Unpolarized by default : common traps caused by the lack of realistic polarization ingredients in quarkonium analyses and MC event generators

- The polarization-acceptance correlation
- Effects on the compatibility of independent measurements
- Can nuclear effects (p-A, Pb-Pb) be studied ignoring the polarization dimension?
- How to handle the cross sections vs. polarizations correlation in global fits
- An emblematic omission: W, Z and Higgs decays

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Cross sections and polarizations are correlated

The *detection acceptances* depend on the *polarization scenario* assumed in the MC simulations used for their evaluation

The experiments report *correction factors* that convert the unpolarized cross sections into the values corresponding to particles produced with fully transverse or fully longitudinal polarization

The dependence of the measured values on the polarization hypothesis is usually much larger than the experimental (statistical and systematic) uncertainties

This correlation is not an experimental uncertainty and should not be treated as one when fitting the data to a certain theory

Δp_T [GeV]	$\langle p_T \rangle$ [GeV]	$\mathcal{B}\, d\sigma/dp_T$ [pb/GeV]	λ_ϑ^{HX} scaling +1	λ_ϑ^{HX} scaling −1
10–11	10.5	1.01E+03 ±0.1 ±7.9	1.31	0.68
11–12	11.5	6.09E+02 ±0.1 ±5.9	1.30	0.68
12–13	12.5	3.82E+02 ±0.2 ±5.0	1.29	0.69
13–14	13.5	2.47E+02 ±0.2 ±4.7	1.28	0.70
14–15	14.5	1.65E+02 ±0.2 ±4.5	1.26	0.71
15–16	15.5	1.14E+02 ±0.2 ±4.4	1.25	0.71
16–17	16.5	7.84E+01 ±0.3 ±4.4	1.24	0.72
17–18	17.5	5.66E+01 ±0.3 ±4.3	1.23	0.73
18–19	18.5	4.13E+01 ±0.4 ±4.3	1.22	0.73
19–20	19.5	3.05E+01 ±0.4 ±4.3	1.21	0.74
20–21	20.5	2.30E+01 ±0.5 ±4.3	1.20	0.75
21–22	21.5	1.76E+01 ±0.5 ±4.3	1.19	0.75
22–23	22.5	1.35E+01 ±0.6 ±4.3	1.19	0.76
23–24	23.5	1.05E+01 ±0.6 ±4.3	1.18	0.77
24–25	24.5	8.35E+00 ±0.7 ±4.4	1.17	0.77
25–26	25.5	6.75E+00 ±0.8 ±4.4	1.17	0.78
26–27	26.5	5.35E+00 ±0.9 ±4.4	1.16	0.78
27–28	27.5	4.31E+00 ±1.0 ±4.4	1.16	0.79
28–29	28.5	3.57E+00 ±1.1 ±4.4	1.15	0.79
29–30	29.5	2.86E+00 ±1.2 ±4.4	1.15	0.80
30–32	30.9	2.21E+00 ±0.9 ±4.4	1.14	0.80
32–34	32.9	1.55E+00 ±1.1 ±4.5	1.13	0.81
34–36	35.0	1.11E+00 ±1.3 ±4.5	1.12	0.82
36–38	37.0	8.22E-01 ±1.5 ±6.5	1.12	0.83
38–42	39.8	5.33E-01 ±1.3 ±6.5	1.11	0.83
42–46	43.8	3.02E-01 ±1.8 ±6.5	1.10	0.85
46–50	47.9	1.86E-01 ±2.3 ±6.5	1.09	0.86
50–60	54.2	8.75E-02 ±2.1 ±10.9	1.08	0.87
60–75	66.0	2.78E-02 ±3.2 ±11.1	1.07	0.89
75–95	82.9	7.97E-03 ±5.4 ±11.2	1.05	0.91
95–120	104.1	1.96E-03 ±10.7 ±11.4	1.04	0.92

A pedagogical exercise

Two hypothetical experiments, A and B, measure the cross section of a particle *X* produced in pp collisions at $\sqrt{s}$ = 14 TeV, *in the same phase space*, $|y| < 2$ and $5 < p_T < 10$ GeV, in the dimuon decay channel; the results are

A: 99.8 ± 0.6 nb   and   B: 105.2 ± 0.7 nb

At first sight, the two values are incompatible (being more than 5 standard deviations apart)

But the polarization of *X* was not measured and is unknown...

