Quarkonium studies at the LHC and future facilities

Quarkonium4AFTER Franco-Chinese collaboration

Hua-Sheng Shao

LPTHE
LABORATOIRE DE PHYSIQUE THEORIQUE ET HAUTES ENERGIES

SORBONNE UNIVERSITÉ
CRÉATEURS DE FUTURS DEPUIS 1257

15th FCPPN/L Workshop
University of Bordeaux
10-14 June 2024

FCPPN/L Collaboration

- **Theory and experiment of quarkonium**

	France	China
Leaders	**H.-S. Shao (LPTHE)**	**Y.-Q. Ma (PKU)**
Permanent	**B. Fuks (LPTHE)** **J.-P. Lansberg (IJCLab)** **S. Wallon (IJCLab)** **M. Ozcelik (IJCLab)** **C. Hadjidakis (IJCLab)** **L. Massacrier (IJCLab)**	**K.-Q. Chao (PKU)** **Y. Gao (PKU)** **L. An (PKU)** **Z. Yang (PKU)** **Y. Zhang (PKU)** **J.-X. Wang (IHEP)** **B. Gong (IHEP)** **Y.-J. Zhang (Beihang)** **J. He (UCAS)** **Z. Tang (USTC)** **X. Bai (USTC)** **H.-F. Zhang (Guiyang)** **Y. Feng (Chongqing)** **G.-Z. Xu (Liaoning)** **Y.-J. Li (Liaoning)** **K. Yi (Nanjing & THU)** **A.-P. Chen (Jiangxi)**
Non-permanent	**A. ABDUL-HAMEED (LPTHE)** **G. Wang (LPTHE)** **L. Simon (LPTHE)** **S. Nabeebaccus (IJCLab)** **M. Nefedov (IJCLab)** **C. Flett (IJCLab)** **Y. Yedelkina (IJCLab)** **K. Lynch (IJCLab)** **J. Bor (IJCLab)** **E. Li (IJCLab)**	

- 35 members
- 26 TH and 9 EXP
- 25 permanent, 6 postdocs, 4 PhD students

Quarkonia As Tools Workshop

- A new series of meetings on the experimental and theoretical studies of quarkonium
  - One week workshop held at Aussois in January (6th edition in 2024)
  - Around 40 participants per year (FCPPN/L collaboration members actively engaged)

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2019 J/ψ

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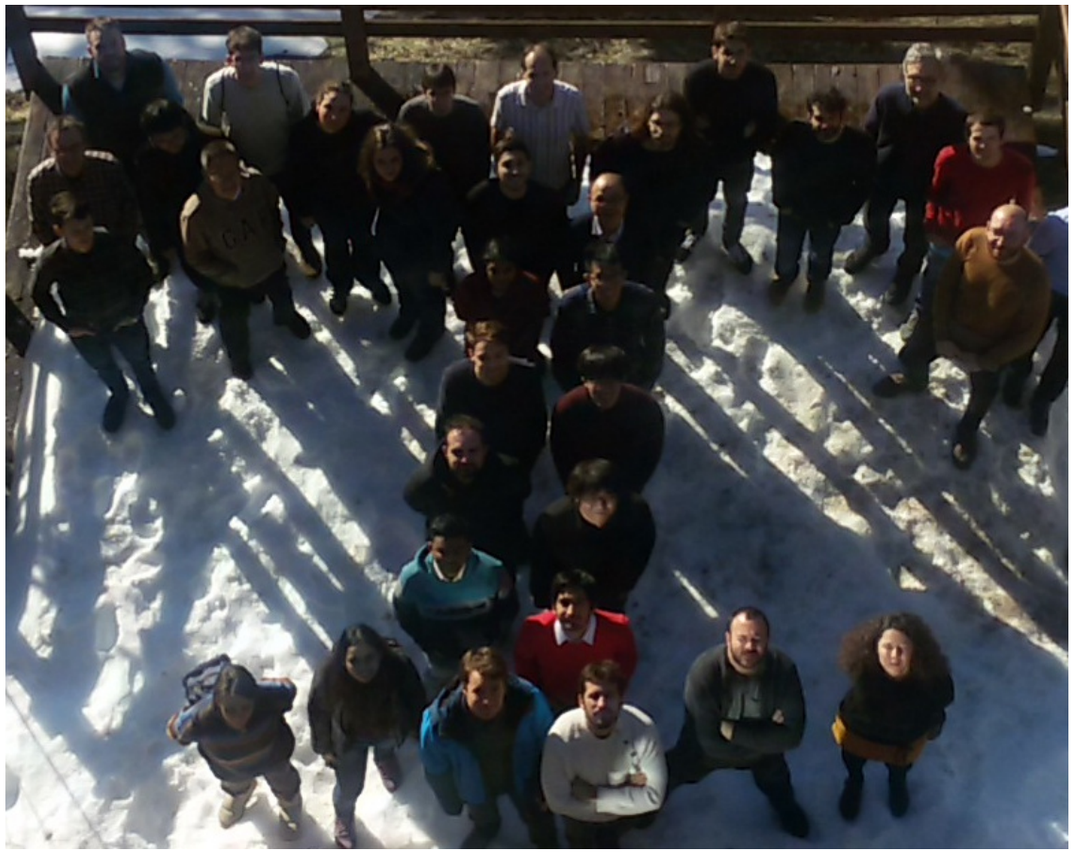
2020 Υ



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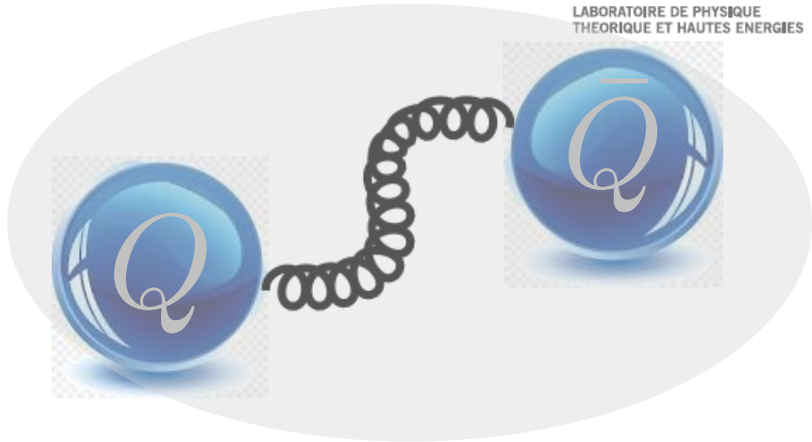
2022 η_c

Heavy Quarkonium : What ?



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Heavy Quarkonium : What ?

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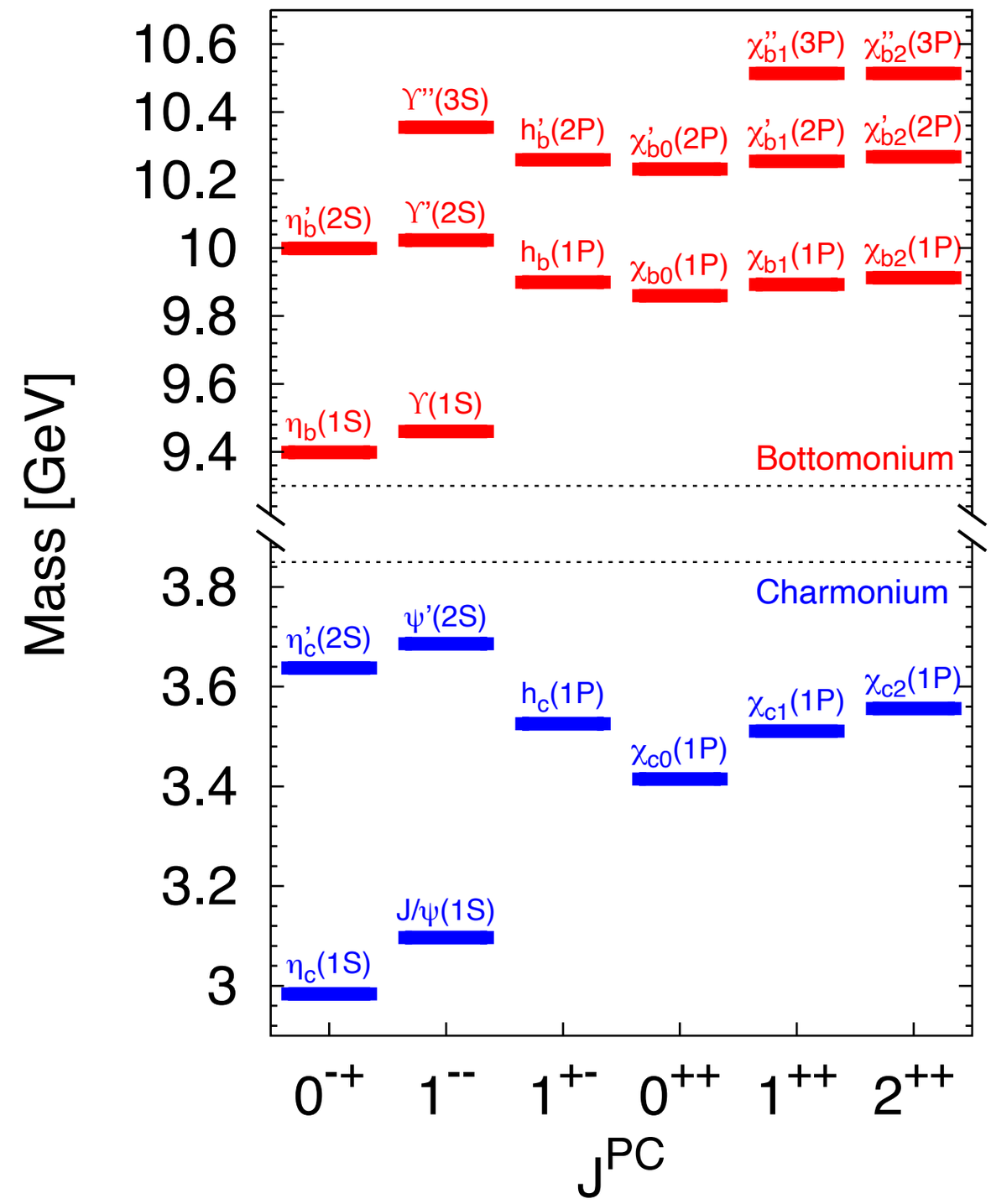
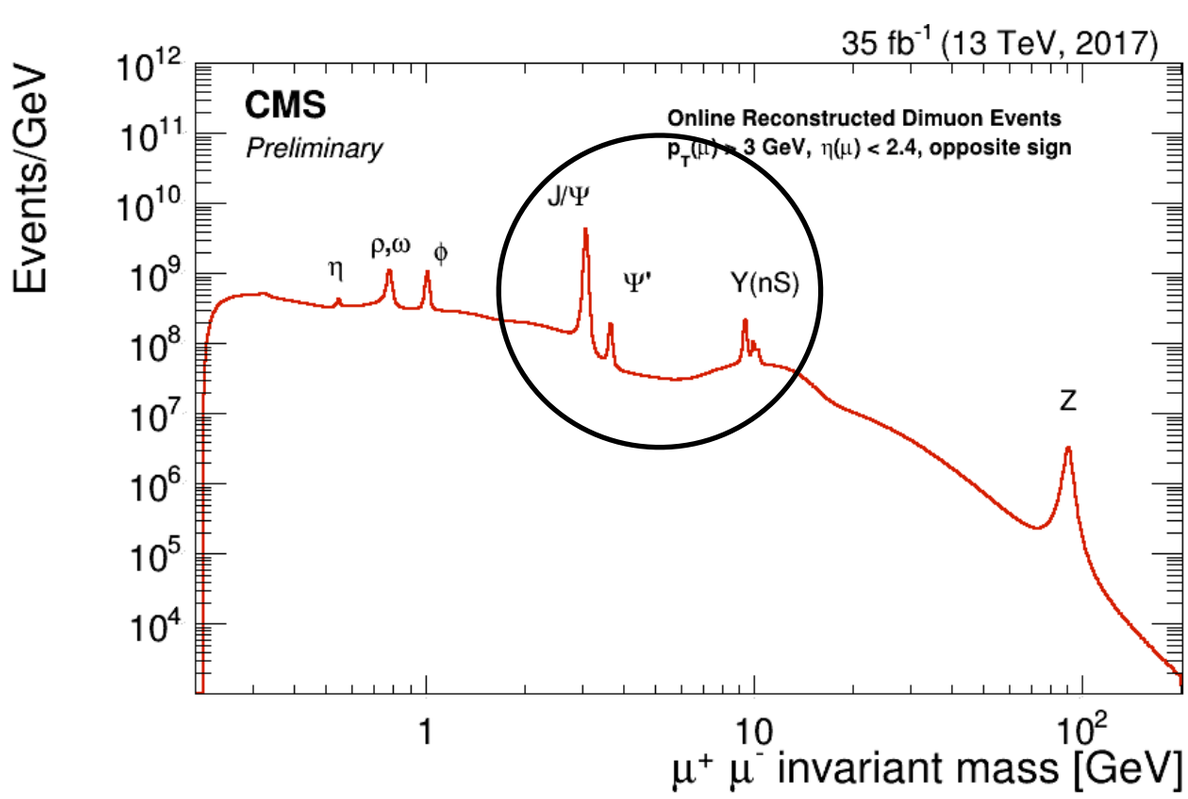
- Rich particle spectrum, rich physics



