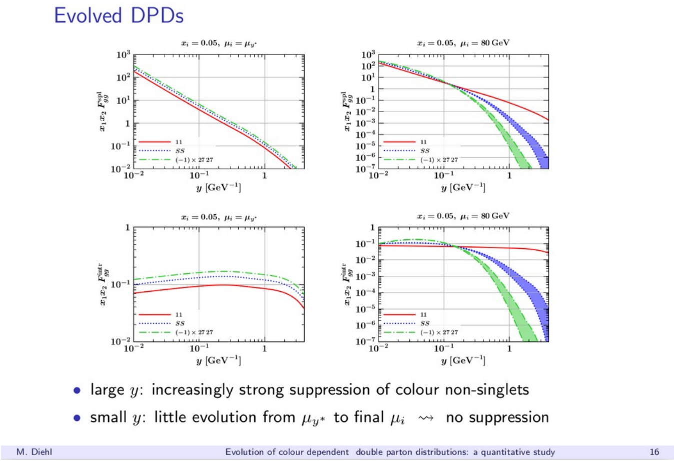
WG2 Theory & Experiment Summary
(a very biased one!)

O.Fedkevych & S. Leontsinis

- Theoretical foundations and generalized parton distribution functions
- First principle calculations from Lattice QCD
- Phenomenological studies

Let’s start with the first-principles results for dPDFs

- Markus Dieh (arXiv:2310.16432) and co-authors developed the theoretical framework to study the evolution of color-dependent dPDFs
- The evolution of transverse-dependent dPDFs and corresponding pheno results were reported by Oskar Grocholski
- The NLO calculations for the massive splitting functions were presented by Peter Plößl
- The results are available in the ChiliPDF lib (arXiv:2112.09703)
- Rudi Rahn (2305.09716) presented the calculations for the matching kernels within the Large Momentum EFT framework (which can be used for Lattice QCD calculations)



State of the art for perturbative splitting DPDs.

At which perturbative orders are the $1 \to 2$ position space splitting kernels known?

	col singlet	col non-singlet
unpol	NLO	NLO
pol	LO	LO

Massless $V_{a_1 a_2, a_0}$ kernels.

	col singlet	col non-singlet
unpol	approx. NLO	LO
pol	LO	LO

Massive $V^{Q}_{a_1 a_2, a_0}$ kernels.

Consider now the impact of including the NLO contributions, focus on the colour singlet!

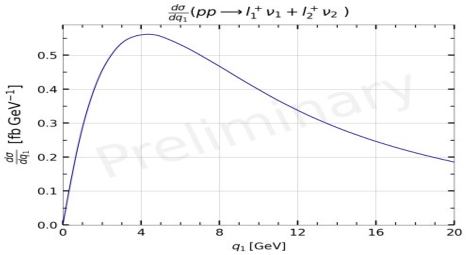
THE KERNELS

- …but the sum of all is pure UV:

$$ {}^{1}C_{a_1 a_2}\left(\frac{x_1}{y_1}, \frac{x_2}{y_2}, \frac{\mu}{|y_1|P^z}, \frac{\mu}{|y_2|P^z}\right) = \mathcal{C}_{a_1}\left(\frac{x_1}{y_1}, \frac{\mu}{|y_1|P^z}\right)\mathcal{C}_{a_2}\left(\frac{x_2}{y_2}, \frac{\mu}{|y_2|P^z}\right) $$

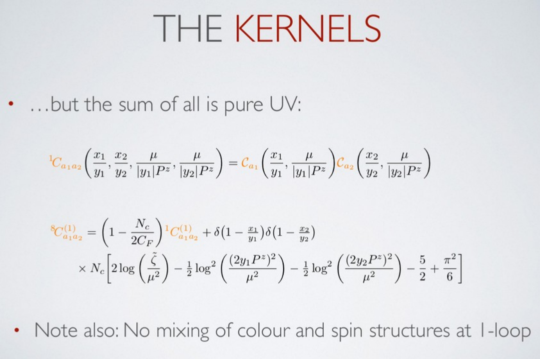
$$ {}^{8}C^{(1)}_{a_1 a_2} = \left(1 - \frac{N_c}{2C_F}\right){}^{1}C^{(1)}_{a_1 a_2} + \delta(1 - \tfrac{x_1}{y_1})\delta(1 - \tfrac{x_2}{y_2}) \times N_c\left[2\log\left(\frac{\tilde{\zeta}}{\mu^2}\right) - \tfrac{1}{2}\log^2\left(\frac{(2y_1P^z)^2}{\mu^2}\right) - \tfrac{1}{2}\log^2\left(\frac{(2y_2P^z)^2}{\mu^2}\right) - \frac{5}{2} + \frac{\pi^2}{6}\right] $$

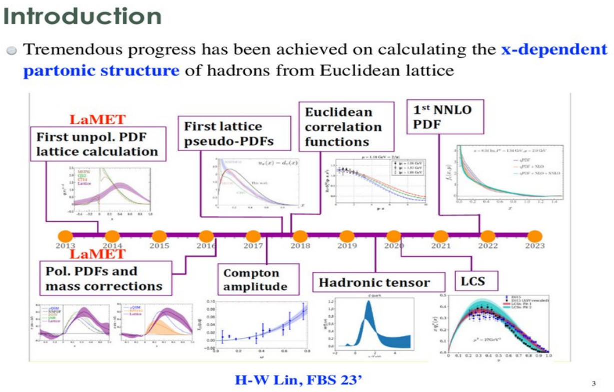
- Note also: No mixing of colour and spin structures at 1-loop

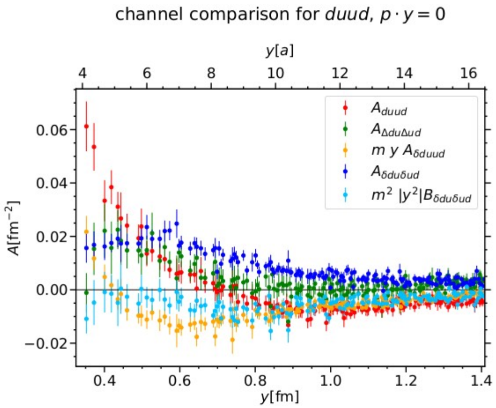


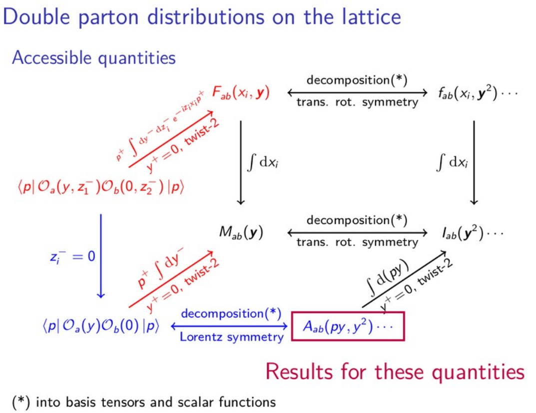
Which smoothly brings us to Lattice QCD results

- Rudi Rahn (2305.09716) presented the calculations for the matching kernels within the Large Momentum EFT framework (which can be used for Lattice QCD calculations)
- Daniel Reitinger provided us an update on the lattice QCD calculation and discussed the impact of polarization dPDF moments for various flavour channels
- Jian-Hui Zhang (2304.12481) demonstrated how the Large Momentum EFT can used in the Lattice QCD calculations and provided an overview of the existing results



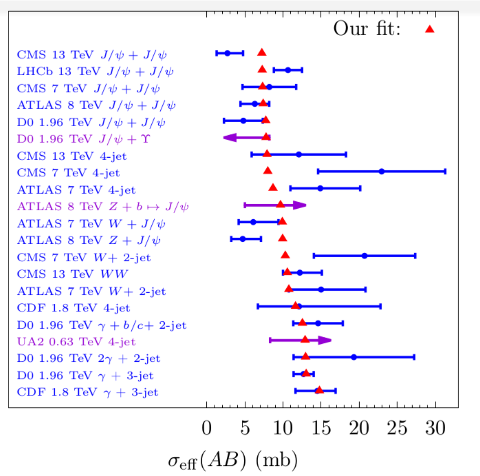






The model-dependent predictions for dPDFs

- Edgar Huayra (arXiv:2305.11106) discussed the impact of partonic correlations on the effective DPS cross section
- Lawrie Smith demonstrated that one can construct the symmetric dPDFs using the MPI model by Sjöstrand & Skands
- Boris Blok applied the hot spot model to extract the value of sigma effective from the data (2212.08848)



Measurement	σ_{eff} at scale 20 GeV	σ_{eff} at scale ~1 GeV
CMS 2021 [27] and ATLAS 2016 [28]	13 ± 3 mb	20 ± 5 mb
CMS2016 [29]	20 ± 5 mb	32 ± 8 mb
Hot spots fit $N_q = 3$		~ 10 mb
Hot spots fit variable N_q		~ 17 mb

We see that with pQCD taken into account the results of DPS measurements and hot spot model for DPS are incompatible. However we do not know the accuracy of the parmeters, thus we shall just say that there is a tension between the effective cross section of DPS in hot spot model and experimental DPS data.

