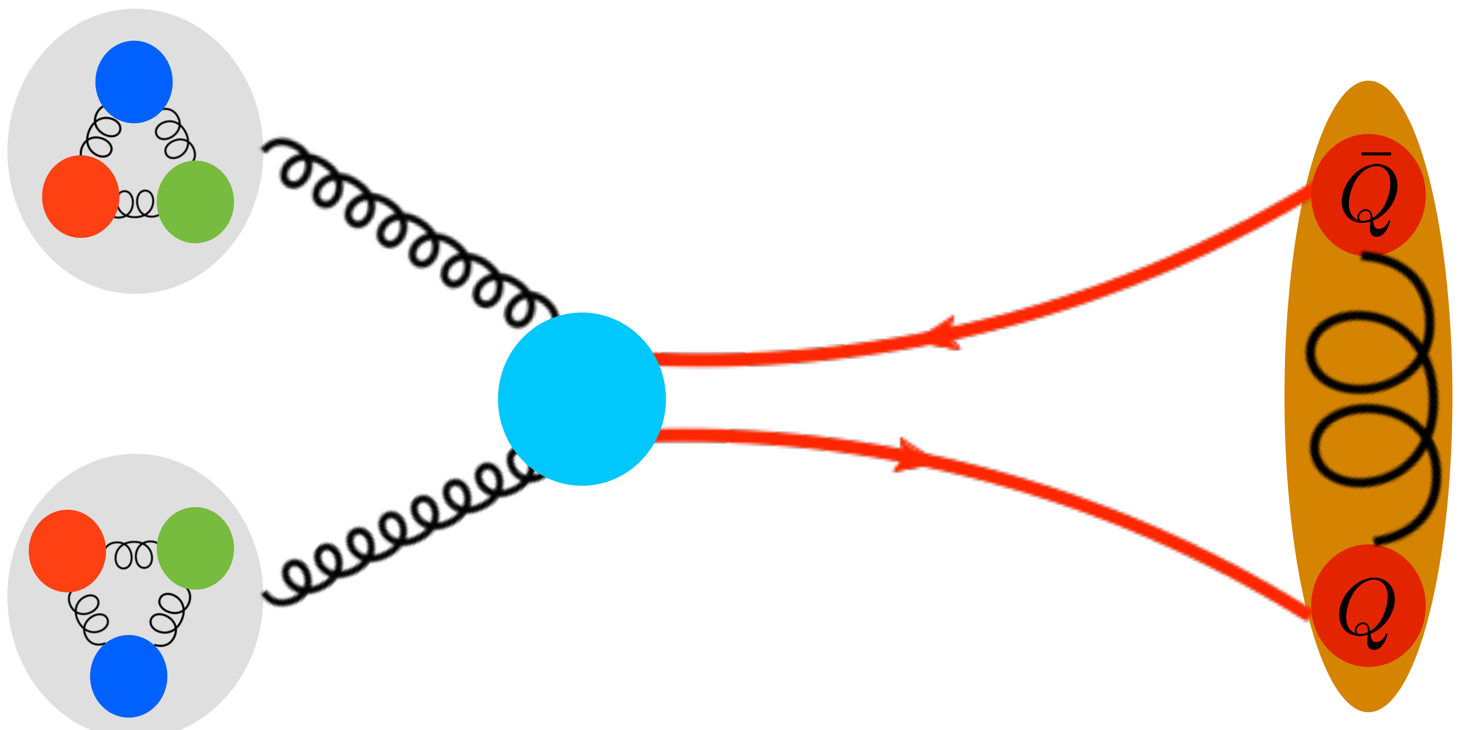
Introduction to HELAC-Onia



Hua-Sheng Shao

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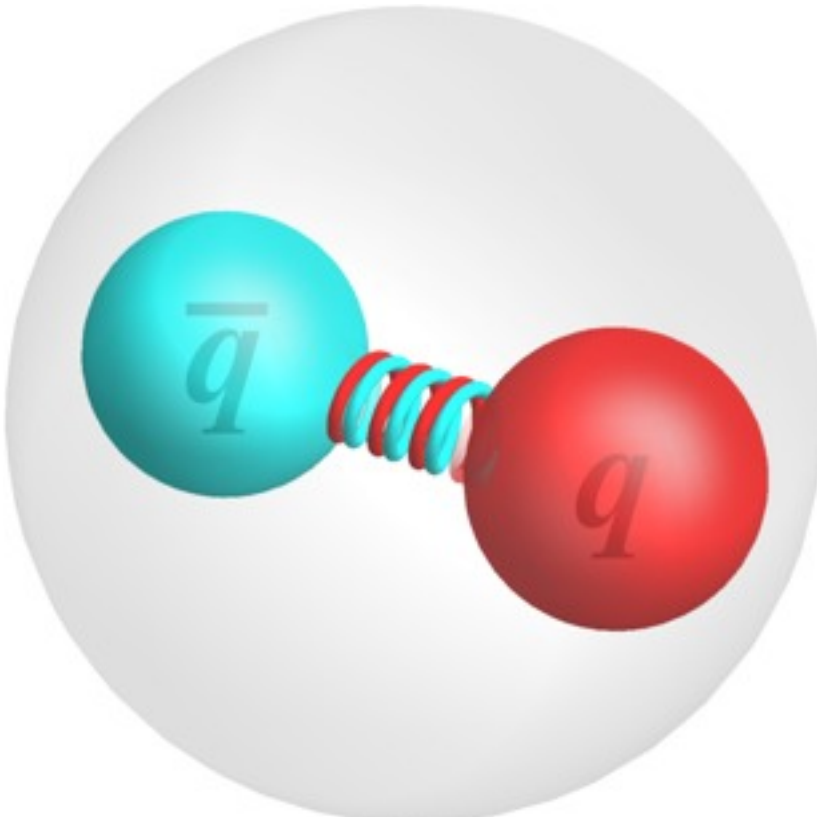
LPTHE
LABORATOIRE DE PHYSIQUE THEORIQUE ET HAUTES ENERGIES

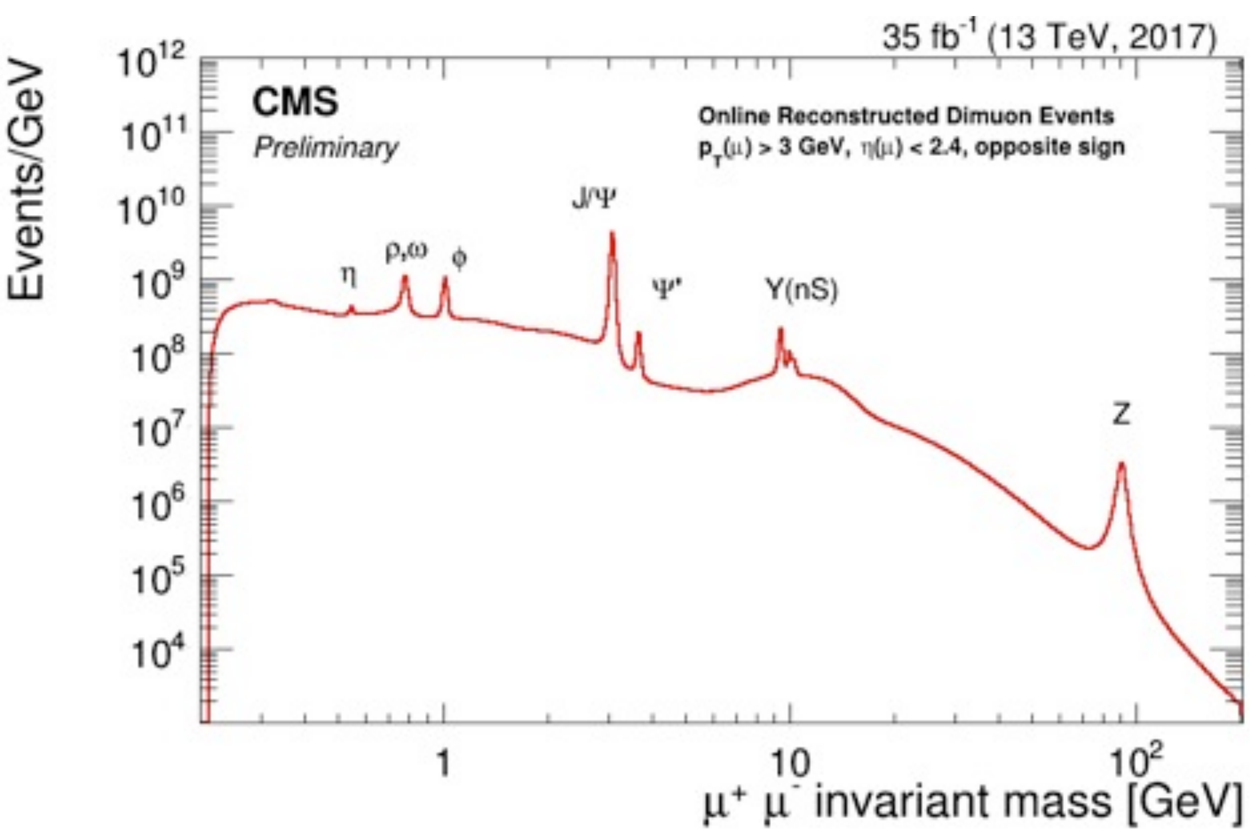
SORBONNE UNIVERSITÉ
CRÉATEURS DE FUTURS DEPUIS 1257

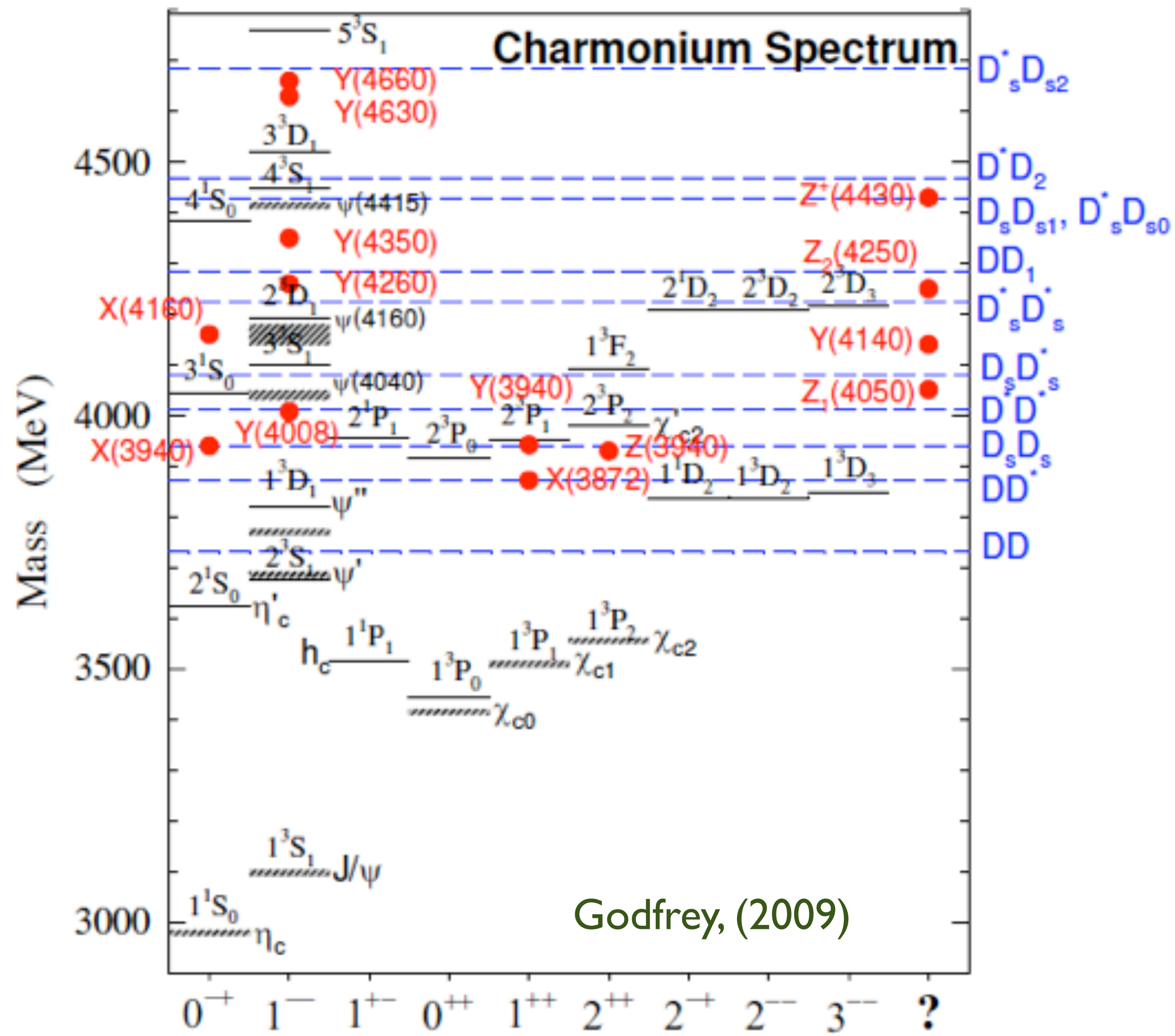
03 June 2021

HEAVY QUARKONIUM: WHAT ?



- A class of mesons composed of two (same or diff.-flavur) heavy quarks





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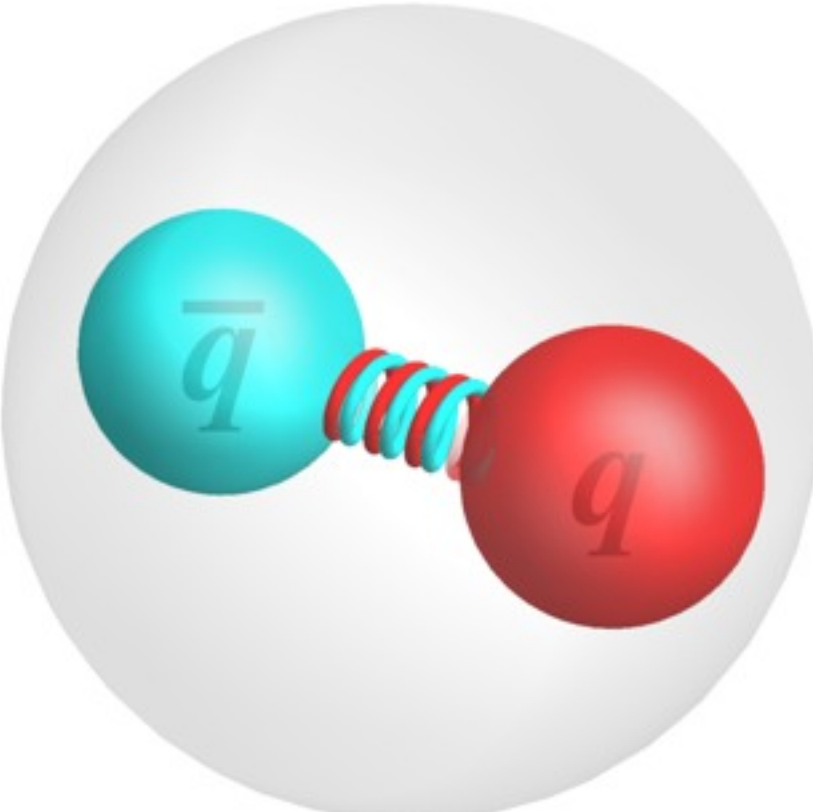

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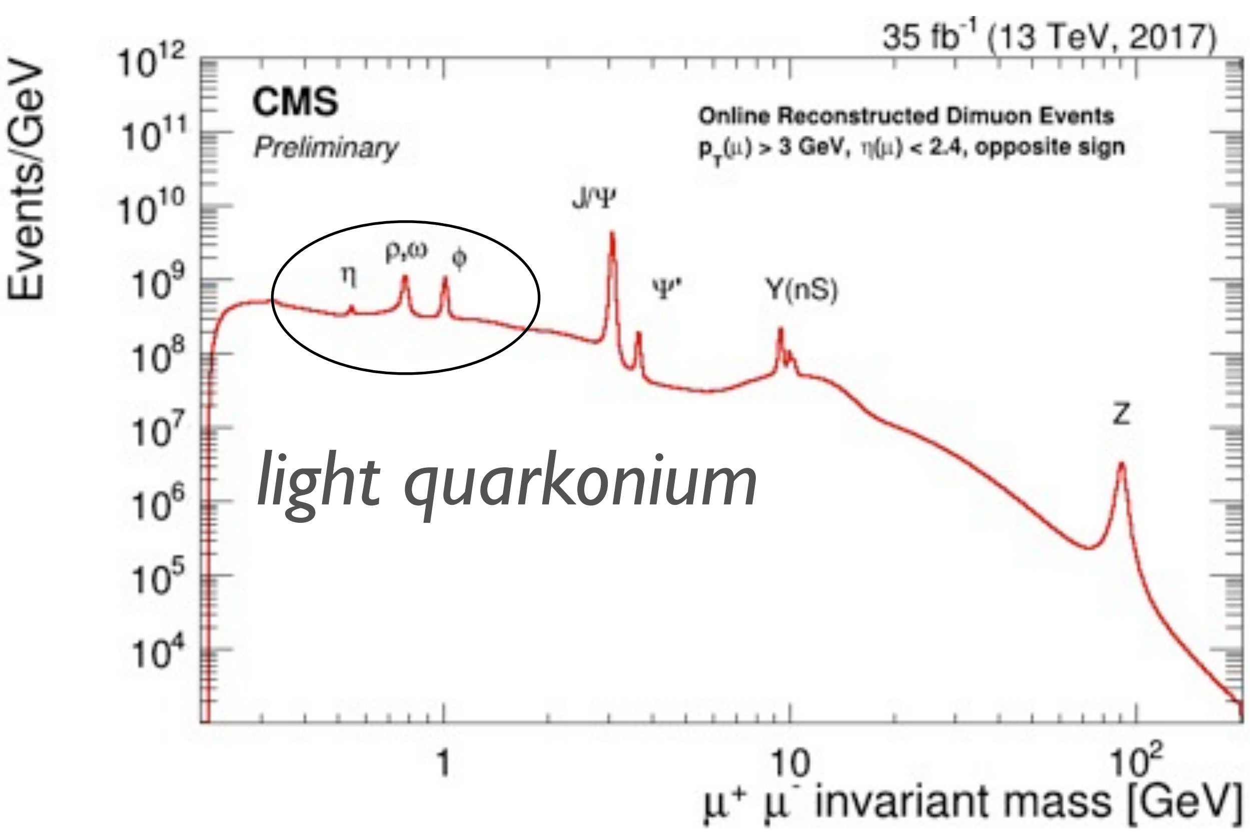

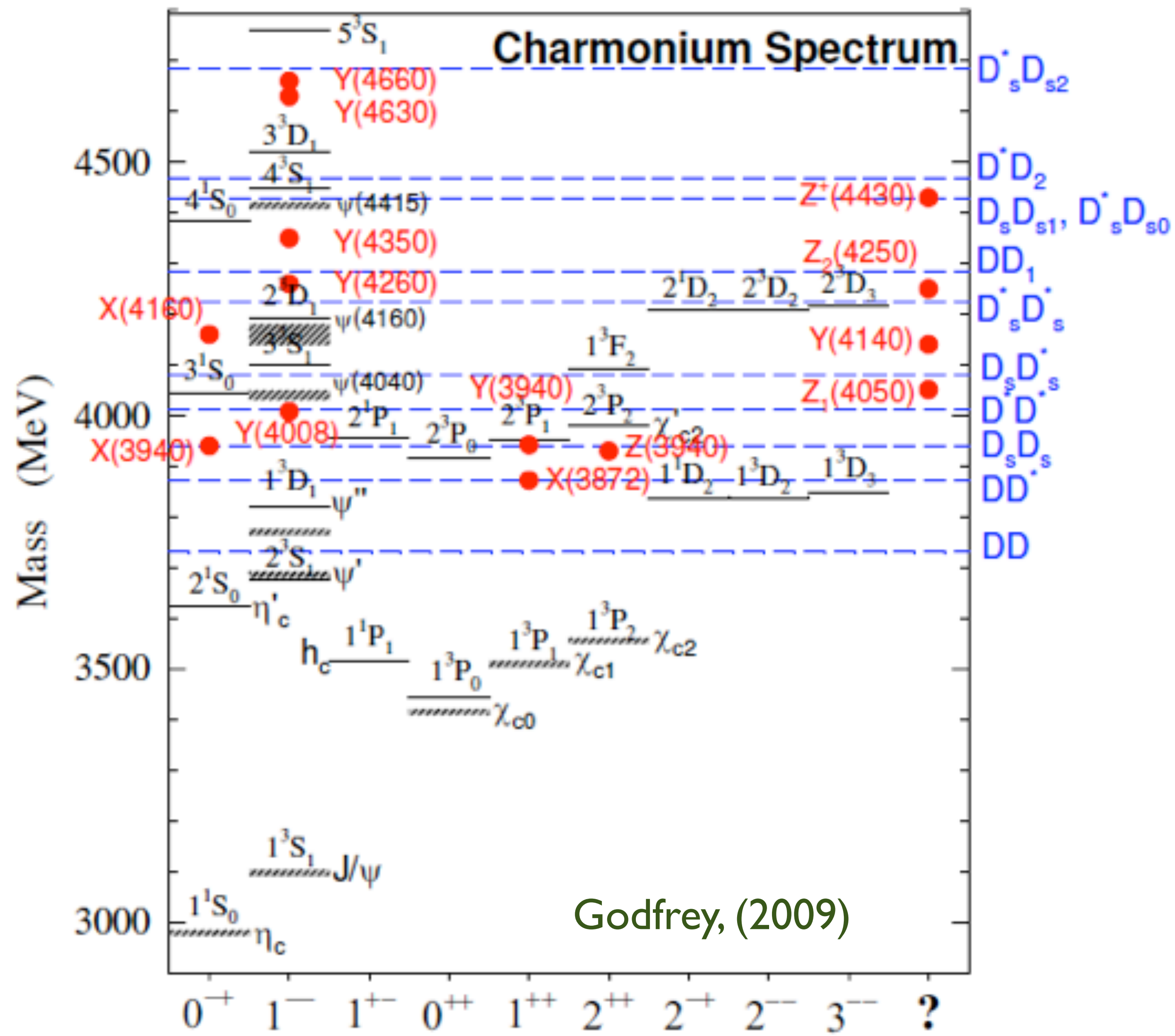

Wednesday, May 26, 21

HEAVY QUARKONIUM: WHAT ?