For the acceptance correction, *both analyses used the same "default scenario"*, where *X* decays isotropically :

$$w(\cos\vartheta) = \text{constant}$$

The event selection criteria (cuts on muon momenta in the laboratory frame, etc.) applied in the two analyses result in the following $\cos\vartheta_{HX}$ coverages :

A: [−0.3,+0.3]   and   B: [−0.5,+0.5]

Can we really conclude that the two measurements are incompatible "at 5 sigma"?

The compatibility depends on the polarization hypothesis

In the assumed *unpolarized* scenario, the ratio between the total (reported) cross section and the one in the visible cos ϑ range, $[-C,+C]$, is simply $\sigma / \sigma_C = 1/C$, so that, indeed, *the two measurements are incompatible*

But if we assume that X is produced with transverse polarization, $w(\cos\vartheta) = 1 + \cos^2\vartheta$, then

$$\sigma / \sigma_C = 4 / [\, C\,(3+C^2)\,]$$

so that the reported values need to be scaled by

$$(\sigma / \sigma_C)^{\text{trans.}} / (\sigma / \sigma_C)^{\text{unpol.}} = 4 / (3+C^2) = \begin{cases} 1.295 & \text{for } C = 0.3 \\ 1.231 & \text{for } C = 0.5 \end{cases}$$

and, hence, *the two measurements become compatible* :

A: 129.2 ± 0.8 nb   and   B: 129.5 ± 0.9 nb

➡ Without corresponding polarization measurements, the (in)compatibility between the two reported cross sections cannot be accurately judged

Moreover, a coherent use of *the same identical polarization hypothesis* by two experiments *does not guarantee that the results are consistent*

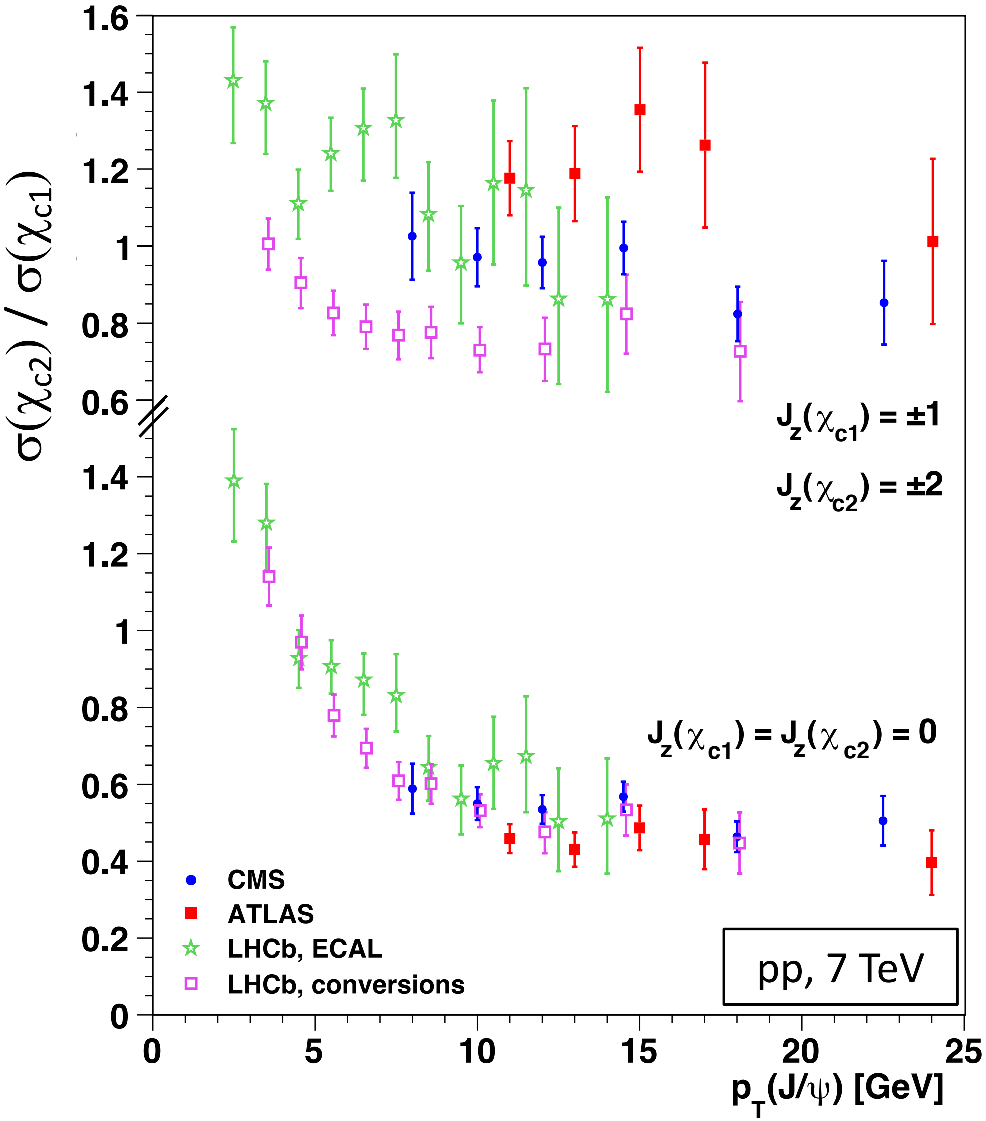
A real-life example: χ_c cross section ratios

