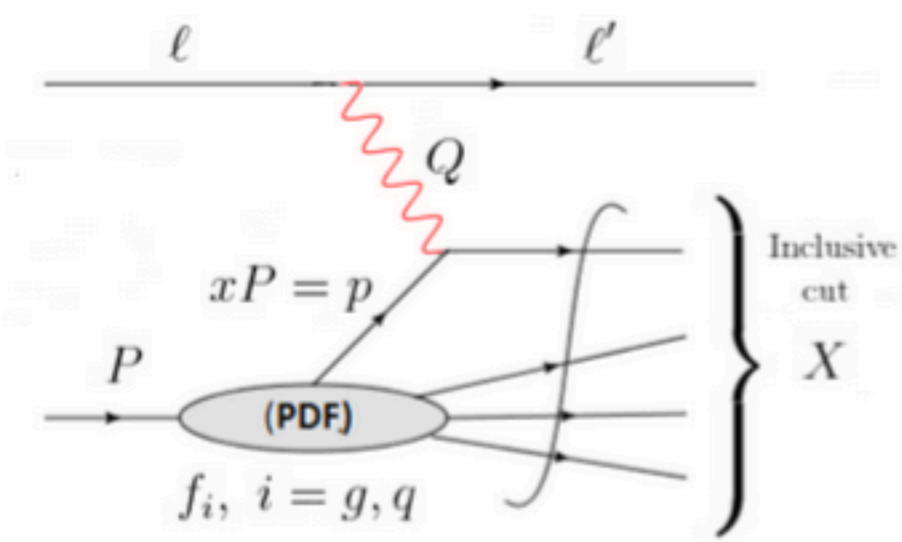

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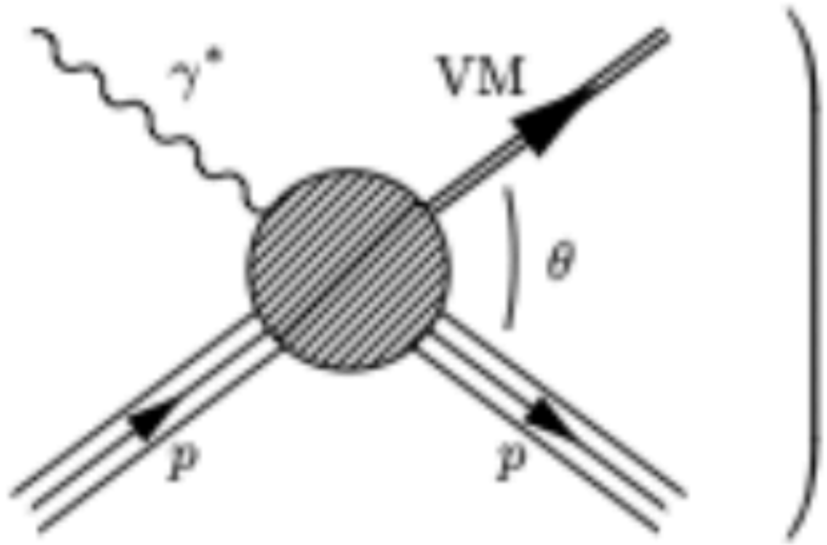

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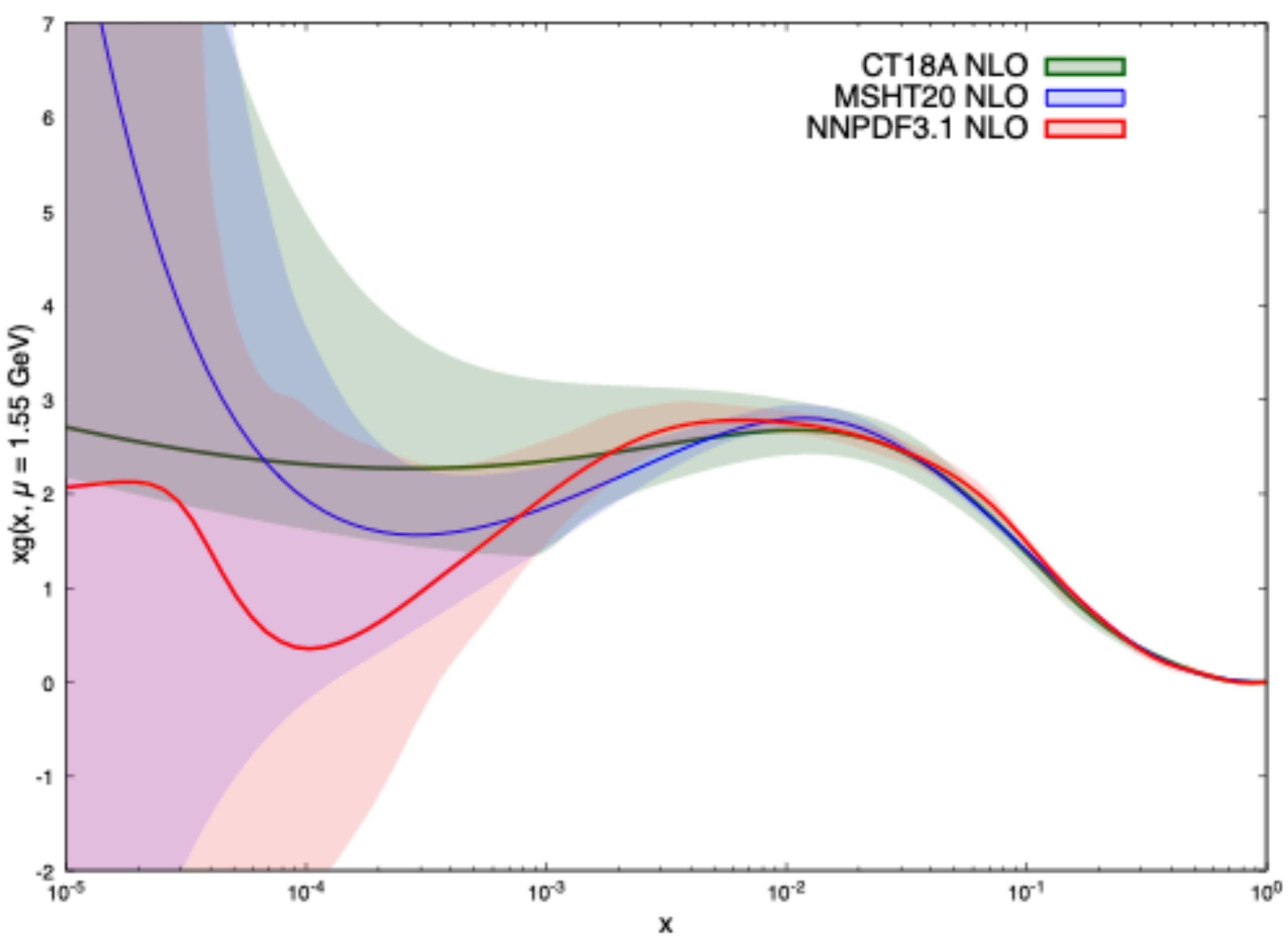
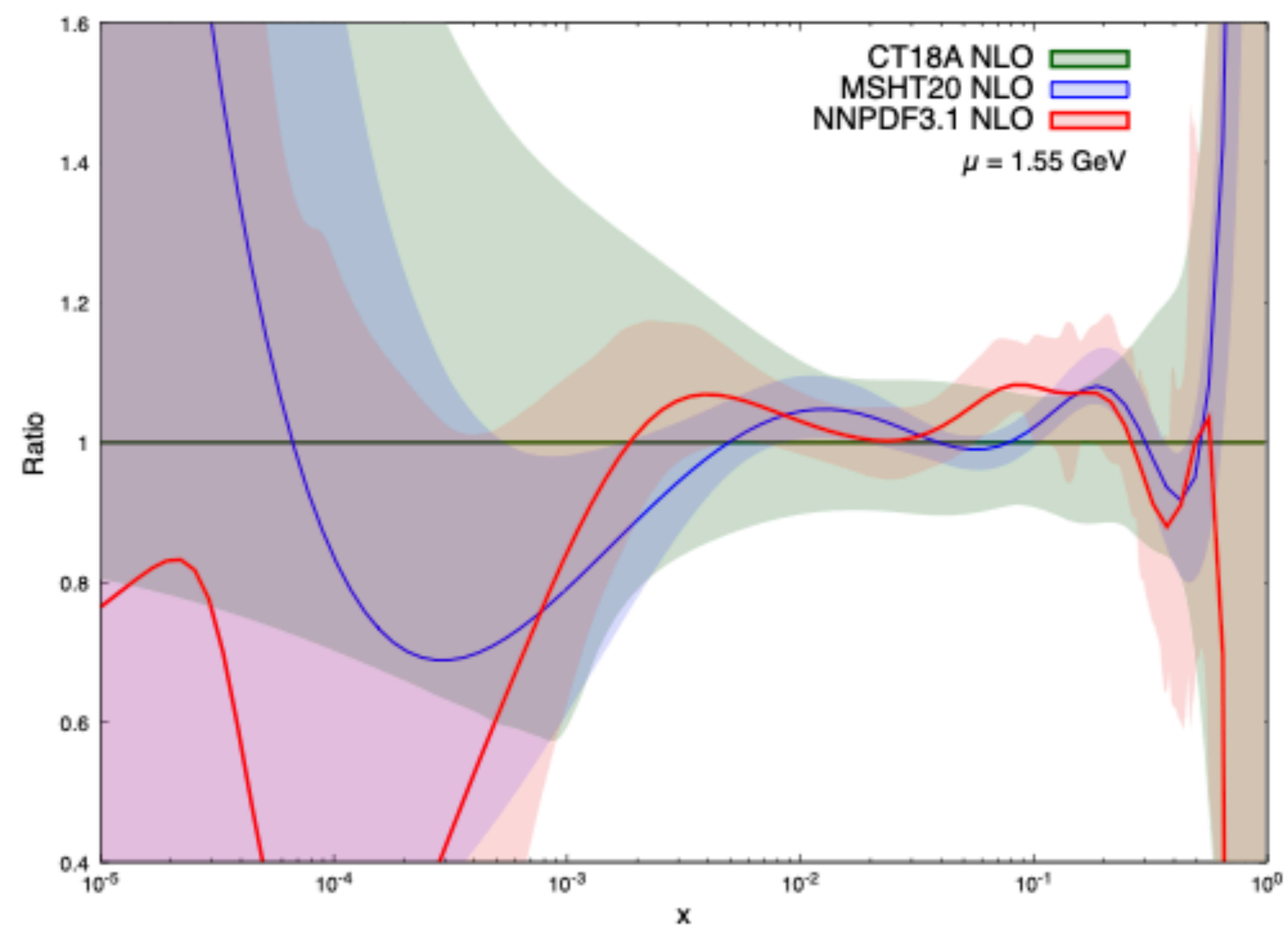
  2. Scale dependence and stability of theoretical predictions