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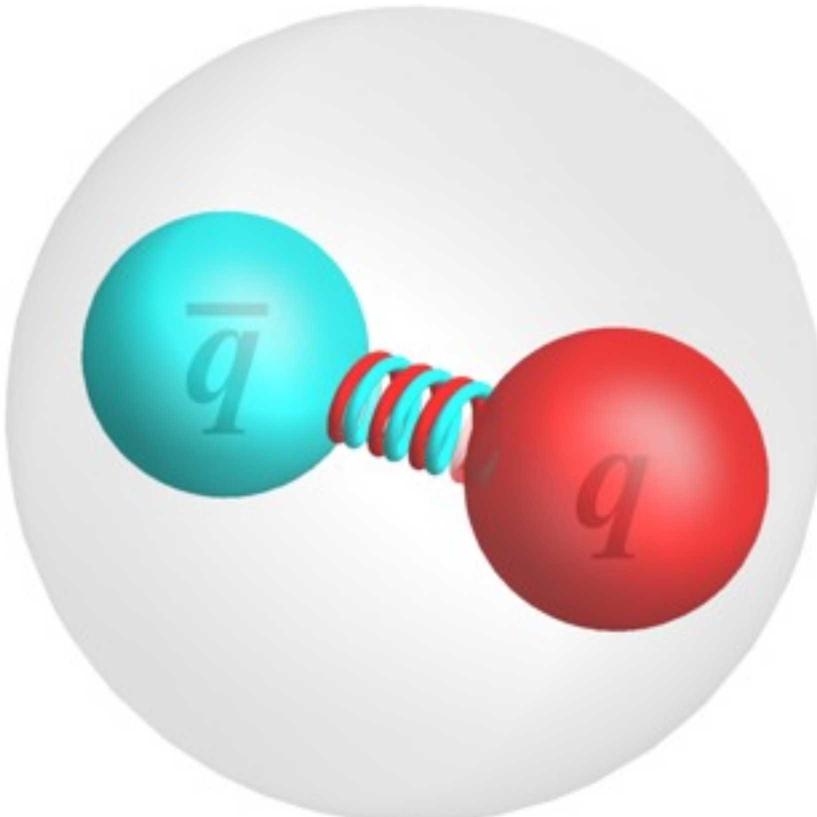

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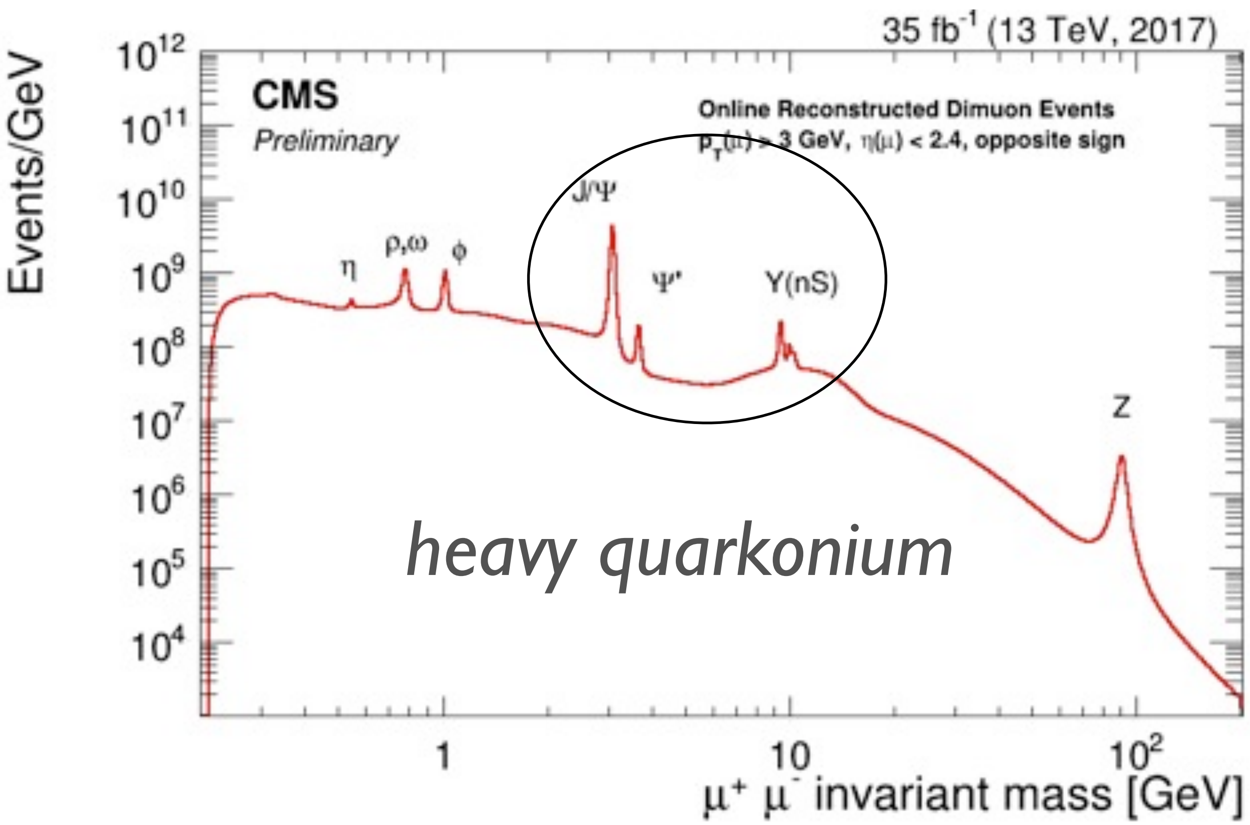

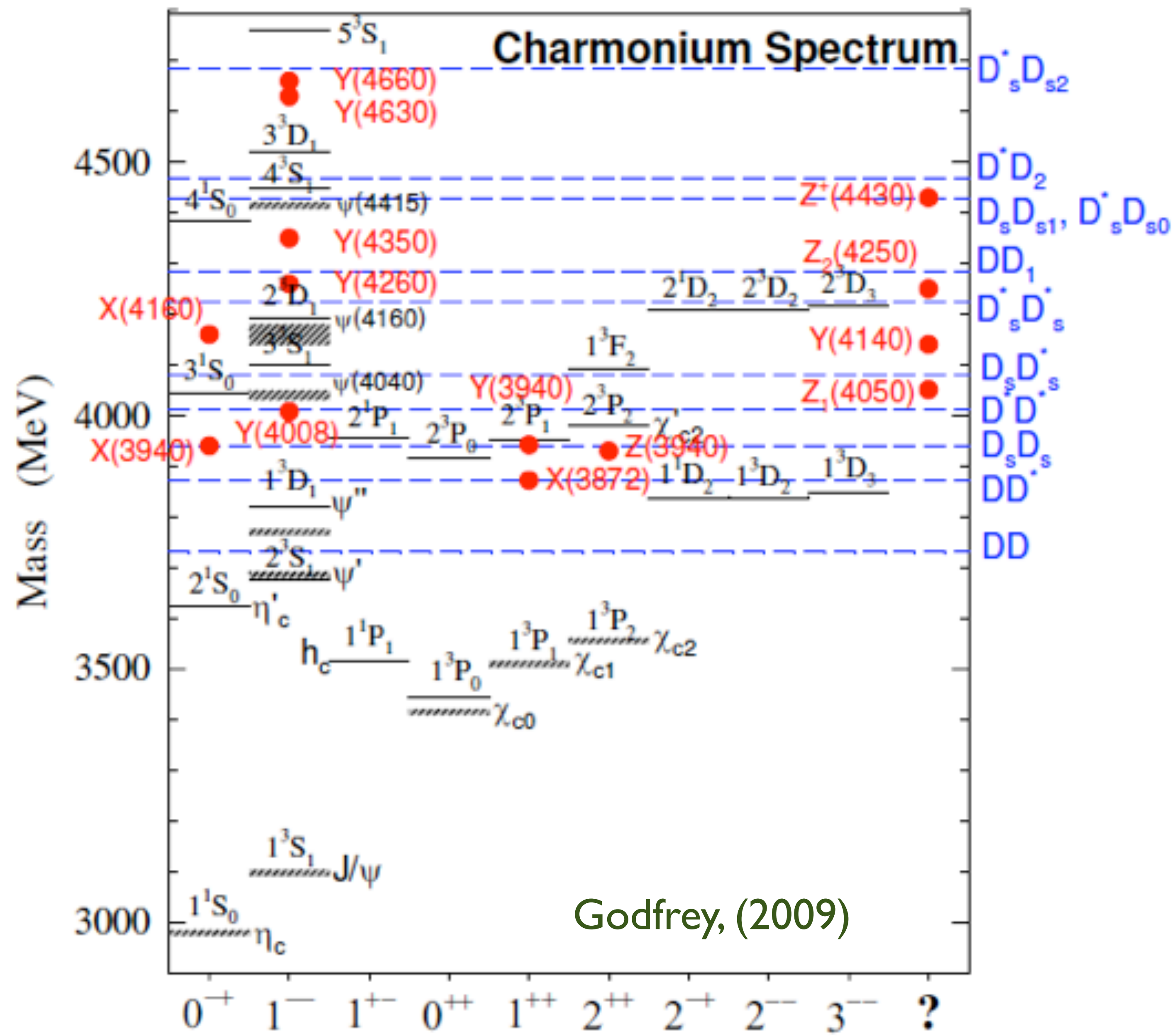

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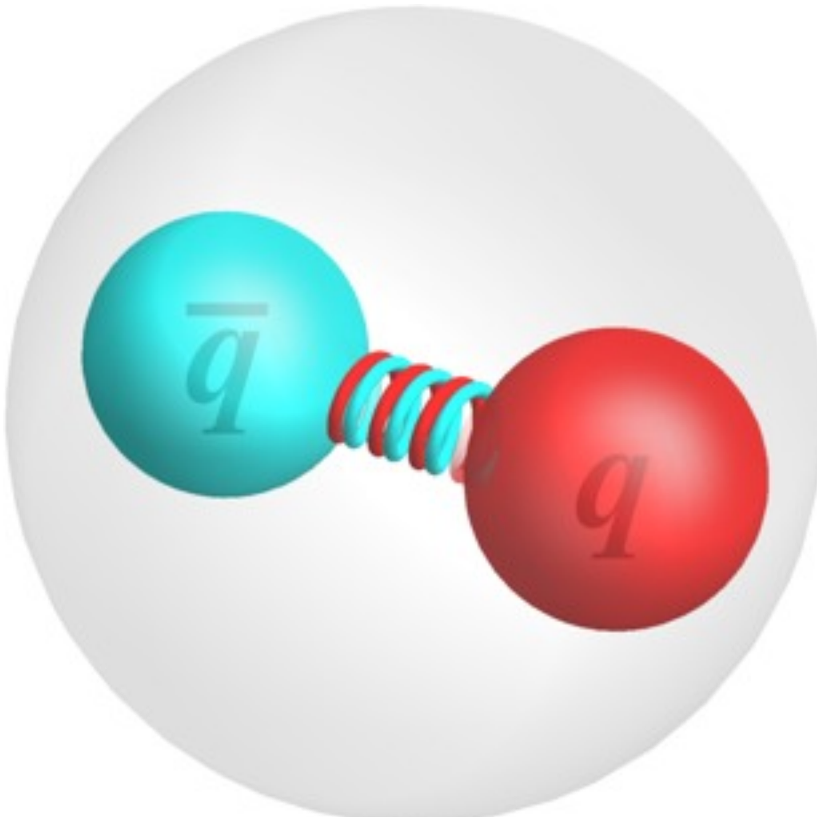

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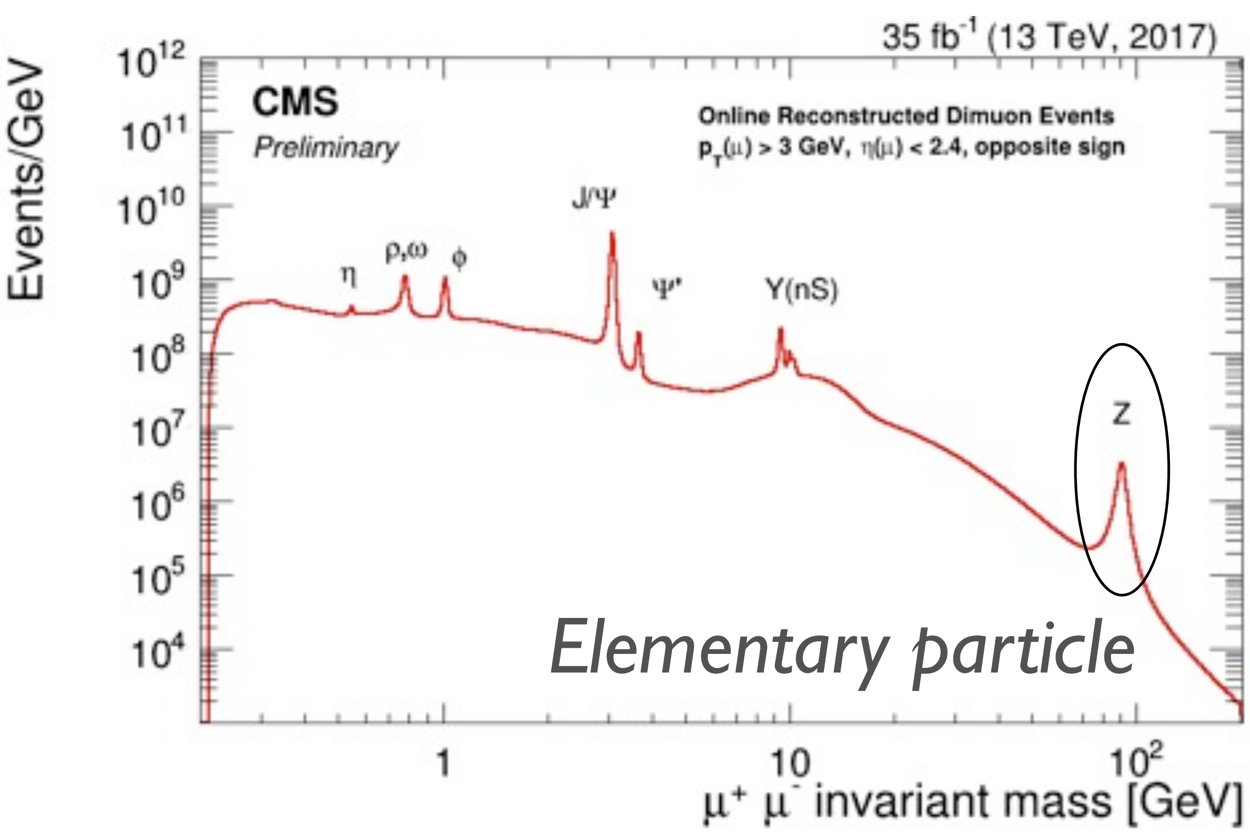

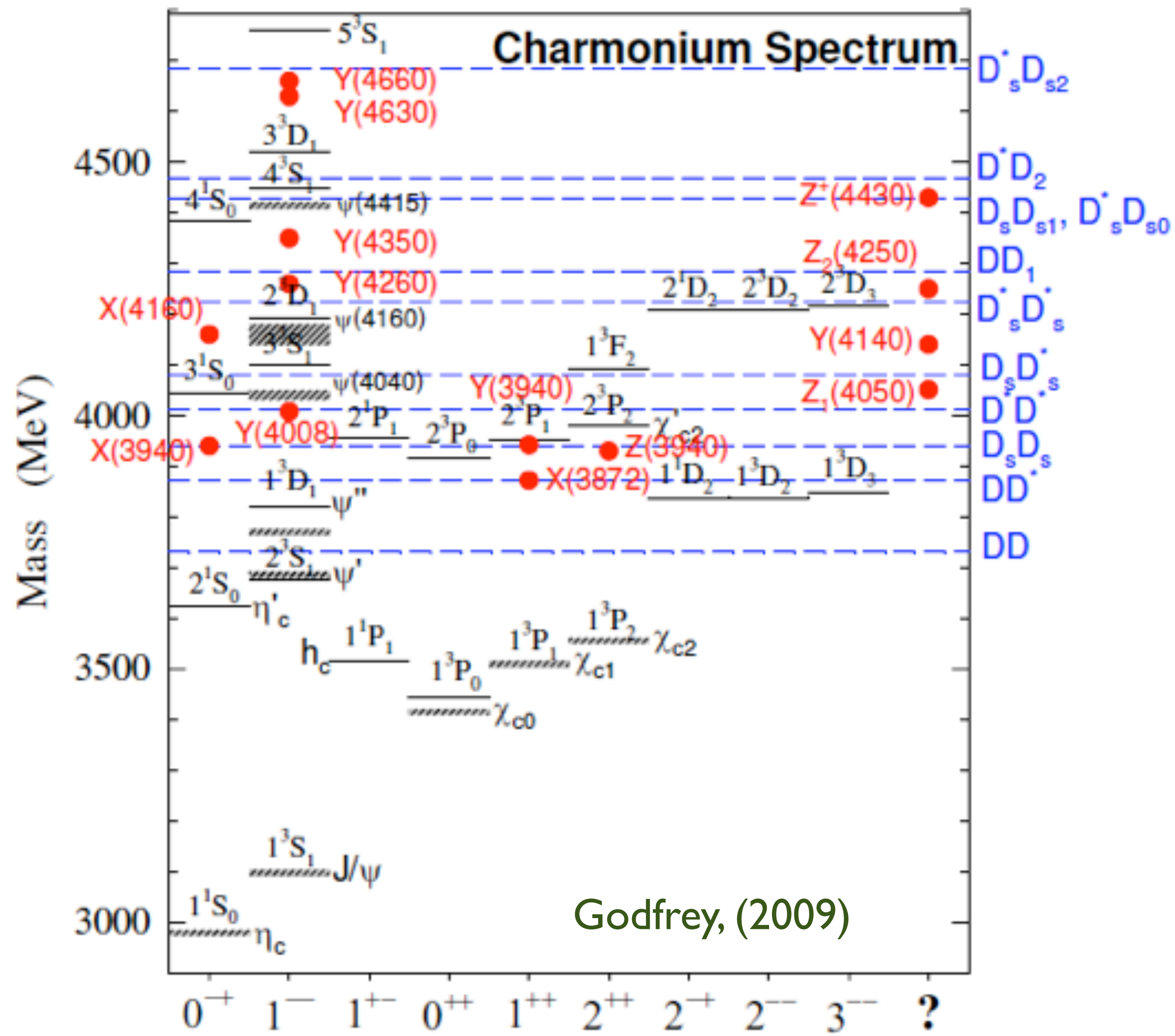

HEAVY QUARKONIUM: WHY ?

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- Heavy quarkonium provides an ideal laboratory to test perturbative QCD and to study the underlying non-perturbative dynamics.

- Almost all of the high-energy experiments with proton, electron and ion beams have measured them and studied the relevant physics:

  - Fundamental parameters: strong coupling constant, CKM
  - Probe gluon distributions in proton: collinear/transverse dynamics
  - Multiple-parton (hard) scatterings
  - Quark-gluon plasma, cold nuclear effect, CP violation etc

HEAVY QUARKONIUM: WHY ?

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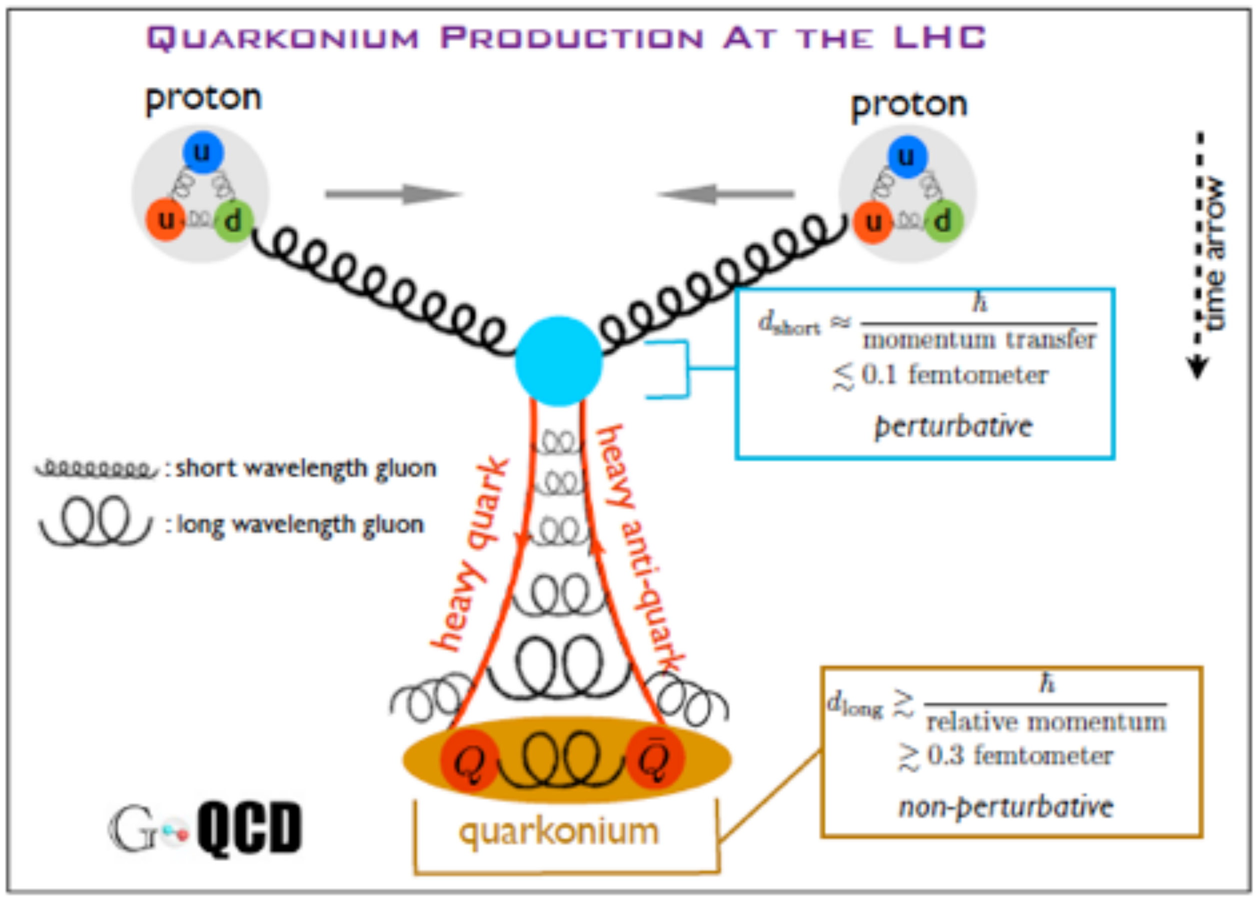
BUT their production mechanism is still unclear !