The χ_{c2} over χ_{c1} cross section ratio provides a good example of the significant impact that the choice of the polarization scenario has on the results and on their compatibility

Very different patterns and consistencies among data sets are seen for two spin alignment hypotheses:

- $J_z(\chi_{c1}) = \pm 1$ and $J_z(\chi_{c2}) = \pm 2$
- $J_z(\chi_{c1}) = 0$ and $J_z(\chi_{c2}) = 0$

In particular, the consistency of the two LHCb measurements, as well as the one between CMS and ATLAS, strongly depend on the assumed polarization scenario



Are studies of nuclear effects blind to the polarization?

Nuclear effects on quarkonium production and suppression are studied by measuring ratios between, e.g., the J/ψ production yields in two different collision systems :

p-W / p-C,   Pb-Pb / pp,   etc.

The analyses (implicitly) assume that the *nuclear effects do not change the polarization*, so that the polarization-acceptance correlation cancels in the ratio and can be neglected

This assumption is not trivial and must be explicitly stated when reporting the measurement : feed-down decays and "sequential (QGP) suppression" can change the *prompt* J/ψ polarization (e.g., from pp to Pb-Pb), even if the directly produced mesons do not change their polarization

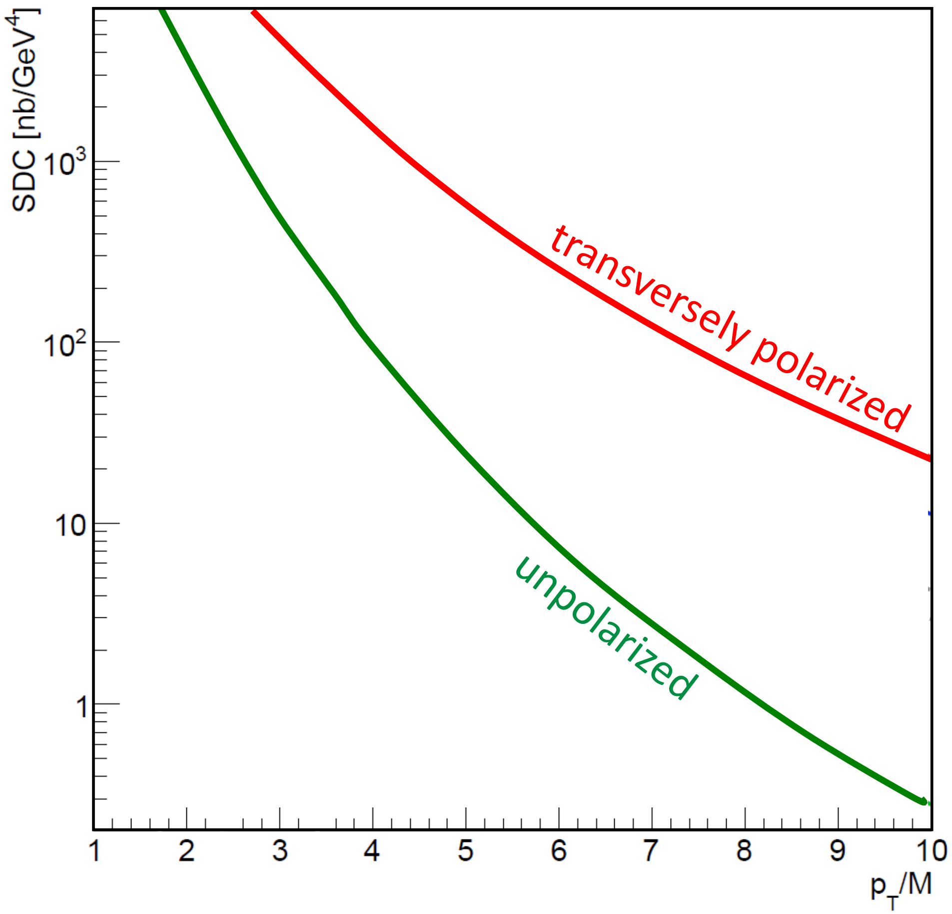
But that is not sufficient: it is also necessary to verify that the *acceptance* in ($\cos\vartheta, \varphi$) is the same in the two data samples (numerator and denominator): *the polarization hypothesis does not cancel in the ratio if the acceptance depends on the collision system*

It often happens that the selection criteria (geometrical and momentum cuts, etc.) applied to the two data samples are different (e.g., from pp to Pb-Pb), leading to two different ($\cos\vartheta, \varphi$) acceptances and, therefore, to two different (polarization-dependent) extrapolation factors :

➡ the yield ratio becomes a function of the assumed polarization, even when this assumption is identical for numerator and denominator

1D fits (only cross sections) can lead to biased results

Consider the following scenario:
a measured p_T-differential quarkonium cross section is fitted to a superposition of two theory components, one unpolarized and the other transversely polarized; the result is that *the polarized term dominates*... but the "measured distribution" was obtained using an acceptance correction computed under the *assumption of unpolarized production !*



The fit should be redone using the data also reported by the experiment for the transverse polarization scenario