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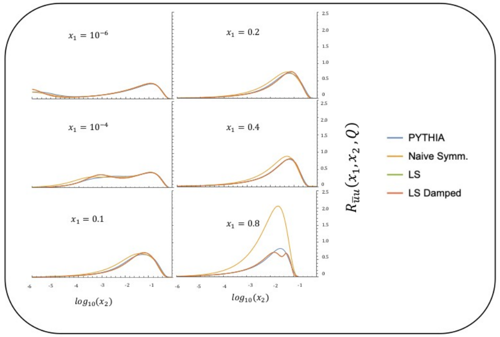
Comparison between schemes

DPDF NSR Response Function

$$R_{j_1 j_2}(x_1, x_2, Q) = \frac{x_2 D_{j_1 j_2}(x_1, x_2, Q)}{f^r_{j_1}(x_1)}$$

NSR Integrand

RESPONSE FUNCTIONS



Pheno results

- Vladimir Saleev provided theoretical predictions for SPS and DPS cross sections for various charm meson production channels
- Luca Rottoli (arXiv:2307.05693) presented a strategy to disentangle multi-parton interactions from the primary scattering in a hadron-hadron collision
- The DPS can be studied at the EIC, as proposed by Matteo Rinaldi
- We gradually move from DPS towards TPS studies (see the talks by David d’Enterria, Marina Maneyro and Hua--Sheng Shao)

Results[6]

Comparison of the theoretical and experimental total cross sections:

Final state	Energy	Cross section	Exp. $\pm$ (stat.) $\pm$ (syst.)	LO PRA $\pm (\Delta_{SPS}) \pm (\Delta_{DPS})$
$J/\psi + D^0$	$\sqrt{s} = 7$ TeV	$\mathcal{B}(J/\psi \to \mu\bar{\mu}) \times \sigma$	$9.7 \pm 0.2 \pm 0.7$ [nb]	$9.6\ ^{+0.4}_{-0.1}\ ^{+26.1}_{-5.9}$ [nb]
$J/\psi + D^+$	$\sqrt{s} = 7$ TeV	$\mathcal{B}(J/\psi \to \mu\bar{\mu}) \times \sigma$	$3.4 \pm 0.1 \pm 0.4$ [nb]	$3.9\ ^{+0.2}_{-0.02}\ ^{+10.8}_{-2.4}$ [nb]
$\Upsilon + D^0$	$\sqrt{s} = 7$ TeV	$\mathcal{B}(\Upsilon \to \mu\bar{\mu}) \times \sigma$	$155 \pm 21 \pm 7$ [pb]	$145\ ^{+16}_{-6}\ ^{+124}_{-65}$ [pb]
$\Upsilon + D^+$	$\sqrt{s} = 7$ TeV	$\mathcal{B}(\Upsilon \to \mu\bar{\mu}) \times \sigma$	$82 \pm 19 \pm 5$ [pb]	$78\ ^{+14}_{-2}\ ^{+140}_{-38}$ [pb]
$\Upsilon + D^0$	$\sqrt{s} = 8$ TeV	$\mathcal{B}(\Upsilon \to \mu\bar{\mu}) \times \sigma$	$250 \pm 28 \pm 11$ [pb]	$255\ ^{+25}_{-9}\ ^{+189}_{-113}$ [pb]
$\Upsilon + D^+$	$\sqrt{s} = 8$ TeV	$\mathcal{B}(\Upsilon \to \mu\bar{\mu}) \times \sigma$	$80 \pm 16 \pm 5$ [pb]	$85\ ^{+8}_{-3}\ ^{+63}_{-37}$ [pb]

Ratios SPS/DPS:

$$R_{\psi D} = \frac{\sigma^{SPS}_{\psi D}}{\sigma^{DPS}_{\psi D}} \simeq \frac{1}{13} \quad \text{and} \quad R_{\Upsilon D} = \frac{\sigma^{SPS}_{\Upsilon D}}{\sigma^{DPS}_{\Upsilon D}} \simeq \frac{1}{10}$$

[6]The data are from LHCb Collaboration[Aaij et.al '16].

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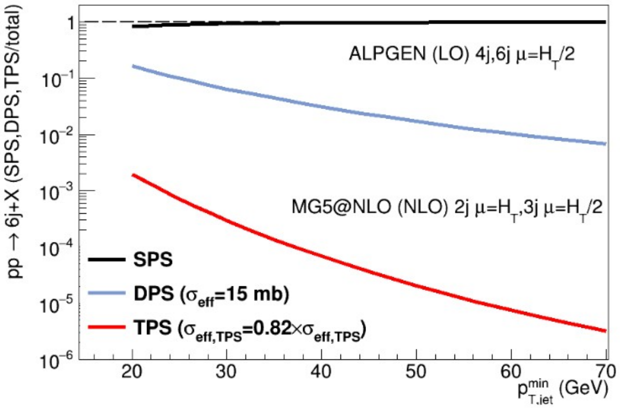
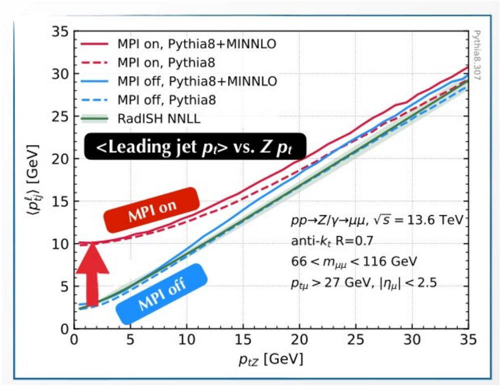
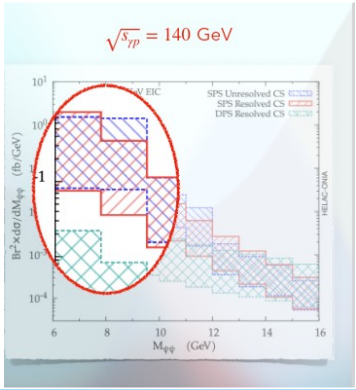
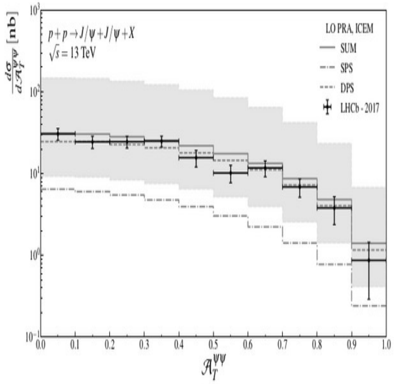