NRQCD FACTORISATION

Power counting	η_Q	ψ, Υ	h_Q	χ_{QJ}
v^3	${}^1S_0^{[1]}$	${}^3S_1^{[1]}$	—	—
v^5	—	—	${}^1P_1^{[1]}, {}^1S_0^{[8]}$	${}^3P_J^{[1]}, {}^3S_1^{[8]}$
v^7	${}^1S_0^{[8]}, {}^3S_1^{[8]}, {}^1P_1^{[8]}$	${}^1S_0^{[8]}, {}^3S_1^{[8]}, {}^3P_J^{[8]}$	—	—

Bodwin, Braaten, Lepage PRD (1994)



- NRQCD factorisation

$$d\sigma(pp \to H_{Q\bar{Q}} + X)$$

$$= \sum_n d\sigma(pp \to Q\bar{Q}[n] + X) \times \langle \mathcal{O}^{H_{Q\bar{Q}}}(n) \rangle$$

- pQCD factorisation

$$d\sigma(pp \to Q\bar{Q}[n] + X)$$

$$= \sum_{a,b} f_{a/p}(x_1) f_{b/p}(x_2) |\mathcal{A}(ab \to Q\bar{Q}[n] + X)|^2$$

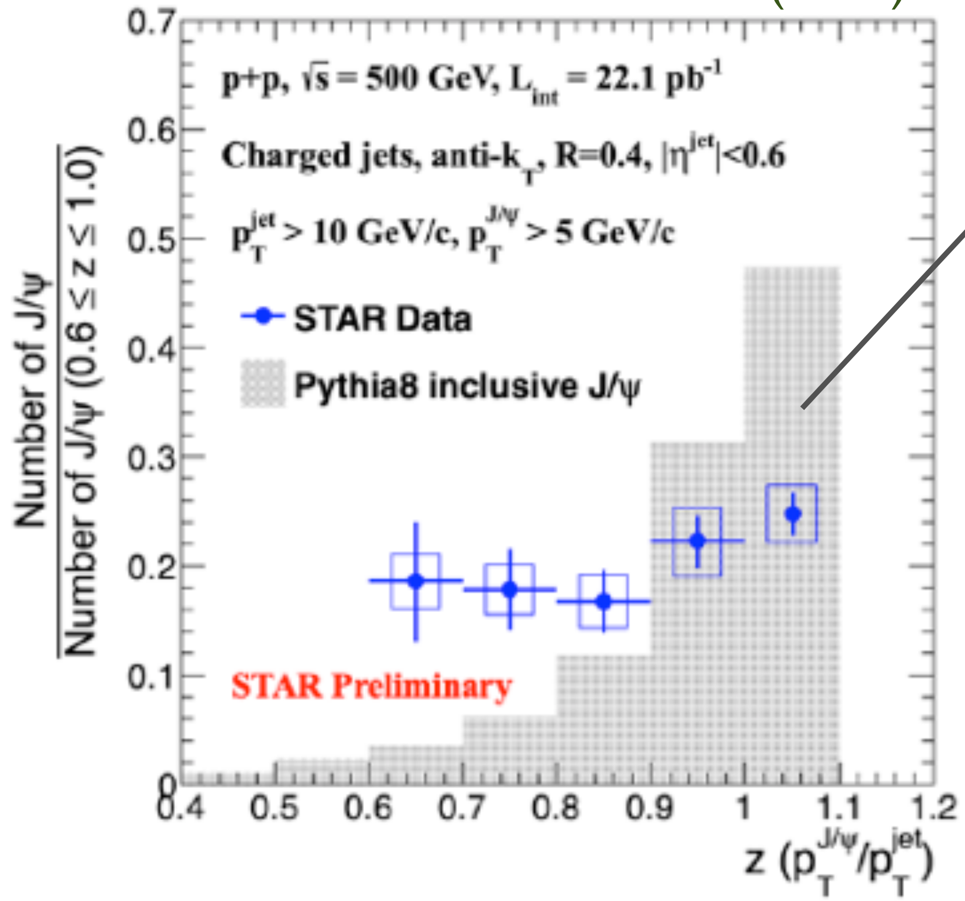
- LDME $\langle \mathcal{O}^{H_{Q\bar{Q}}}(n) \rangle$ and PDF $f_{i/p}(x)$ are non-perturbative and (should be) universal.

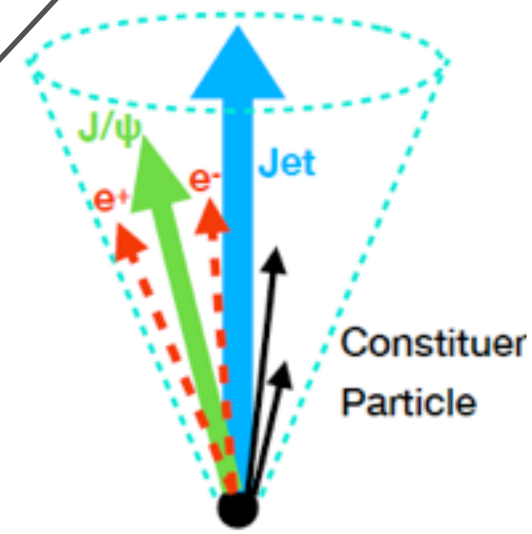
HEAVY QUARKONIUM: WHY ?

- **An example to show "how poor is our understanding" ?**

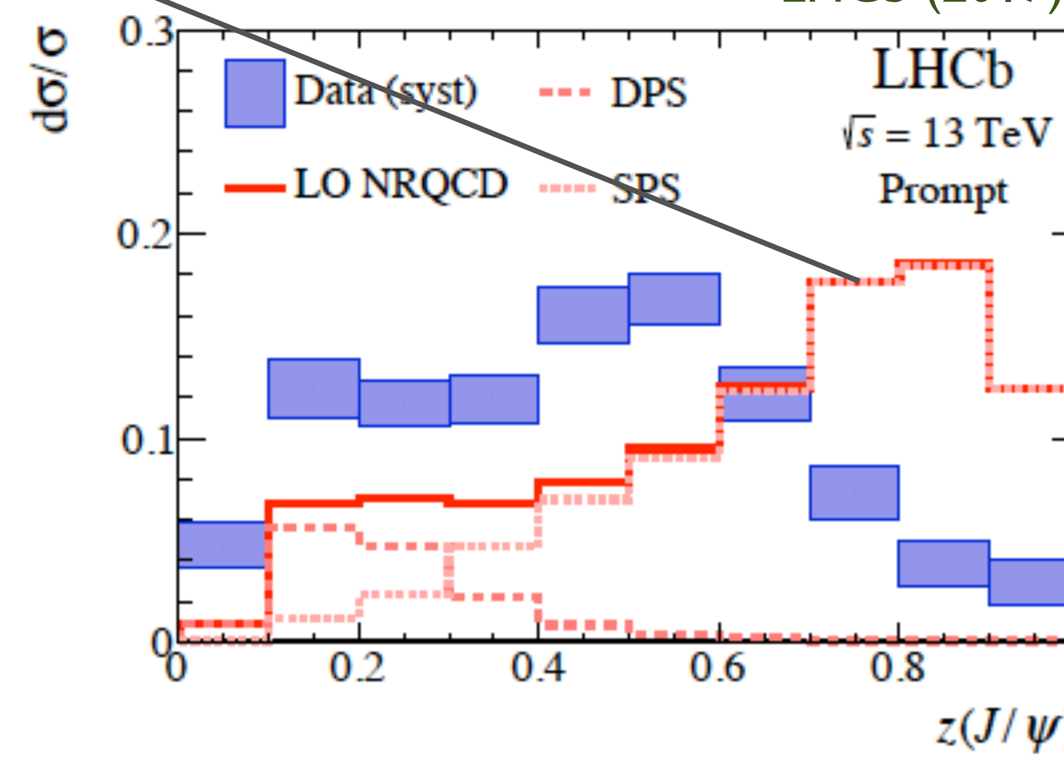
Pythia 8

STAR (2020)





LHCb (2017)



RHIC

LHC

Data has more event activities than Monte Carlo !

There are many similar examples !

HEAVY QUARKONIUM: WHY ?

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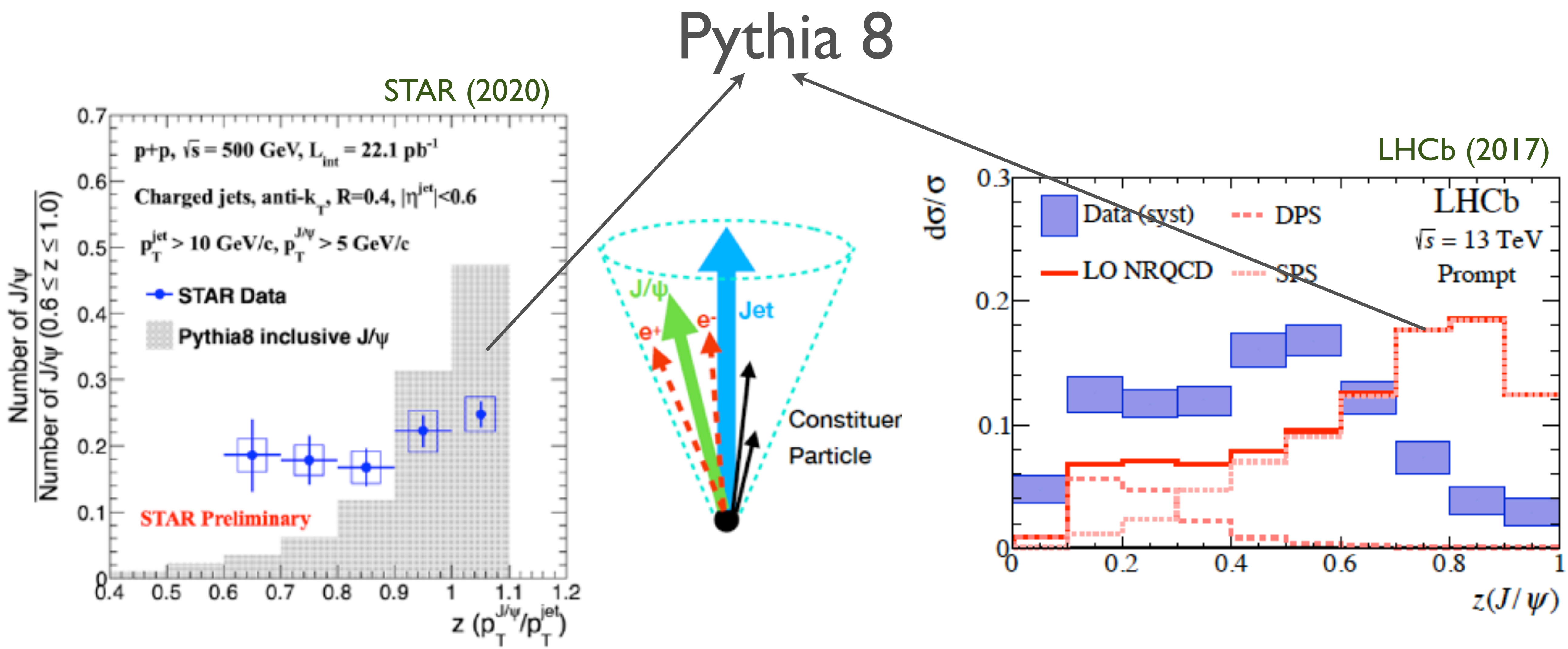
- **An example to show “how poor is our understanding” ?**



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→ ***A longstanding puzzle : Polarisation !***

WHY WE ARE INTERESTED IN POLARISATION ?

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- A colour-octet story starts from anomalously large yields

Braaten et al. (hep-ph/9405407)

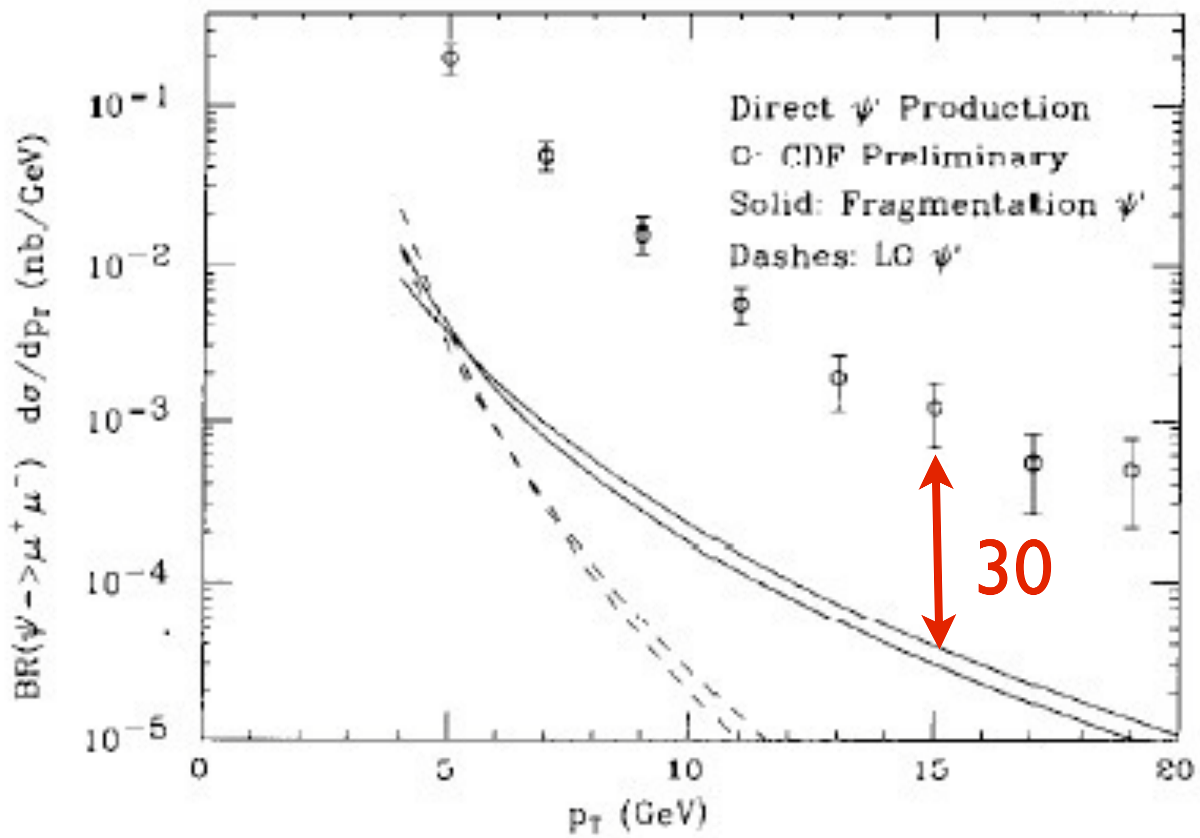

Fig. 4. Preliminary CDF data for prompt ψ' production (O) compared with theoretical predictions of the total fragmentation contribution (solid curves) and the total leading-order contribution (dashed curves).

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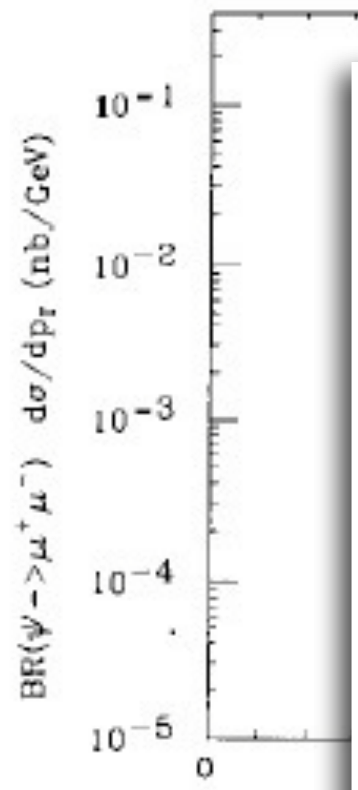

Fig. 4. Preliminar
compared with the
contribution (solid
(dashed curves).

Color-Octet Fragmentation and the ψ' Surplus at the Tevatron

Eric Braaten and Sean Fleming

Department of Physics and Astronomy, Northwestern University, Evanston, IL 60208

hep-ph/9411365

Abstract

The production rate of prompt ψ''s at large transverse momentum at the Tevatron is larger than theoretical expectations by about a factor of 30. As a solution to this puzzle, we suggest that the dominant ψ' production mechanism is the fragmentation of a gluon into a $c\bar{c}$ pair in a pointlike color-octet S-wave state, which subsequently evolves nonperturbatively into a ψ' plus light hadrons. The contribution to the fragmentation

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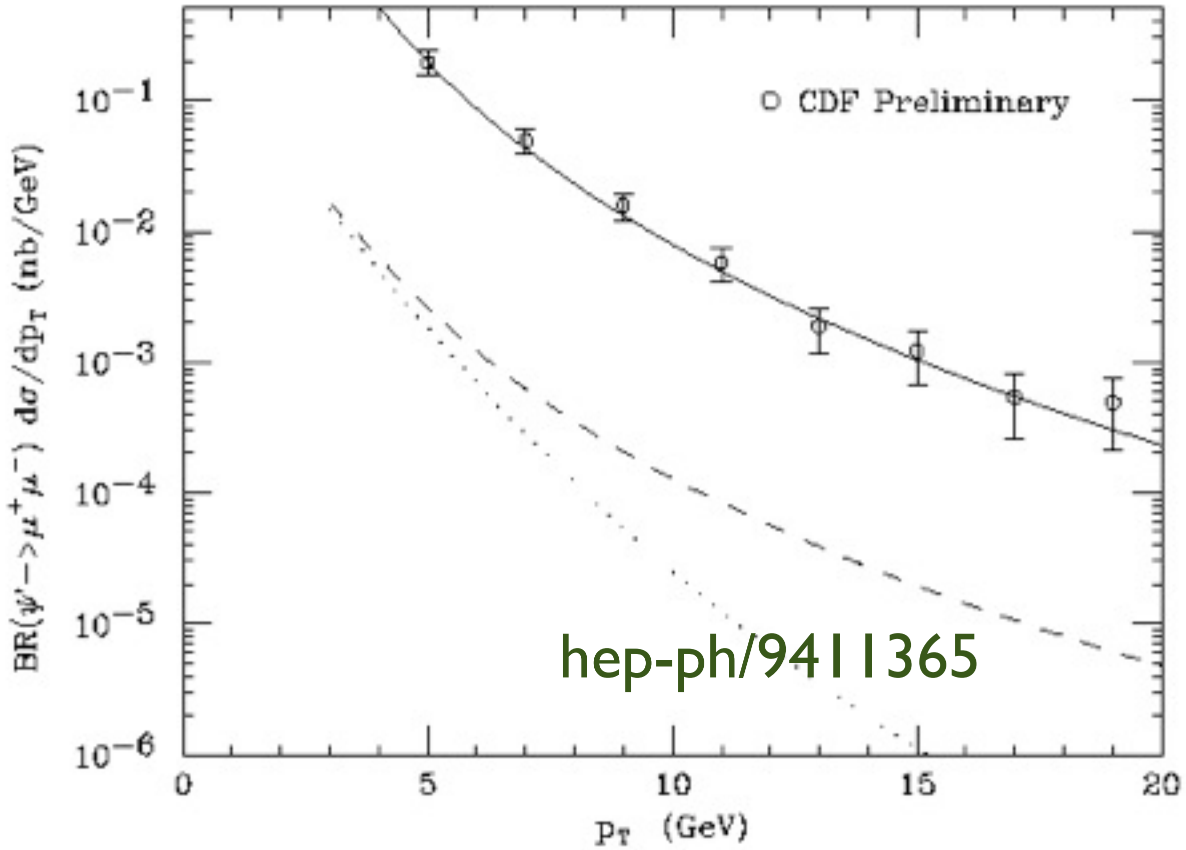

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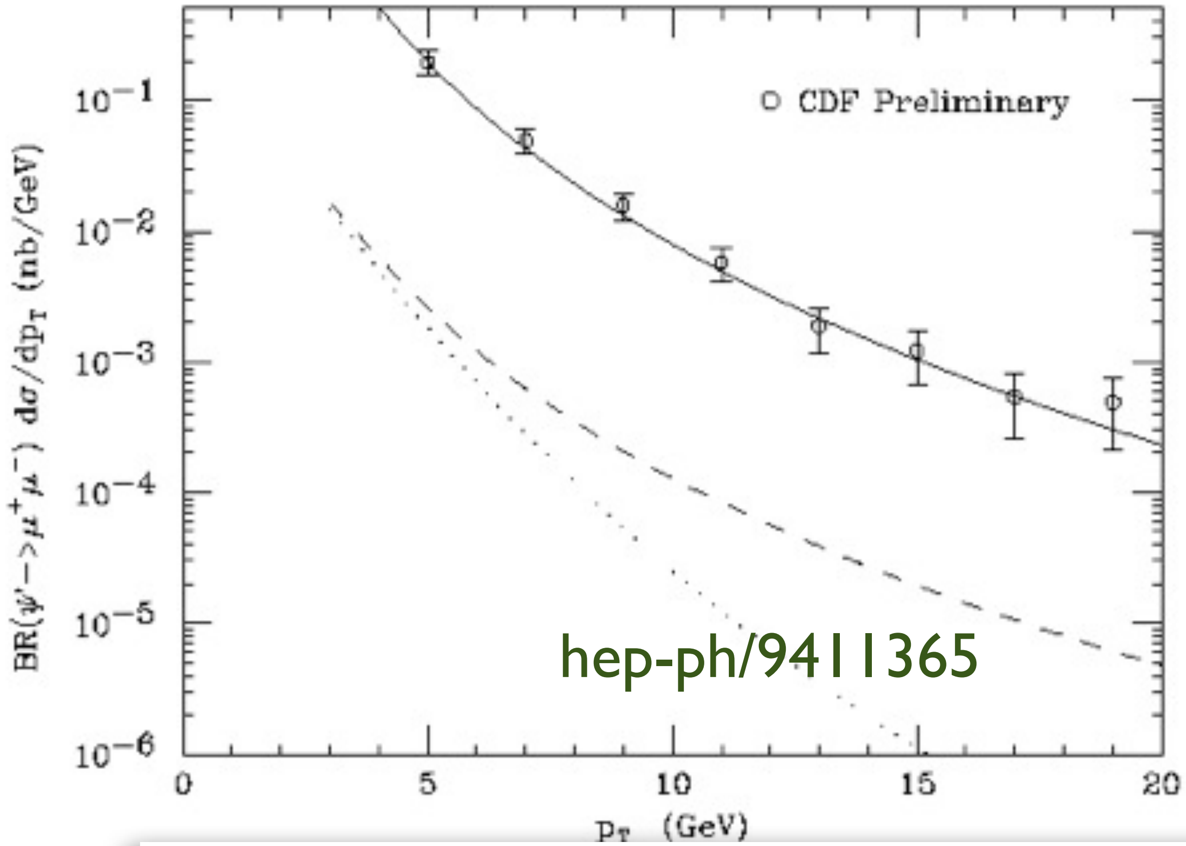

Fig. 4.
compare
contribu
(dashed

)ctet Fragmentation

Surplus at the Tevatron

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Abstract

and in rapidity could provide evidence for this new production mechanism. It has recently been pointed out by Cho and Wise [14] that measurements of the spin alignment of the ψ''s, which is reflected in the angular distribution of their leptonic decays, might provide a clear signature for the color-octet fragmentation mechanism. This mechanism produces ψ''s that are 100% transversely polarized at leading order in α_s, while other mechanisms tend to produce unpolarized ψ''s.