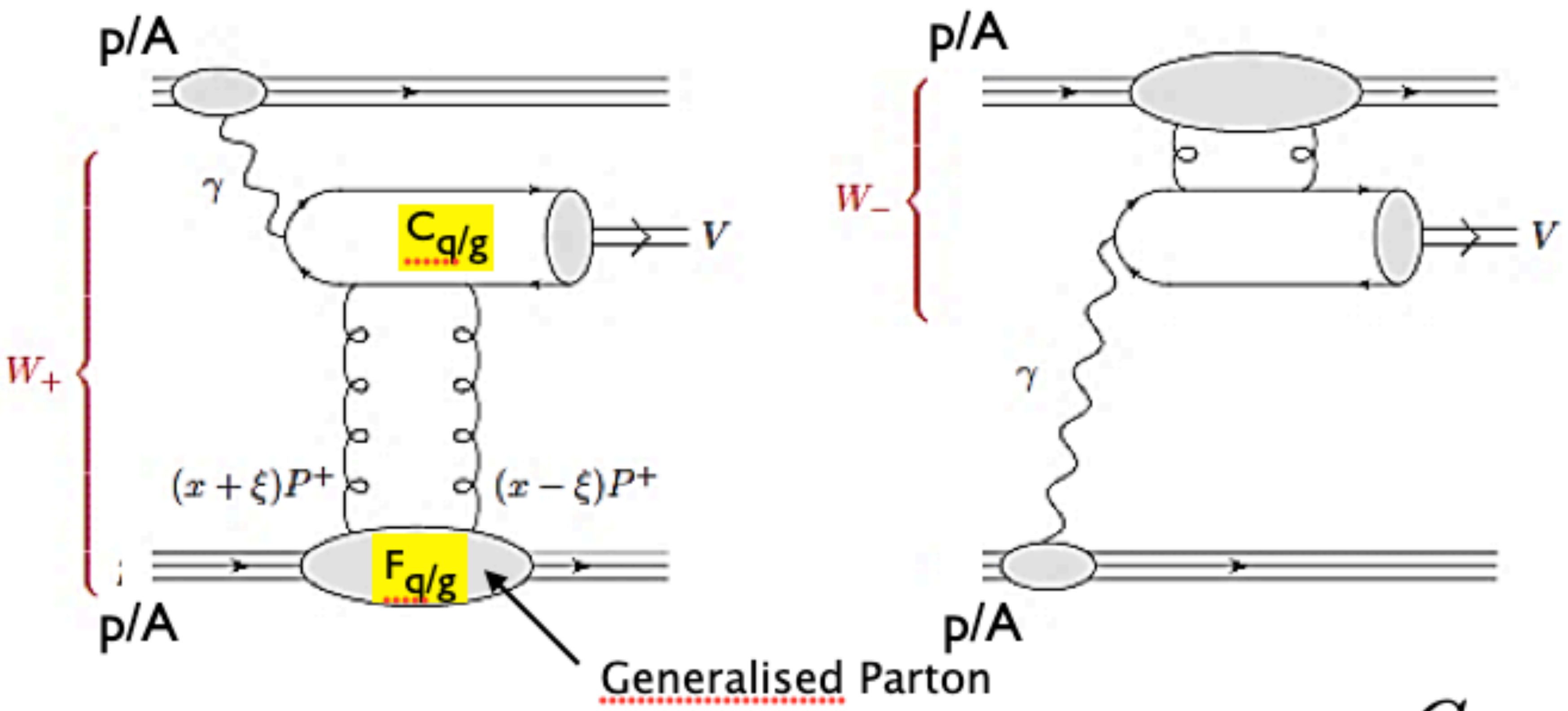
Scope: how to counteract these problems and so allow exclusive J/psi data to probe gluon PDF down to $x \sim 3 \times 10^{-6}$ & $\mu = O(M_{J/\psi}/2)$





General Set up and Framework

Exclusive J/psi photoproduction in p+p (A+A) UPC collisions in collinear factorisation



Setup for $\gamma p \to J/\psi p$ follows:
Ivanov, Schäfer, Szymanowski, Krasnikov, 04