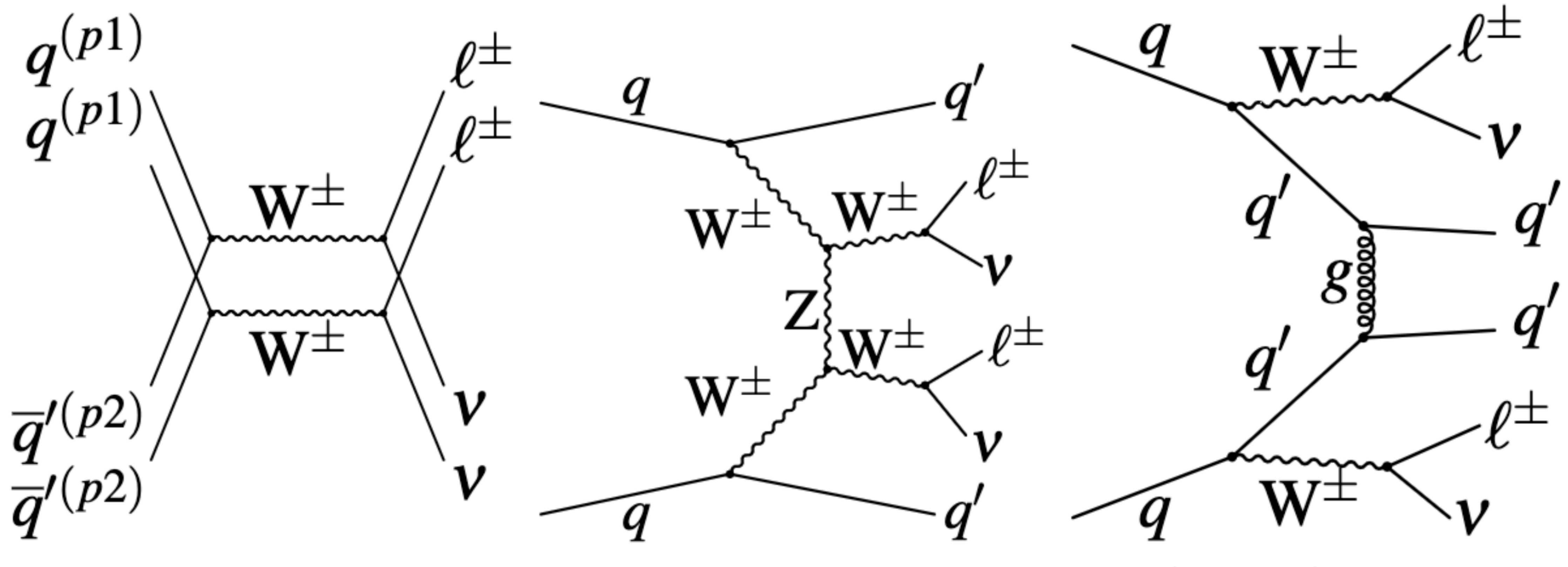


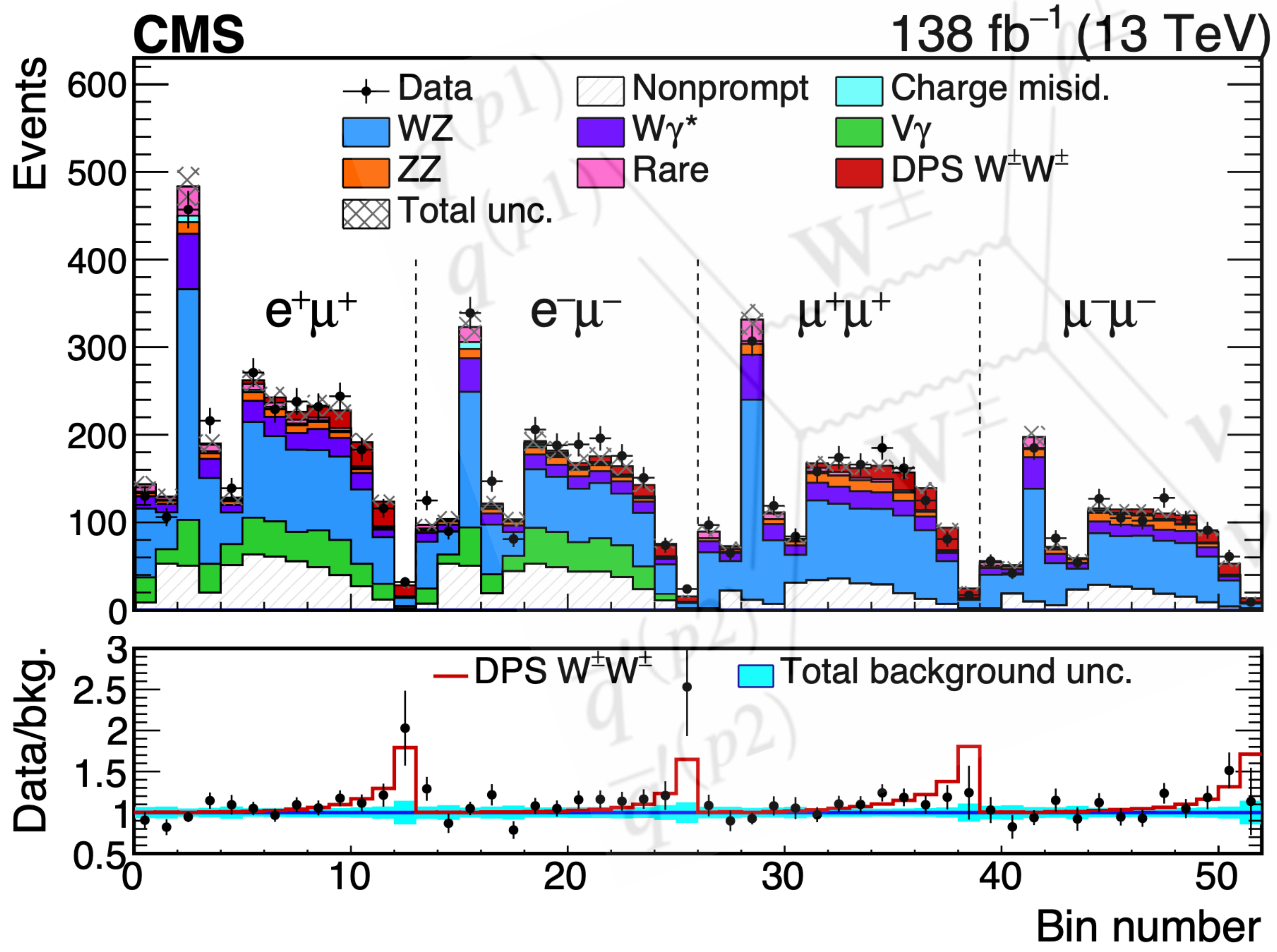


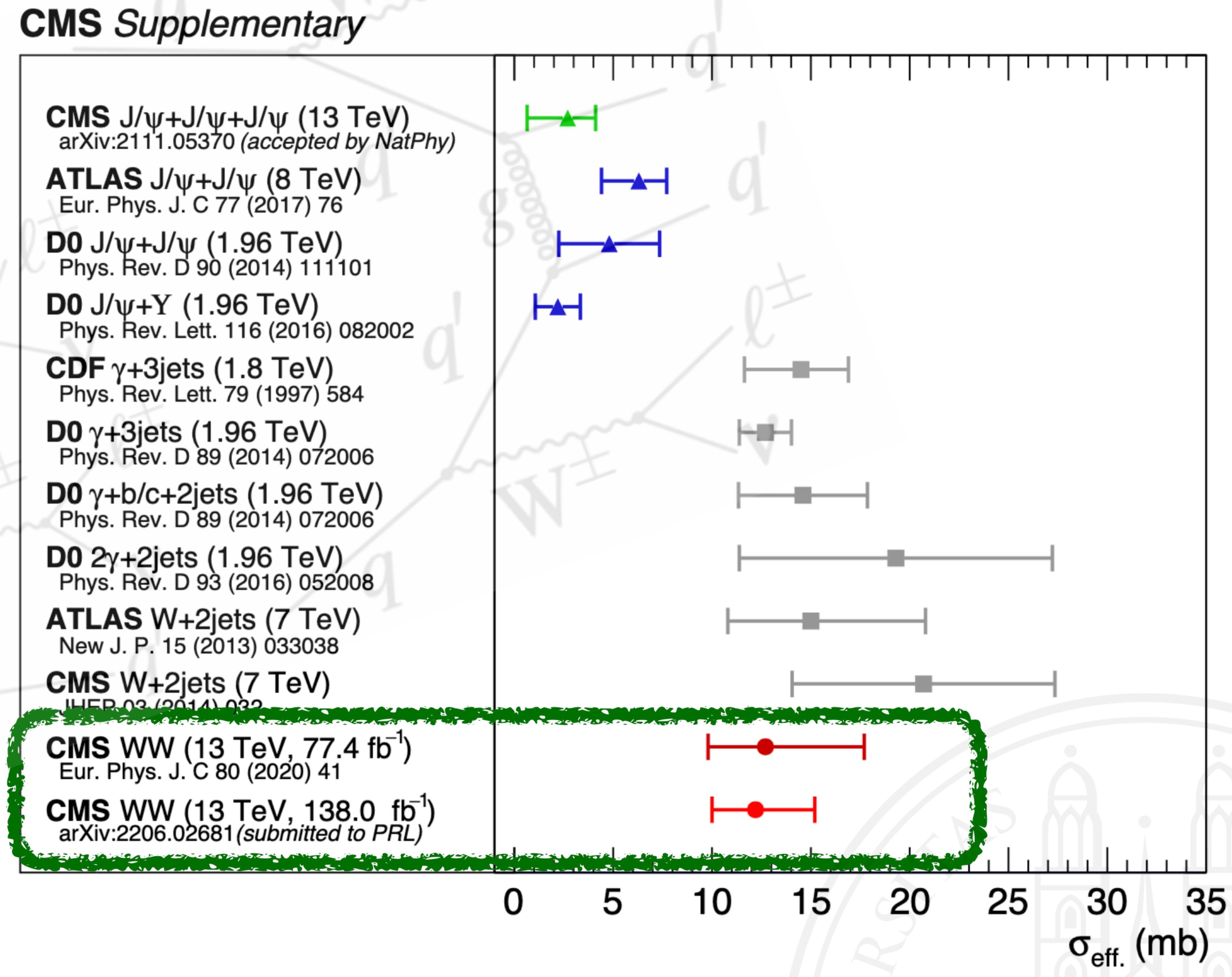


WG2 summary

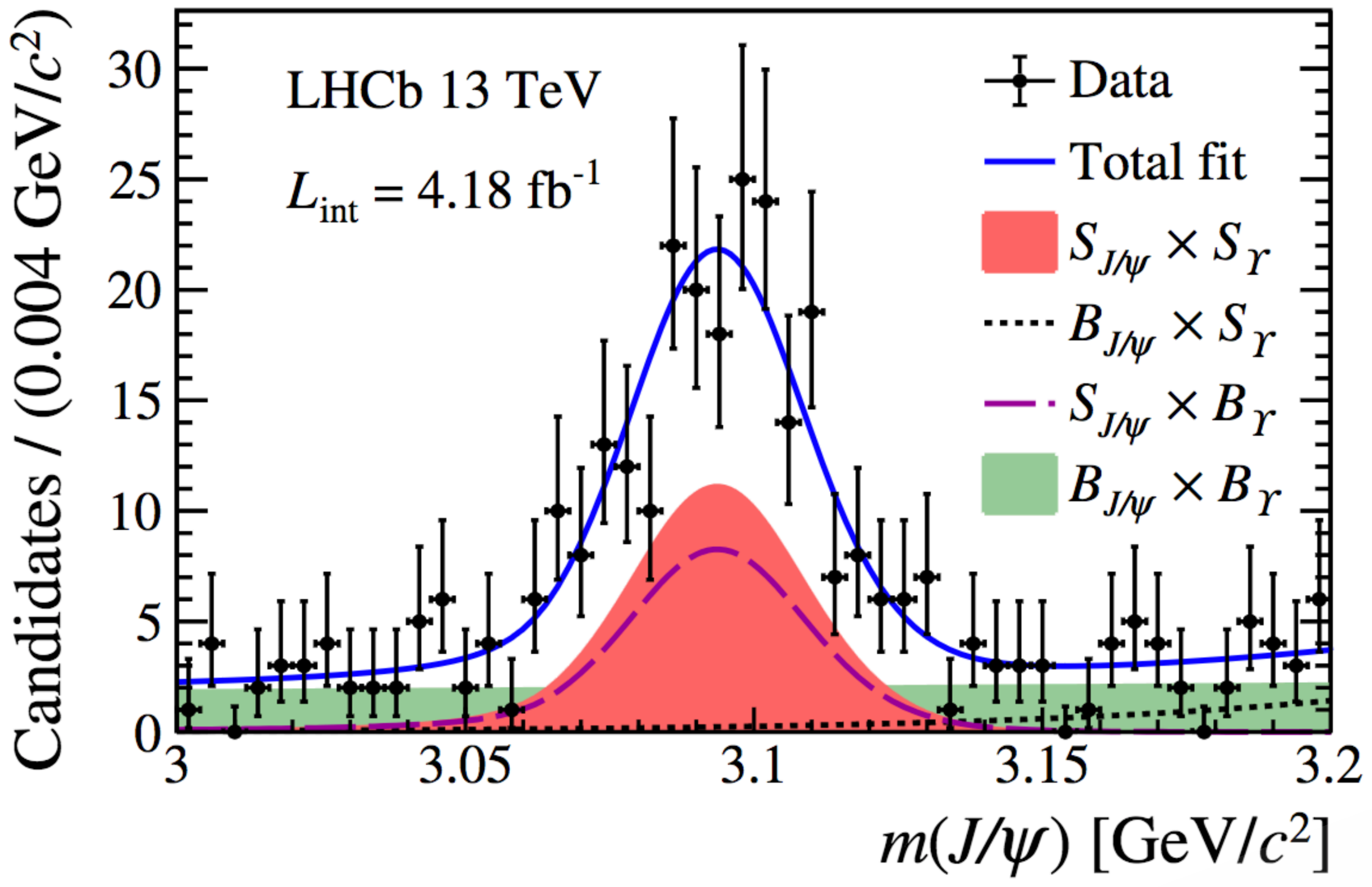
Same sign WW production with **CMS** Phys.Rev.Lett. 131 (2023) 091803