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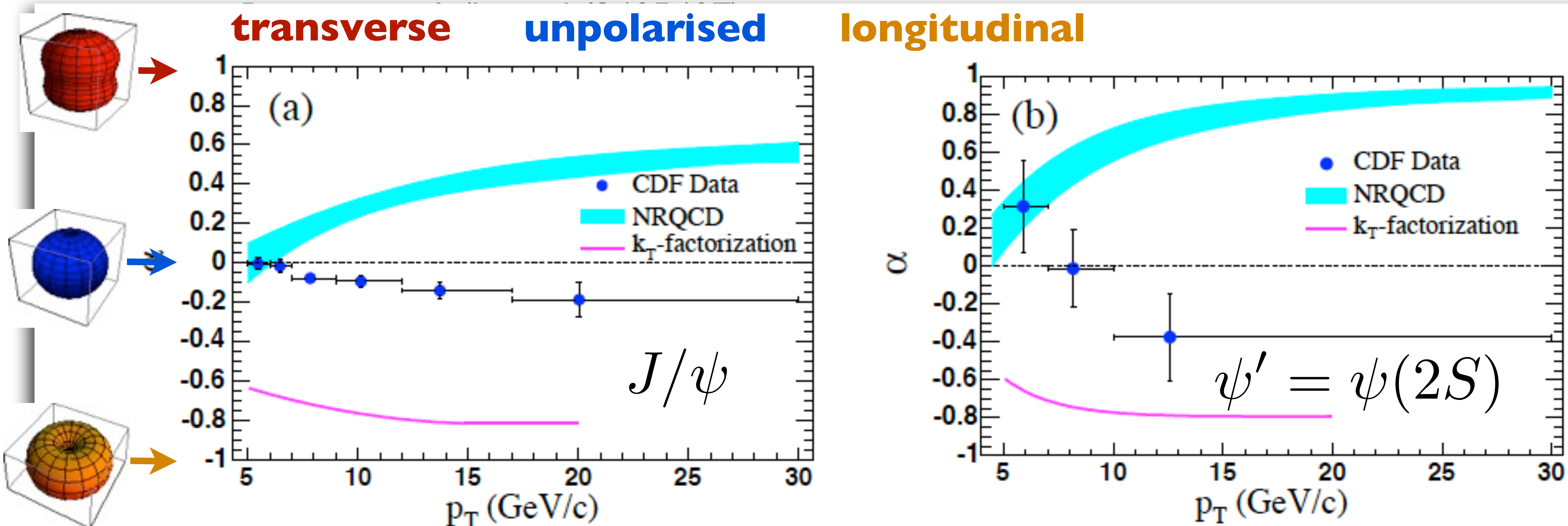

CDF (0704.0638)

FIG. 4: Prompt polarizations as functions of p_T: (a) J/ψ and (b) $\psi(2S)$. The band (line) is the prediction from NRQCD [4] (the k_T-factorization model [9]).

(dashed

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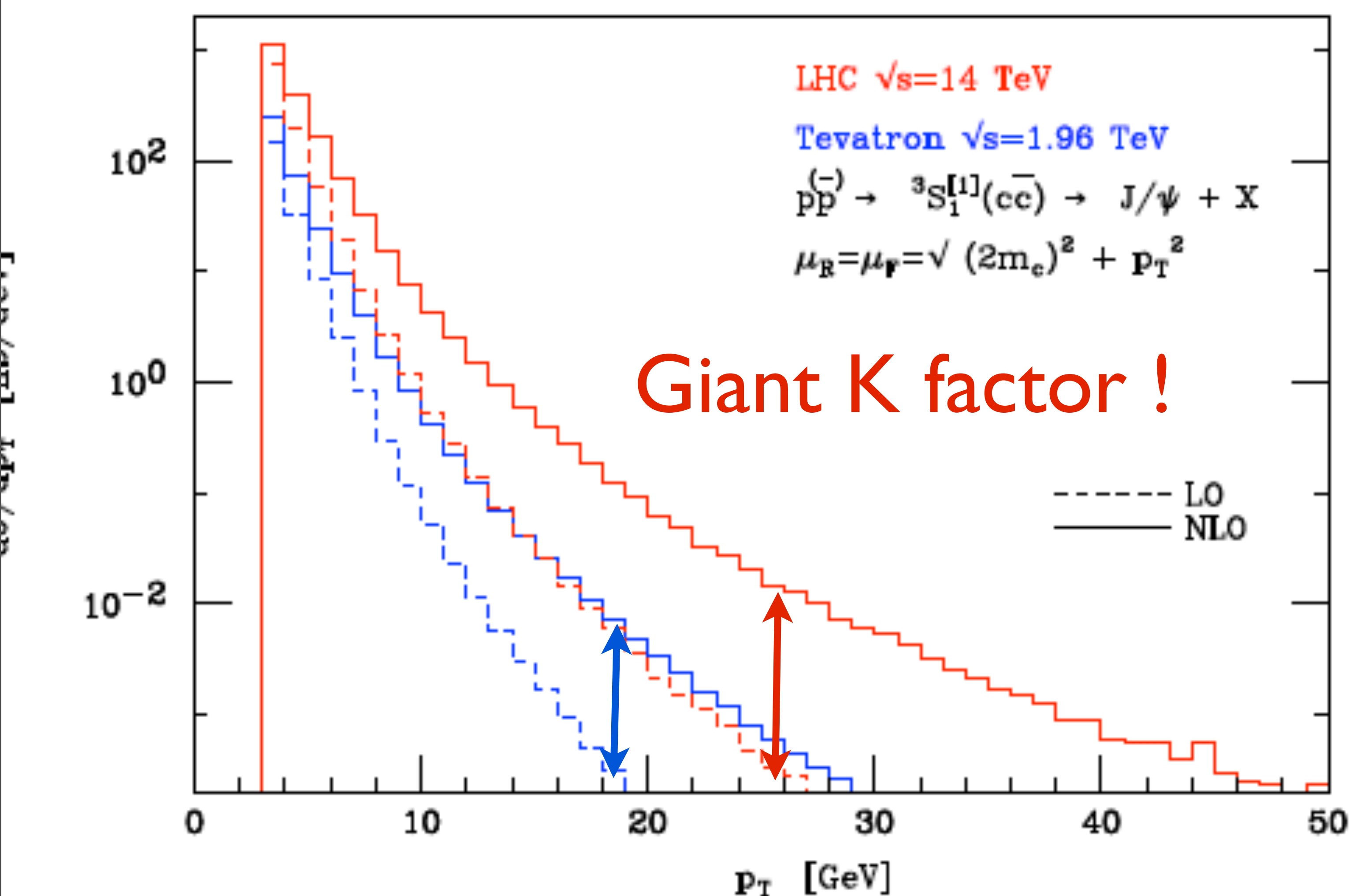
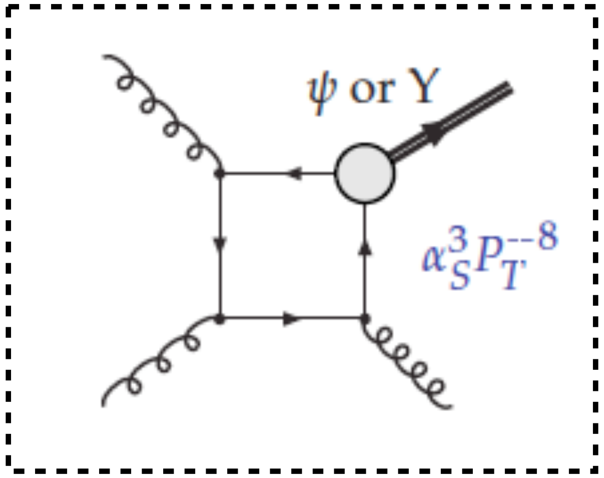
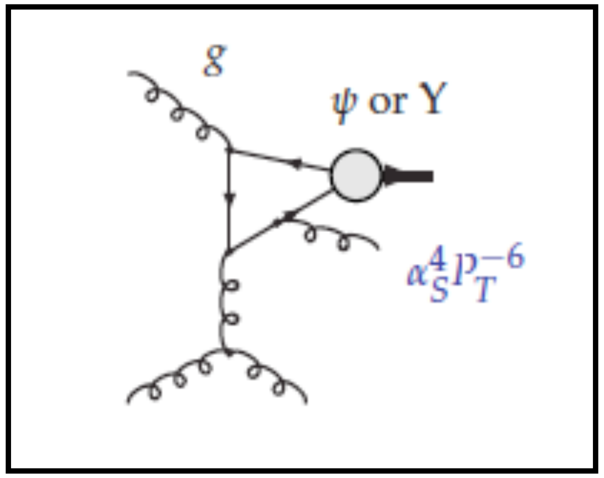
- **The NLO era: physic picture was altered !**

Campbell et al. (hep-ph/0703113)







LO

⇑

NLO

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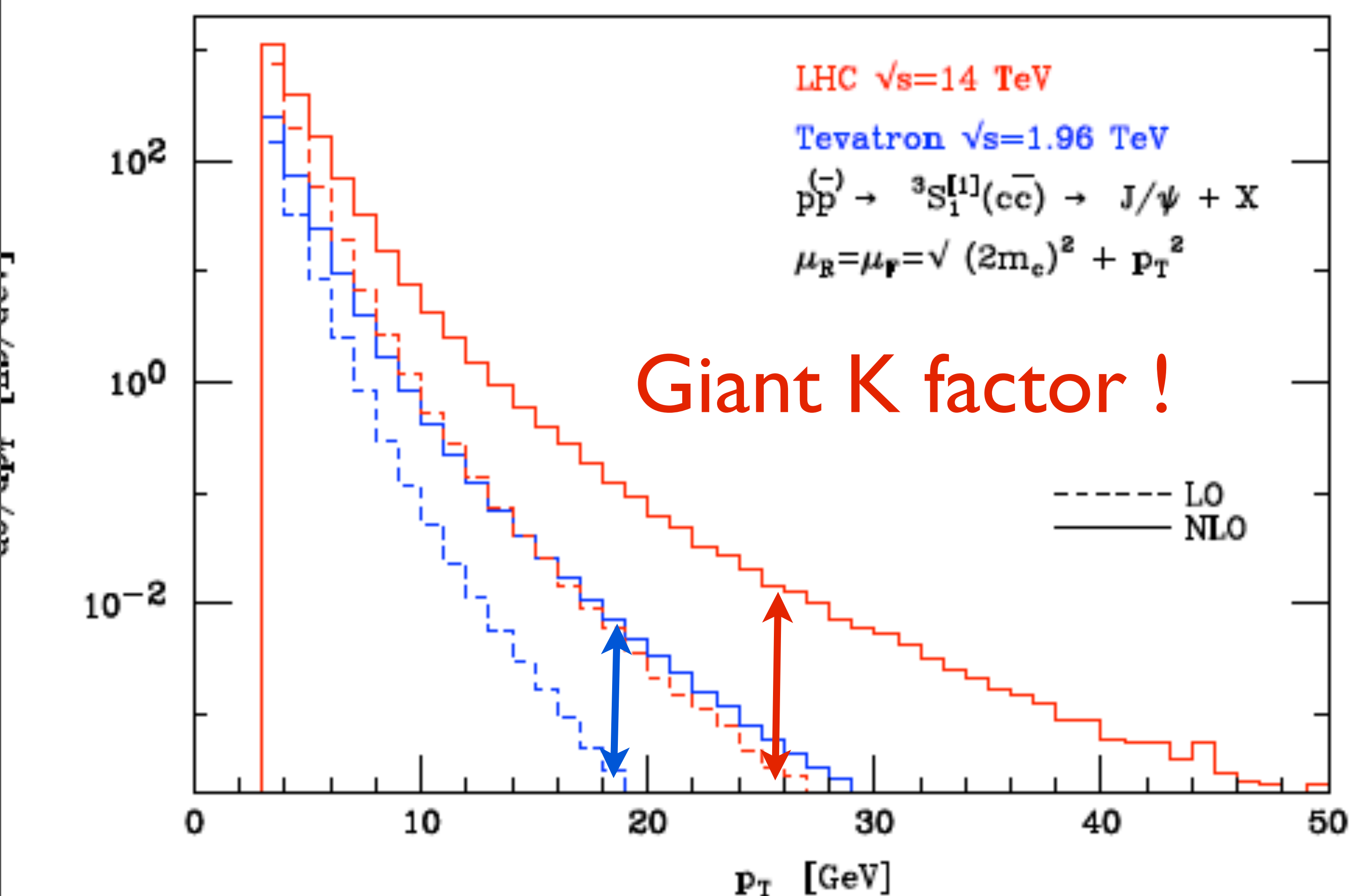
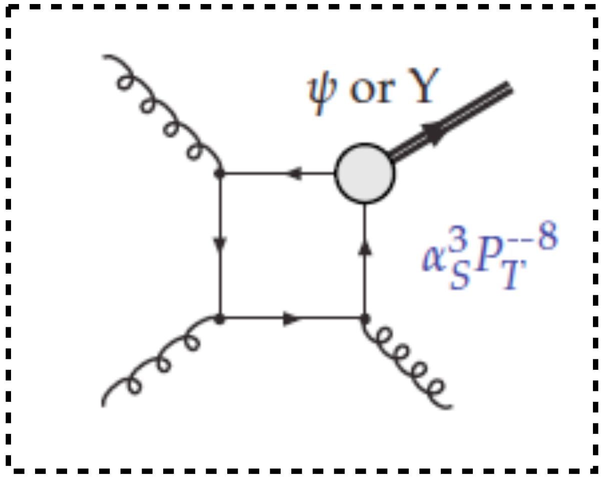
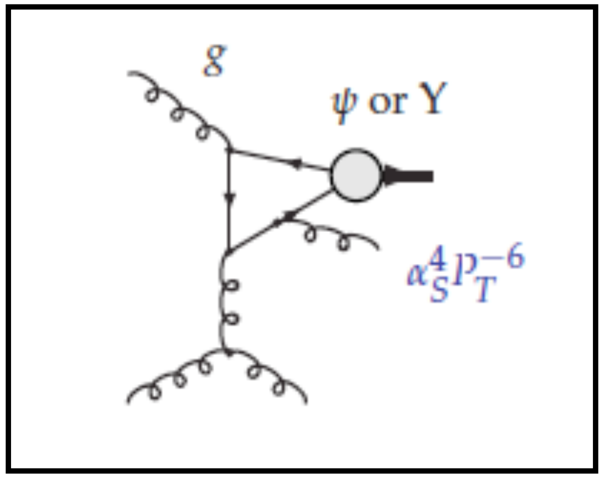




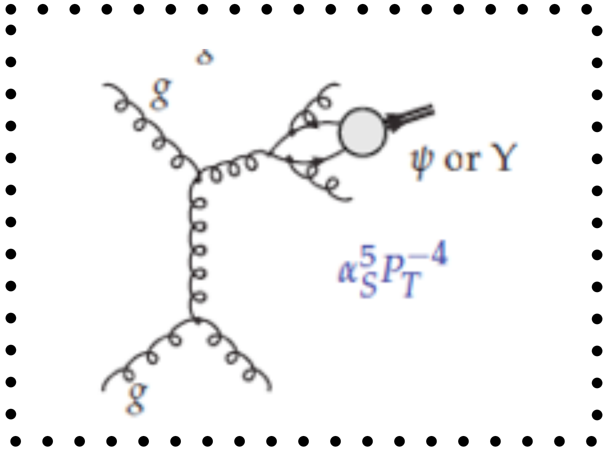
LO

⇑



NLO

? ⇑



NNLO

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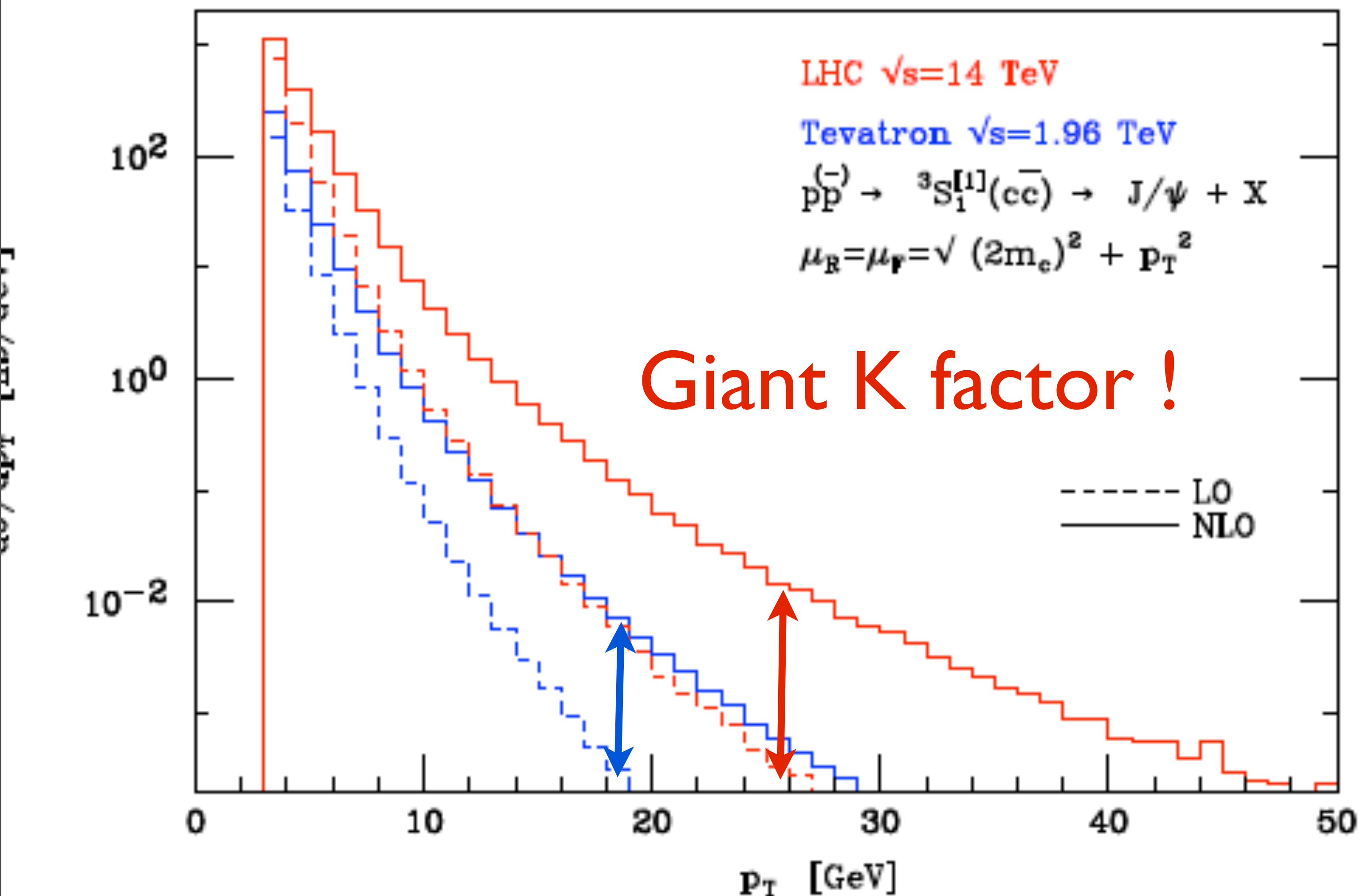

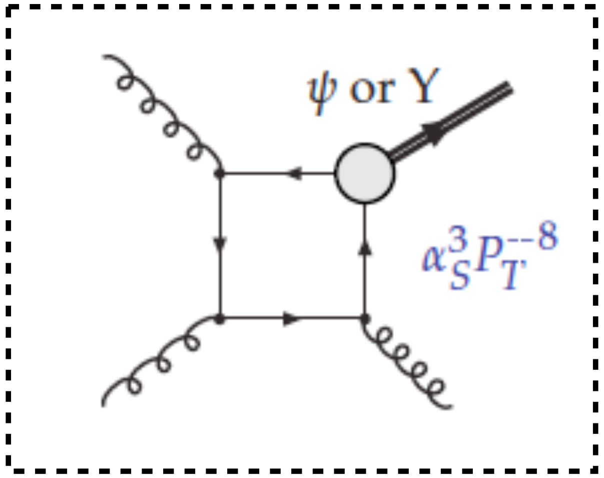

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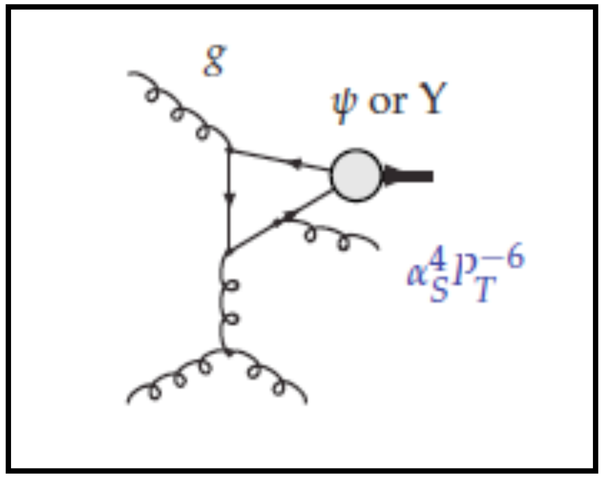
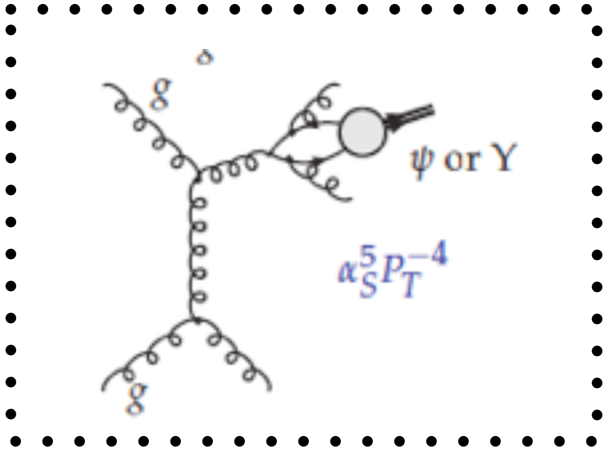


NLO

?