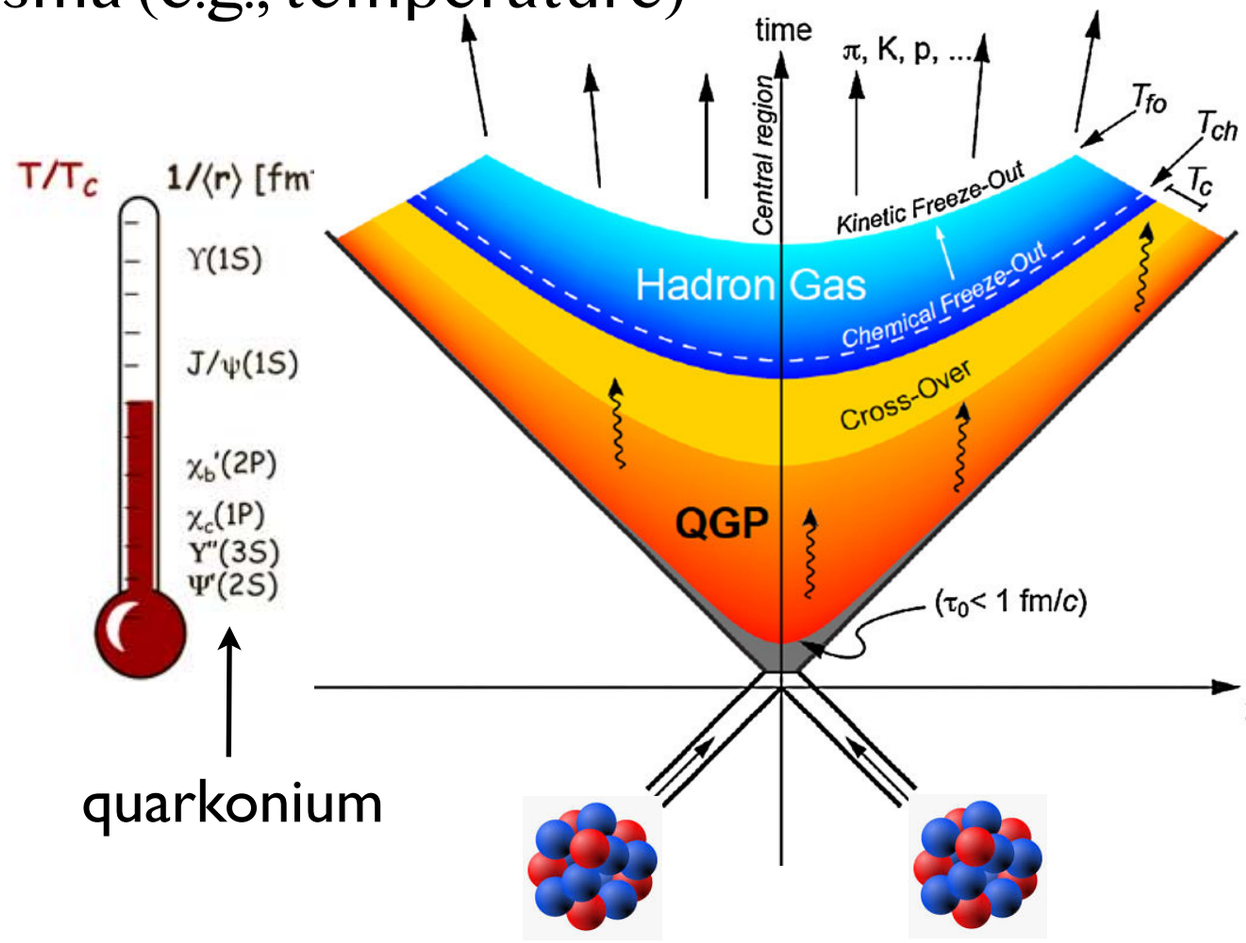
Heavy Quarkonium : What ?

- The (theoretically) simplest hadrons
- Rich particle spectrum, rich physics
- Everywhere in high-energy experiments



Heavy Quarkonium : Why ?

- Quarkonia as probes of quark-gluon plasma in nuclear collisions
  - Learning Quantum Chromodynamics (QCD) phase transition in early universe
  - Determining the properties of the plasma (e.g., temperature)



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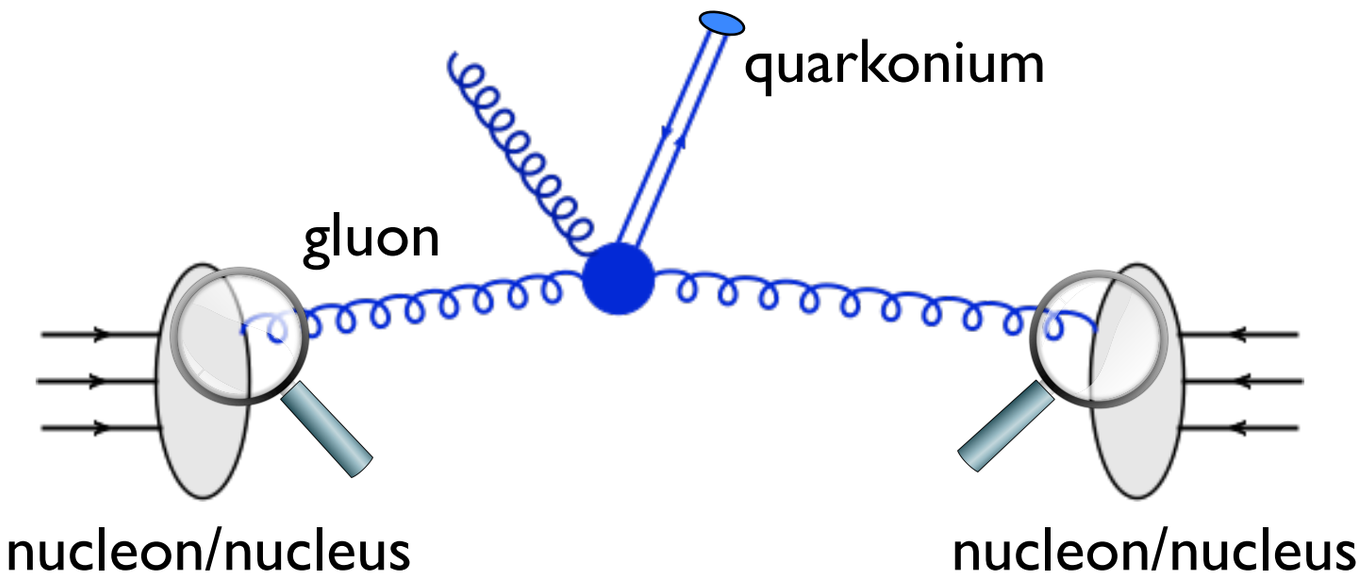
  - Understanding the emergence of nucleons and nuclei from quarks and gluons
  - Quarkonium observables tell us how the glue binds us all



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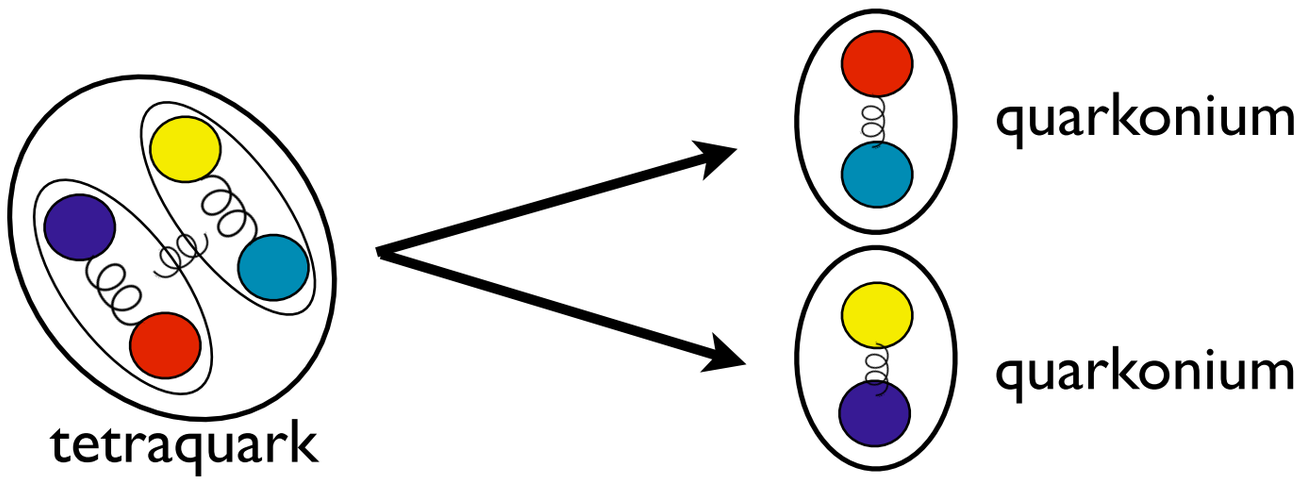

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`+ many other physics applications ...`

⇨ The backbone of the applications is our knowledge of quarkonium production

Heavy Quarkonium : Why ?