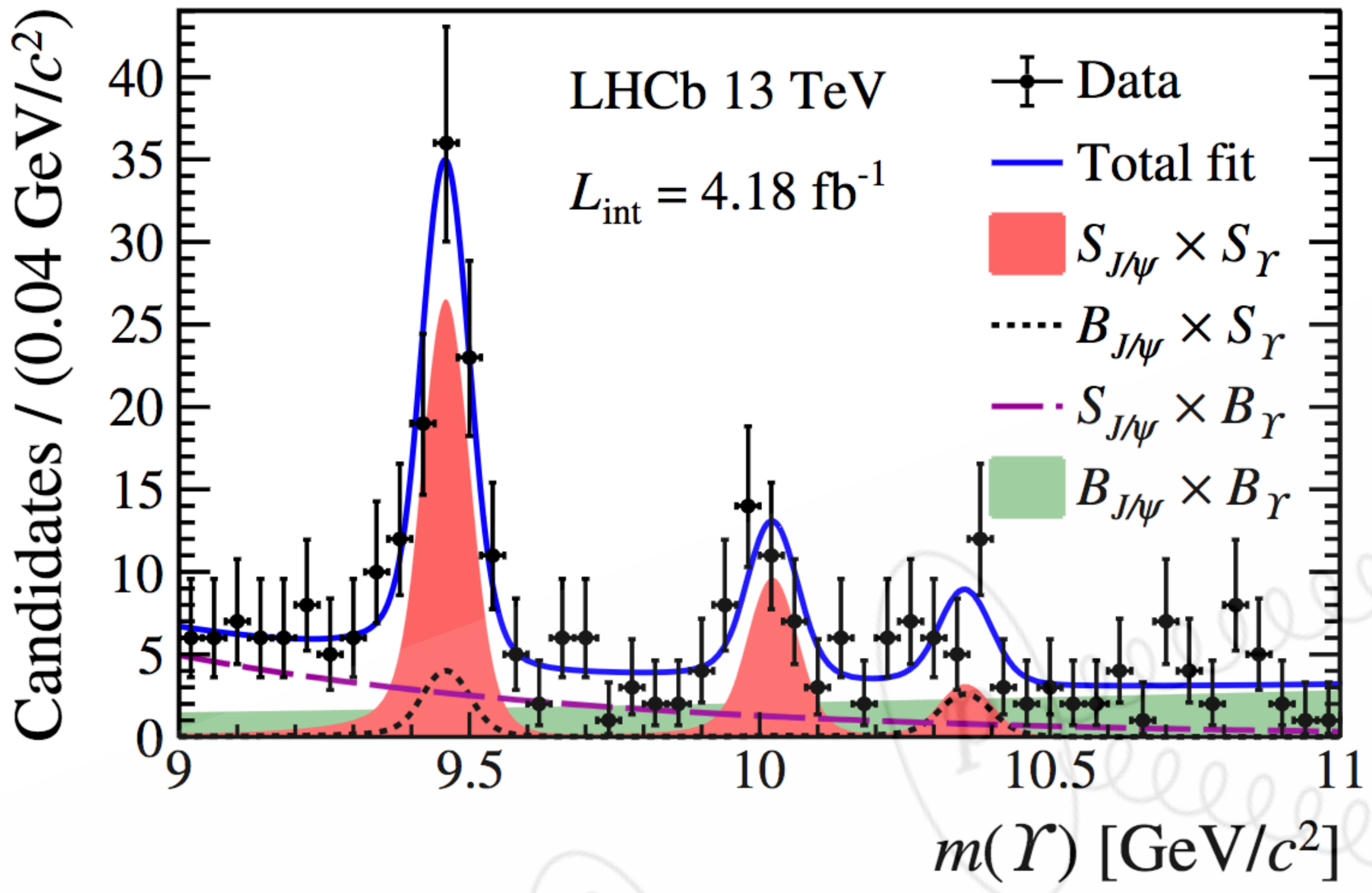


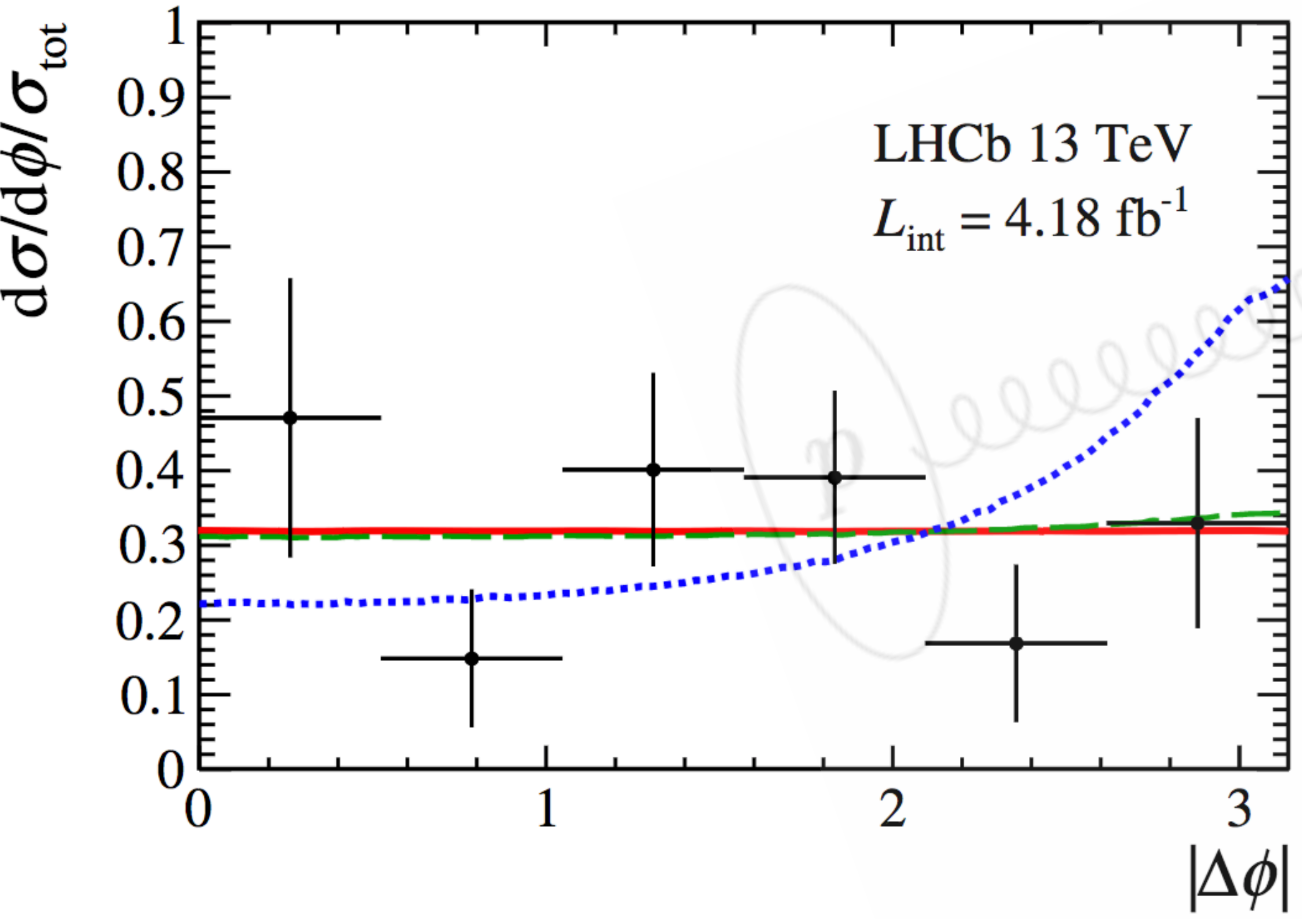


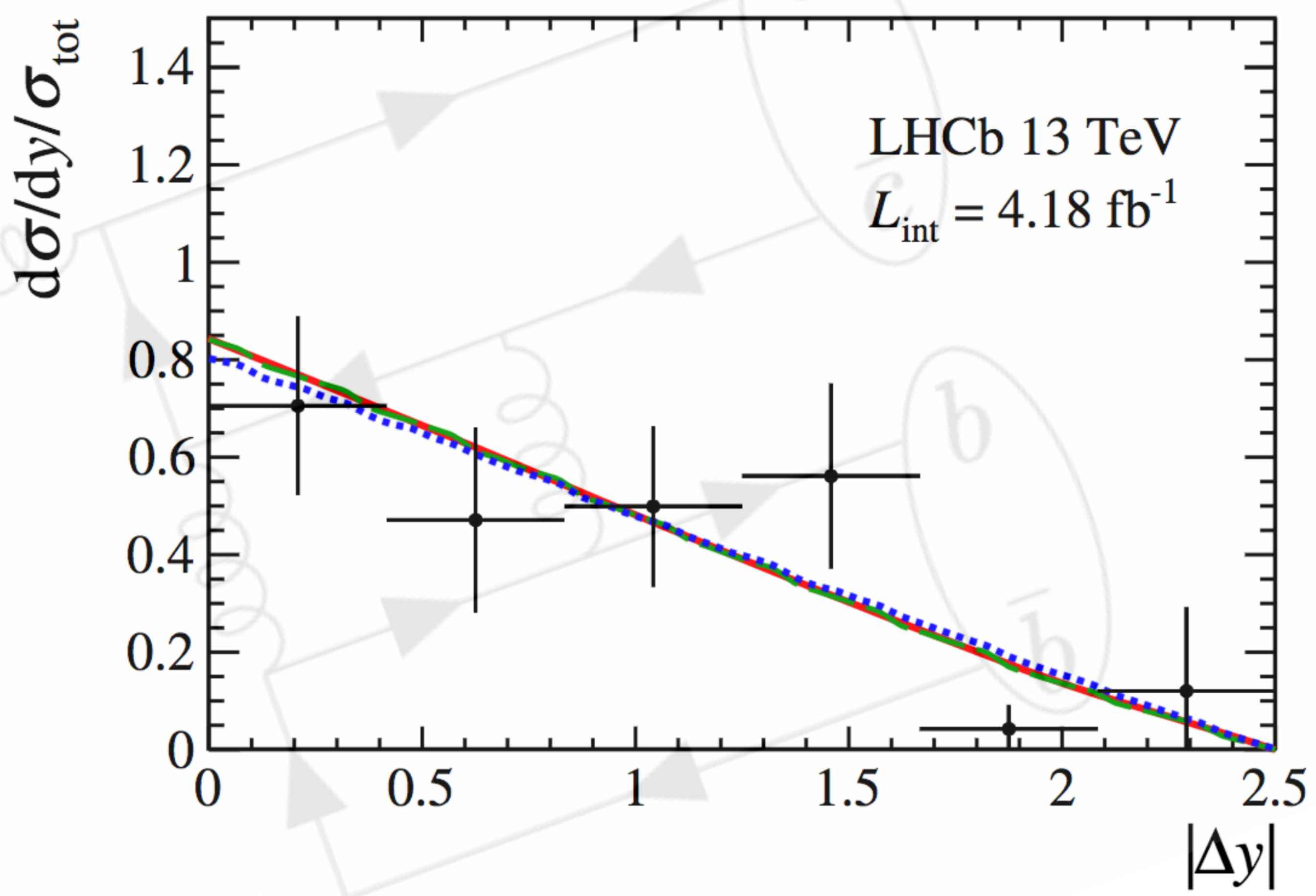


J/ψ+Υ production with **LHCb** — JHEP 08 (2023) 093

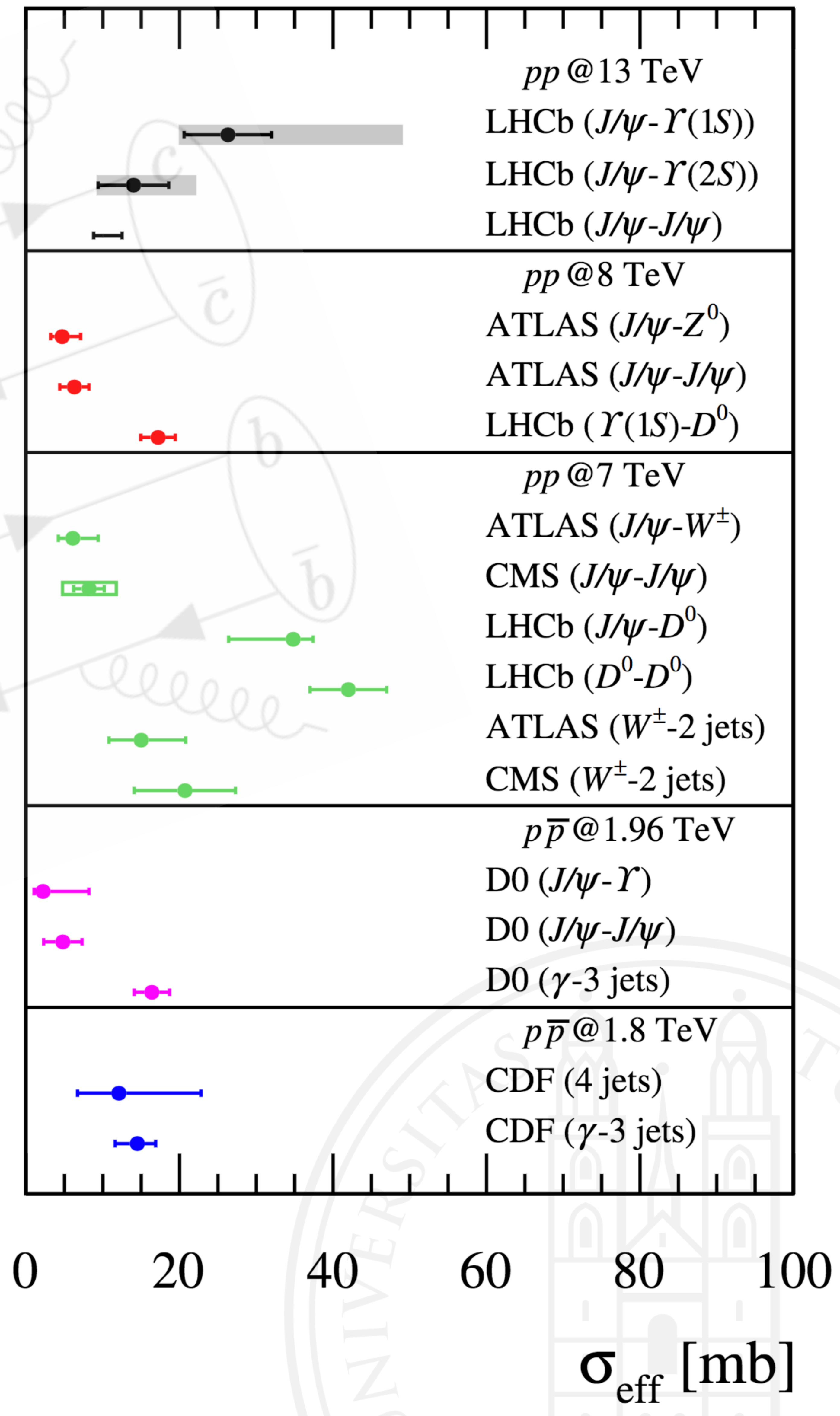