NNLO

Similar stories for other channels

DO WE HAVE A GLOBAL FIT ?

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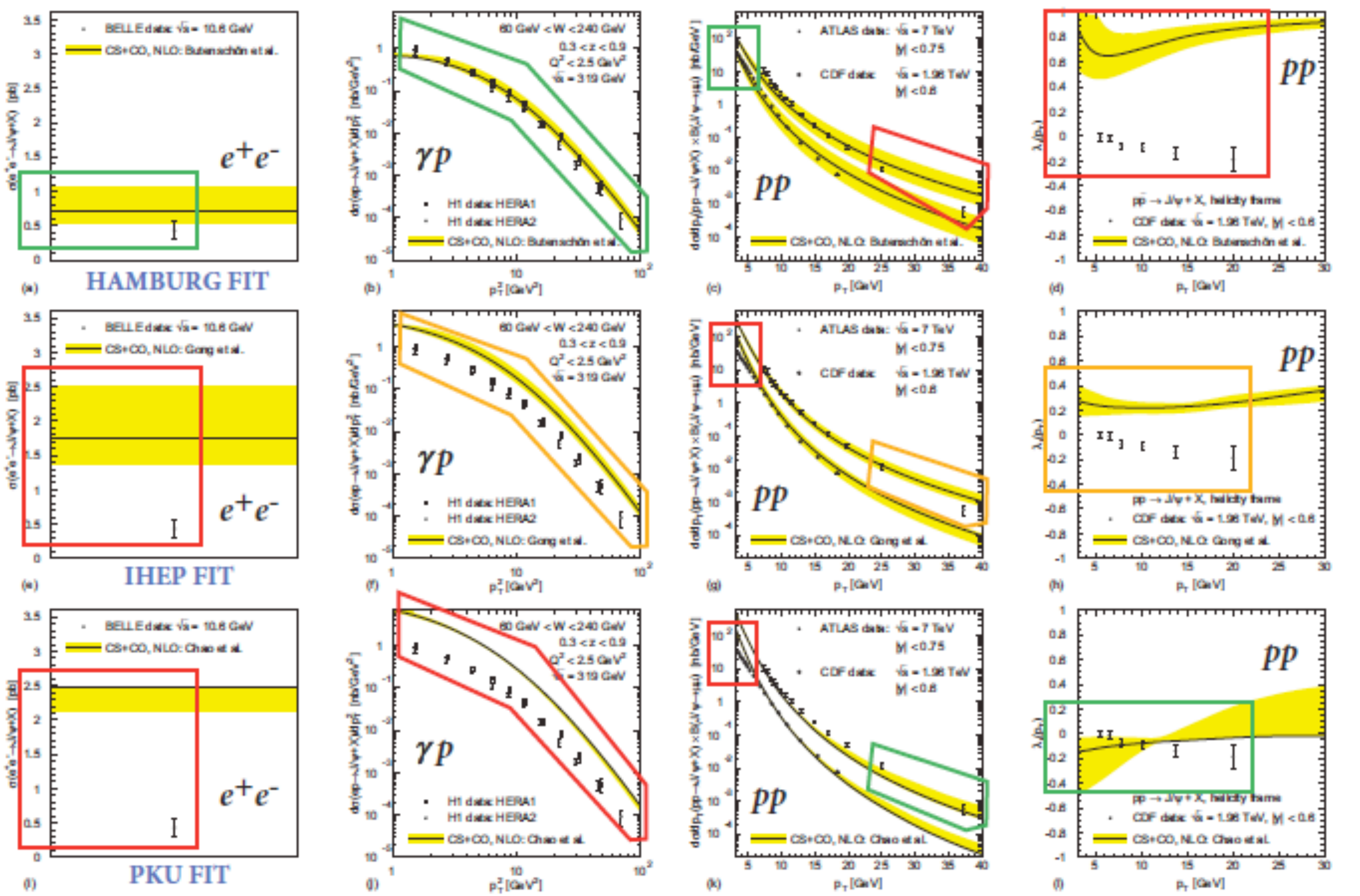
Slide from Jean-Philippe Lansberg

Plot from M. Butenschön (ICHEP 2012); Discussion in JPL, arXiv:1903.09185



Clearly pointing we are lacking of a coherent picture !

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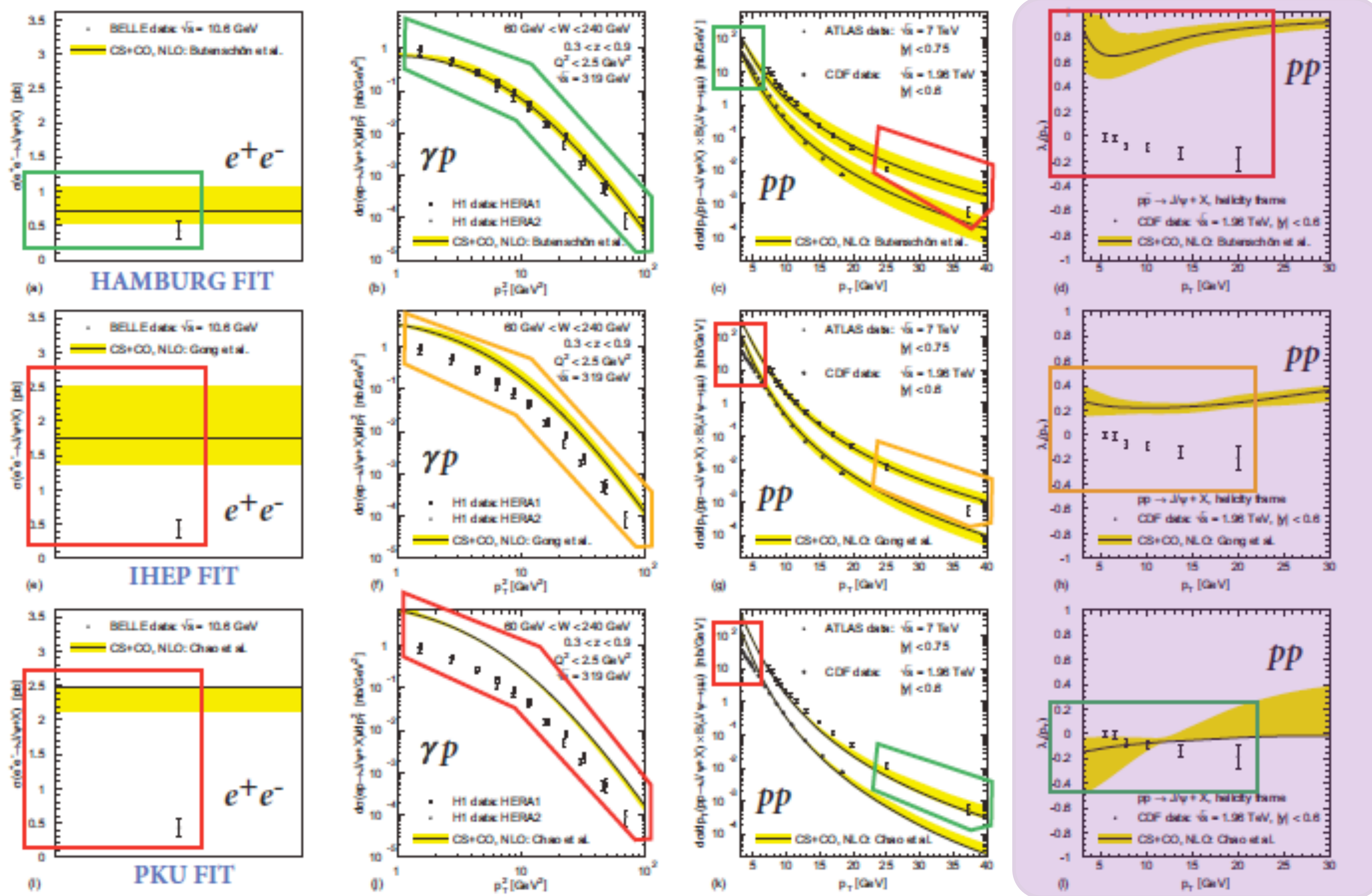

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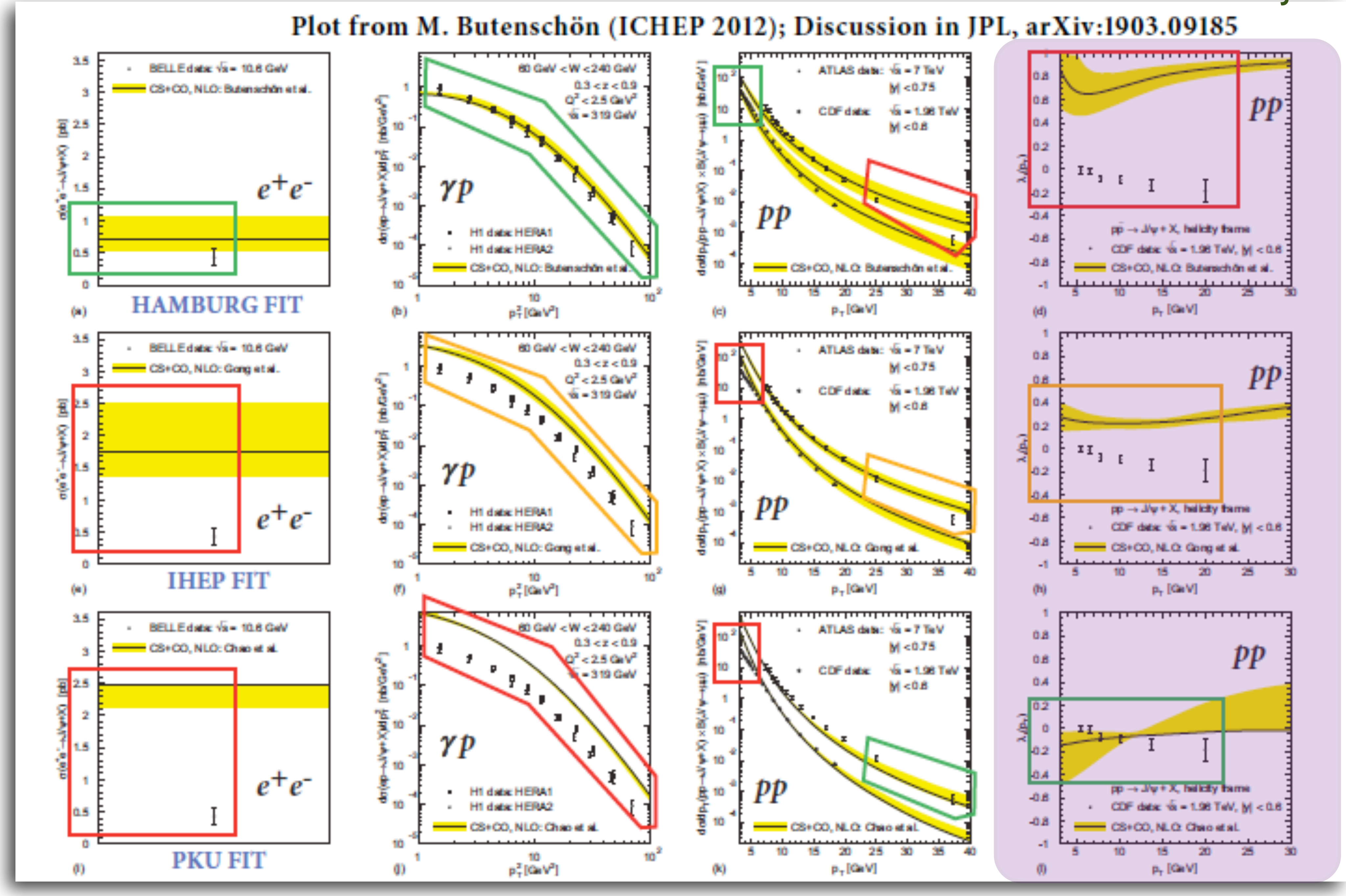

Clearly pointing we are lacking of a coherent picture !

... and more data came challenge theorists

η_c, quarkonium-jet profile etc

A BIT INTRODUCTION ON POLARISATION

- **Angular distribution in a vector decay**

HSS et al. (1209.4610)

$$\begin{aligned}
\mathcal{W}^V(\theta,\phi) \;\propto\;& 1+\lambda_\theta\cos^2\theta+\lambda_\phi\sin^2\theta\cos\phi \\
+\;& \lambda_{\theta\phi}\sin 2\theta\cos\phi+\lambda_\phi^\perp\sin^2\theta\sin 2\phi \\
+\;& \lambda_{\theta\phi}^\perp\sin 2\theta\sin\phi+2\eta_\theta\cos\theta \\
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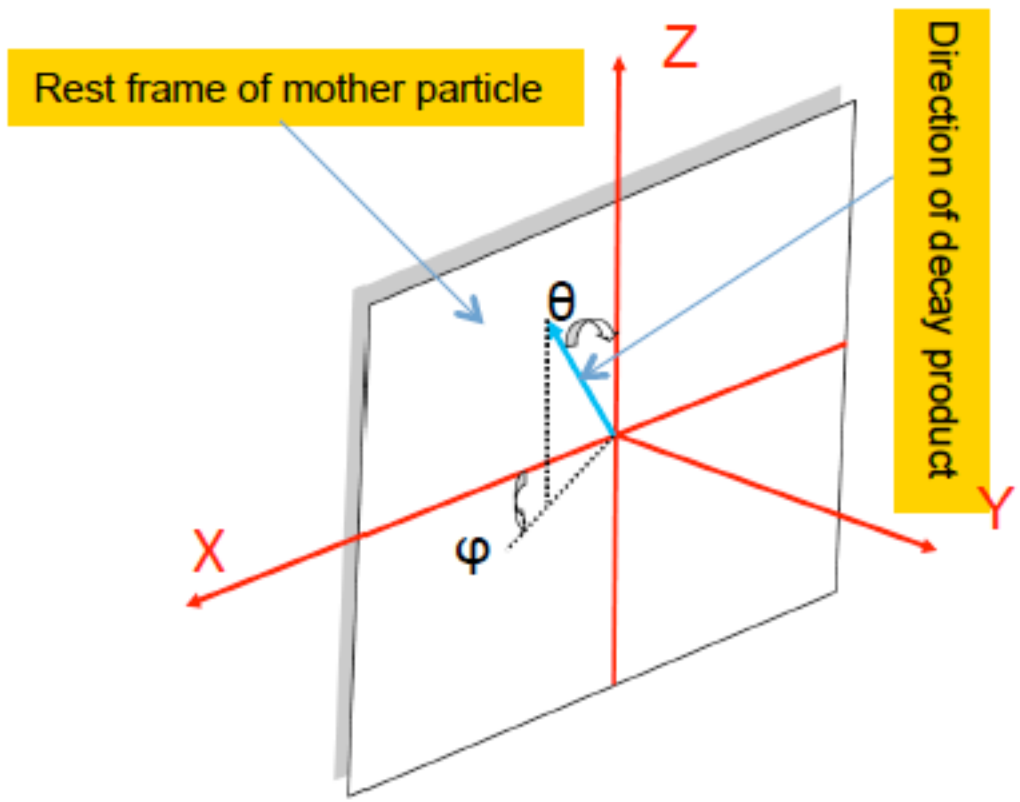
\end{aligned}$$



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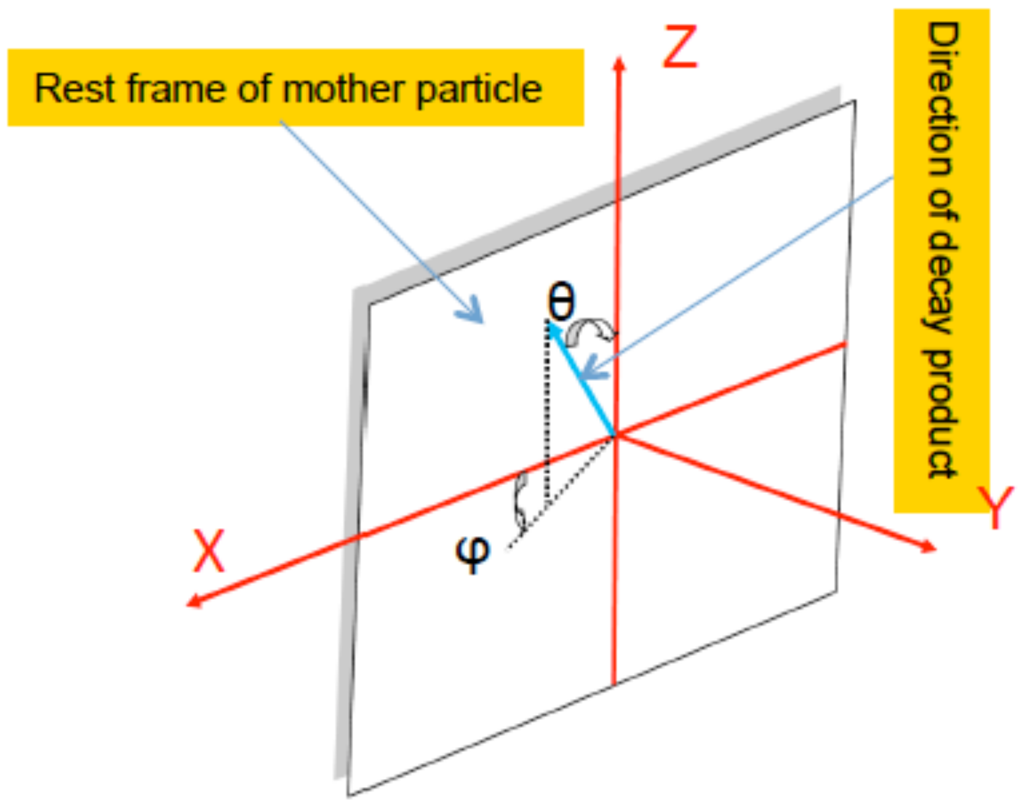
Parity invariance



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LPTHE Laboratoire de Physique Théorique et Hautes Energies

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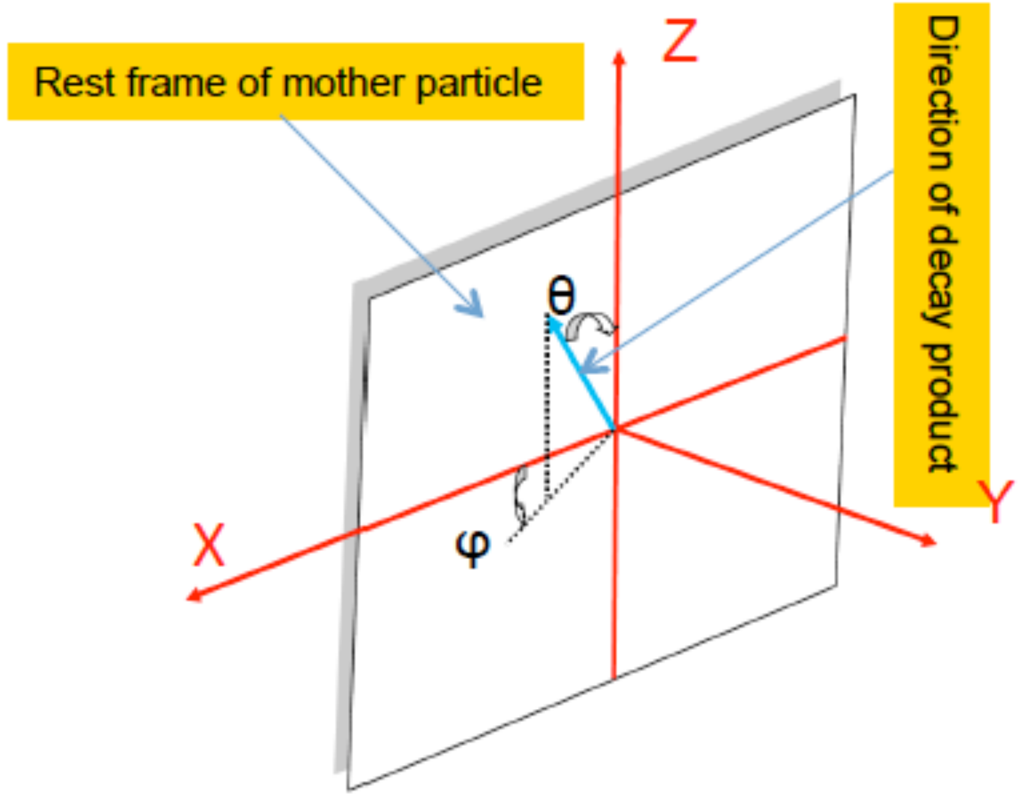
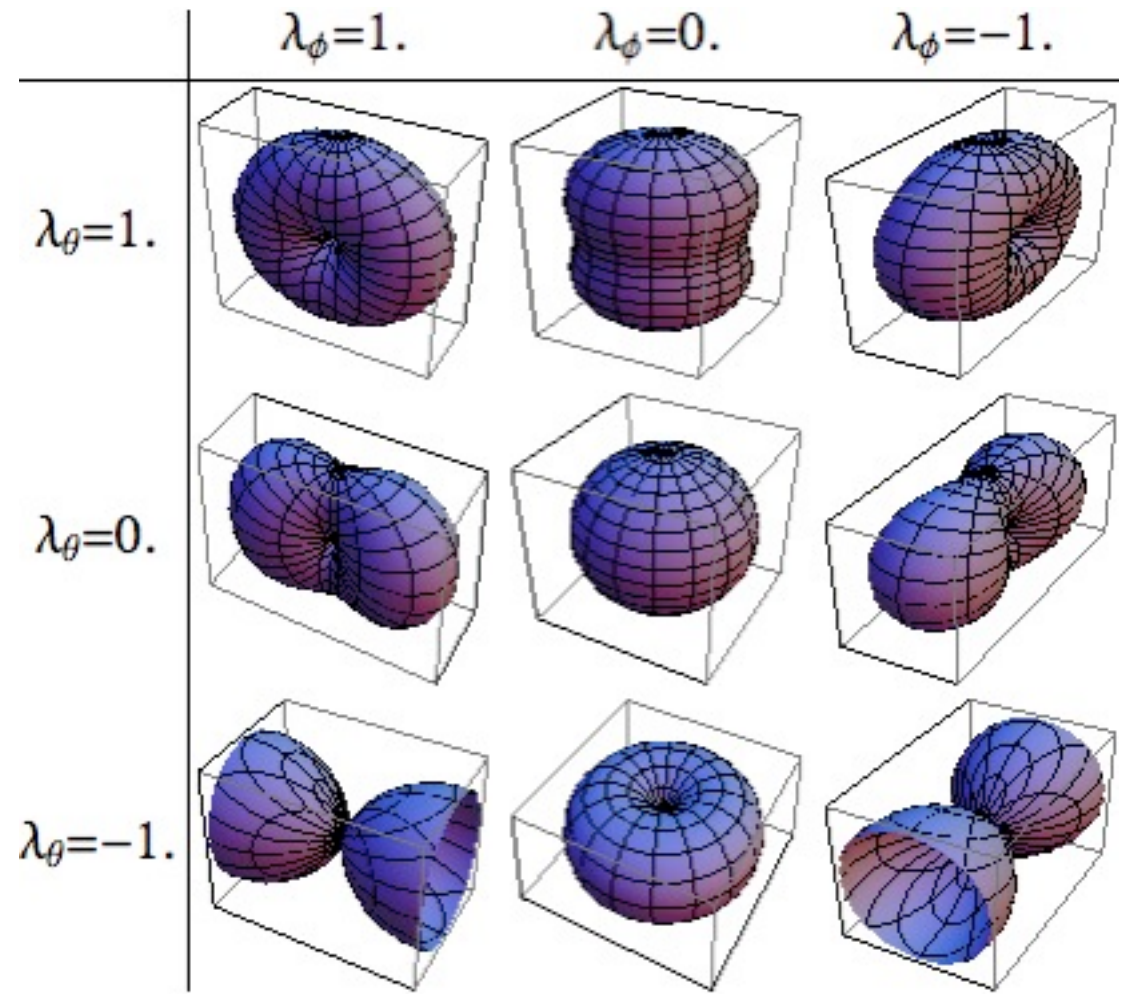


