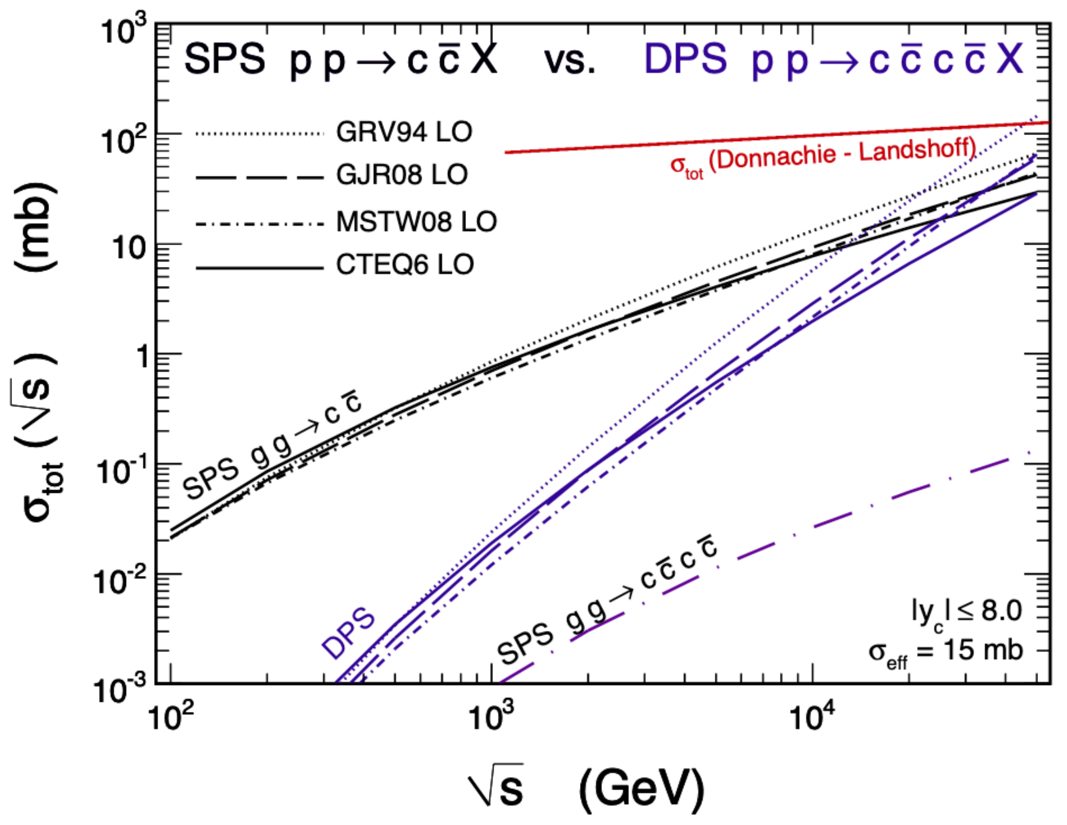
Recent Double Parton Scattering Measurements