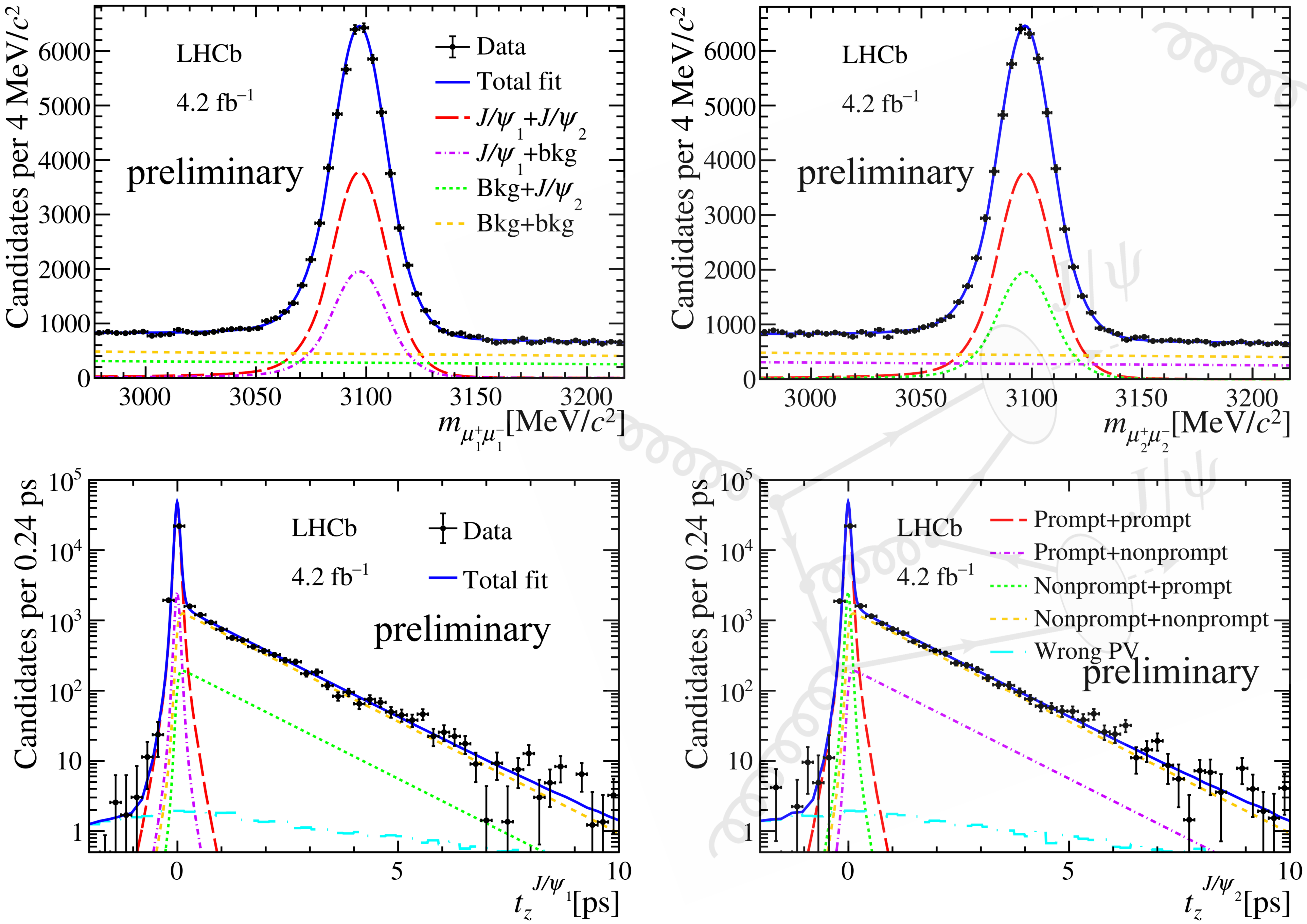
Signal	Raw yields	N_{cor}	Significances
J/ψ-$\Upsilon(1S)$	76 ± 12	840 ± 140	$7.9\,\sigma$
J/ψ-$\Upsilon(2S)$	30 ± 7	370 ± 100	$4.9\,\sigma$
J/ψ-$\Upsilon(3S)$	10 ± 6	—	$1.7\,\sigma$