Most studies focus on

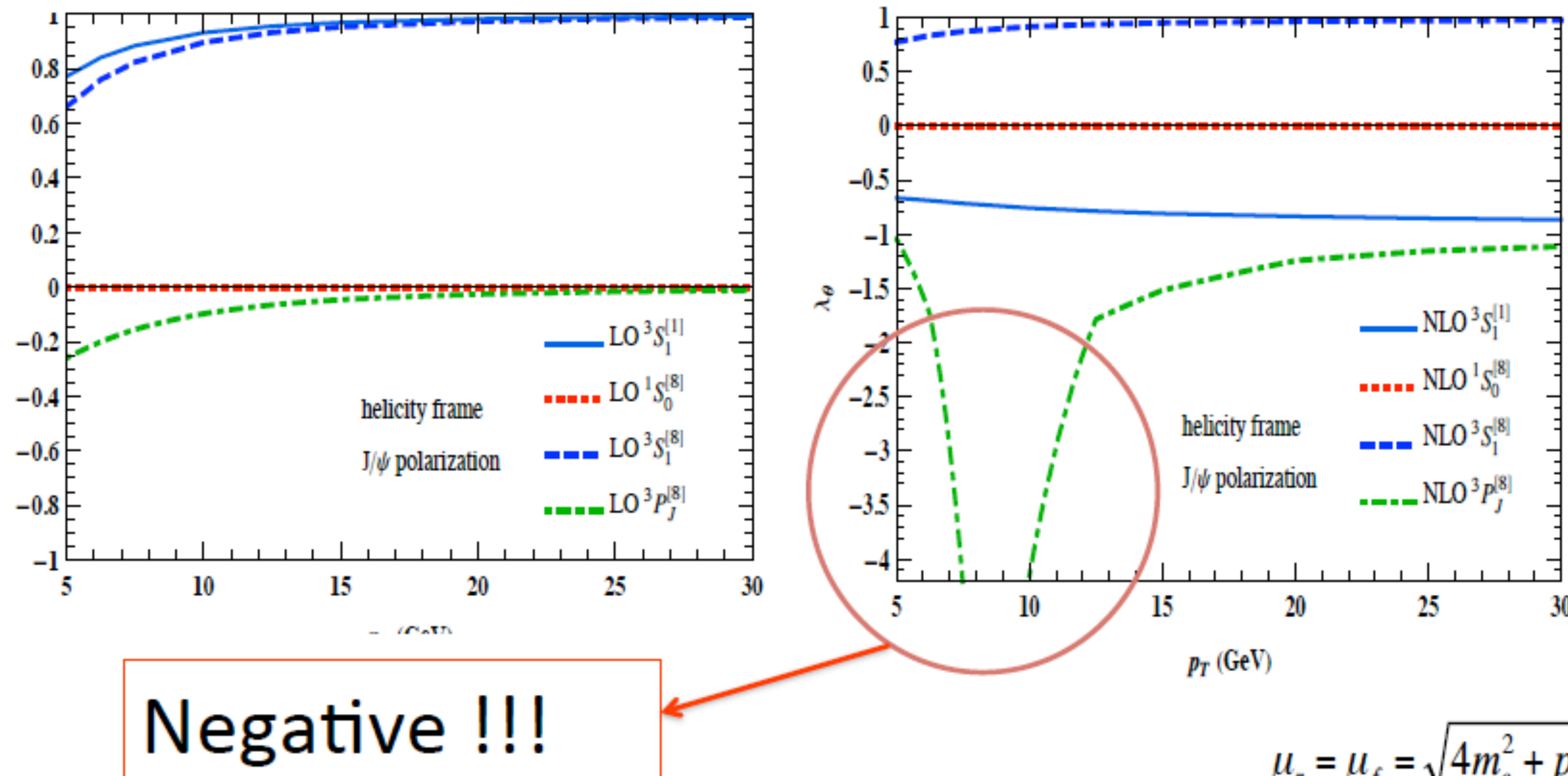


PSI POLARISATION

- **Negative P-wave due to over-subtraction !**

See e.g. HSS (1809.02369)

Chao et al. (1201.2675)



$$\mu_r = \mu_f = \sqrt{4m_c^2 + p_T^2}$$

$$\mu_\Lambda = m_c$$

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tricky in fit &
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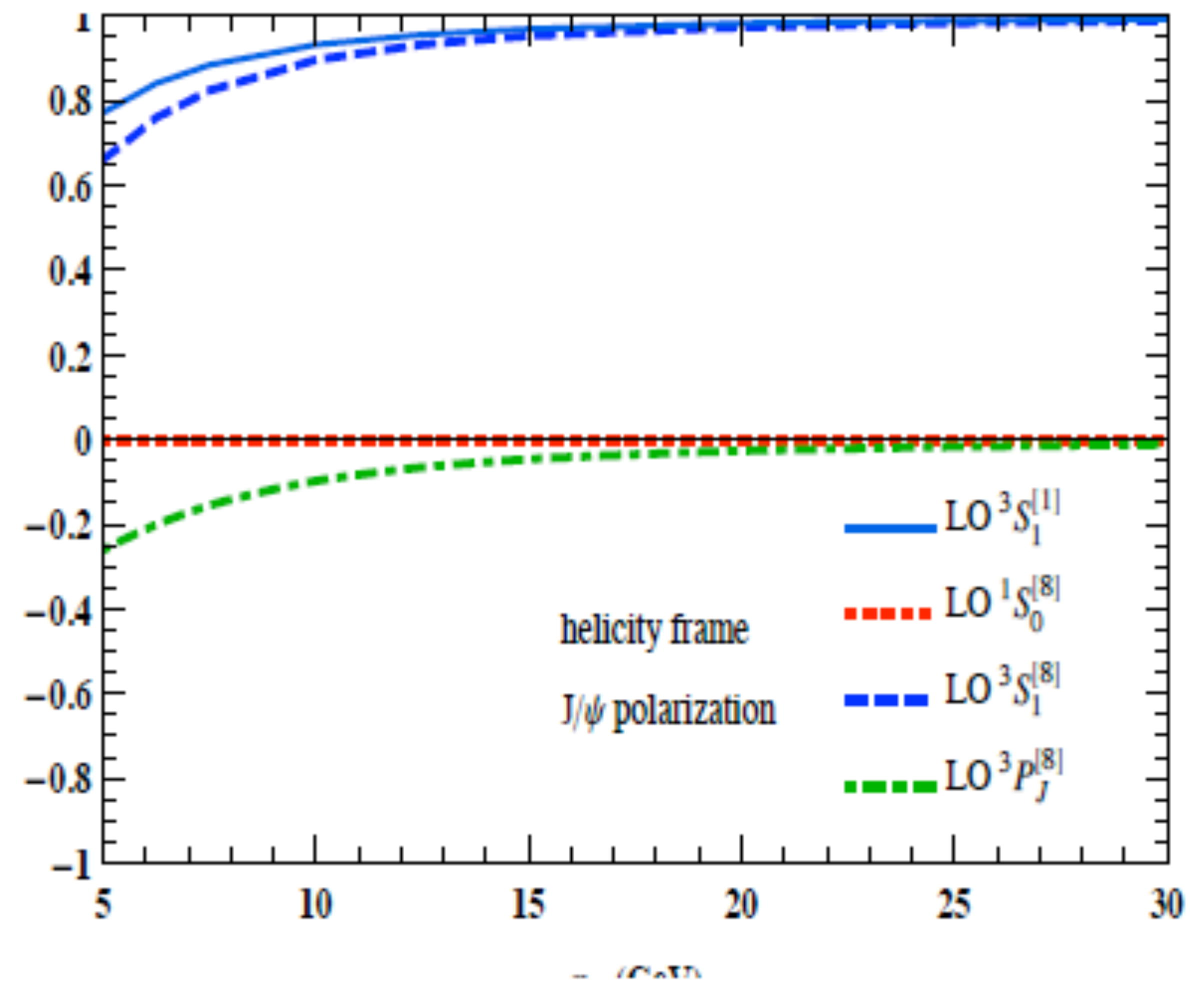
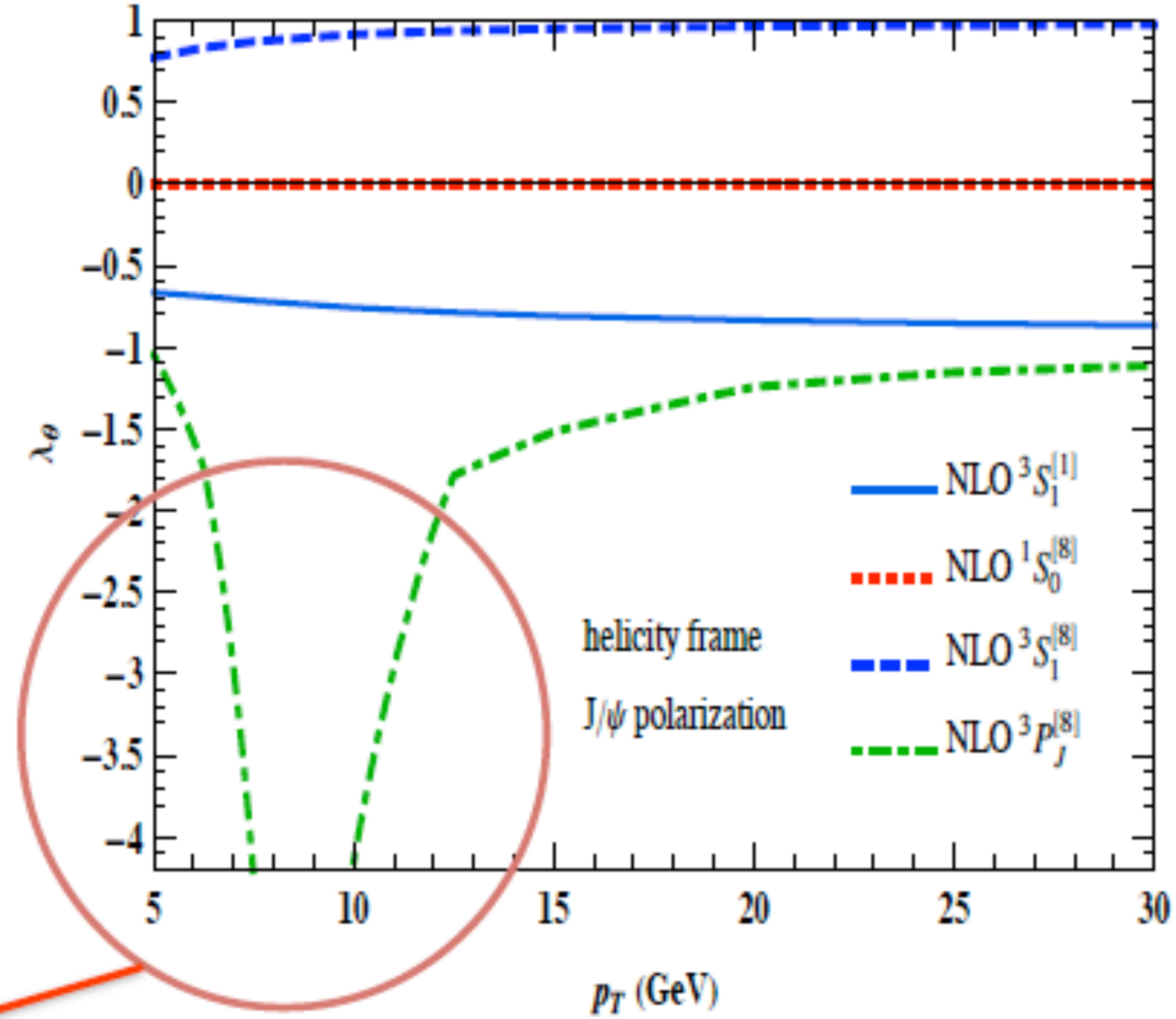




Negative !!!

$$\mu_r = \mu_f = \sqrt{4m_c^2 + p_T^2}$$

$$\mu_\Lambda = m_c$$

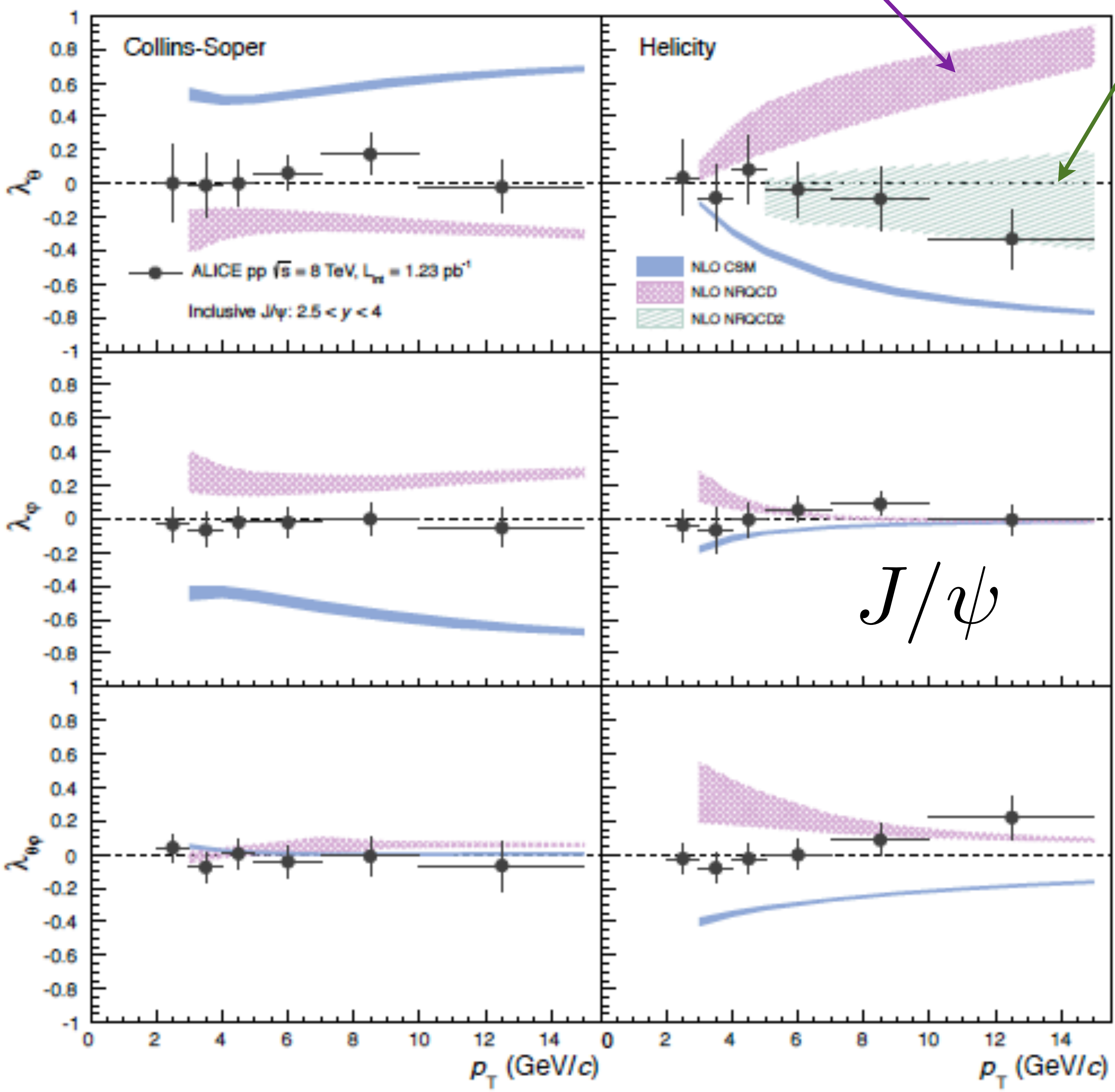
PSI POLARISATION

- **Two representative LHC results**

ALICE (1805.04374)

Hamburg

PKU



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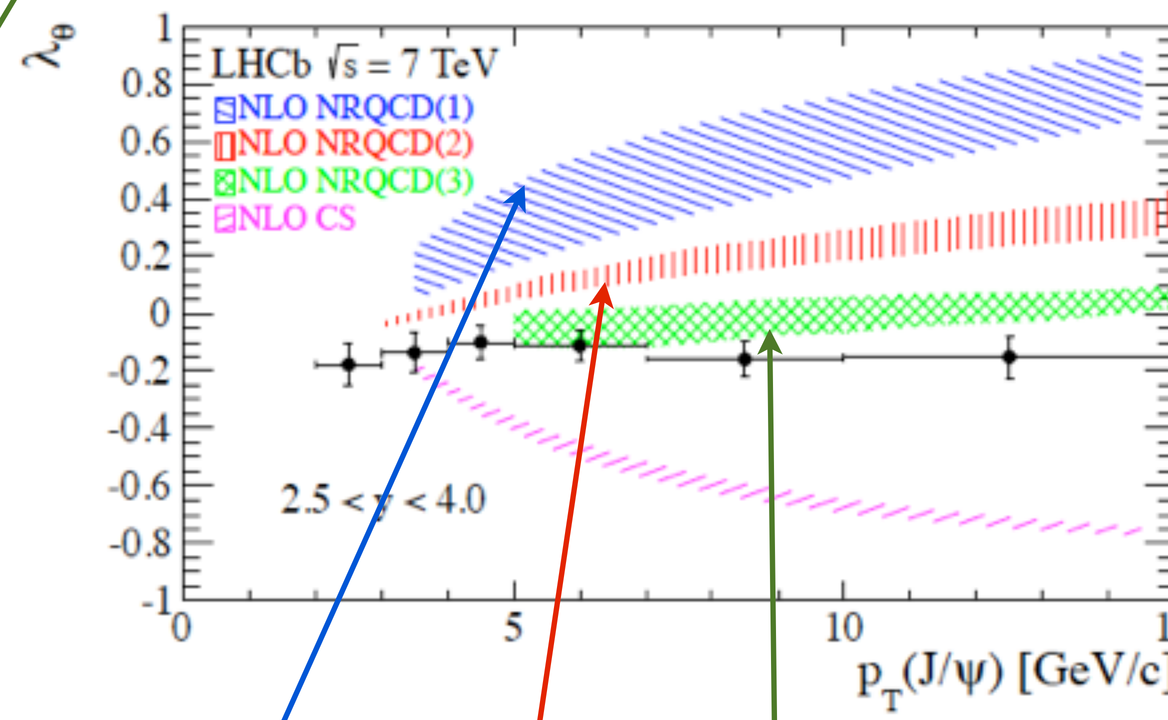

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LABORATOIRE DE PHYSIQUE THEORIQUE ET HAUTES ENERGIES

HELAC-Onia: An automatic matrix element generator for heavy quarkonium physics☆

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Keywords:
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Dyson–Schwinger equations
Off-shell currents

ABSTRACT

By the virtues of the Dyson–Schwinger equations, we upgrade the published code `HELAC` to be capable to calculate the heavy quarkonium helicity amplitudes in the framework of NRQCD factorization, which we dub `HELAC-Onia`. We rewrote the original `HELAC` to make the new program be able to calculate helicity amplitudes of multi *P*-wave quarkonium states production at hadron colliders and electron–positron colliders by including new *P*-wave off-shell currents. Therefore, besides the high efficiencies in computation of multi-leg processes within the Standard Model, `HELAC-Onia` is also sufficiently numerical stable in dealing with *P*-wave quarkonia (e.g. $h_{c,b}$, $\chi_{c,b}$) and *P*-wave color-octet intermediate states. To the best of our knowledge, it is a first general-purpose automatic quarkonium matrix elements generator based on recursion relations on the market.

Program summary

Program title: `HELAC-Onia`.

Catalogue identifier: AEPR_v1_0

Program summary URL: http://cpc.cs.qub.ac.uk/summaries/AEPR_v1_0.html

Program obtainable from: CPC Program Library, Queen's University, Belfast, N. Ireland

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Catalogue identifier: AEPR_
Program summary URL: htt
Program obtainable from: C

COMPUTER PHYSICS COMMUNICATIONS

LPTHE
LABORATOIRE DE PHYSIQUE THEORIQUE ET HAUTES ENERGIES

HELAC-Onia 2.0: an upgraded matrix-element and event generator for heavy quarkonium physics

Hua-Sheng Shao

PH Department, TH Unit, CERN, CH-1211, Geneva 23, Switzerland
E-mail:huasheng.shao@cern.ch

ABSTRACT

We present an upgraded version (denoted as version 2.0) of the program HELAC-ONIA for the automated computation of heavy-quarkonium helicity amplitudes within non-relativistic QCD framework. The new code has been designed to include many new and useful features for practical phenomenological simulations. It is designed for job submissions under cluster enviroment for parallel computations via PYTHON scripts. We have interfaced HELAC-ONIA to the parton shower Monte Carlo programs PYTHIA 8 and QEDPS to take into account the parton-shower effects. Moreover, the decay module guarantees that the program can perform the spin-entangled (cascade-)decay of heavy quarkonium after its generation. We have also implemented a reweighting method to automatically estimate the uncertainties from renormalization and/or factorization scales as well as parton-distribution functions to weighted or unweighted events. A futher update is the possiblity to generate one-dimensional or two-dimensional plots encoded in the analysis files on the fly. Some dedicated examples are given at the end of the writeup.