S. Leontsinis
University of Zurich

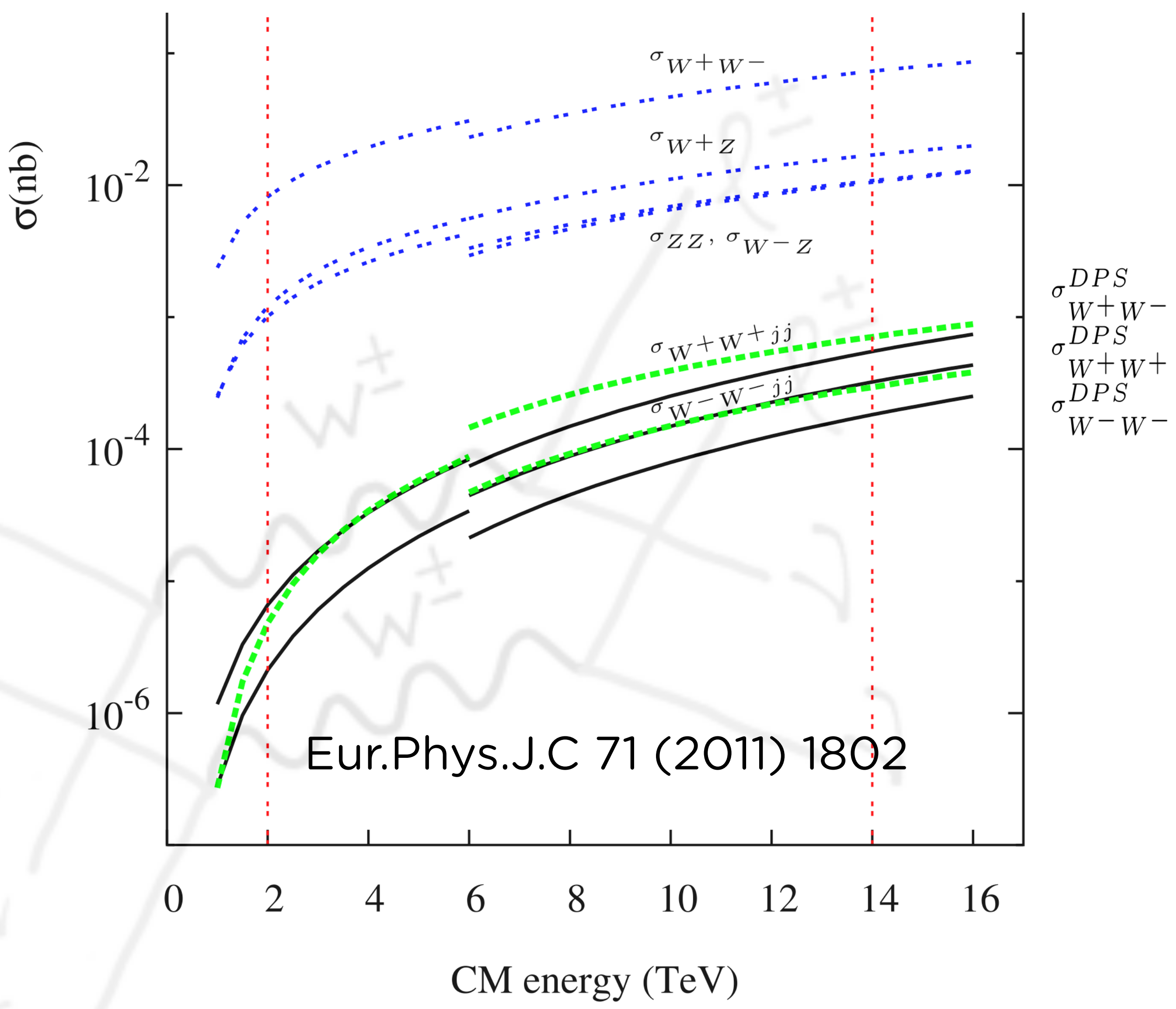
QCD@LHC 2023
7th September 2023

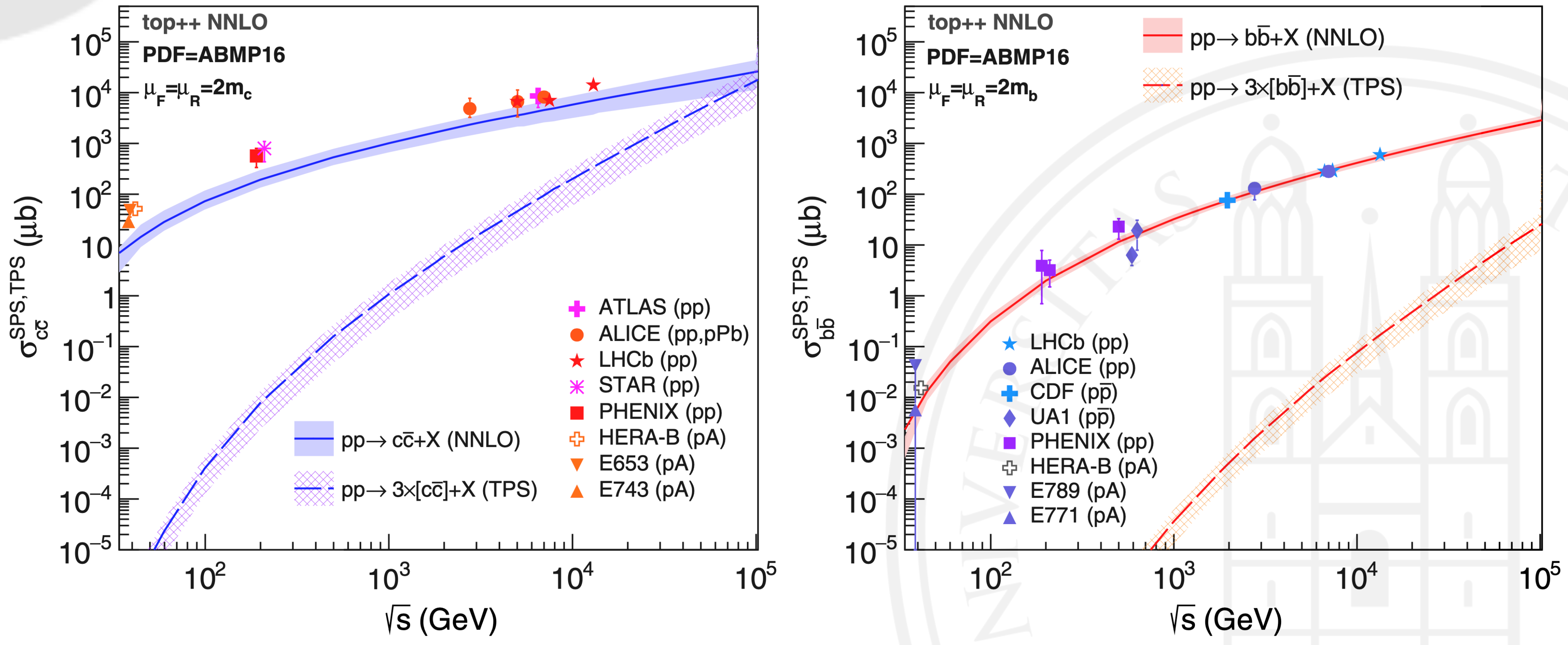
Introduction

- nPS processes are important for fundamental studies
  - background of new physics signatures
  - probe of the partonic structure of the proton
  - input for the tuning of MC generators
- nPS sensitive to interplay between perturbative and non-perturbative QCD
  - models can be tuned using data measurements