Do we understand how quarkonia are produced

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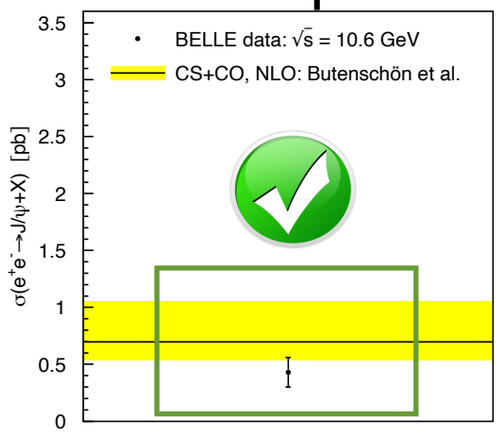
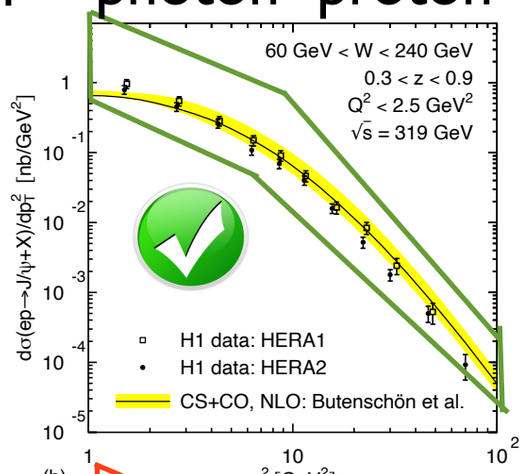
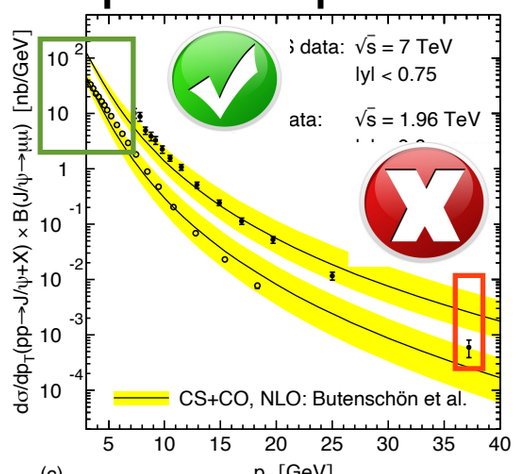
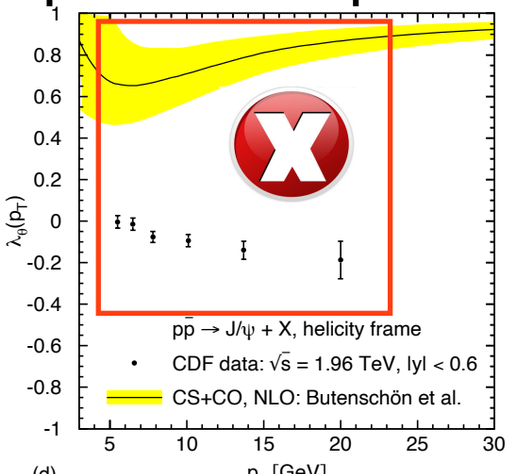
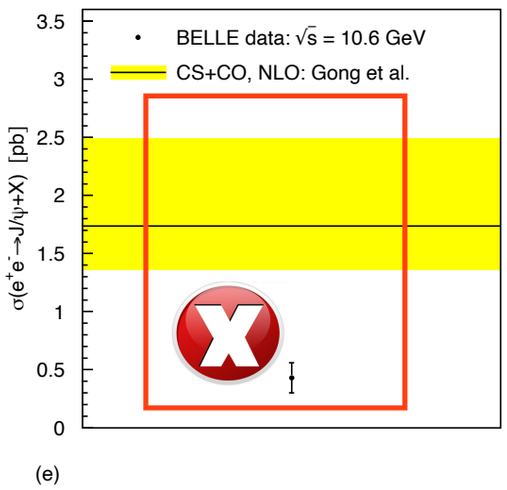
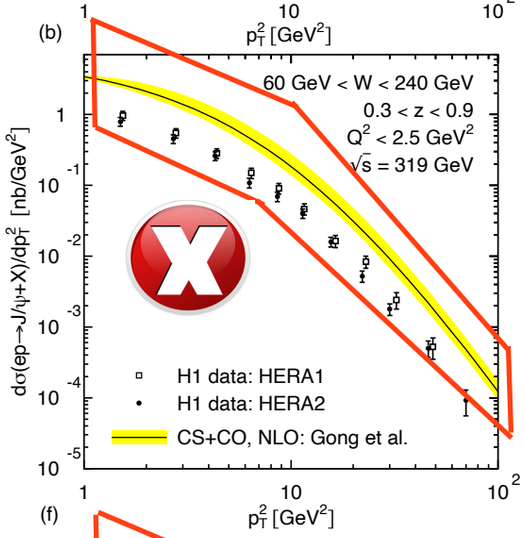
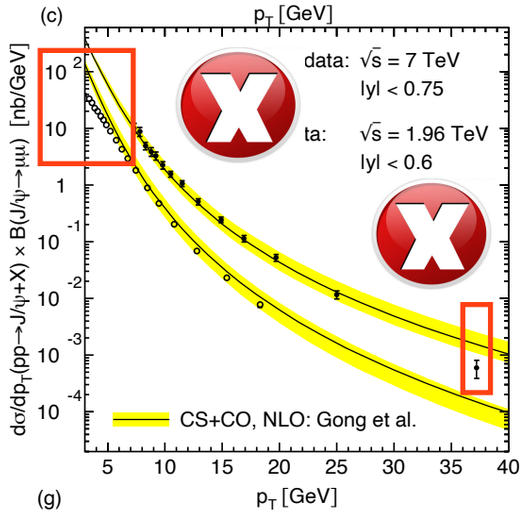
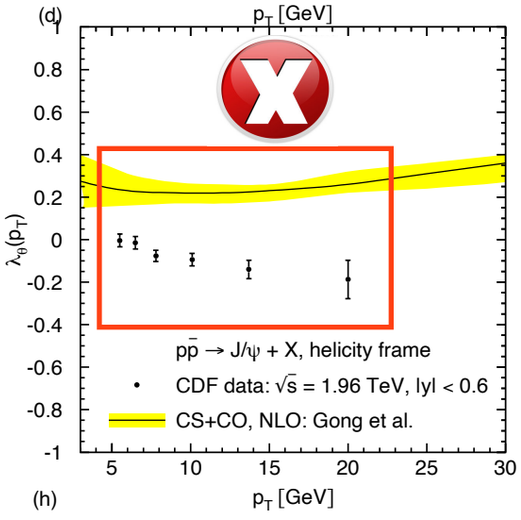
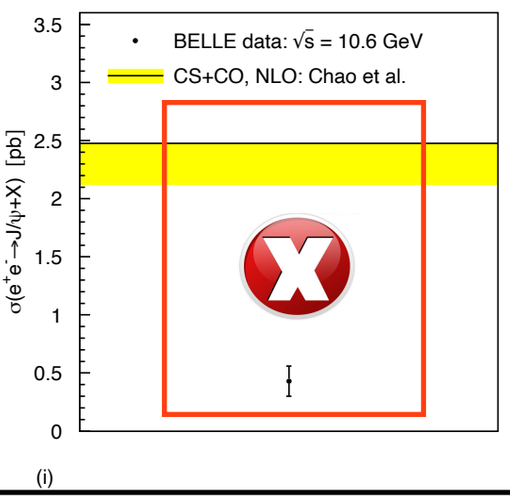
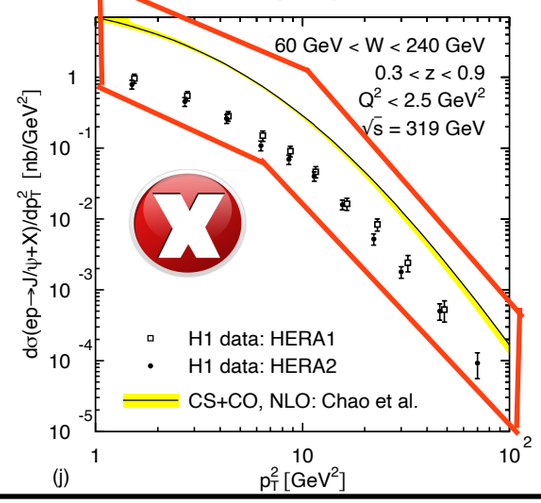
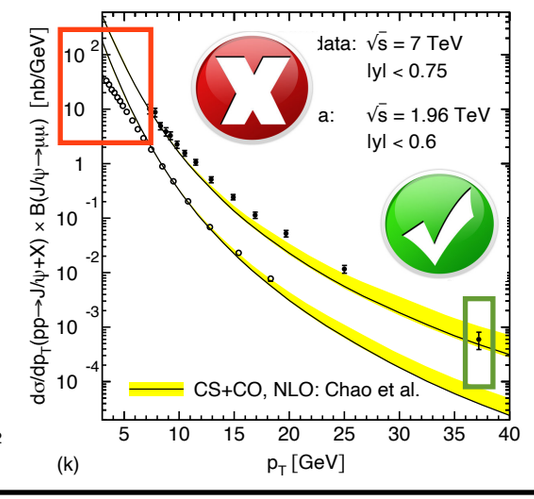
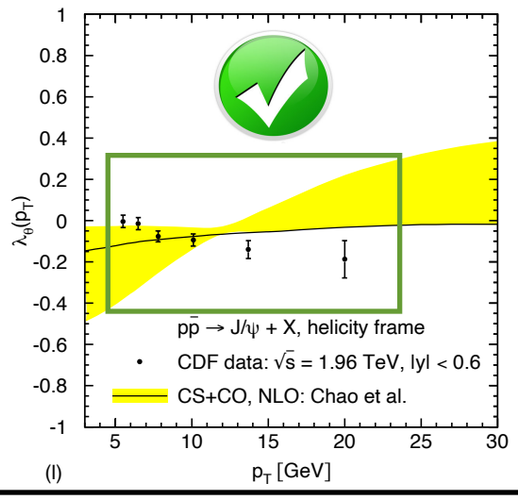
Experiment

	electron+positron	photon+proton	proton+proton	proton+antiproton
①				
②				
③				

Theory

Heavy Quarkonium : Why ?

Do we understand how quarkonia are produced

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Contradictions in theory vs experiment & theory vs theory ?

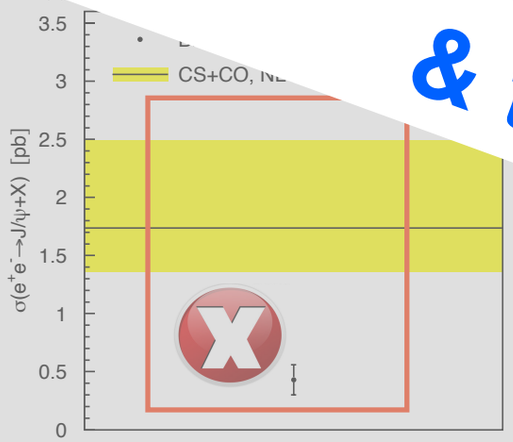
No !