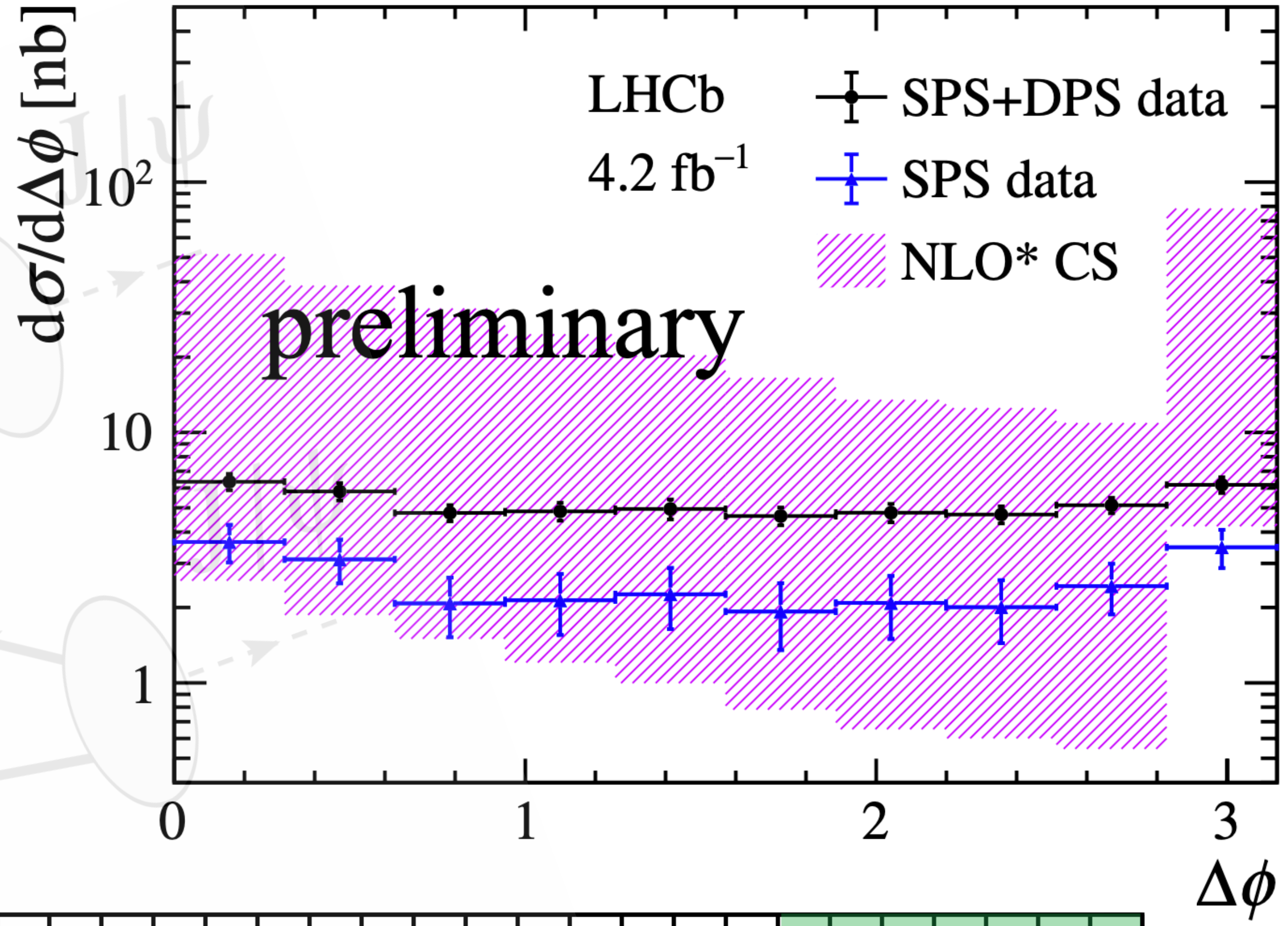


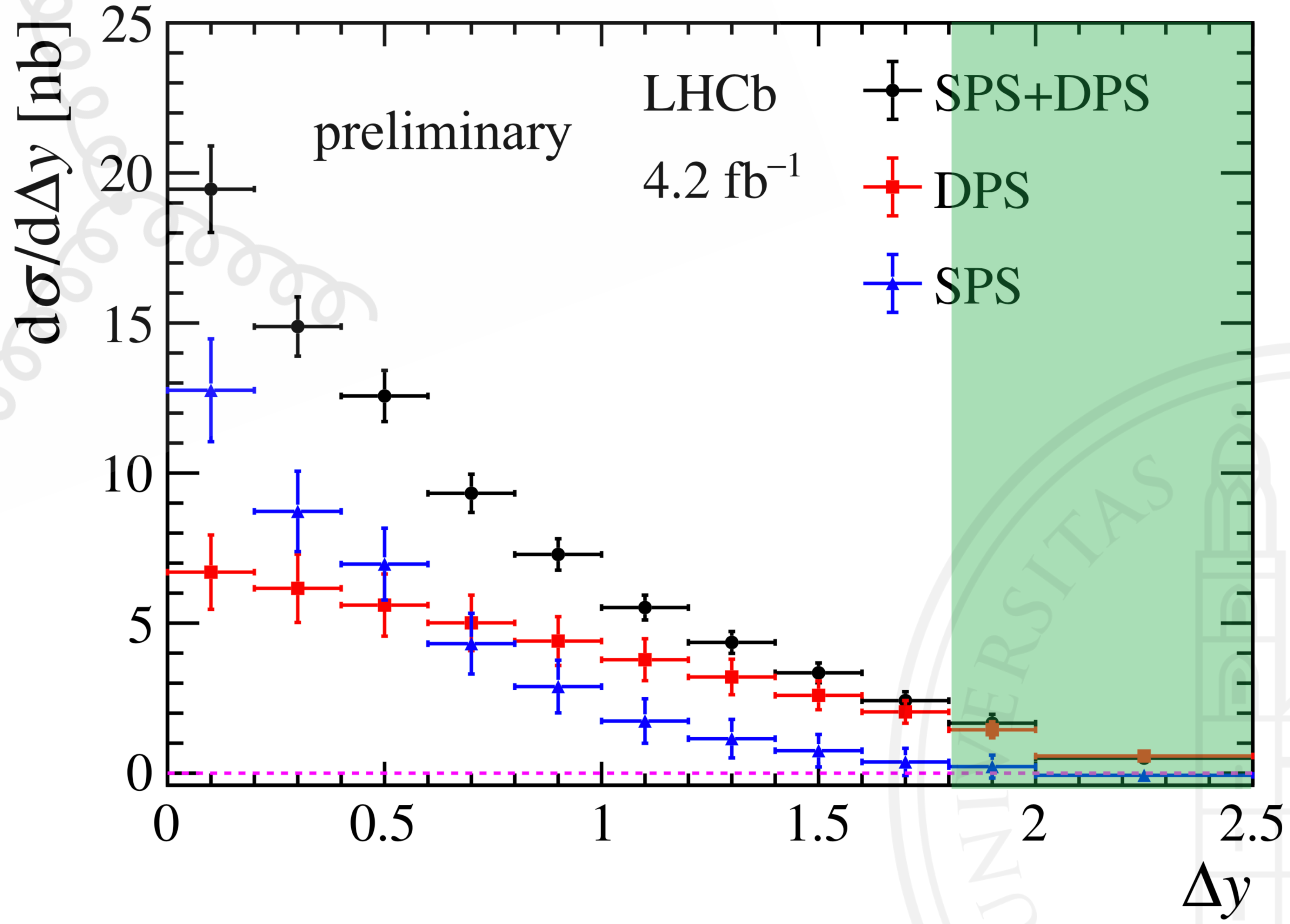
J/ψ pair production with **LHCb**

LHCb-PAPER-2023-022

- $N\left(\mathrm{J}/\psi + \mathrm{J}/\psi\right) = (2.187 \pm 0.020) \times 10^4$
- $\sigma\left(\mathrm{J}/\psi + \mathrm{J}/\psi\right) = 16.36 \pm 0.28\,(\mathrm{stat}) \;\; \pm 0.88\,(\mathrm{syst})\,\mathrm{nb}$