$C_{q/g}$

Photoproduction:

- hep-ph/0401131

Ivanov, Schäfer, Szymanowski, Krasnikov, 04

Electroproduction:

- arXiv:1903.00171
- arXiv:2105.07657

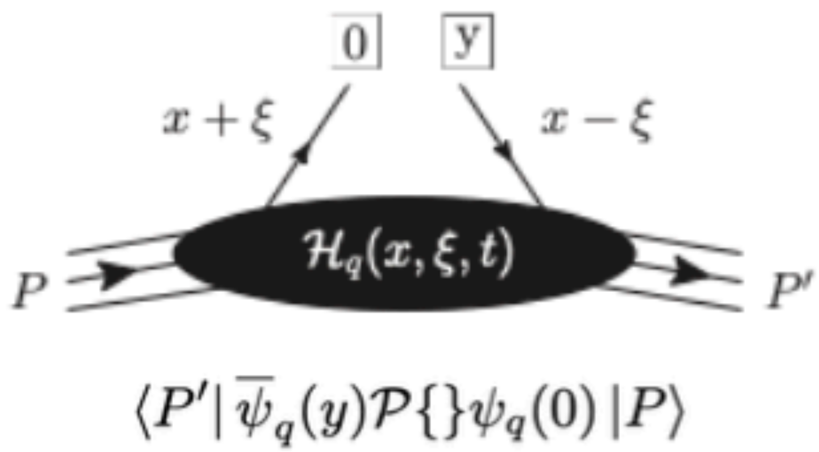
Chen, Qiao, 19
CAF, Gracey, Jones, Teubner, 21

- Factorisation: $F_{q/g} \otimes C_{q/g} \otimes \phi^V_{Q\bar{Q}}$
- Leading zeroth order term in rel. velocity (NRQCD)
- Colour singlet exchange between hard and soft sectors

$$A \propto \int_{-1}^{1} \mathrm{d}x \left[C_g(x,\xi)F_g(x,\xi) + \sum_{q=u,d,s} C_q(x,\xi)F_q(x,\xi) \right]$$

GPDs and the Shuvaev transform

GPDs generalise PDFs: outgoing/incoming partons carry different momentum fractions *Müller 94; Radyushkin 97; Ji 97*



Shuvaev: Relates GPDs to PDFs at small x under physically motivated assumptions c.f analyticity

Shuvaev 99   Martin et al. 09

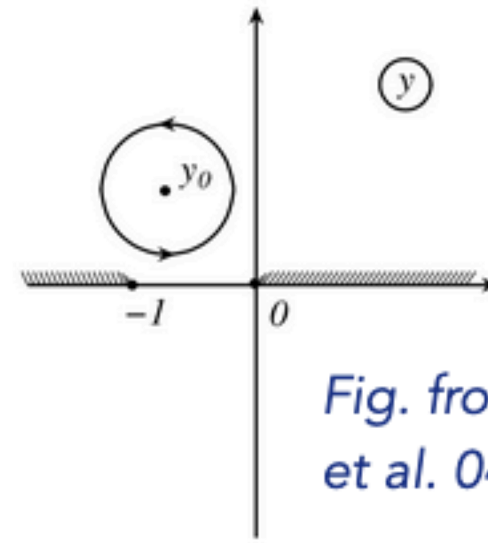


Fig. from Ivanov et al. 04

Idea: Conformal moments of GPDs = Mellin moments of PDFs
(up to corrections of O(xi^2) @ LO and O(xi) @ NLO)

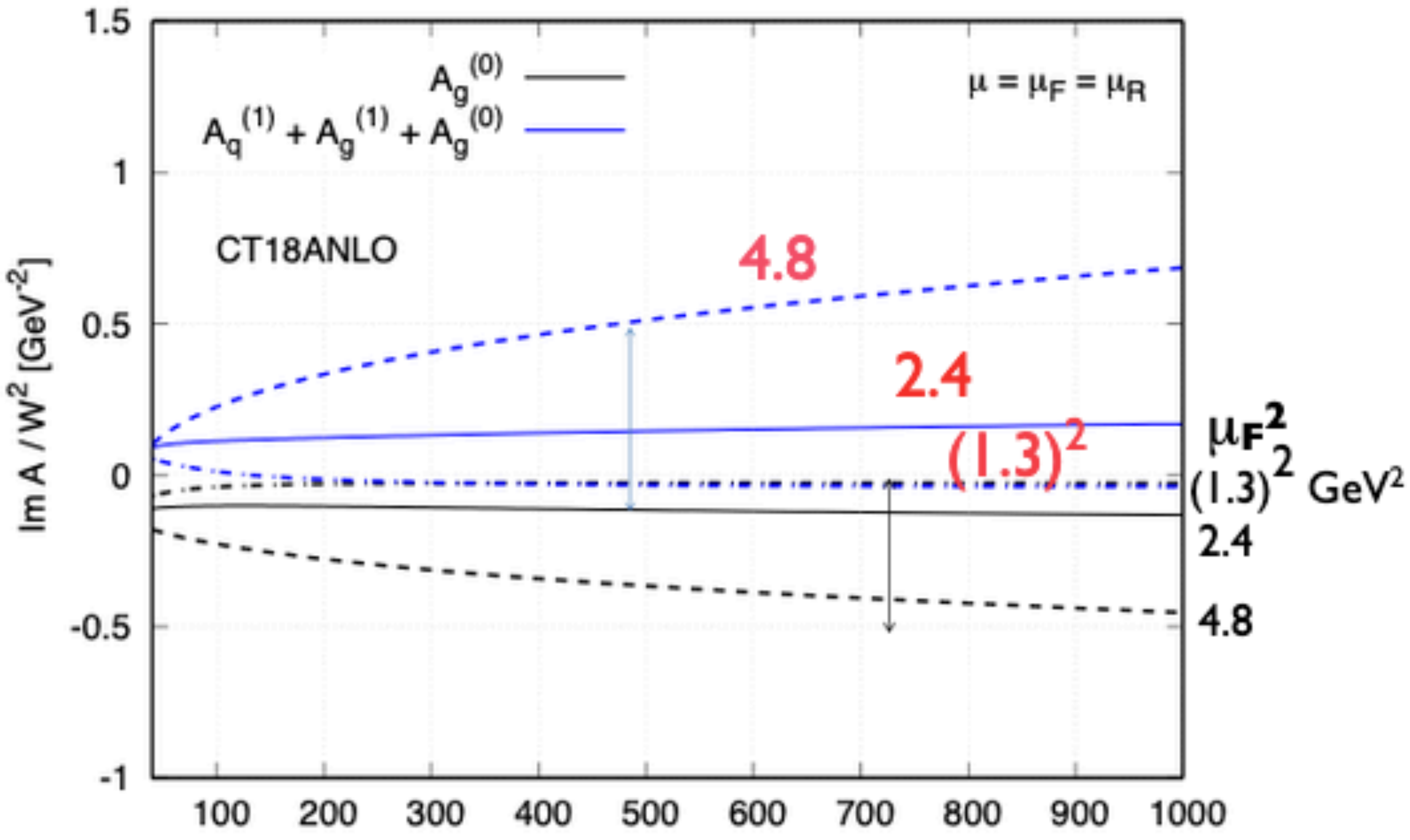
- Construct GPD grids in multidimensional parameter space x, xi/x, qsq with forward PDFs from LHAPDF
- Costly computationally due to slowly converging double integral transform
- Regge theory considerations => Shuvaev transform valid in space-like (DGLAP) region only. In time-like (ERBL) region imaginary part of coefficient function is zero