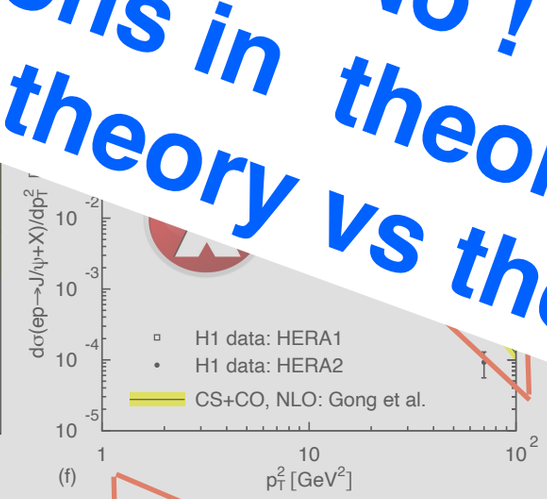
Experiment

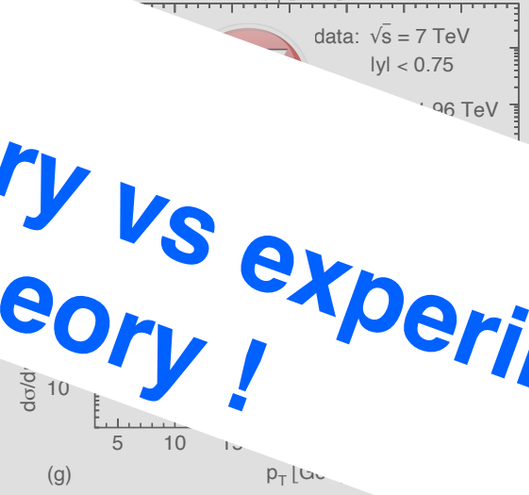
electron+positron | photon+proton | proton+proton | proton+antiproton

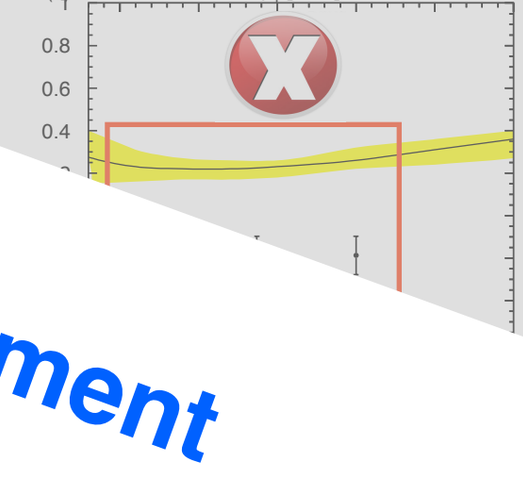
Theory

②









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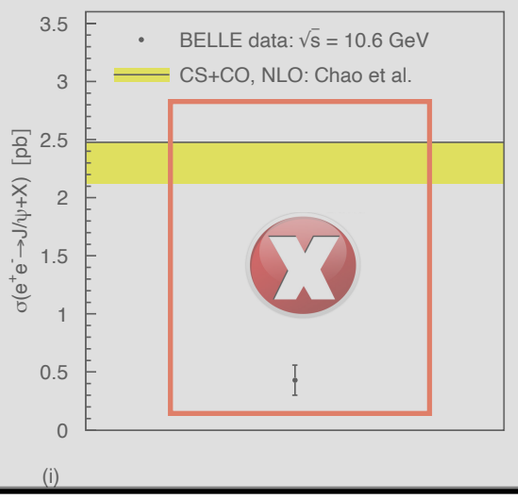
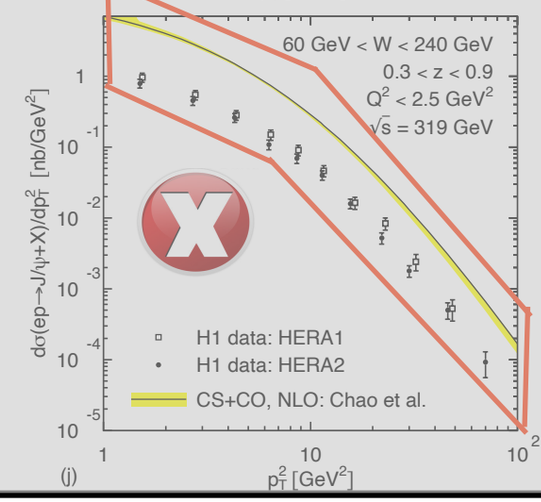
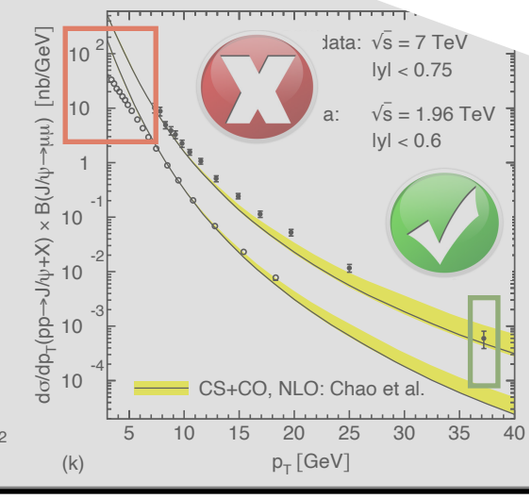
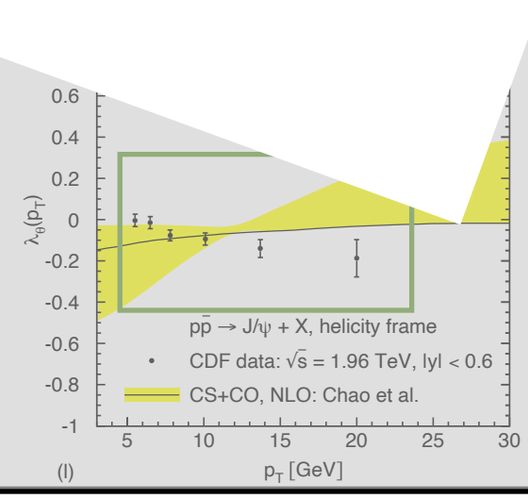








FCPPN/L Projects

- **Three possible directions for the collaboration**

  - Improving accuracy and precision of quarkonium production cross sections

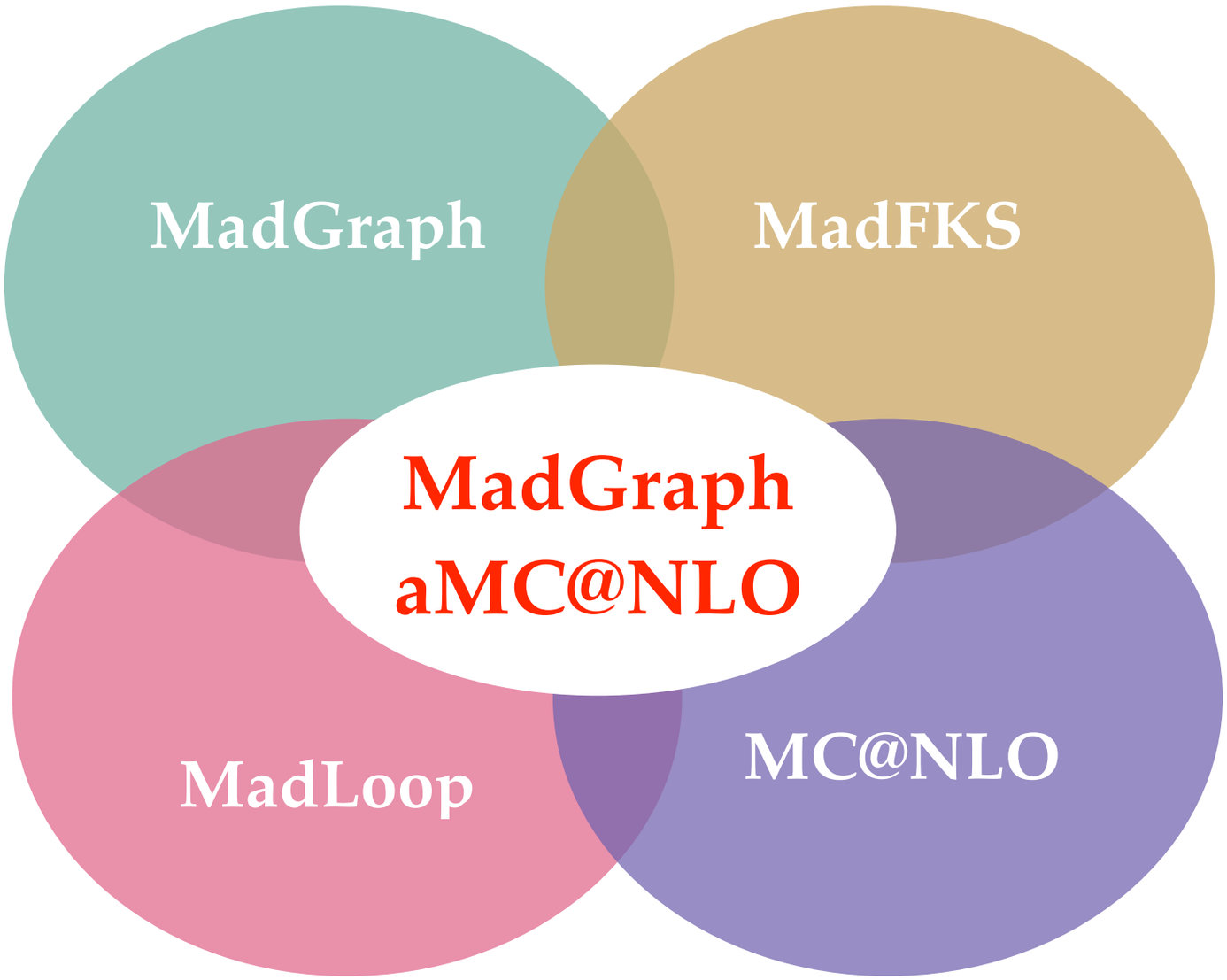
  - Quarkonia as tools : learning new physics from quarkonium

  - Exploring the physics opportunities of quarkonium at future facilities

Accuracy & Precision

NLO+PS automation for quarkonium

- For elementary particles, the standard theory for the interpretations of the LHC measurements are NLO+PS



My Dream: NLO+PS for quarkonium !

NLO Anatomy

- **Three parts need to be computed in a NLO calculation**

$$\sigma_{\rm NLO} = \int d\Phi^{(n)} \mathcal{B} + \int d\Phi^{(n)} \mathcal{V} + \int d\Phi^{(n+1)} \mathcal{R}$$

Born cross section

Virtual correction

Real correction

$$\text{Virtual} = \frac{A}{\epsilon^2} + \frac{B}{\epsilon} + V \qquad \text{Real} = -\frac{A}{\epsilon^2} - \frac{B}{\epsilon} + R$$

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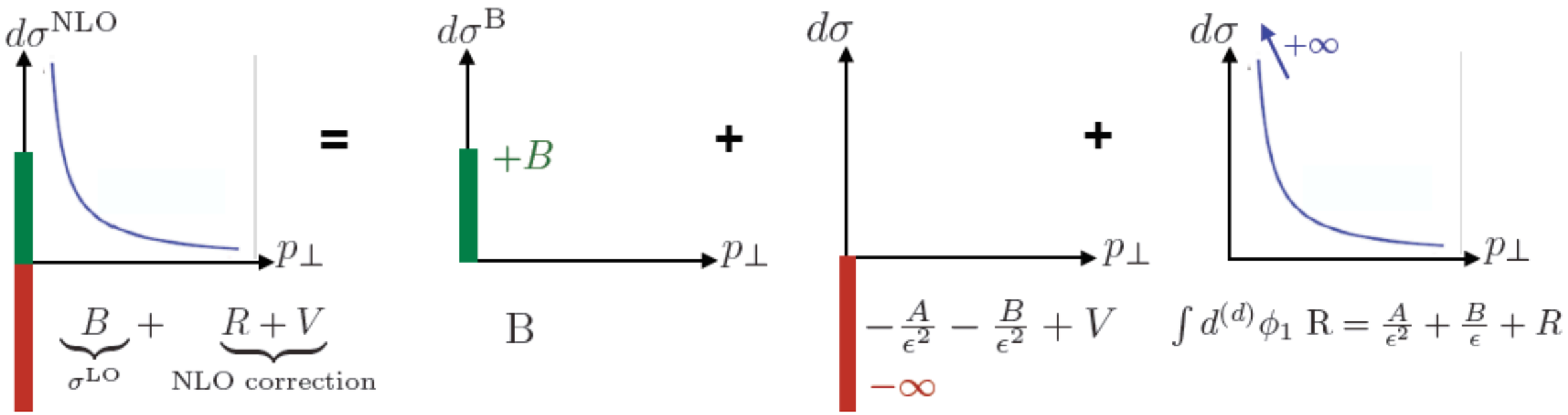