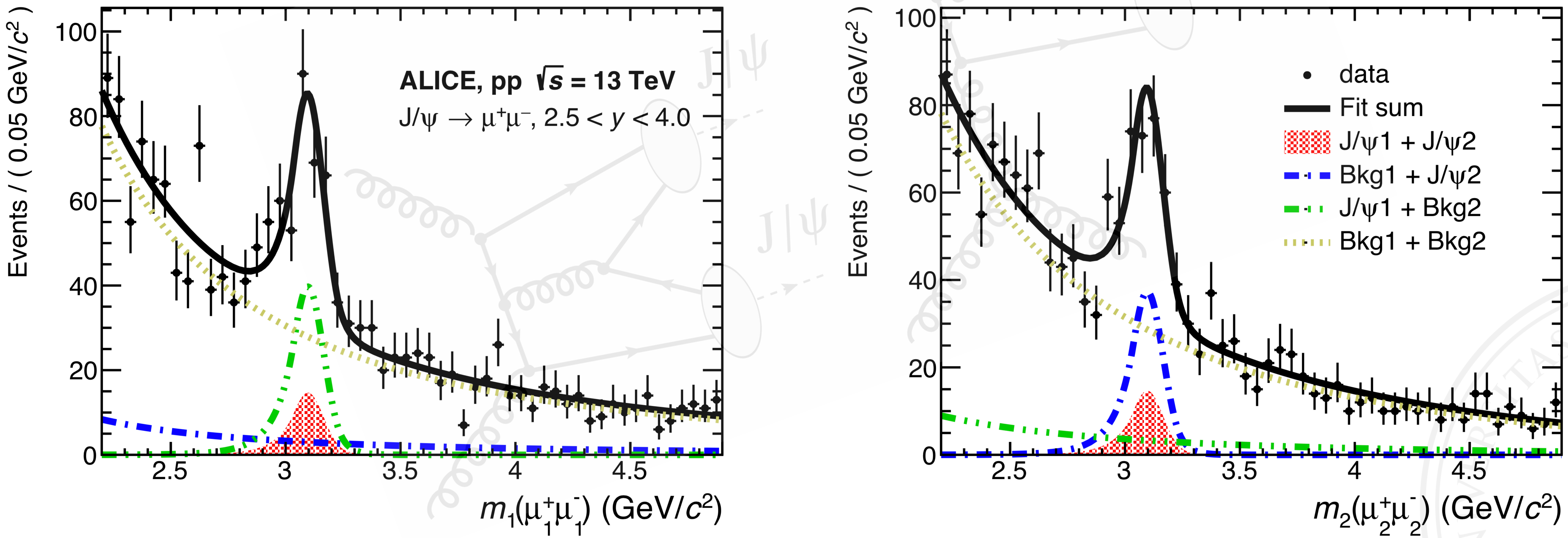






J/ψ pair production with **ALICE** arXiv:2303.13431

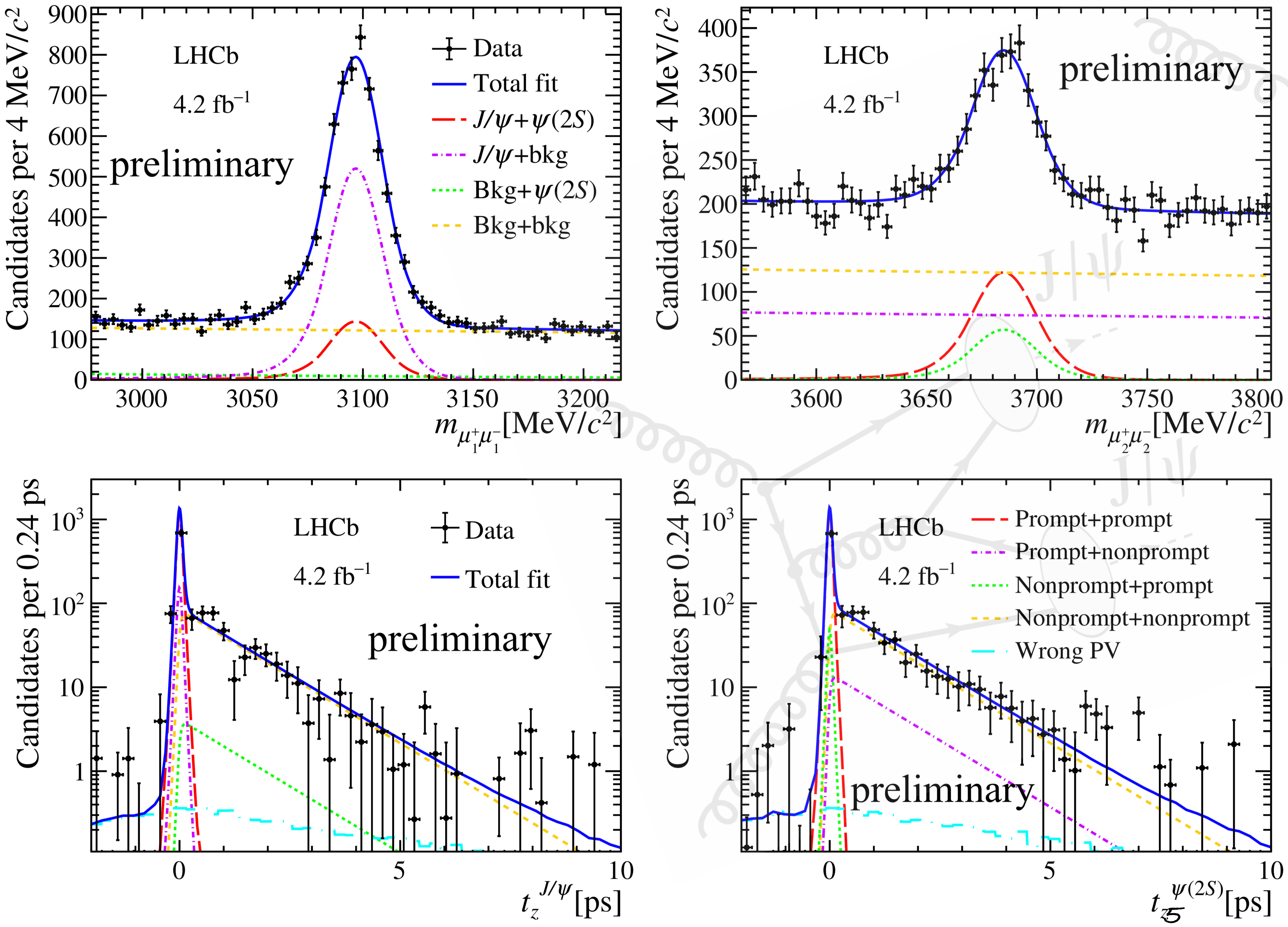
- $N\left(\mathrm{J}/\psi + \mathrm{J}/\psi\right) = 59.3 \pm 13.5\,(\mathrm{stat}) \pm 4.4\,(\mathrm{syst})$
- Assuming all di-J/ψ events are DPS
- DPS effective cross section from
  - prompt: $\sigma_{\mathrm{eff}} = 6.7 \pm 1.4\,(\mathrm{stat}) \pm 1.1\,(\mathrm{syst})\,\mathrm{mb}$
  - non-prompt: $\sigma_{\mathrm{eff}} = 6.7 \pm 1.6\,(\mathrm{stat}) \pm 2.7\,(\mathrm{syst})\,\mathrm{mb}$



WG2 summary

J/ψ+ψ(2S) production with **LHCb** — LHCb-PAPER-2023-023

- $N\left(\mathrm{J}/\psi+\psi(2S)\right) = 629 \pm 50$
- $\sigma\left(\mathrm{J}/\psi+\psi(2S)\right) = 4.49 \pm 0.71\,(\mathrm{stat}) \pm 0.26\,(\mathrm{syst})\,\mathrm{nb}$

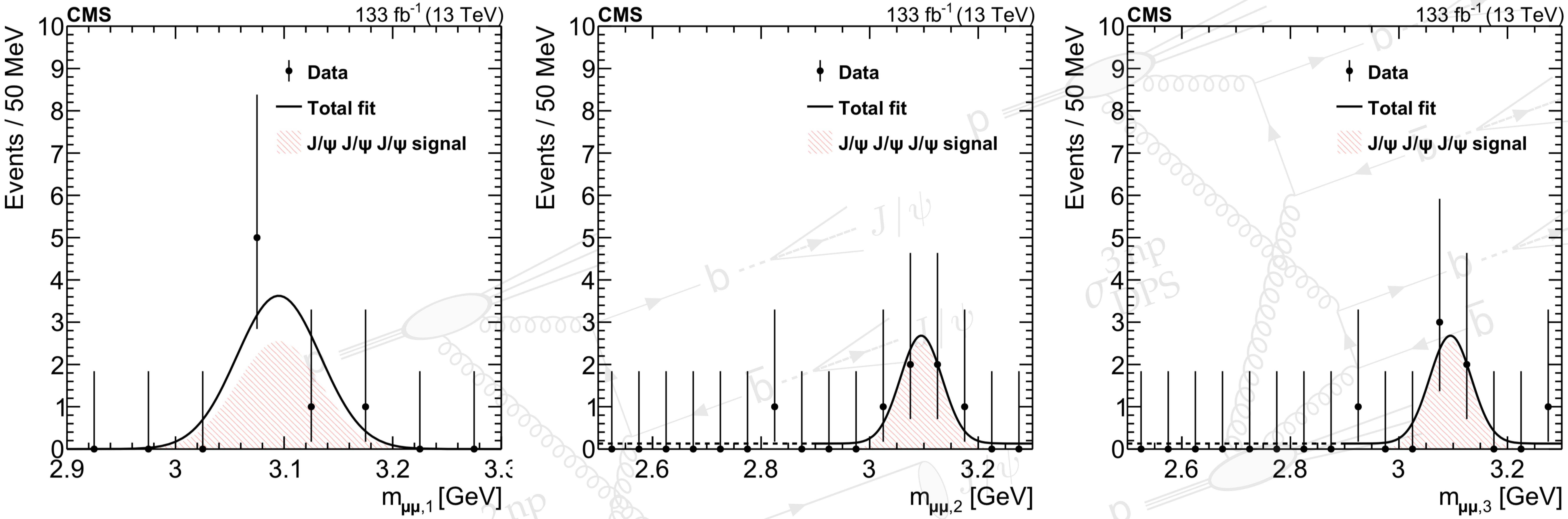


$$\sigma_{\mathrm{eff}} = \frac{\sigma(\mathrm{J}/\psi)\sigma(\psi(2S))}{\sigma\left(\mathrm{J}/\psi+\psi(2S)\right)} = 7.1 \pm 1.1\,(\mathrm{stat}) \pm 0.8\,(\mathrm{syst})\,\mathrm{mb}$$