- Rate of nPS processes increases with $\sqrt{s}$
  - parton densities increase
  - cross section of nPS
- $$\frac{\sigma_{\mathrm{nPS}}}{\sigma_{\mathrm{SPS}}} \sim \left(\frac{\Lambda^2}{Q_h^2}\right)^{(n-1)}$$
  - in certain processes, contributions from DPS are significant
- We have results from many experiments, using many final states and in different $\sqrt{s}$



arXiv:1212.5427

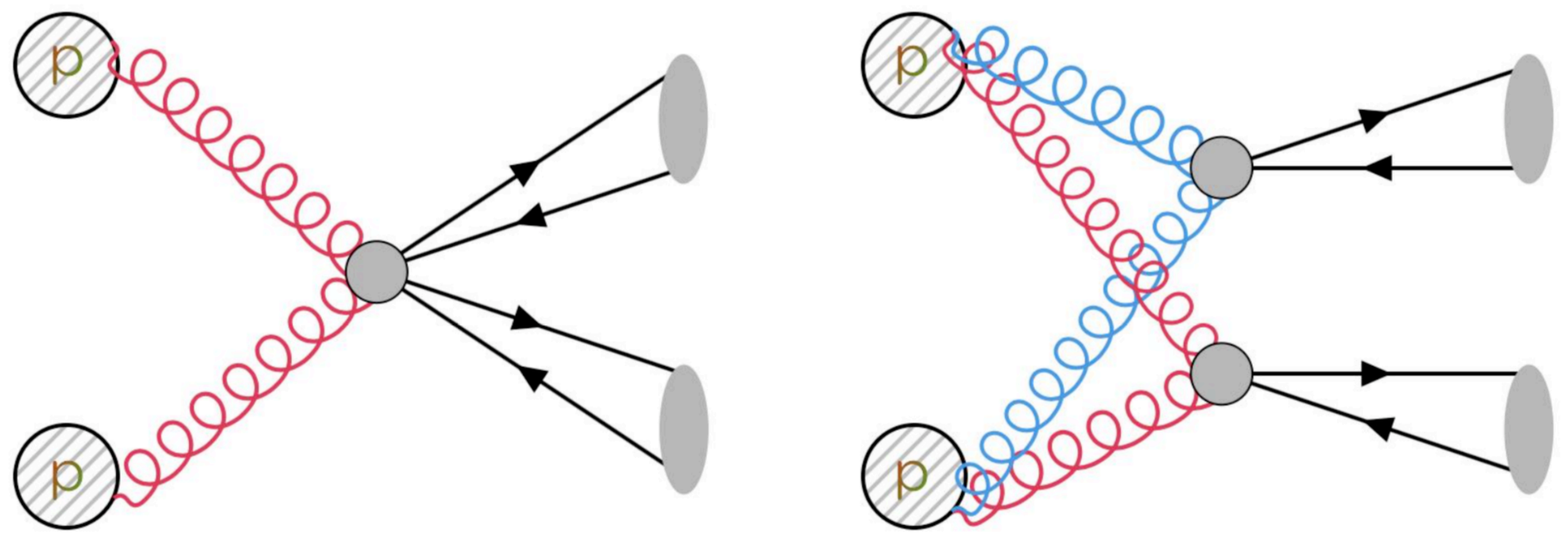




PRL 118, 122001 (2017)