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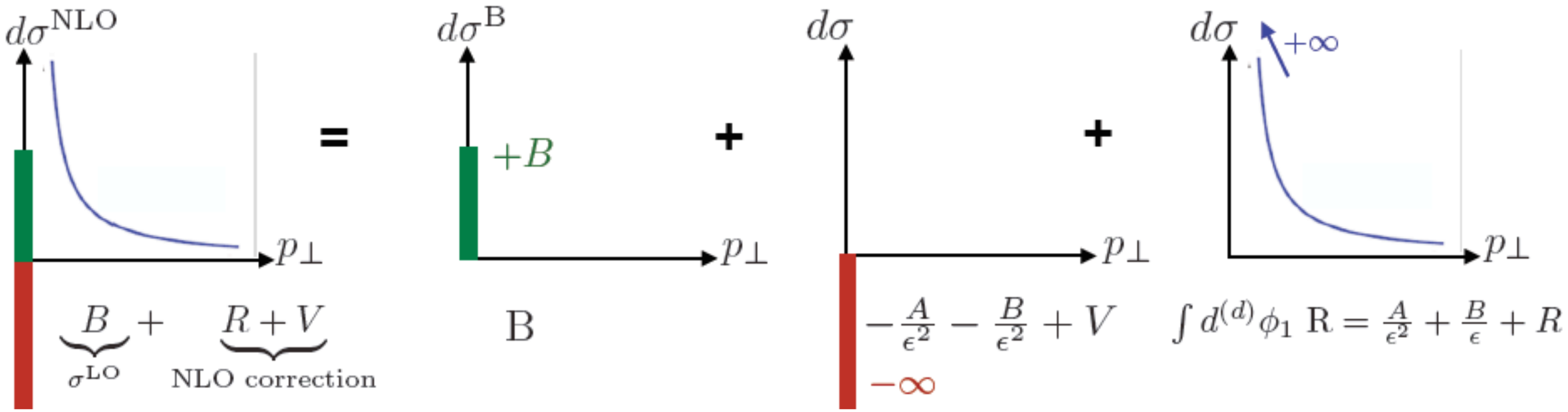

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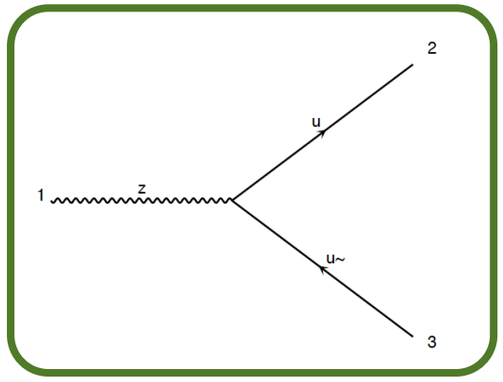
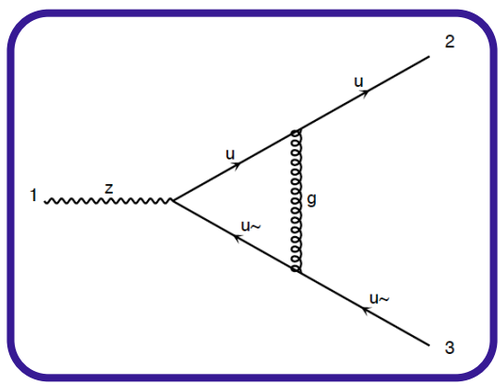
$$\mathcal{O}(\alpha_s^b) \qquad \mathcal{O}(\alpha_s^{b+1}) \qquad \mathcal{O}(\alpha_s^{b+1})$$

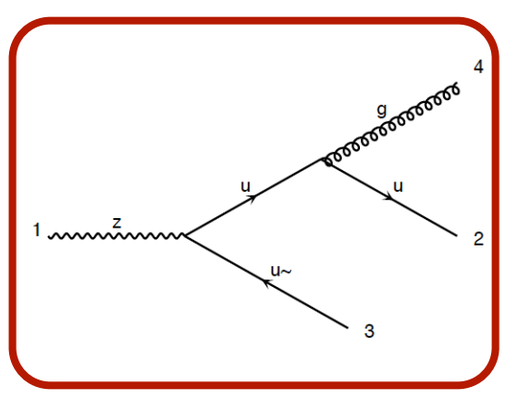
Born cross section

Virtual correction

Real correction







Finite

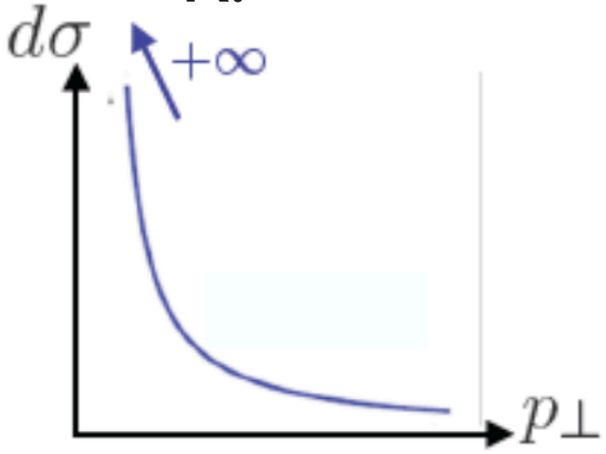
Divergent

Divergent

MadGraph **MadLoop** **MadFKS**

NLO Automation: IR Subtraction

- **Why do we need IR subtraction for real radiative corrections ?**
  - Real matrix element R has a complex structure. The phase space integration over it is usually really hard.
  - Phase space integration relies on Monte Carlo importance sampling methods.
  - This is possible only after IR divergences have been properly removed.
  - One introduces a much simpler function S (called subtraction term) that matches the exact singular behaviour of the real matrix element R.



$$\int d^{(d)}\phi_1 \, \mathrm{R} = \frac{A}{\epsilon^2} + \frac{B}{\epsilon} + R$$

$$\int d\phi_1 \mathcal{R} \to \underbrace{\int d\phi_1 (\mathcal{R} - \mathcal{S})}_{\text{Regular \& MC integration possible.}} + \int d\phi_1 \mathcal{S}$$

Integrated counter term, to be added back, but easier to integrate

Their divergence cancels with those of virtual corrections

$\mathcal{S} \to$ Subtraction counter term

NLO Automation

$$\sigma_{\rm NLO} = \int d\phi_n \mathcal{B} + \int d\phi_n \mathcal{V} + \int d\phi_n \int d\phi_1 \mathcal{S} + \int d\phi_{n+1} (\mathcal{R} - \mathcal{S})$$

Automatic tree level matrix element generator

SM and BSM

MadGraph

MadFKS

Automation of real correction using FKS subtraction

MadGraph aMC@NLO

Automation of virtual corrections

MadLoop

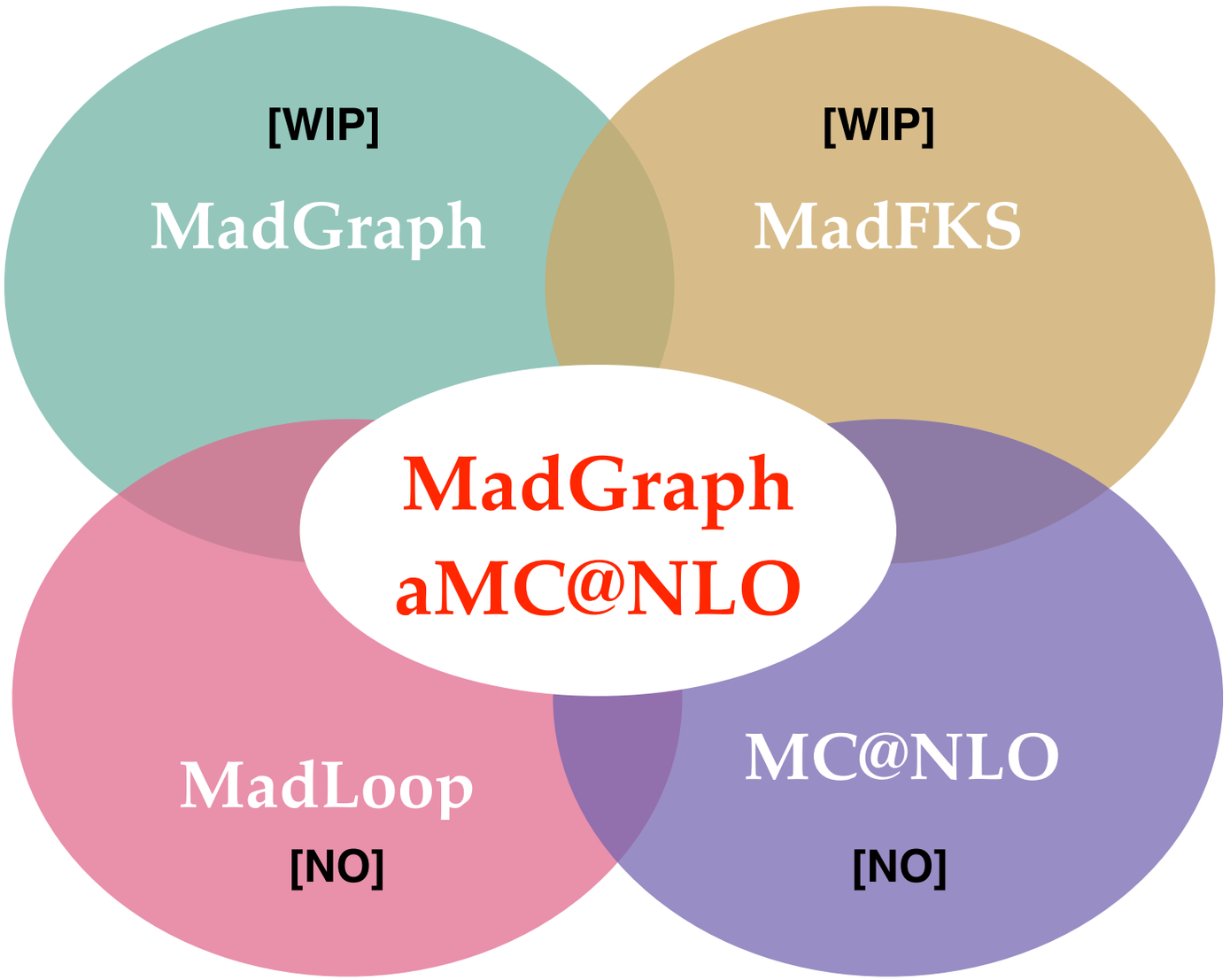
MC@NLO

Matching to PS &

Multi-jet ME+PS merging

NLO Automation

- **Quarkonium requires many new TH developments**
  - Both on the conceptual and technical points of views



Automatic tree level matrix element generator

SM and BSM

Automation of real correction using FKS subtraction

Automation of virtual corrections

Matching to PS &

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NLO Automation: IR Subtraction