Triple J/ψ meson production with **CMS**

NP 19 (2023) 338

- $N\left(\mathrm{J}/\psi + \mathrm{J}/\psi + \mathrm{J}/\psi\right) = 5.0^{+2.6}_{-1.9}$
- $\sigma\left(\mathrm{J}/\psi + \mathrm{J}/\psi + \mathrm{J}/\psi + X\right) = 272^{+141}_{-104}\,(\mathrm{stat}) \pm 17\,(\mathrm{syst})\,\mathrm{fb}$



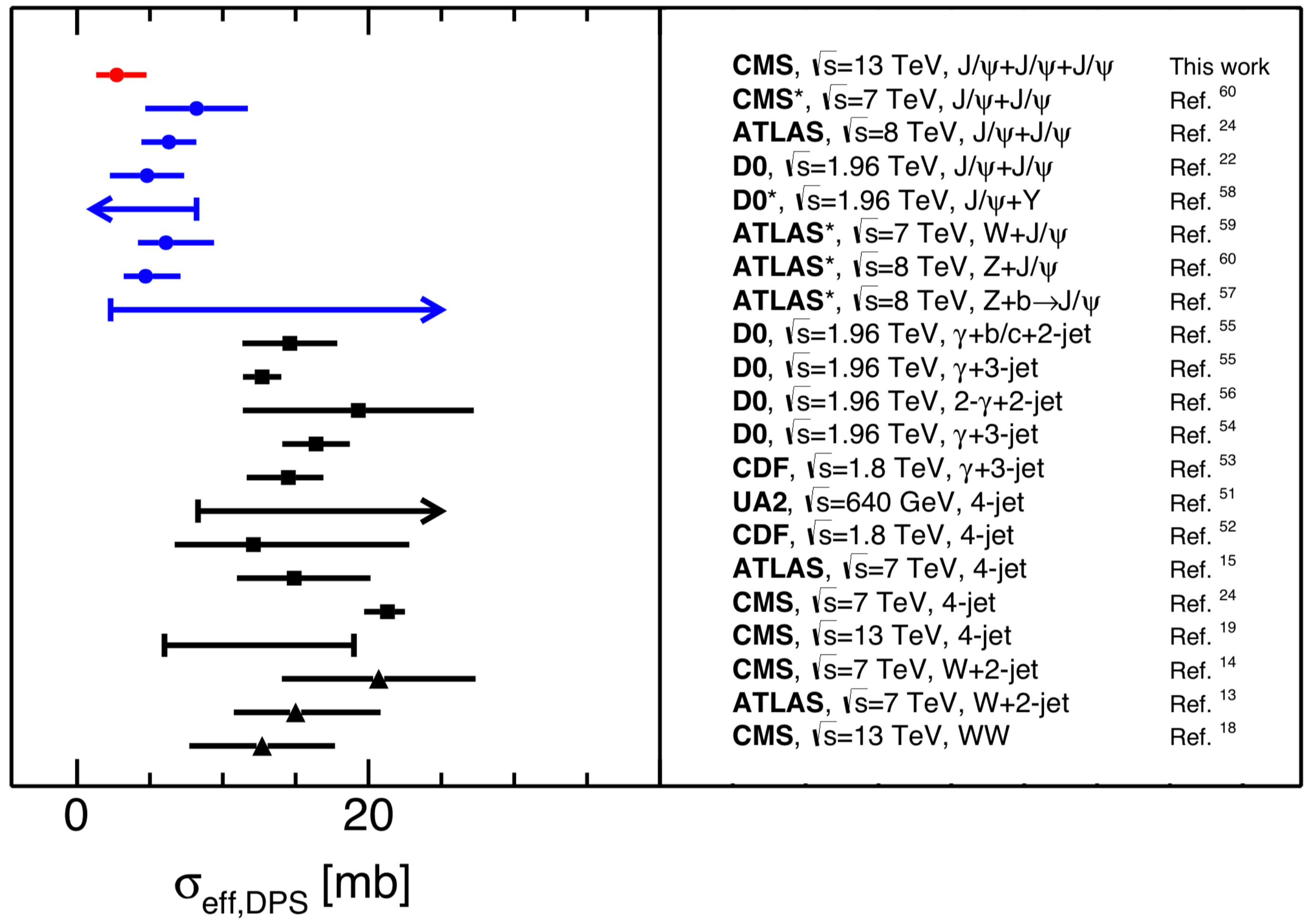
$\sigma_{\mathrm{eff}} = 2.7^{+1.4}_{-1.0}\,(\mathrm{exp})\ ^{+1.5}_{-1.0}\,(\mathrm{theo})\,\mathrm{mb}$

Triple J/ψ fractions: ~6% SPS, ~74% DPS and ~20% TPS

WG2 summary

Remarks

- More and more processes are newly discovered/studied
  - still space to fill in phase-space
  - processes are in our datasets - we just have to look for them
- But..
  - Still plenty of phase space unexplored ..?
  - Input to theory limited ..?
    - Or stats too low
  - worth having this table updated together with the TPS processes



Observables	Experiments	CSM	CEM	NRQCD	Interest
$J/\psi + J/\psi$	+ALICE LHCb, CMS, ATLAS, D0, NA3	NLO, NNLO*	NLO	LO	Test of the CSM; DPS; Gluon TMDs;
$J/\psi + \psi(2S)$ or $J/\psi + \chi_c$	LHCb	LO	NLO	LO	DPS vs SPS;
$J/\psi + \Upsilon$	D0 +LHCb	LO	NLO	LO	Test of the CSM; DPS;
$\Upsilon + \Upsilon$	CMS	NLO (?)	NLO	LO	Test of the CSM; DPS; Gluon TMDs;
J/ψ+charm	LHCb	LO	–	LO	$c \to J/\psi$ fragmentation & CTs; DPS.
J/ψ+bottom or J/ψ+nonprompt J/ψ	LHCb	–	–	LO	Test of the COM; DPS;
Υ+bottom or Υ+nonprompt J/ψ	LHCb	LO	–	LO	Test of the CSM/COM; DPS;
Υ+charm	LHCb	LO	–	LO	DPS;
$J/\psi + Z$	ATLAS	NLO	NLO	Partial NLO	Test of the CSM/COM; DPS;
$J/\psi + W$	ATLAS	LO	NLO	NLO (?)	Test of the COM; DPS;
$\Upsilon + Z$	–	NLO	–		Test of the CSM/COM; DPS;
$\Upsilon + W$	–	LO	–		Test of the COM; DPS;

Phys. Rept. 889 (2020) 1-106

The very first DPS paper was published 40 years ago...

PHYSICAL REVIEW D VOLUME 22, NUMBER 11 1 DECEMBER 1980

Double Drell-Yan annihilations in hadron collisions: Novel tests of the constituent picture

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The production in hadron collisions of a pair of virtual photons, each having a large invariant mass, proceeds via two mechanisms: (a) two independent Drell-Yan-type annihilations of quark pairs in a single interaction and (b) the pair annihilation process $q\bar{q}\rightarrow\gamma^*\gamma^*$. We argue that both mechanisms allow intriguing tests of constituent structure and its associated scaling laws and we show that, despite their α^4 production rate, events of this type are accessible with existing π and proton beams.

Only recently it was confirmed that the DPS cross section in pA scales in a non-trivial way!

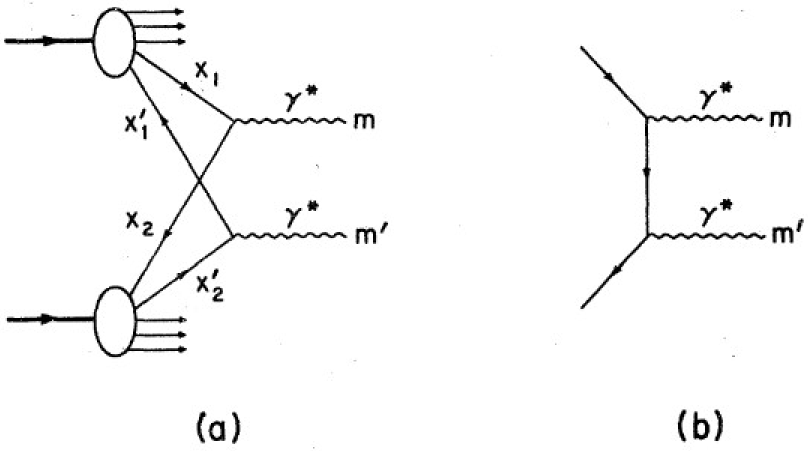

FIG. 1. Production of two high-mass virtual photons by (a) double and (b) single quark-antiquark annihilation.

2 for proton-induced interactions. In agreement with our previous estimates, we have assumed that both mechanisms contribute about equally to σ_2. The diagram of Fig. 1(b) almost certainly depends on A as A^1. As the quarks in the diagram of Fig. 1(a) can come from different nucleons, the dependence is somewhere between $A^{4/3}$ and A^2. It is worthwhile to notice that by using targets with multiple nuclear composition, one can unambiguously separate the two production mechanisms experimentally. The numbers for π beams