Stability of NLO prediction I+II

NLO in MSbar scheme

hep-ph/0401131

A. Bad perturbative convergence |$NLO_{correctn.}$| > |LO| and
B. Strong dependence on scale μ_F opp. sign



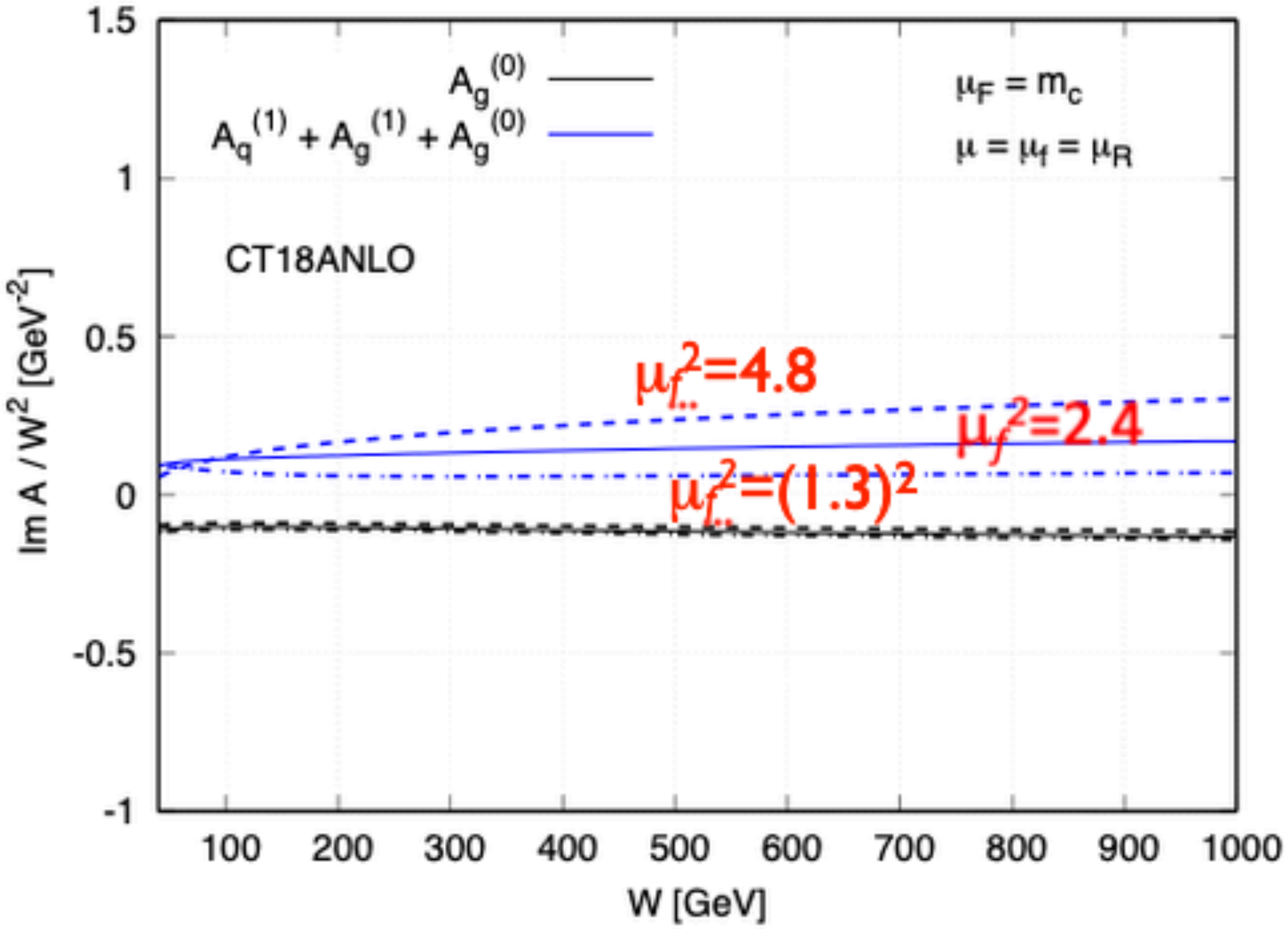
γp CM Energy → W [GeV]