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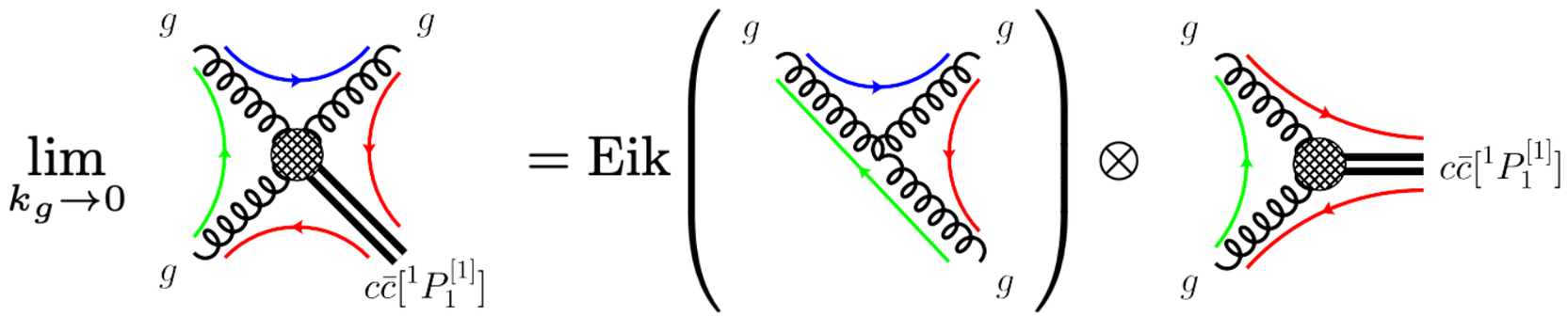
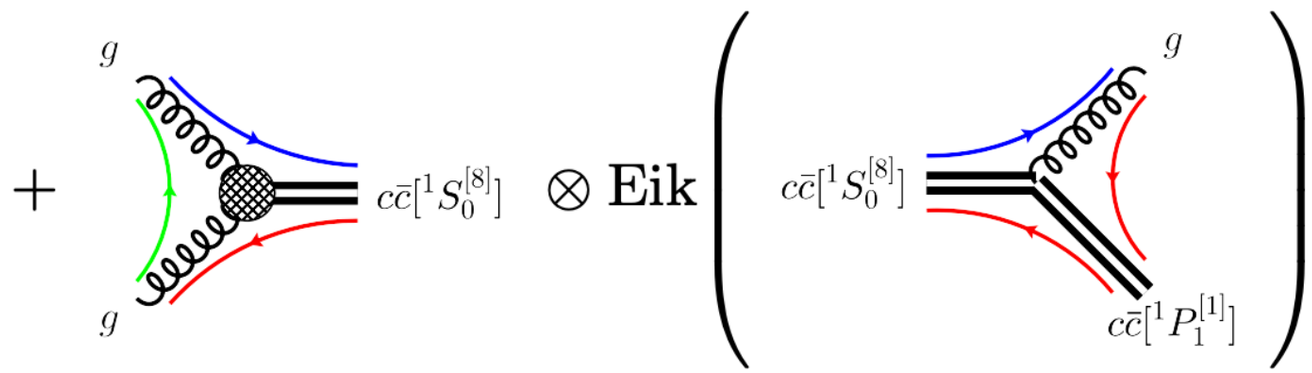
  - For instance …, soft limit of quarkonium real matrix element

A. Abdul-Hameed, L. Simon, HSS (arXiv:2402.19221)





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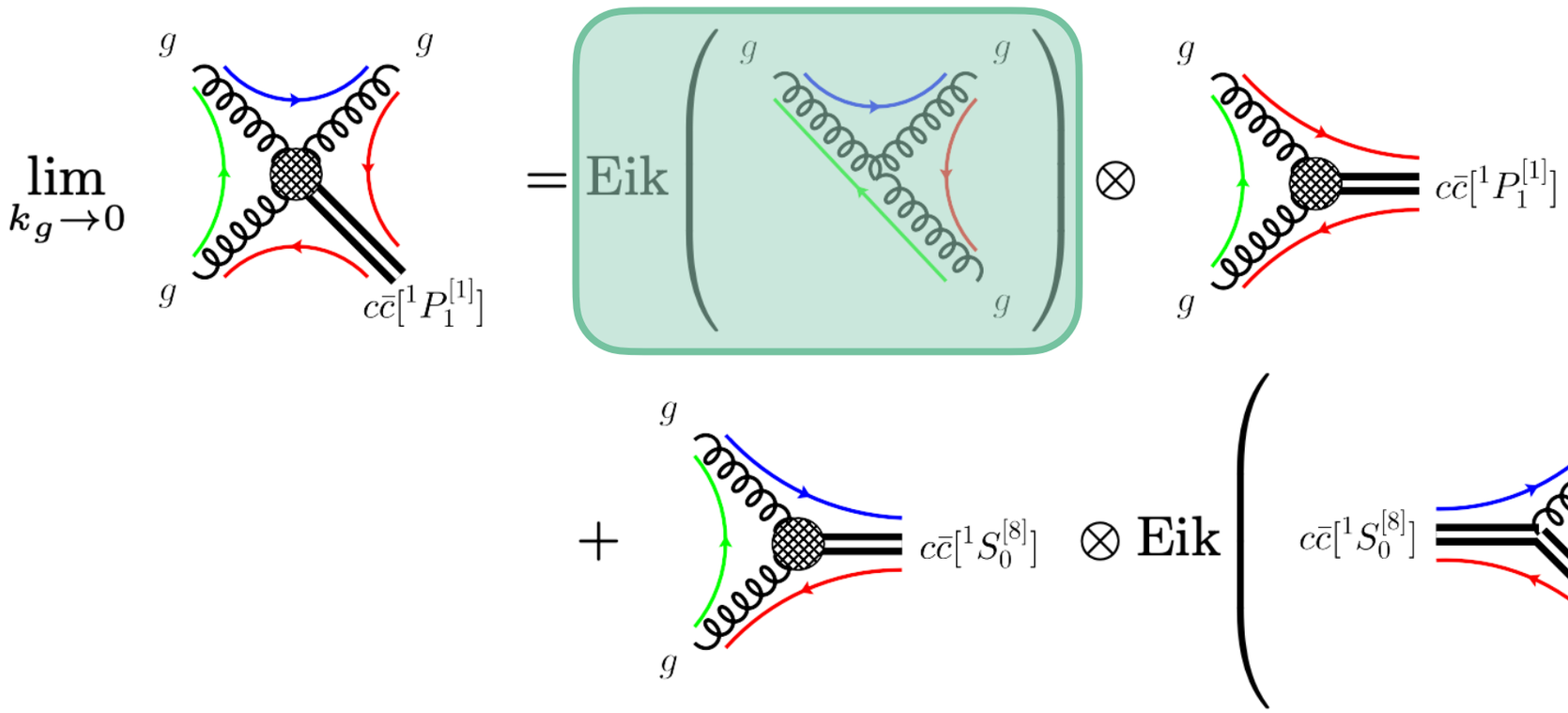

Standard eikonal factor

NLO Automation: IR Subtraction

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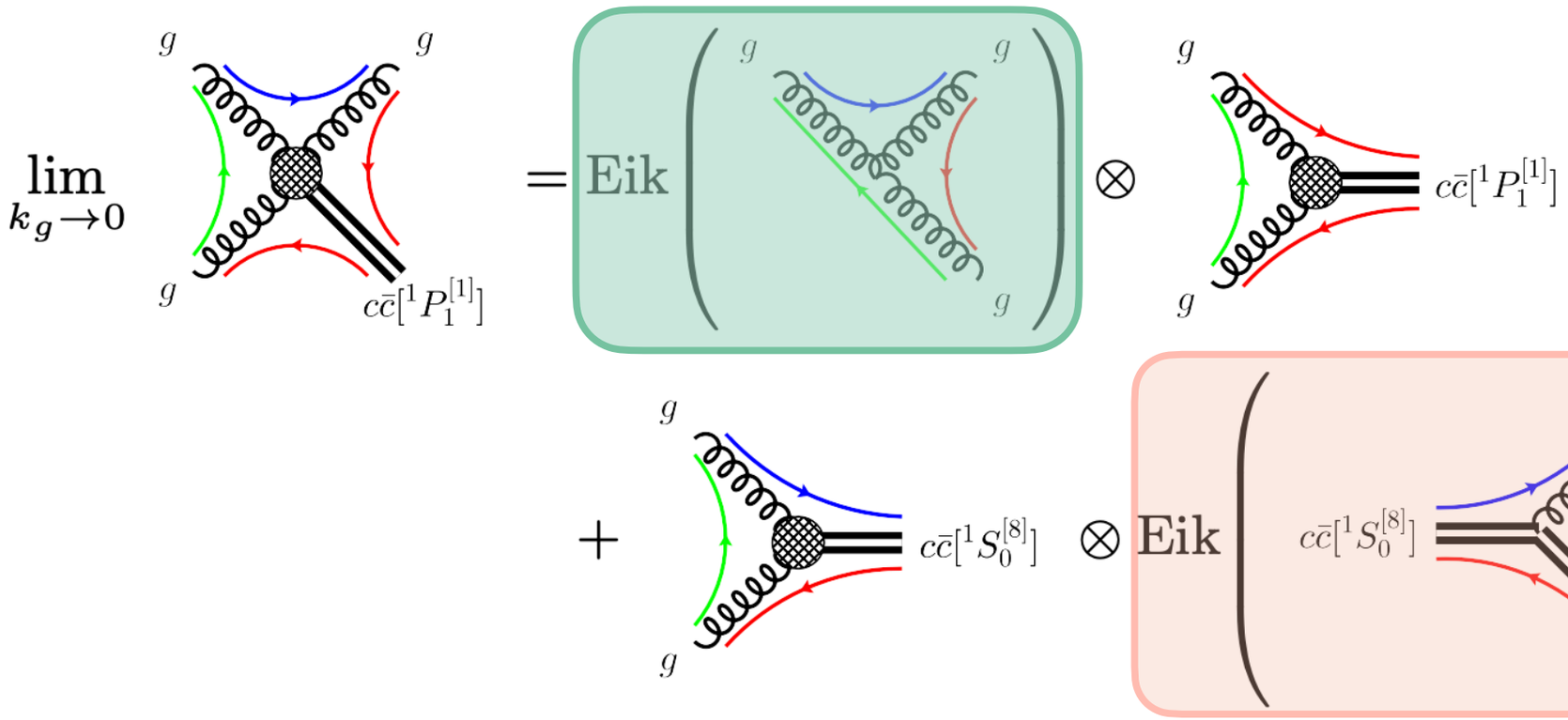
  - For instance …, soft limit of quarkonium real matrix element

A. Abdul-Hameed, L. Simon, HSS (arXiv:2402.19221)



Standard eikonal factor

Non-standard new eikonal factor (NEW !)