HELAC-Onia is an automatic matrix element generator for the calculation of the heavy quarkonium helicity amplitudes in the framework of nonrelativistic QCD factorization based on the public program HELAC-PHEGAS. The program is able to calculate helicity amplitudes of multiply P-wave quarkonium state production at hadron colliders and electron-positron colliders by including new P-wave off-shell currents. Besides the high efficiencies in computation of multi-leg processes within the Standard Model, HELAC-Onia is also sufficiently numerical stable in dealing with P-wave quarkonia and P-wave color-octet intermediate states. It provides options of generating hard events, interfacing to PYTHIA 8 and generating histograms with event manipulation.

Compilers

- gfortran
- gcc
- python 2.X

References

- *"HELAC-Onia: An automatic matrix element generator for heavy quarkonium physics"*
  H.-S. Shao
  Comput.Phys.Commun. **184** (2013) 2562-2570 [arXiv:1212.5293[hep-ph]].
- *"HELAC-Onia 2.0: an upgraded matrix-element and event generator for heavy quarkonium physics"*
  H.-S. Shao
  Comput.Phys.Commun. **198** (2016) 238-259 [arXiv:1507.03435[hep-ph]].

Downloads

- NEW! **HELAC-Onia Version 2.3.8**
- HELAC-Onia on HELAC-PHEGAS webpage

Contact

If you have questions, comments, suggestions or bug reports, please email to huasheng.shao@lpthe.jussieu.fr.

Requirements:

gfortran 4.X

gcc 4.X

python >= 2.6 < 3.0

- **First version released on 10 Jan 2013.**
- **Download from** http://hshao.web.cern.ch/hshao/helaconia.html
- **More and more functionalities are adding ...**

BASICS

- Based on NRQCD framework. Bodwin, Braaten, Lepage PRD (1994)
- Based on off-shell recursion relations.

  Berends, Giele NPB (1988); Kanaki, Papadopoulos CPC (2000)
- General tree-level amplitudes and event generation in Standard Model.
- One or more S-wave quarkonium tree-level amplitudes.
- Unweighted events can be generated to parton shower Monte Carlo programs via Les Houches Event file.

FEATURE: A FEW KEYWORDS

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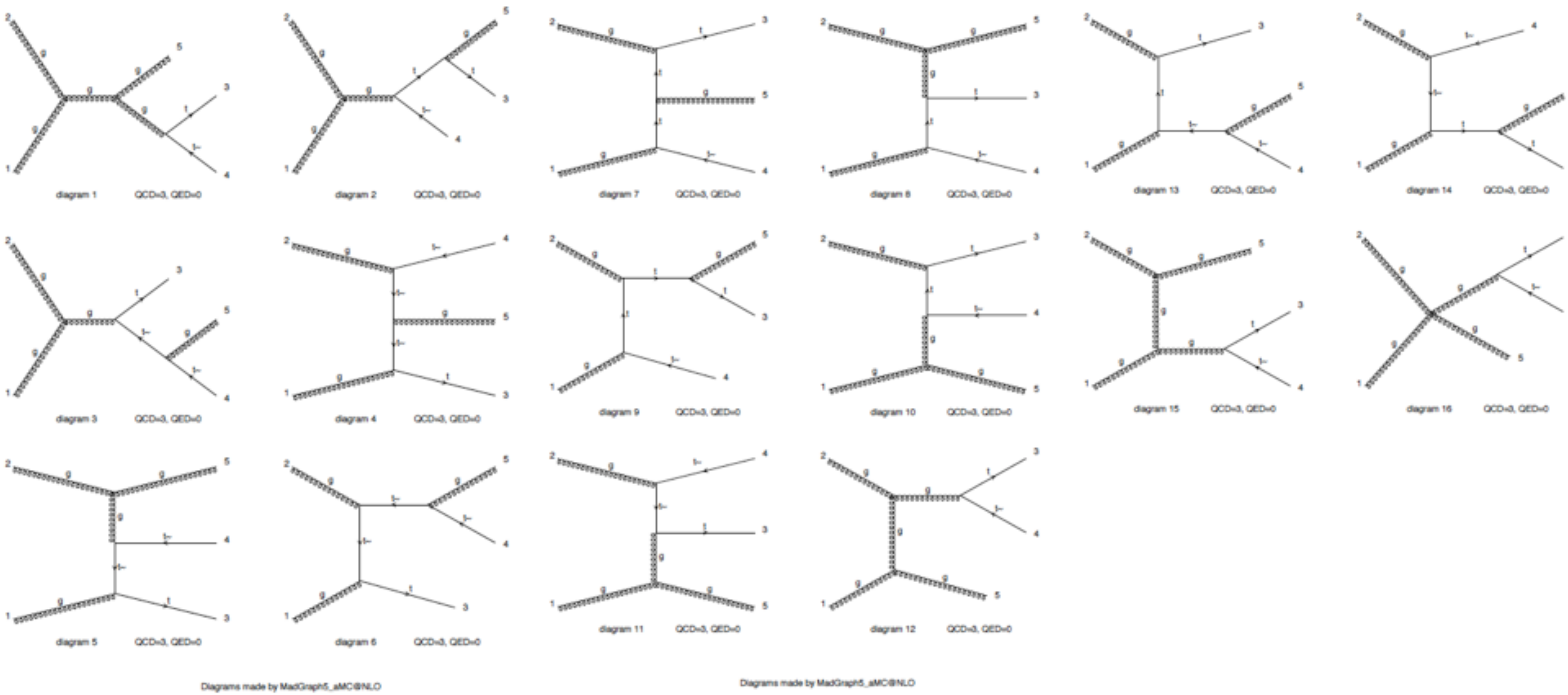
- **One or more S-wave and P-wave quarkonia tree-level helicity amplitude in NRQCD**
  - Color: octet and singlet
  - Fock states: S-wave and P-wave
  - Model is restricted to SM: possible for BSM extension
  - Unique opportunity to produce multiple onia
  - Event generation
  - Yields vs polarizations
  - Spin-entangled decays
  - Interface to parton shower Monte Carlo programs
  - Automatically take into account multiple transitions
  - Proton-nuclear collisions
  - etc

RECURSION RELATIONS

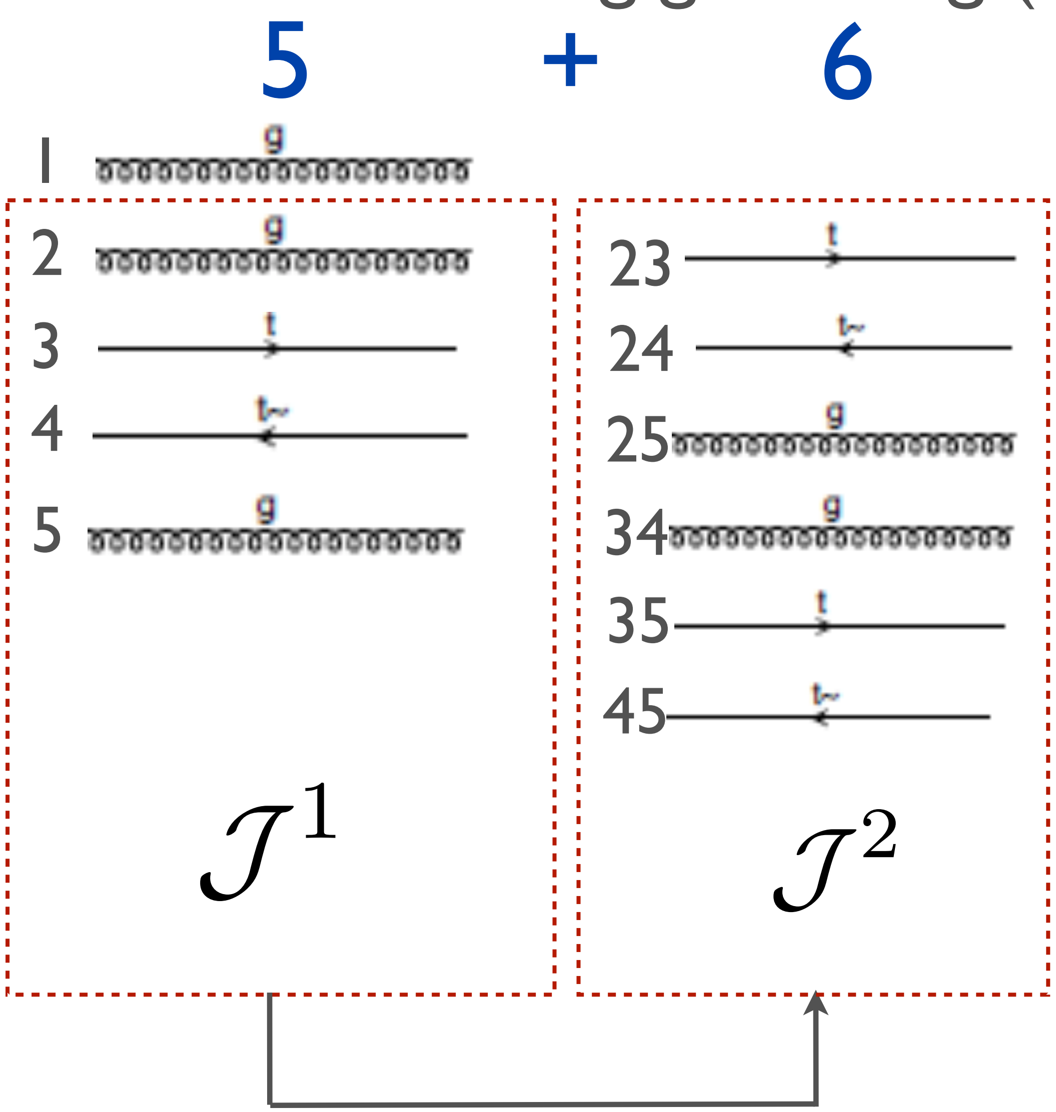
- **Based on off-shell recursion relations.**
  - Let us consider g g > t t~ g (16 Feynman diagrams)



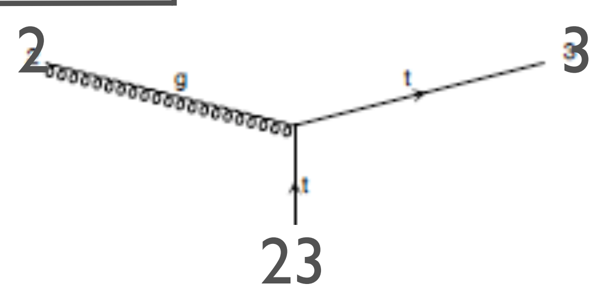
- # of matrix calculations = 5 external WFs + (3*16-1) vertices = 52

RECURSION RELATIONS

- **Based on off-shell recursion relations.**
  - Let us consider g g > t t~ g (16 Feynman diagrams)



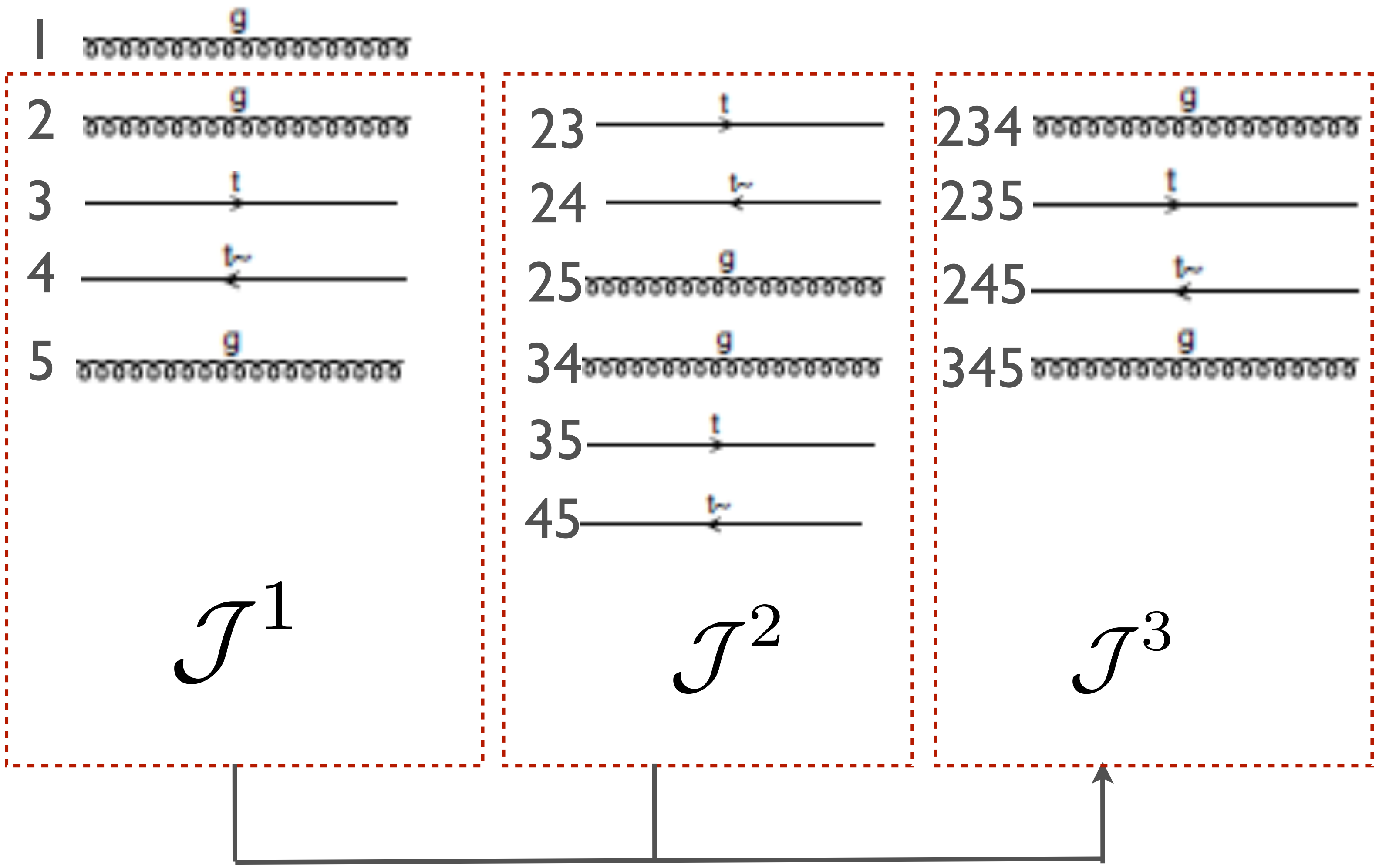
$\mathcal{J}^2 = \mathcal{J}^1 + \mathcal{J}^1$ e.g.



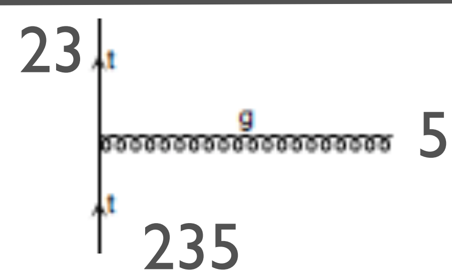
RECURSION RELATIONS

- **Based on off-shell recursion relations.**
  - Let us consider g g > t t~ g (16 Feynman diagrams)

5 + 6 + 4*3



$\mathcal{J}^3 = \mathcal{J}^2 + \mathcal{J}^1$ e.g.



$\mathcal{J}^3 = \mathcal{J}^1 + \mathcal{J}^1 + \mathcal{J}^1$ no 4-pt vertex because there are only 2 gluons at level 1

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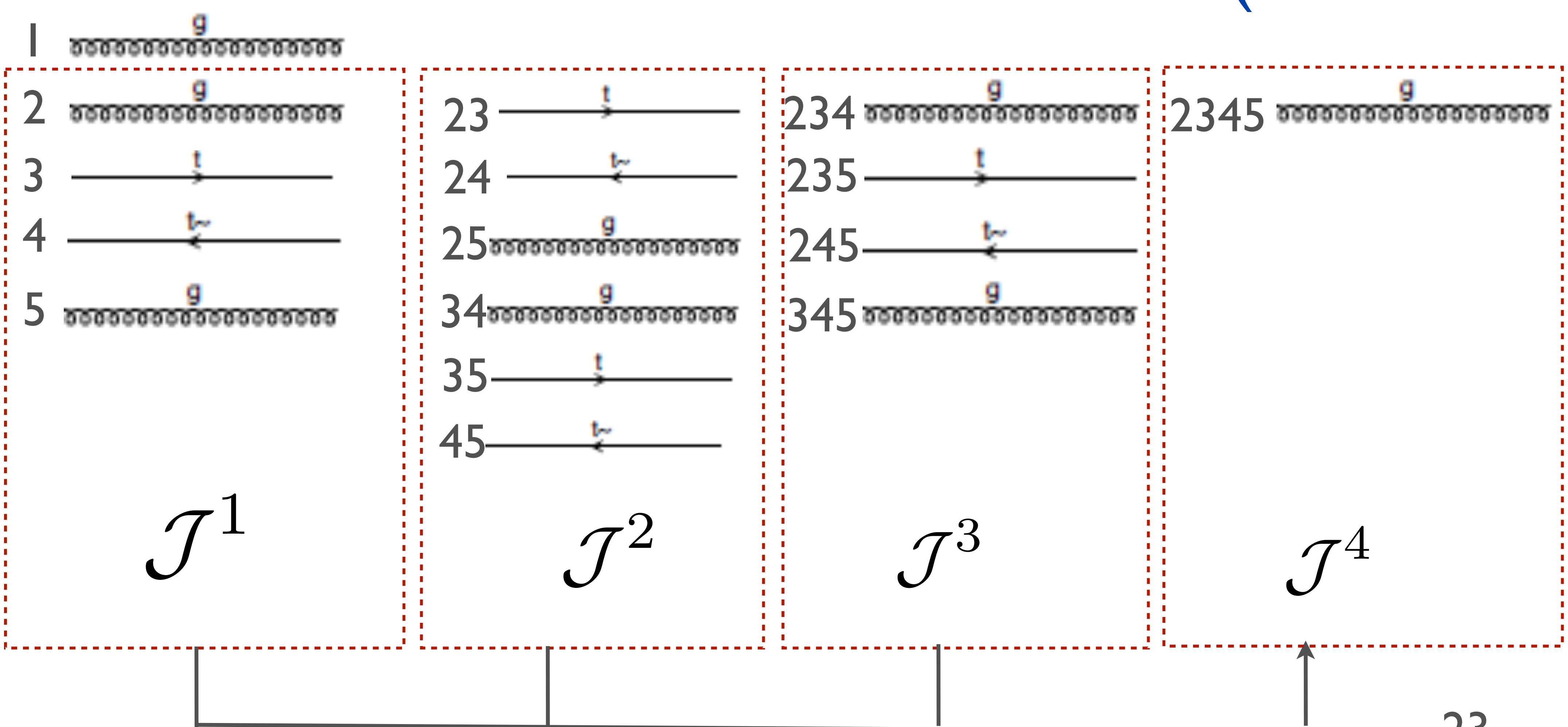
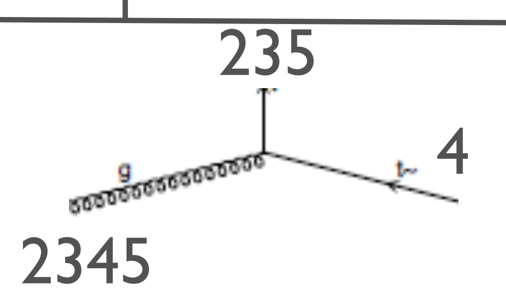
- **Based on off-shell recursion relations.**
  - Let us consider g g > t t~ g (16 Feynman diagrams)

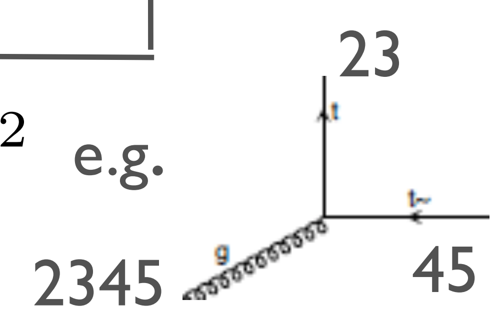
5 + 6 + 4*3 + (4+3



$\mathcal{J}^4 = \mathcal{J}^3 + \mathcal{J}^1$ e.g.



$\mathcal{J}^4 = \mathcal{J}^2 + \mathcal{J}^2$ e.g.



RECURSION RELATIONS

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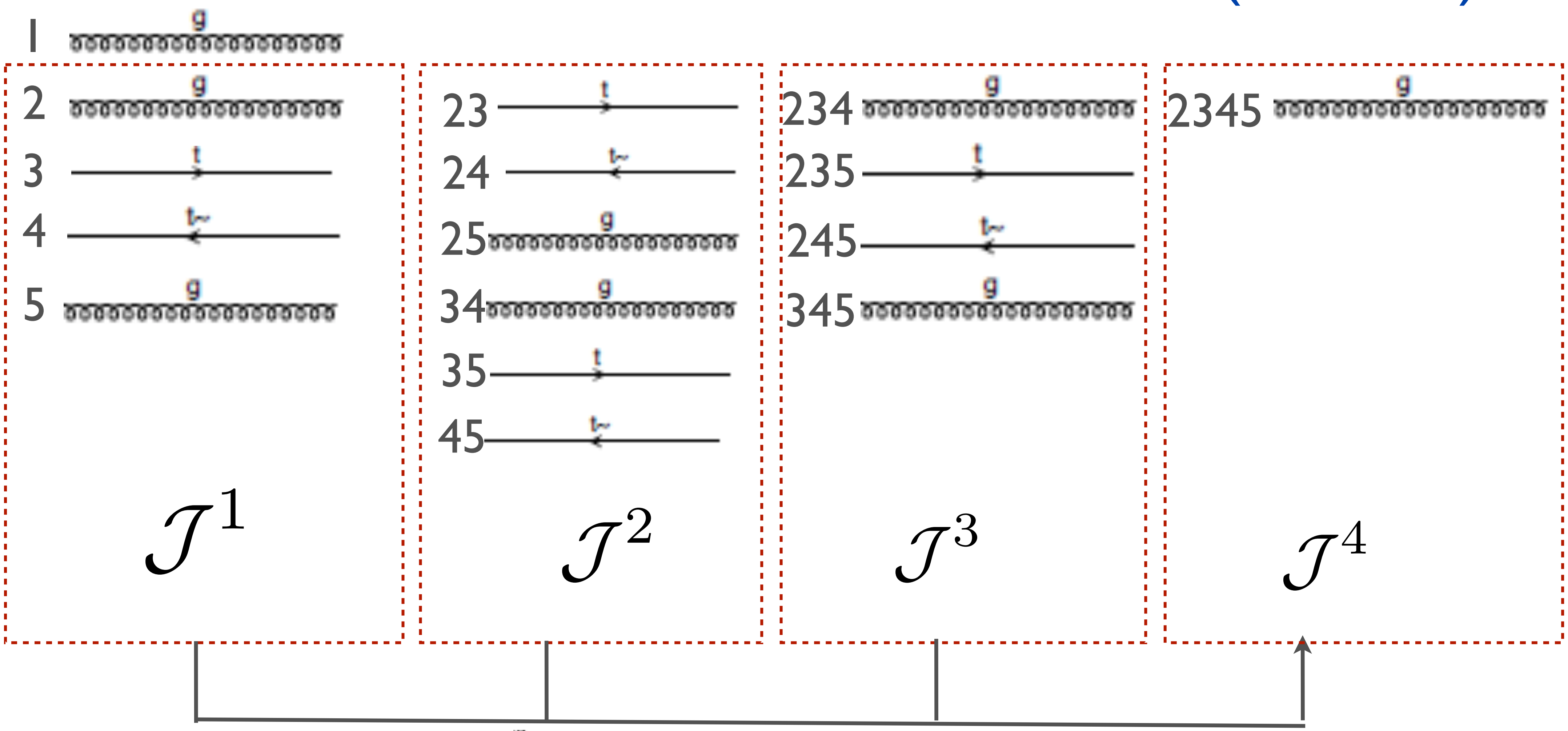
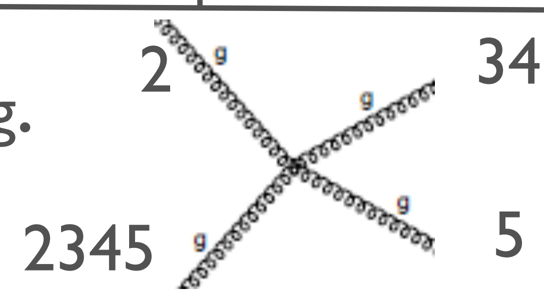
- **Based on off-shell recursion relations.**
  - Let us consider g g > t t~ g (16 Feynman diagrams)

5 + 6 + 4*3 + (4+3+1)



$\mathcal{J}^4 = \mathcal{J}^2 + \mathcal{J}^1 + \mathcal{J}^1$ e.g.