'Effective' small−x resummation

1507.06942

Resummation of

$(\alpha_S \ln(1/\xi)\ \ln(\mu_F/m))^n$



Stability of NLO prediction II+III

'Effective' small-x resummation

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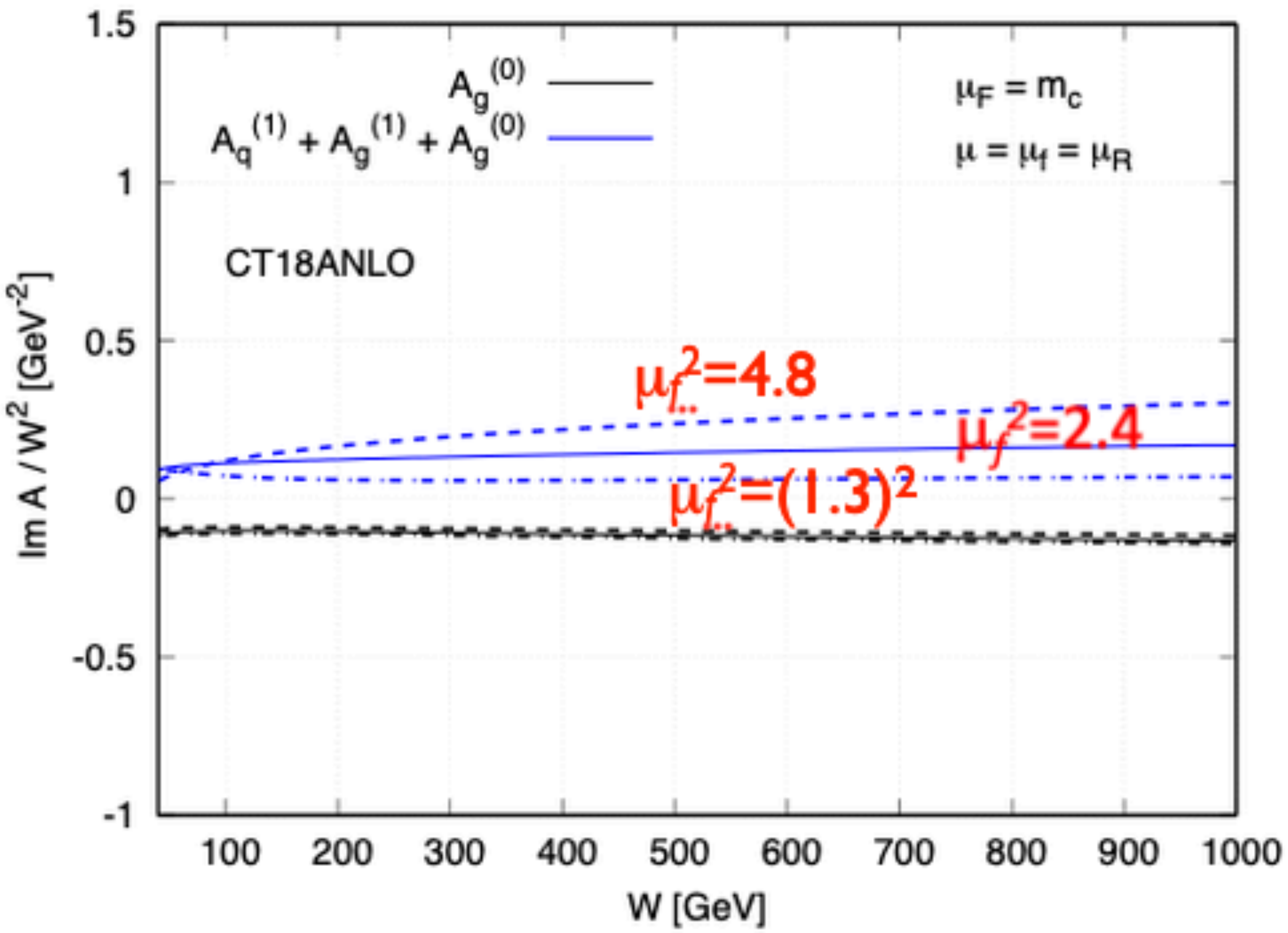
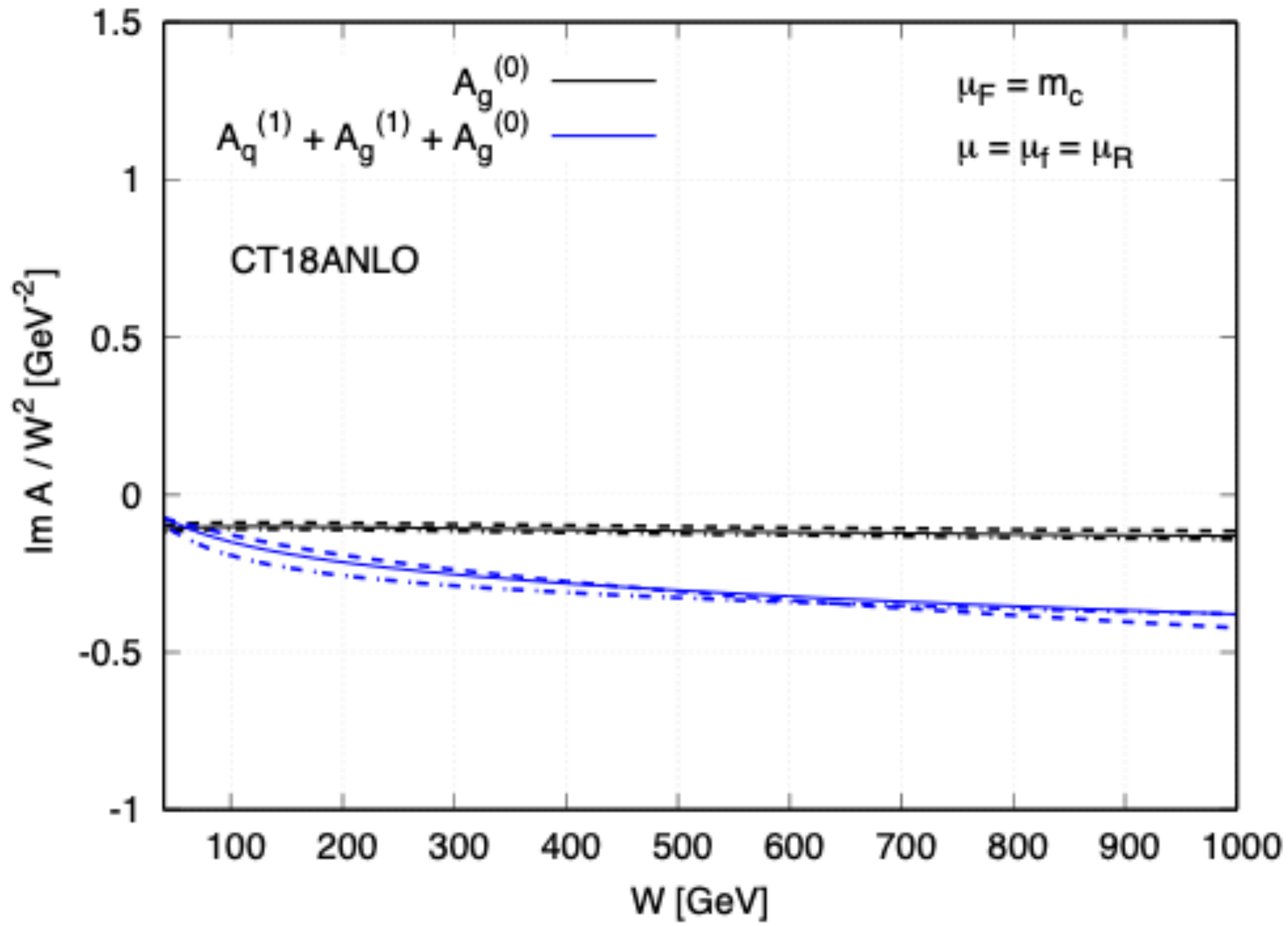
Resummation of $(\alpha_S \ln(1/\xi) \ln(\mu_{F/m}))^n$



Low $l_t < Q_0$ subtraction

1610.02272

Subtract DGLAP contribution NLO ($|\ell^2| < Q_0^2$) from known NLO MSbar coefficient function to avoid a double counting with input GPD at Q_0.



Predictions based on three global PDF analyses differ dramatically in large energy LHC region but are compatible in lower energy HERA region*

Extraction of low x gluon PDF via exclusive J/psi

Left

Approach 1: Fit a low x gluon PDF ansatz to the data

Right

Approach 2: Bayesian reweight current global PDF analyses

	λ	n	$\chi^2_{\rm min}$	$\chi^2_{\rm min}$/d.o.f
NNPDF3.0	0.136	0.966	44.51	1.04
MMHT14	0.136	1.082	47.00	1.09
CT14	0.132	0.946	48.25	1.12