Quarkonia As Tools

Quarkonia As Tools

- MPI (DPS, TPS), TMD, GPD, (nuclear) PDF, tetraquark, QGP …
  - Almost all members in the team are actively working on the related topics (both experimentally and theoretically)

LHCb by Y. Gao, L. An, Z. Yang, Y. Zhang, J. He (arXiv:2311.14085)

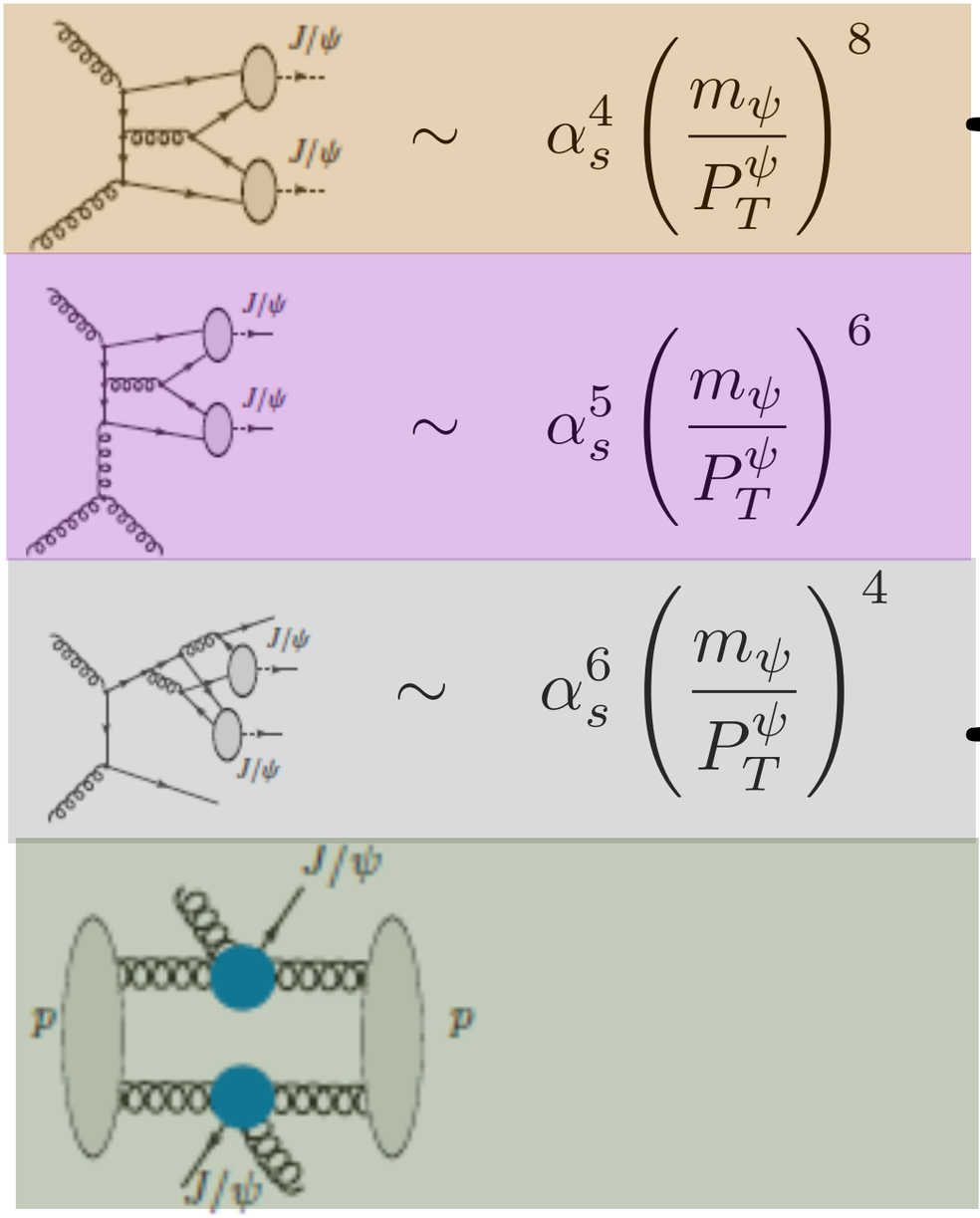
CERN-EP-2023-242
LHCb-PAPER-2023-022
March 14, 2024

Measurement of J/ψ-pair production in pp collisions at $\sqrt{s} = 13\,\text{TeV}$ and study of gluon transverse-momentum dependent PDFs

LHCb collaboration[†]

Quarkonia As Tools

- DPS vs SPS

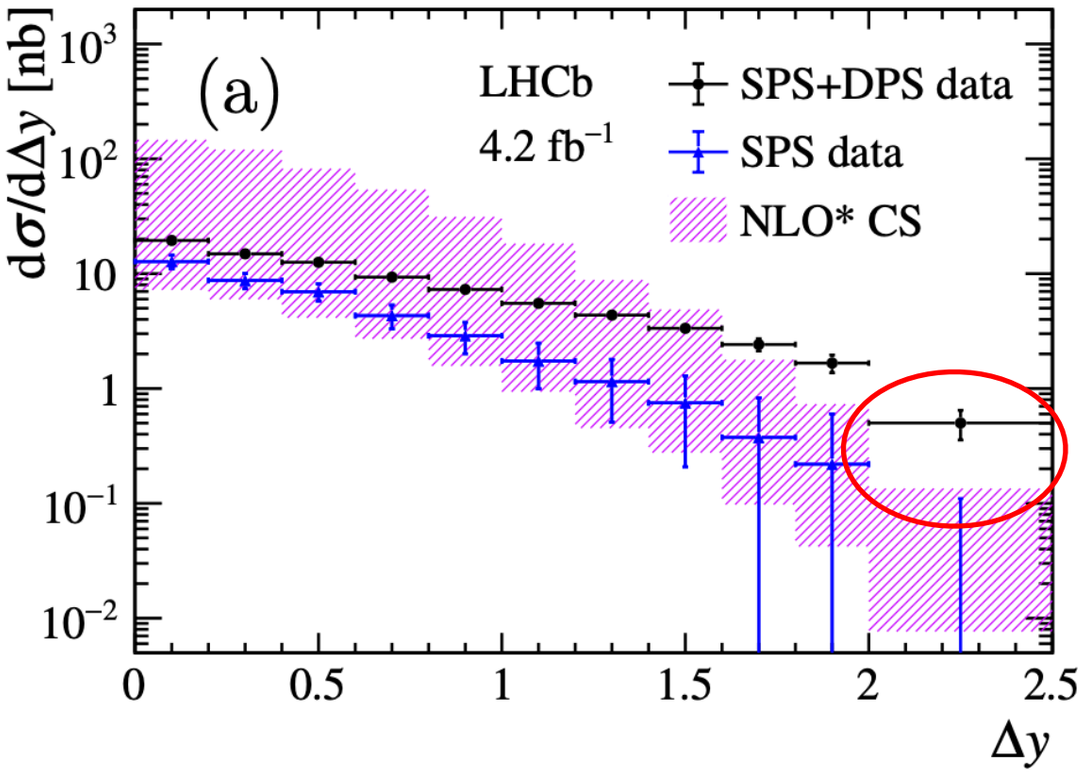


SPS

DPS

TH: HSS, J.-P. Lansberg, Y.-J. Zhang, K.-T. Chao …

EXP: Y. Gao, L. An, Z. Yang, Y. Zhang, J. He …

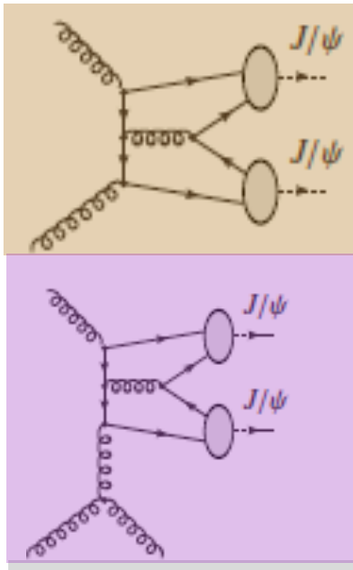


Quarkonia As Tools

- DPS vs SPS

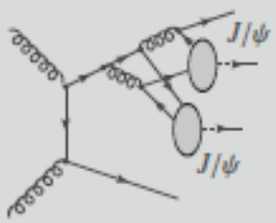
TH: HSS, J.-P. Lansberg, Y.-J. Zhang, K.-T. Chao …