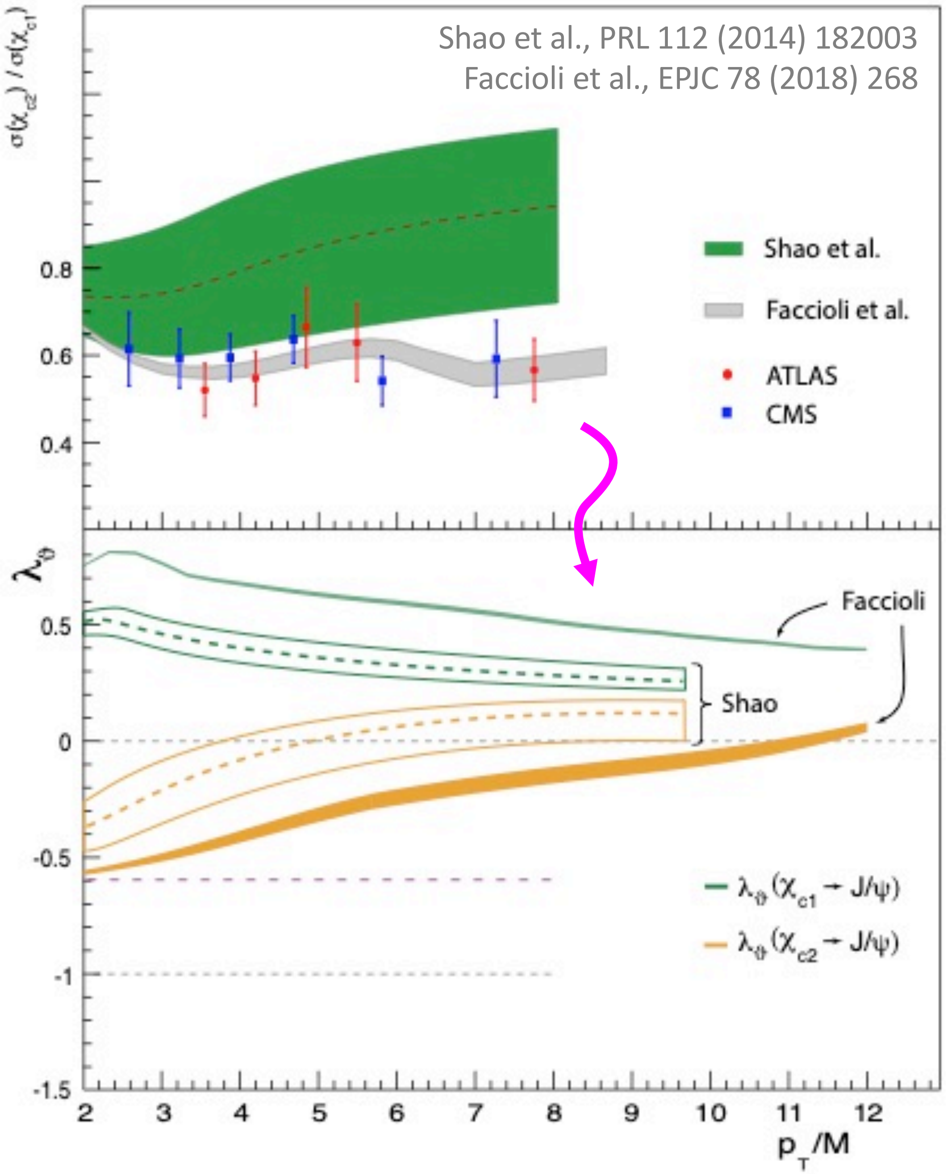
Maybe the new fit will indicate dominance of unpolarized production...

The correct procedure is to include the polarization dimension in a global fit, by *simultaneously* considering the measured cross sections, the measured polarizations, and the acceptance corrections published for different polarization scenarios

Example: NRQCD fit of the χ_c cross section ratio

In NRQCD, one single parameter *r* determines the χ_{c2} / χ_{c1} yield ratio, $\lambda_\vartheta(\chi_{c1})$ and $\lambda_\vartheta(\chi_{c2})$

$$r \equiv m_c^2 \left\langle \mathcal{O}^{\chi_{c0}}({}^3\mathbf{S}_1^{[8]}) \right\rangle \Big/ \left\langle \mathcal{O}^{\chi_{c0}}({}^3\mathbf{P}_0^{[1]}) \right\rangle$$



The same theory (SDCs) and (almost) the same data can lead to very different *r* values

- Shao et al.: ***r* = 0.27 ± 0.06**

polarization "uncertainty" from *maximum* range of correlated variations of $\lambda_\vartheta(\chi_{c1})$ and $\lambda_\vartheta(\chi_{c2})$

- Faccioli et al.: ***r* = 0.217 ± 0.003**

acceptance corrections corresponding to the *final* polarization prediction (*iterative* procedure); no added "polarization uncertainty"

It is crucial to consider the correlations between cross sections and polarizations (there is no "*polarization uncertainty*")

Quarkonium from W, Z and Higgs decays (1)

Rare decays involving quarkonia are studied at the LHC as Standard Model tests, such as:

$W^{\pm} \to K^{\pm}/\pi^{\pm}\,\gamma$ $\quad$ $Z \to K^{0}/\pi^{0}\,\gamma$

$W^{\pm} \to \rho^{\pm}/\phi^{\pm}\,\gamma$ $\quad$ $Z \to J/\psi/\rho^{0}/\phi^{0}\,\gamma$ $\quad$ $H \to J/\psi\,\gamma$