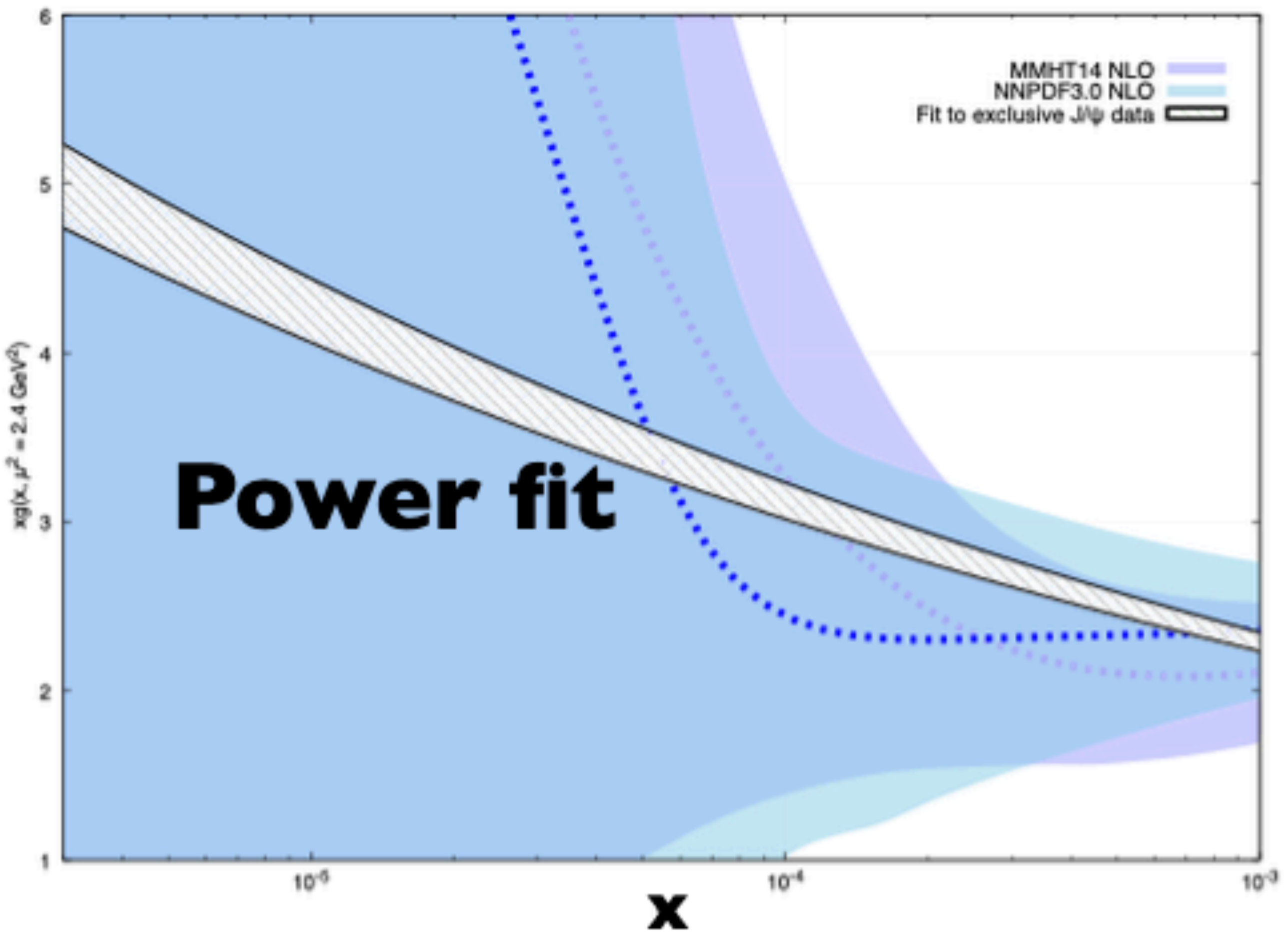
$$xg^{\rm new}(x,\mu_0^2) \;=\; nN_0\,(1-x)\,x^{-\lambda}$$