EXP: Y. Gao, L. An, Z. Yang, Y. Zhang, J. He …

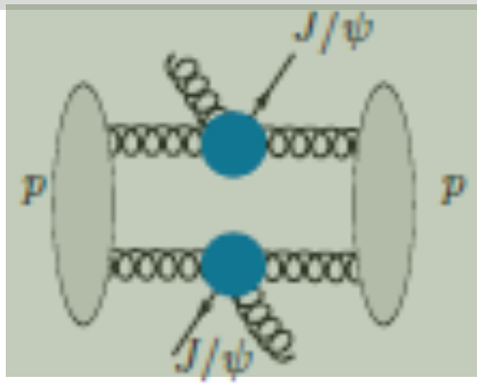


$$\sim \quad \alpha_s^4 \left(\frac{m_\psi}{P_T^\psi}\right)^8$$

$$\sim \quad \alpha_s^5 \left(\frac{m_\psi}{P_T^\psi}\right)^6$$

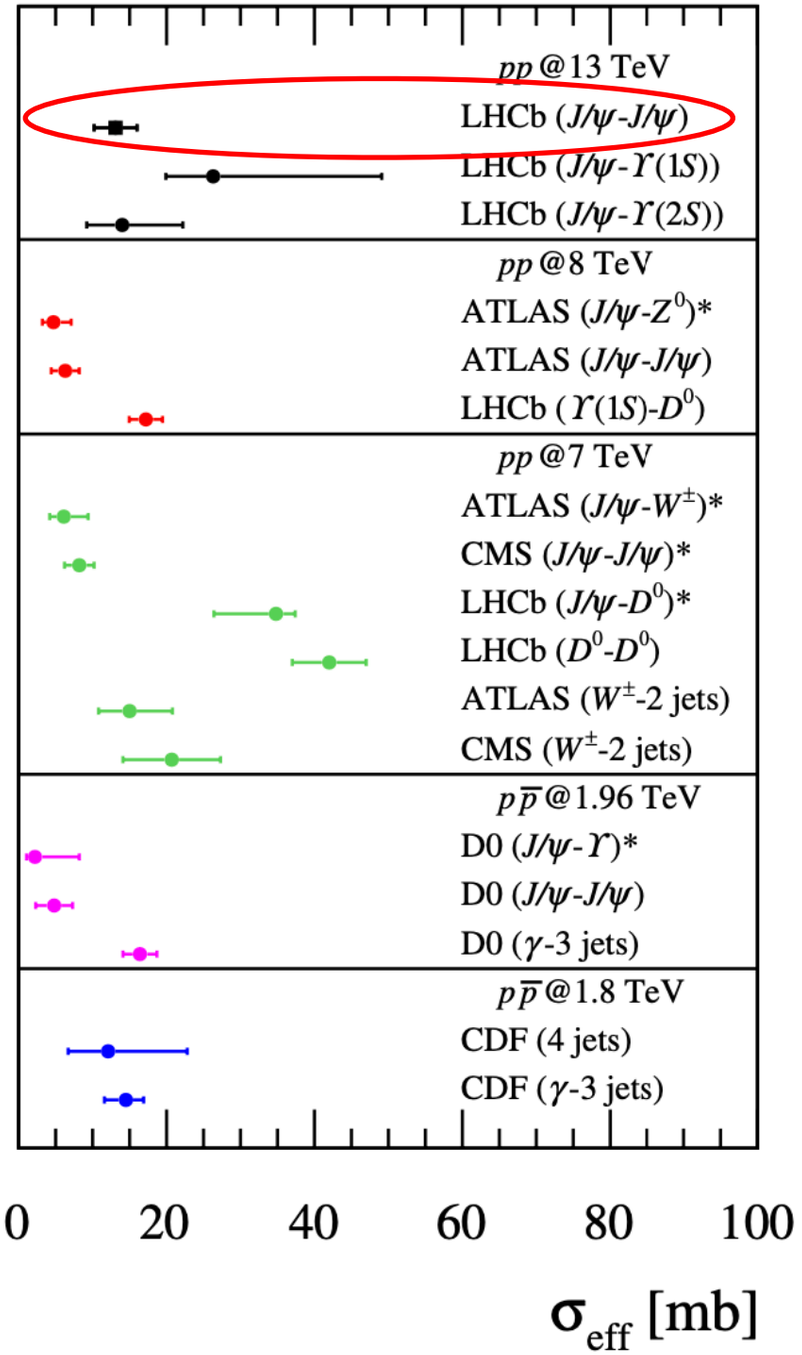


$$\sim \quad \alpha_s^6 \left(\frac{m_\psi}{P_T^\psi}\right)^4$$



SPS

DPS

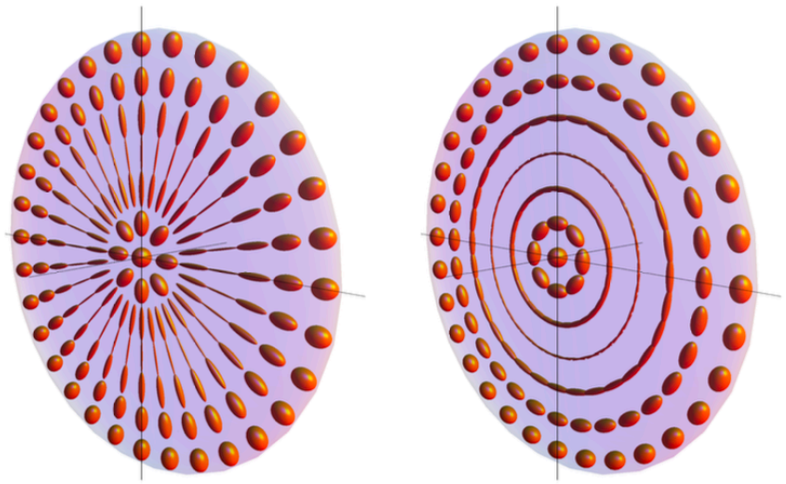


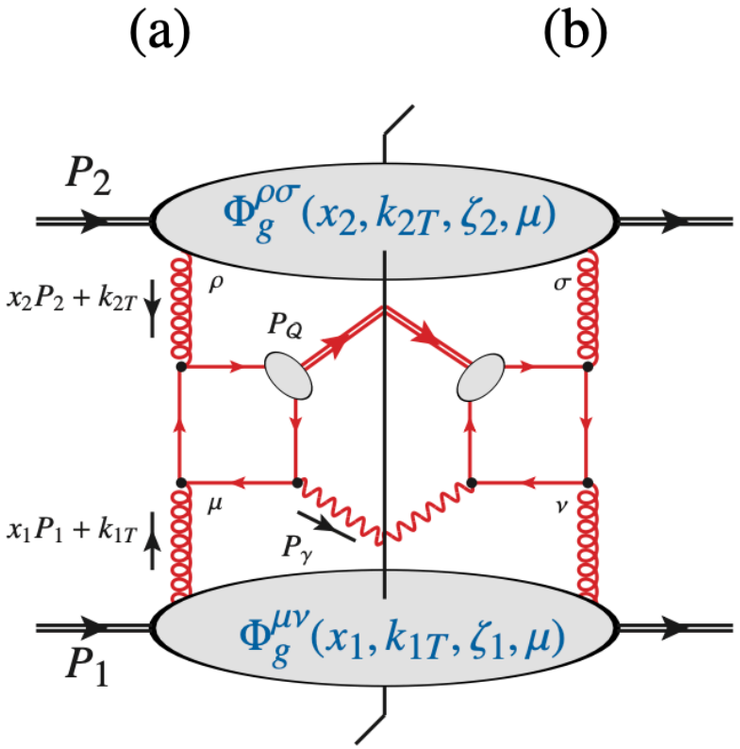
Quarkonia As Tools

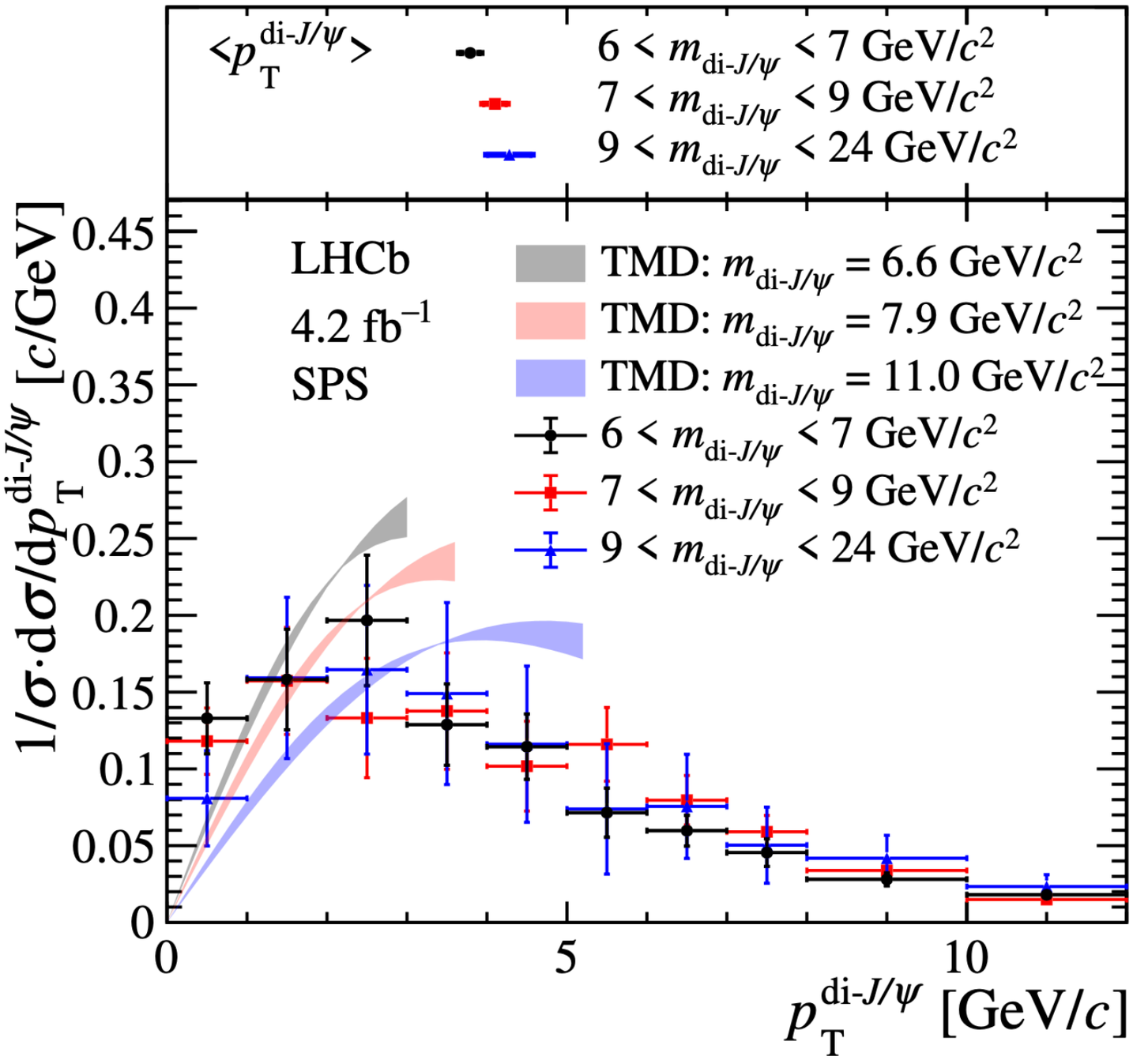
- TMD: linearly-polarized gluon

TH: J.-P. Lansberg, J Bor …

EXP: Y. Gao, L. An, Z. Yang, Y. Zhang, J. He …







Future Facilities

Quarkonium studies at future facilities

LPTHE
LABORATOIRE DE PHYSIQUE THEORIQUE ET HAUTES ENERGIES

HL-LHC

Progress in Particle and Nuclear Physics 122 (2022) 103906

Contents lists available at ScienceDirect

Progress in Particle and Nuclear Physics

journal homepage: www.elsevier.com/locate/ppnp

Review

Prospects for quarkonium studies at the high-luminosity LHC

Émilien Chapon [1,a], David d'Enterria [2,a], Bertrand Ducloué [3,a], Miguel G. Echevarria [4,a], Pol-Bernard Gossiaux [5,a], Vato Kartvelishvili [6,a], Tomas Kasemets [7,a], Jean-Philippe Lansberg [8,*,b], Ronan McNulty [9,a], Darren D. Price [10,a], Hua-Sheng Shao [11,a], Charlotte Van Hulse [9,a], Michael Winn [12,a], Jaroslav Adam [13], Liupan An [14], Denys Yen Arrebato Villar [5], Shohini Bhattacharya [15], Francesco G. Celiberto [16,17,18,19], Cvetan Cheshkov [20], Umberto D'Alesio [21], Cesar da Silva [22], Elena G. Ferreiro [23], Chris A. Flett [24,25], Carlo Flore [8], Maria Vittoria Garzelli [26,14,27], Jonathan Gaunt [28,10], Jibo He [29], Yiannis Makris [17], Cyrille Marquet [30], Laure Massacrier [8], Thomas Mehen [31], Cédric Mezrag [12], Luca Micheletti [32], Riccardo Nagar [33], Maxim A. Nefedov [34], Melih A. Ozcelik [8], Biswarup Paul [21], Cristian Pisano [21], Jian-Wei Qiu [35], Sangem Rajesh [21], Matteo Rinaldi [36], Florent Scarpa [8,37], Maddie Smith [6], Pieter Taels [30], Amy Tee [6], Oleg Teryaev [38], Ivan Vitev [22], Kazuhiro Watanabe [35], Nodoka Yamanaka [39,40], Xiaojun Yao [41], Yanxi Zhang [2,42]

7 members contribute !

EIC

Physics case for quarkonium studies at the Electron Ion Collider

Editors: Daniël Boer[a,1], Carlo Flore[b,1], Daniel Kikoła[c,1], Jean-Philippe Lansberg[b,1], Charlotte Van Hulse[b,1]

[a] Van Swinderen Institute for Particle Physics and Gravity, University of Groningen, 9747 AG Groningen, The Netherlands
[b] Université Paris-Saclay, CNRS/IN2P3, IJCLab, 91405 Orsay, France
[c] Faculty of Physics, Warsaw University of Technology, ul. Koszykowa 75, 00-662 Warsaw, Poland

Abstract

The physics case for quarkonium-production studies accessible at the future US Electron Ion Collider is described.

Quarkonium studies at future facilities

Fixed-target experiments at the LHC

LPTHE
LABORATOIRE DE PHYSIQUE THEORIQUE ET HAUTES ENERGIES

5 members contribute !

Physics Reports 911 (2021) 1–83

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A fixed-target programme at the LHC: Physics case and projected performances for heavy-ion, hadron, spin and astroparticle studies

C. Hadjidakis [1,a], D. Kikoła [2,a], J.P. Lansberg [1,*,a], L. Massacrier [1,a], M.G. Echevarria [3,4,b], A. Kusina [5,b], I. Schienbein [6,b], J. Seixas [7,8,9,b], H.S. Shao [10,b], A. Signori [11,3,12,b], B. Trzeciak [13,14,b], S.J. Brodsky [15], G. Cavoto [16], C. Da Silva [17], F. Donato [18], E.G. Ferreiro [19,20], I. Hřivnáčová [1], A. Klein [17], A. Kurepin [21], C. Lorcé [22], F. Lyonnet [23], Y. Makdisi [24], S. Porteboeuf Houssais [25], C. Quintans [8], A. Rakotozafindrabe [26], P. Robbe [1], W. Scandale [27], N. Topilskaya [21], A. Uras [28], J. Wagner [29], N. Yamanaka [1,32,30,31], Z. Yang [33], A. Zelenski [24]

1. High-x physics
2. Spin physics
3. Heavy-ion physics

Contributing the CERN Physics Beyond Collider and ESPP update

Conclusion

- Our quarkonium FCPPL consortium did well before pandemics, and is willing to keep the fruitful collaboration !
  - Fruitful Franco-Chinese exchanges on various topics
  - Regular publications, meetings and communications

- Since its discovery 50 years ago, quarkonium remains to be understood

- Many (new) ideas both on the theory and experimental sides for understanding quarkonium itself and taking it as tools

- Several envisioned future facilities worldwide motivate us to reinforce/strengthen our collaboration !

Conclusion

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Thank you for your attention !