Because of acceptance correlations, the measurements of these branching fractions (BFs) depend on the shape of the *4D angular distribution* of the reconstructed cascade decays

Whenever quarkonia (heavy or light) are involved, the MC event generators (at least most of them, if not all) assume that both the W / Z decays and the J/ψ / ρ / ϕ decays have flat decay distributions (as if nothing is known about these decays and this is the "least biased prior")

But in the SM these decay distributions are *fully determined and surely non-flat*

- The $W^{\pm} \to K^{\pm}/\pi^{\pm}\,\gamma$ and $Z \to K^{0}/\pi^{0}\,\gamma$ decays should have the same angular distribution as the $Z \to \mu^{+}\mu^{-}$ decay

- The $W^{\pm} \to \rho^{\pm}/\phi^{\pm}\,\gamma$ and $Z \to J/\psi/\rho^{0}/\phi^{0}\,\gamma$ decays have *strongly anisotropic* distributions, both for the W / Z and for the J/ψ / ρ / ϕ (the latter one depending on the decay channel)

- In $H \to J/\psi\,\gamma$, the J/ψ should be *fully transverse* along its direction in the H rest frame

Quarkonium from W, Z and Higgs decays (2)

In all these decays the full angular distributions are *completely fixed* by angular momentum conservation and by existing precise measurements of the Z boson polarization in the dilepton decay (and/or by the corresponding SM calculation also for the W); but the experiments seem to *inject ad-hoc hypotheses "by hand"* in the MC event generation

In some cases, the assumptions are purely operative and do not correspond to any reasonable physics expectation, such as in the $Z \rightarrow J/\psi\ \gamma$ case:

- in one analysis the J/ψ is assumed to be *unpolarized*, other hypotheses being considered to study systematic effects [CMS, EPJC 79 (2019) 94; arXiv:1810.10056]
- in another analysis the "effects of the helicity of the quarkonium states on the dimuon kinematics *are accounted for*", but it is not explained how this was done (and if it was done at the level of the MC event generation) [ATLAS, PRL 114 (2015) 121801; arXiv:1501.03276]

The measurements (central values and uncertainties, or upper limits) are *not fully compatible*, in their definitions, between experiments having different acceptances

The correct (in the SM) distributions are known and should be used in all analyses, of course, but at the very least the "assumptions" should be common across experiments and clearly spelled out in the publications

The best would be to integrate the SM distributions in the most widely used MC generators

Summary (1)

When measuring cross sections or cross section ratios (between particles or collision systems), the assumed *polarization scenario* determines the kinematics of the reconstructed decay and, therefore, the detection *acceptance*

In current *MC event generators*, quarkonia are produced *unpolarized* and all related decay distributions are isotropic;
this "default hypothesis" is, in the absence of direct measurements or (SM) calculations, just as good or as bad as assuming, for example, transverse or longitudinal polarizations

If the polarization is unknown, even the *compatibility between measurements* can depend on the hypothesis assumed for the acceptance corrections

In *global fits*, the acceptance-polarization *correlation* must be handled as a parametrized ingredient; neglecting it can lead to biased interpretations

Measurements of *nuclear effects* in p-nucleus collisions and *suppression patterns* in Pb-Pb collisions, in the form of ratios, are supposed to be insensitive to the polarization dimension; *this is not true if the two data samples have different acceptances*, even if feed-down effects are neglected

Summary (2)

W, Z and Higgs SM decays involving quarkonia are generated as fully isotropic, even though *the shapes of their 4D angular distributions are known* [*];
this can lead to inconsistencies among BF measurements and affect their interpretations

[*] "Particle Polarization in High Energy Physics;
an Introduction and Case Studies on Vector Particle Production at the LHC",
by P. Faccioli and C. Lourenço, Lecture Notes in Physics, Vol. 1002 (in print)
https://link.springer.com/book/9783031088742