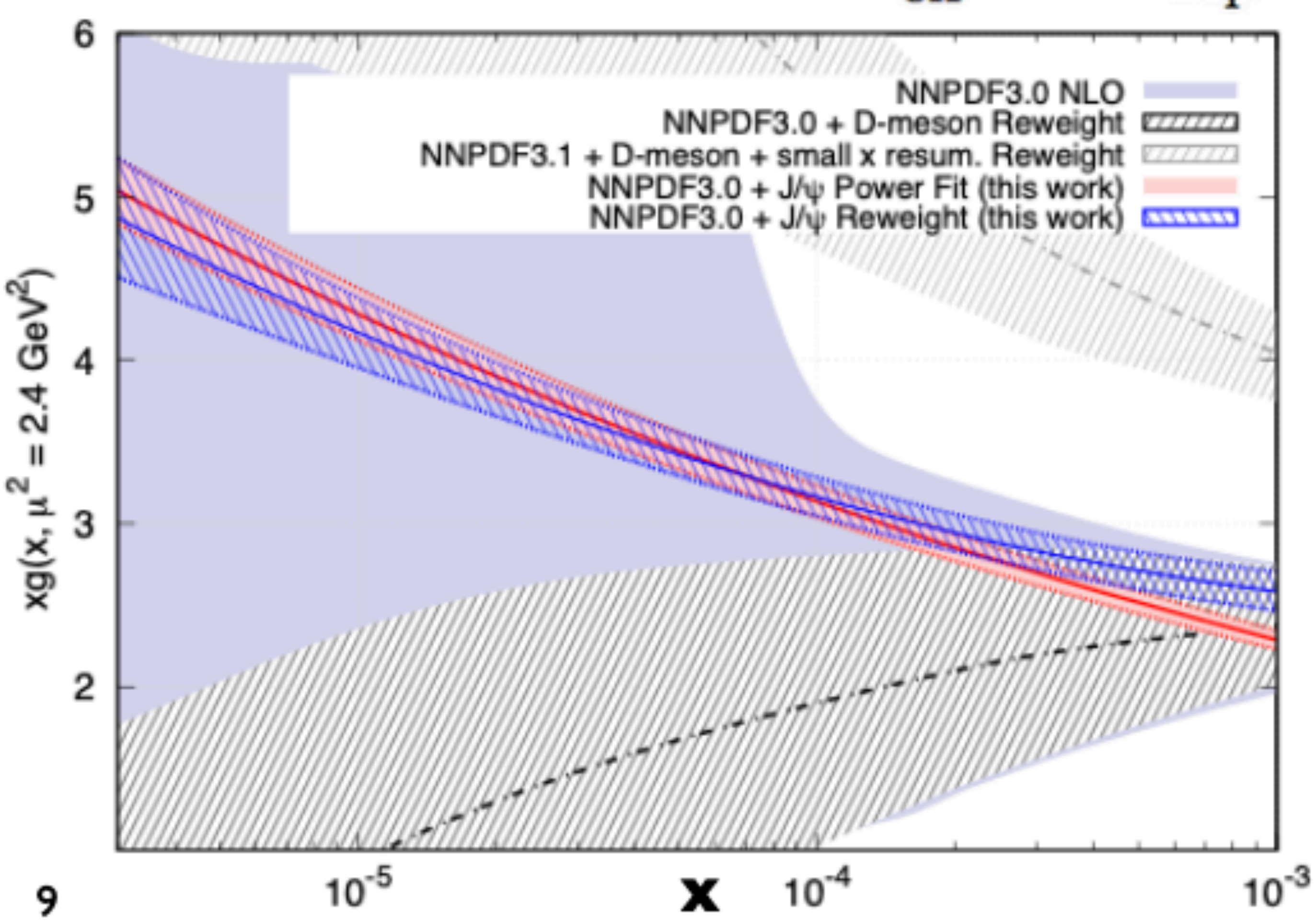
lambda = 0.136 +/- 0.006

n = 0.966 +/- 0.025

CAF, Martin, Ryskin, Teubner 2006.13857

$N_{\rm eff} \ll N_{\rm rep}$



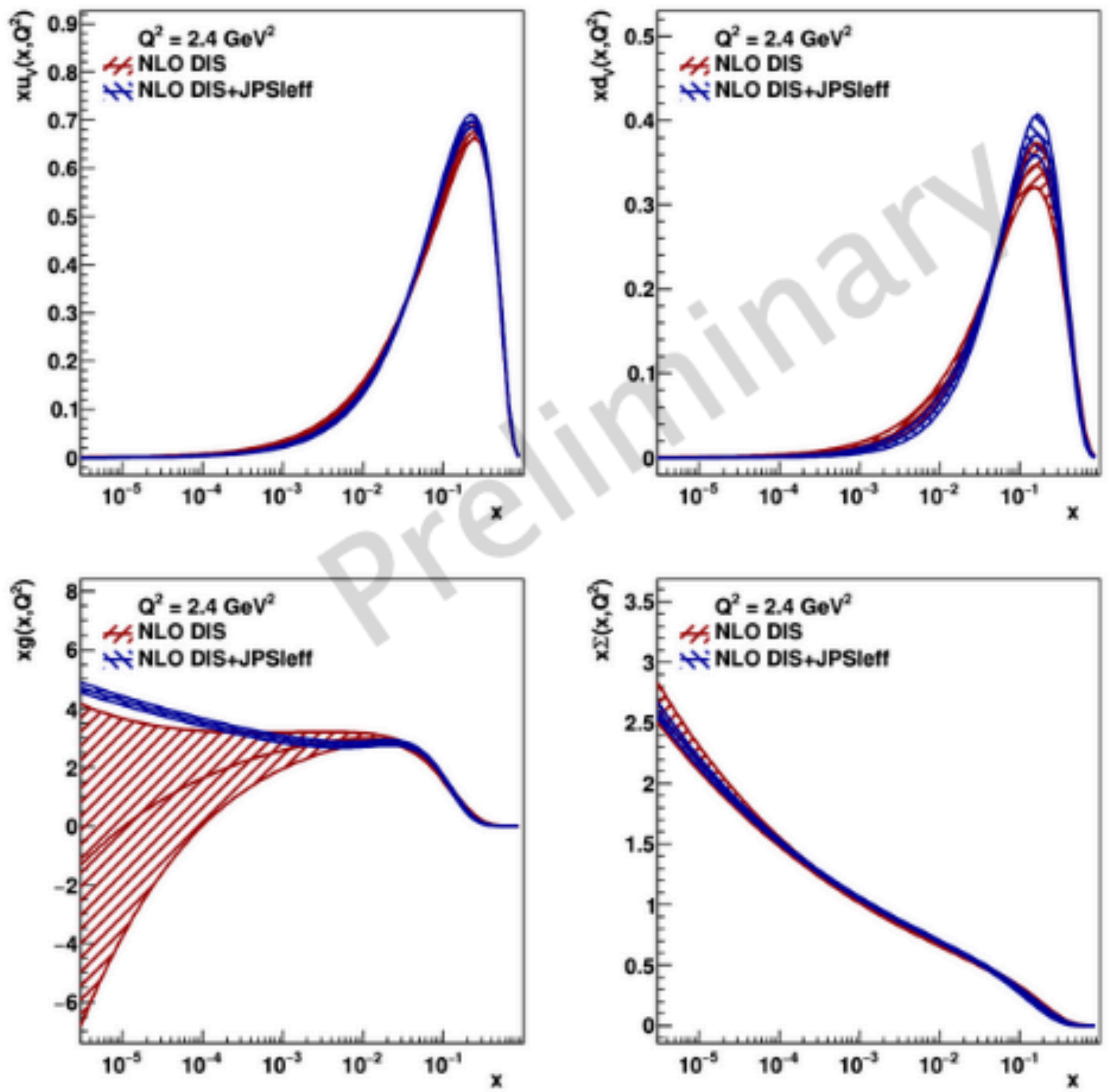


xFitter implementation and next steps

- Incorporate new 'JPSI' reaction via xFitter's ReactionTheory class
  - i) PDF profiling w/ exclusive J/psi data and
  - ii) PDF fitting w/ exclusive J/psi+HERA DIS RunI+II datasets
  - iii) PDF fitting with generated gluon PDF pseudo-data

default DIS:
chi2=1357/1131
~1.19

DIS+JPSIeff:
chi2=1400/1151
~1.22



Summary & Outlook

Summary

- Towards full implementation of LO inclusive quarkonium + associated production for **S wave** Fock states in MG5. Incorporation into EU virtual access project **NLOAccess**
- First fitting results using **xFitter** integrated with framework with tamed collinear factorisation at NLO for exclusive J/psi photoproduction

Outlook

- Extension to states with leading **P wave** Fock states --> global NRQCD picture, and/or BSM
- Ultimately NLO in mind with few **caveats**.
- Predictions for exclusive J/psi photoproduction employing HEF-CF **matching** formulae and **full** GPD evolution

Thank you

Automation of quarkonium cross sections

Facilitates:

- Global data/theory comparisons
- 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.

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

Automation of quarkonium cross sections cont.

Motivated:

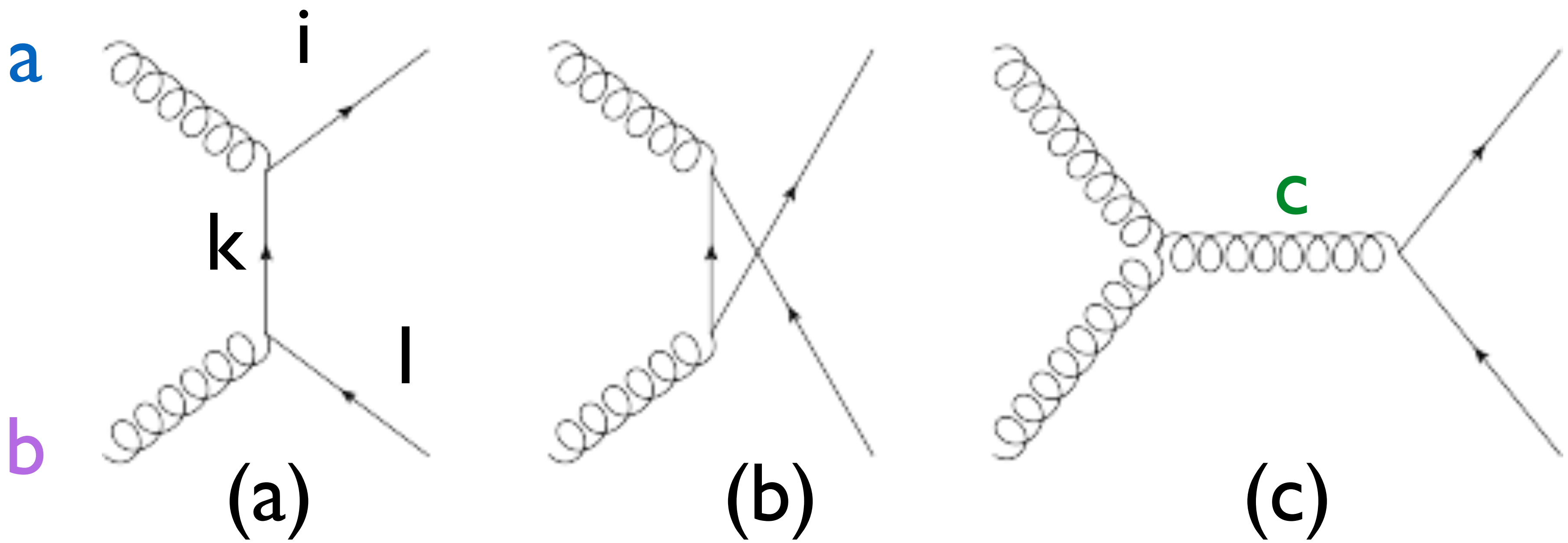
Tool	Features
• MadOnia Artoisenet, Maltoni, Stelzer JHEP 02 (2008) 102	(Deprecated) module within MadGraph4 - was not ported to current version (v5) Single quarkonium production phenomenology
• Helac-Onia Shao Comput.Phys.Commun. 184 (2013) Comput.Phys.Commun. 198 (2016)	One or more S-wave and/or P-wave 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)

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)