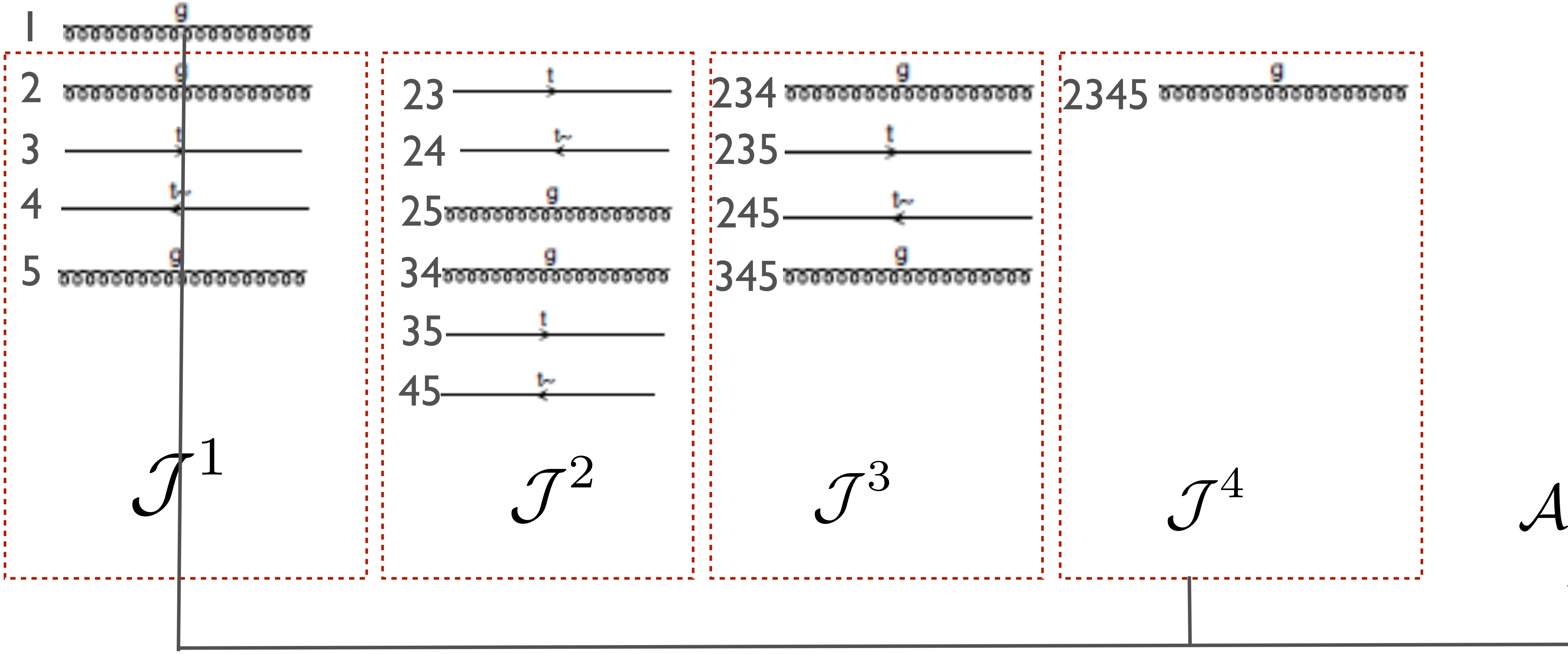


$\mathcal{J}^4 = \mathcal{J}^1 + \mathcal{J}^1 + \mathcal{J}^1 + \mathcal{J}^1$ no 5-pt vertex in QCD

RECURSION RELATIONS

- **Based on off-shell recursion relations.**
  - Let us consider g g > t t~ g (16 Feynman diagrams)

5 + 6 + 4*3 + (4+3+1) + 1 = 32



32 < 52 !!!

$a^n < n!$ with large n=# of external legs

$$\mathcal{A} = \mathcal{J}^4 + leg\ 1$$

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THREE EXAMPLES

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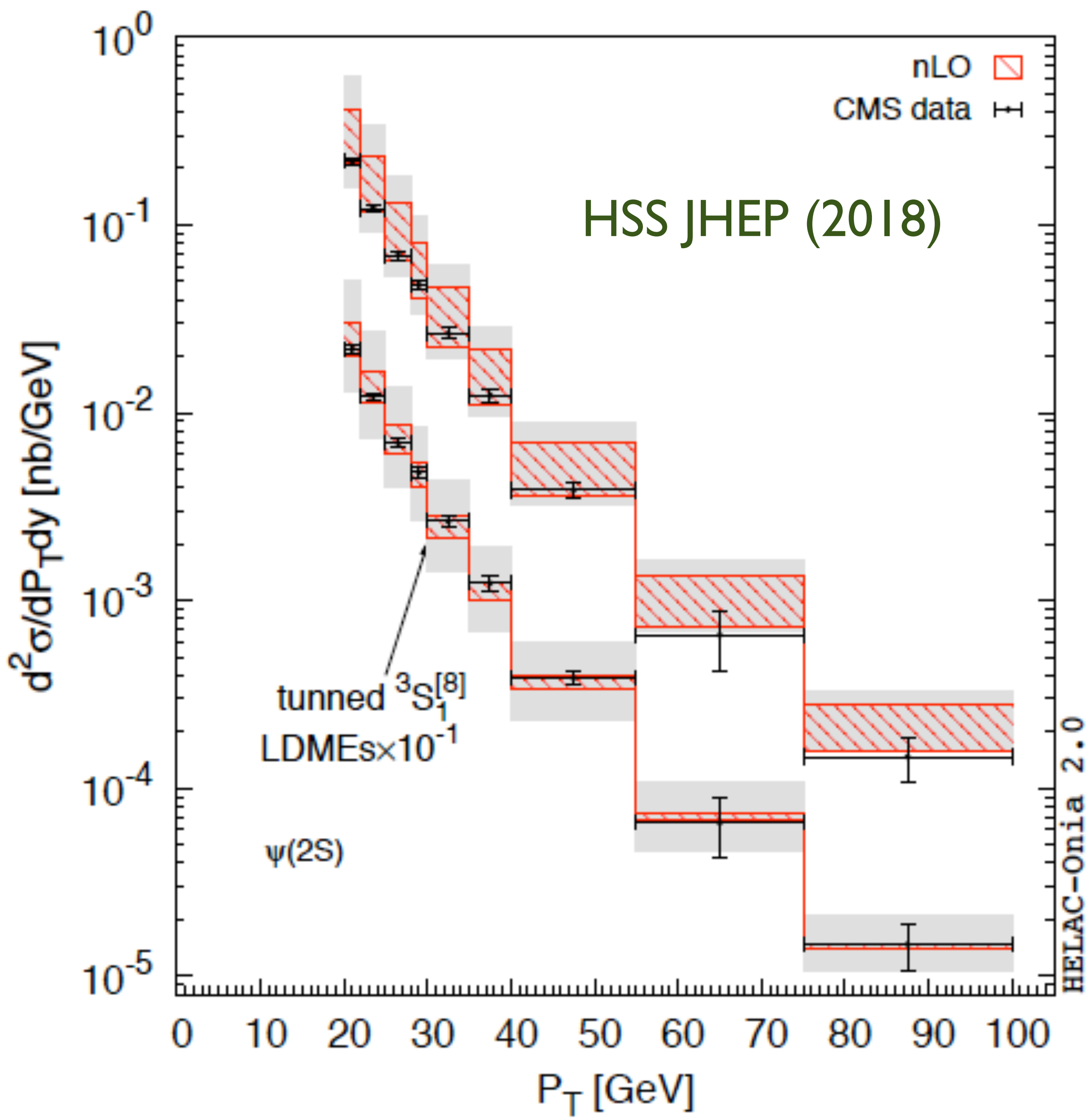
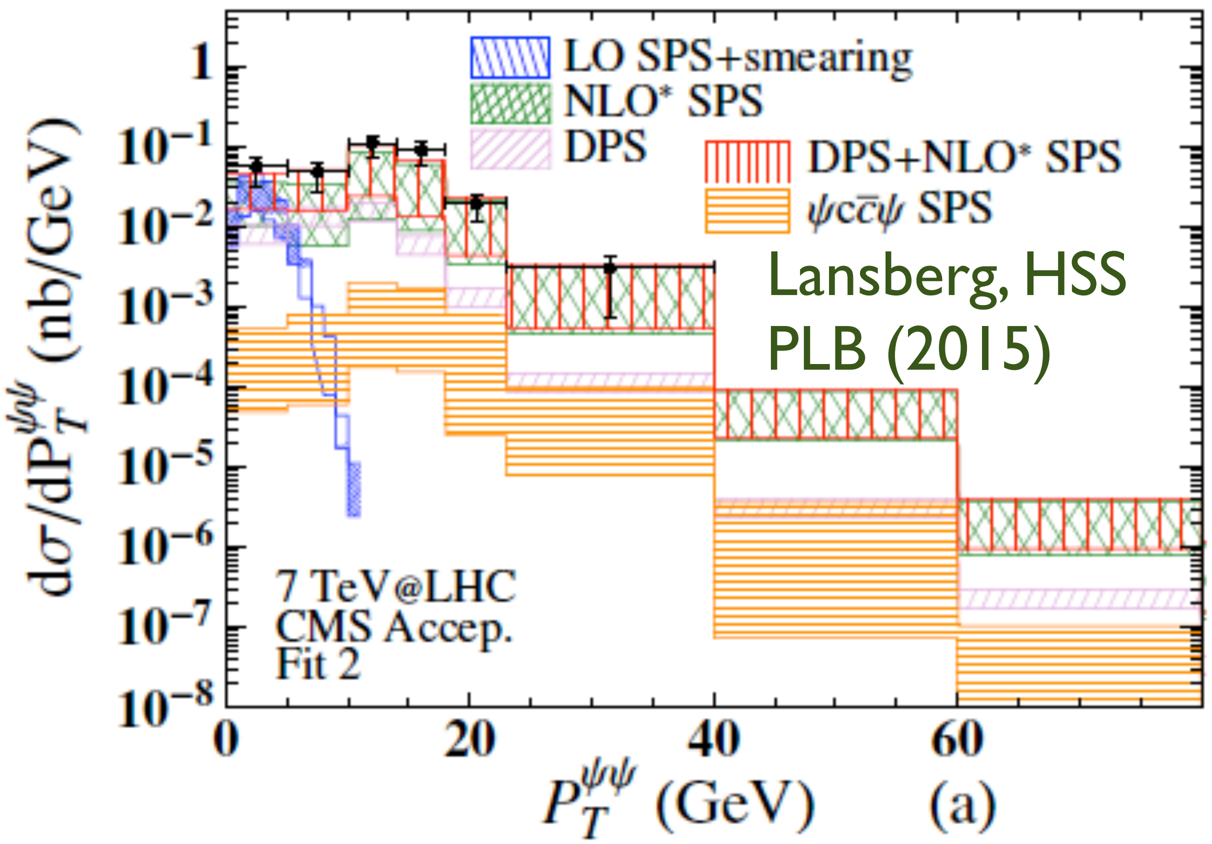


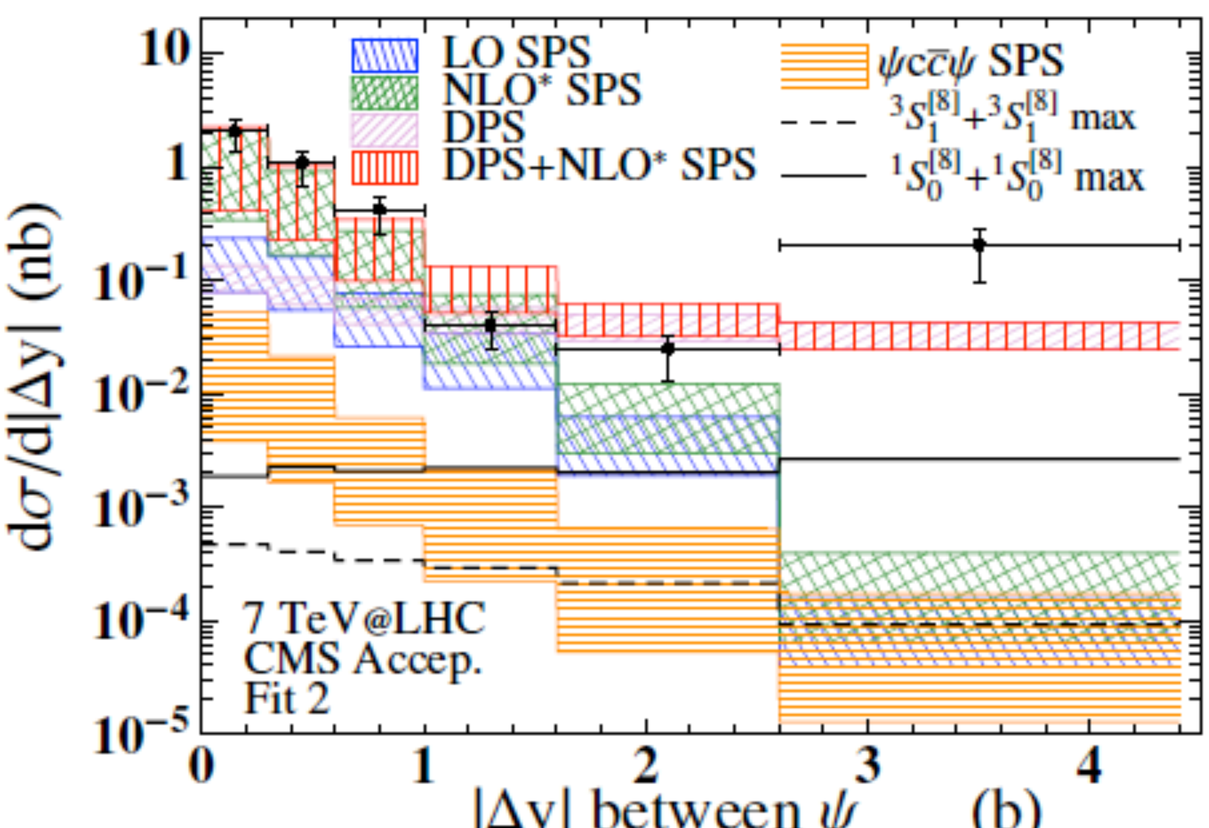
$$pp \to \psi + nj, n = 1, 2, 3$$

- Different P_T powers (LP,NLP)
- S- and P-wave
- Colour-singlet vs Colour-octet
- Feed-down from excited states
- Need a special "jet merging"

HSS JHEP (2018)

THREE EXAMPLES





$$pp \to \psi + \psi + nj, n = 0, 1$$

- Different P_T powers (LP,NLP,NNLP)
- SPS vs DPS
- Colour-singlet dominants
- Feed-down from excited states
- A simple invariant mass cut

Lansberg, HSS PLB (2015)

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THREE EXAMPLES

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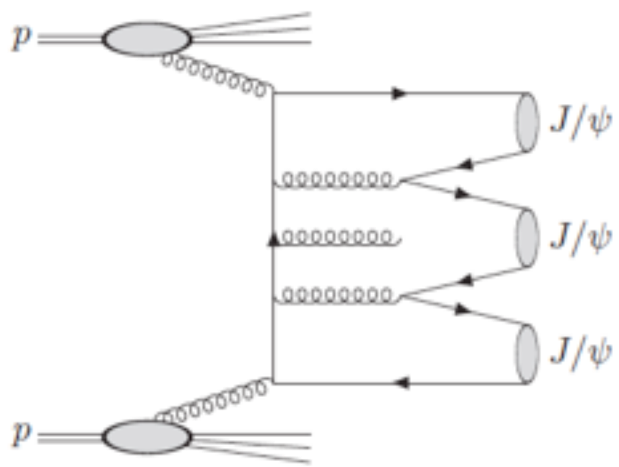
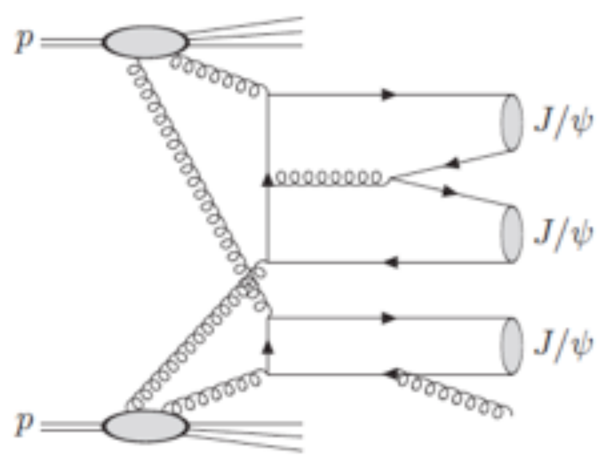
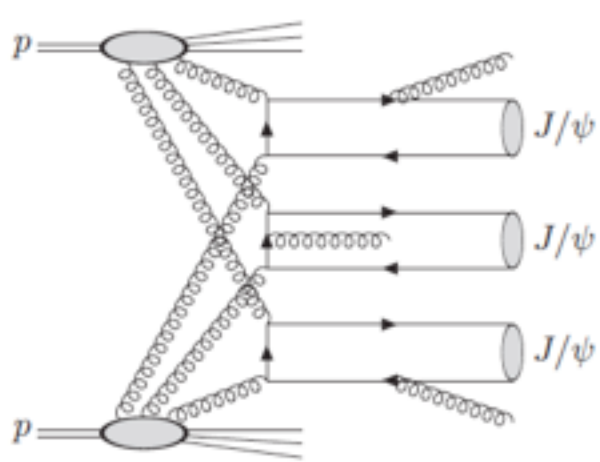


(a) SPS



(b) DPS

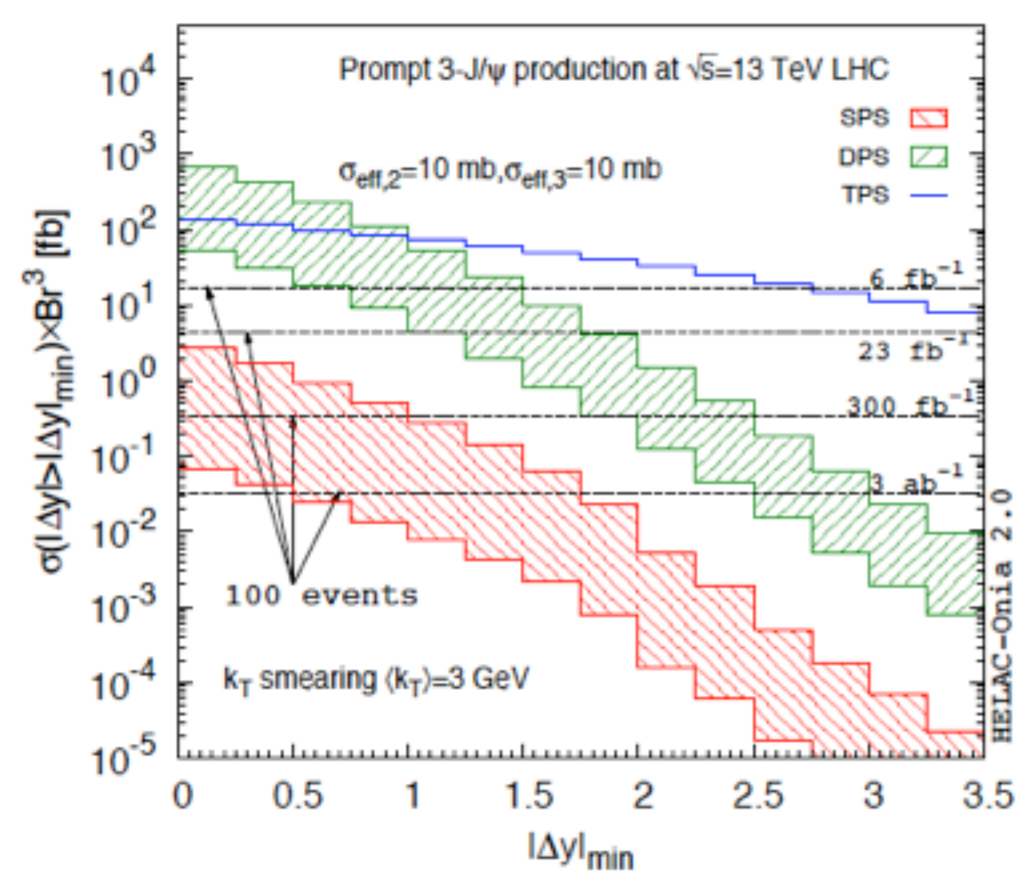


(c) TPS

$$pp \to \psi + \psi + \psi + X$$

- > 20K Feynman diagrams
- SPS vs DPS vs TPS
- Feed-down from excited states

HSS, Zhang PRL (2019)



Thank you for your attention !