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

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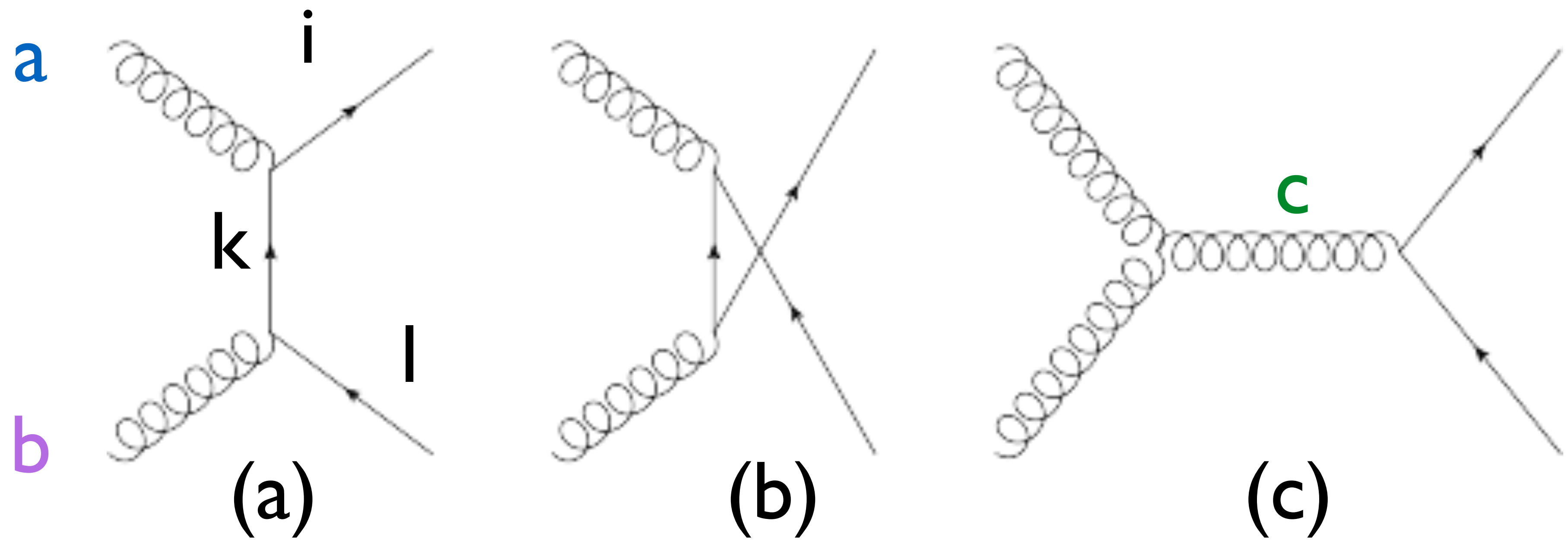

$$\mathcal{A} = A_a + A_b + A_c$$

$$A_a = c_1 A_{11}$$

$$\text{CO}: c_1 = \text{Tr}(t^a t^b t^c) \qquad A_b = c_2 A_{22}$$

$$c_2 = \text{Tr}(t^b t^a t^c) \qquad A_c = c_1 A_{31} + c_2 A_{32}$$

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

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

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

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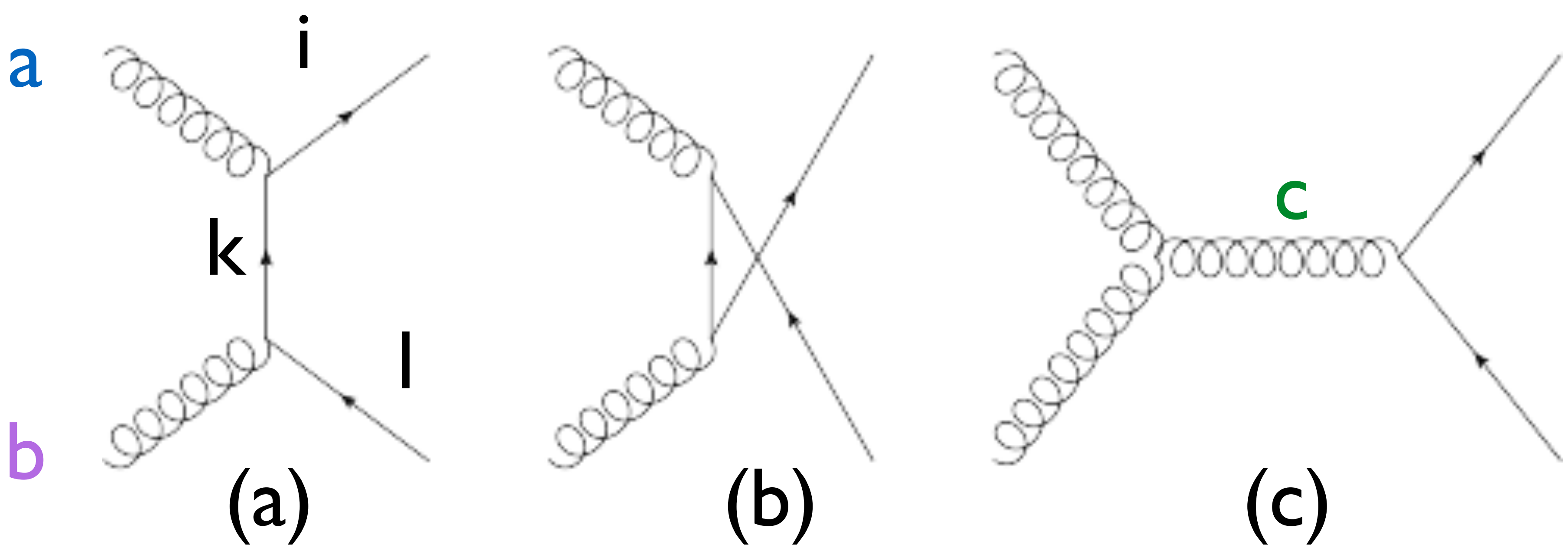


- Colour projectors for ***m*** colour singlet and octet quarkonia production and associated productions implemented.

- madgraph/core { color_algebra.py, color_amp.py, helas_objects.py

implementation of new functions with projectors → color_amp.py

call of new functions for use in helas routines → helas_objects.py

Amplitude generation & spin projectors

Generic quarkonium spin projector:

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

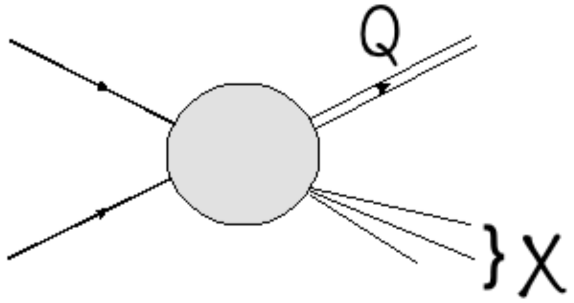
$S = 0, \gamma_5; 1, \not{\epsilon}(P)$

$P = p_1 + p_2$

$M^2 = P^2$

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 (*) :

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

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

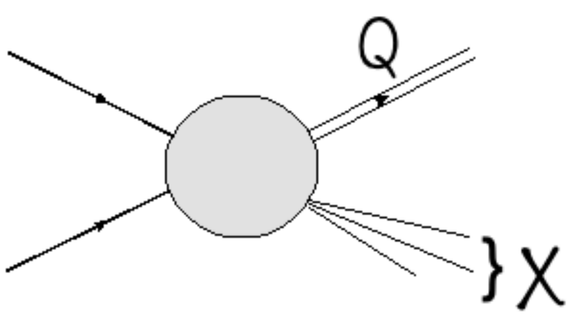
$\bar{\nu}_{\text{eff}}(P,\lambda)$ $\qquad$ $u_{\text{eff}}(P,\lambda)$

Amplitude generation & spin projectors

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

$\bar{v}_{\rm eff}(P,\lambda)$ $\quad$ $u_{\rm eff}(P,\lambda)$

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



Counteract: we introduce new effective wavefunctions

Declaration of new effective spinors in aloha/template_files/aloha_functions.f

Call to these new functions in madgraph/iolibs/helas_calls_objects.py