DPS effective cross section

- First appearance of Double Parton Scattering in theory in the 80s
- DPS is a proton-proton scattering process where two partons from each proton interact separately
- DPS cross section can be expressed as:



$$\frac{d\sigma_{\mathrm{DPS}}}{dx_1\,dx_2\,d\bar{x}_1\,d\bar{x}_2} = \frac{1}{C}\int_{x_1}^{1-x_2}\frac{dx_1'}{x_1'}\int_{x_2}^{1-x_1'}\frac{dx_2'}{x_2'}\int_{\bar{x}_1}^{1-\bar{x}_2}\frac{d\bar{x}_1'}{\bar{x}_1'}\int_{\bar{x}_2}^{1-\bar{x}_1'}\frac{d\bar{x}_2'}{\bar{x}_2'}$$
$$\times \sum_{a_1a_2b_1b_2} {}^{R}\hat{\sigma}^{(1)}_{a_1b_1}(x_1'\bar{x}_1's,\mu_1)\,{}^{R}\hat{\sigma}^{(2)}_{a_2b_2}(x_2'\bar{x}_2's,\mu_2)$$
$$\times \int d^2\boldsymbol{y}\,{}^{R}F_{a_1a_2}(x_1',x_2',\boldsymbol{y},\mu_1,\mu_2,\zeta)\,{}^{R}F_{b_1b_2}(\bar{x}_1',\bar{x}_2',\boldsymbol{y},\mu_1,\mu_2,\bar{\zeta})$$

From Riccardo Nagar's thesis

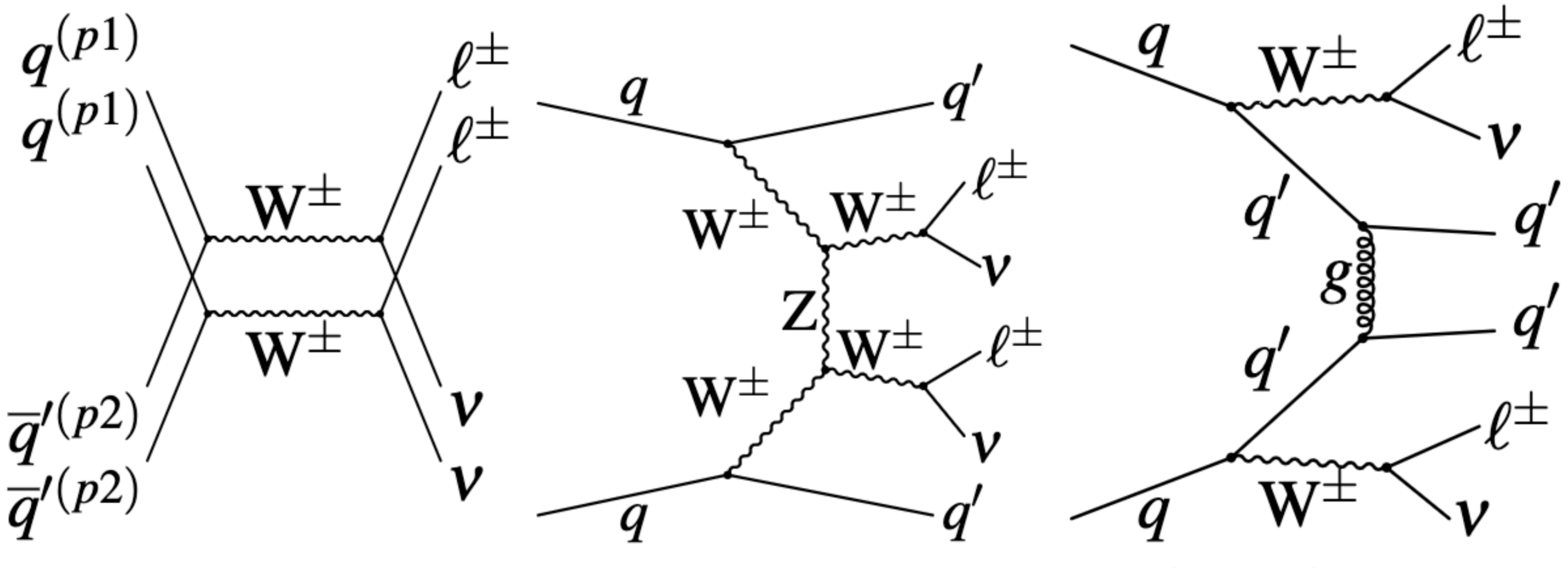
- Ignoring any correlations between the individual partons (m=2 if ψ_1 != ψ_2):

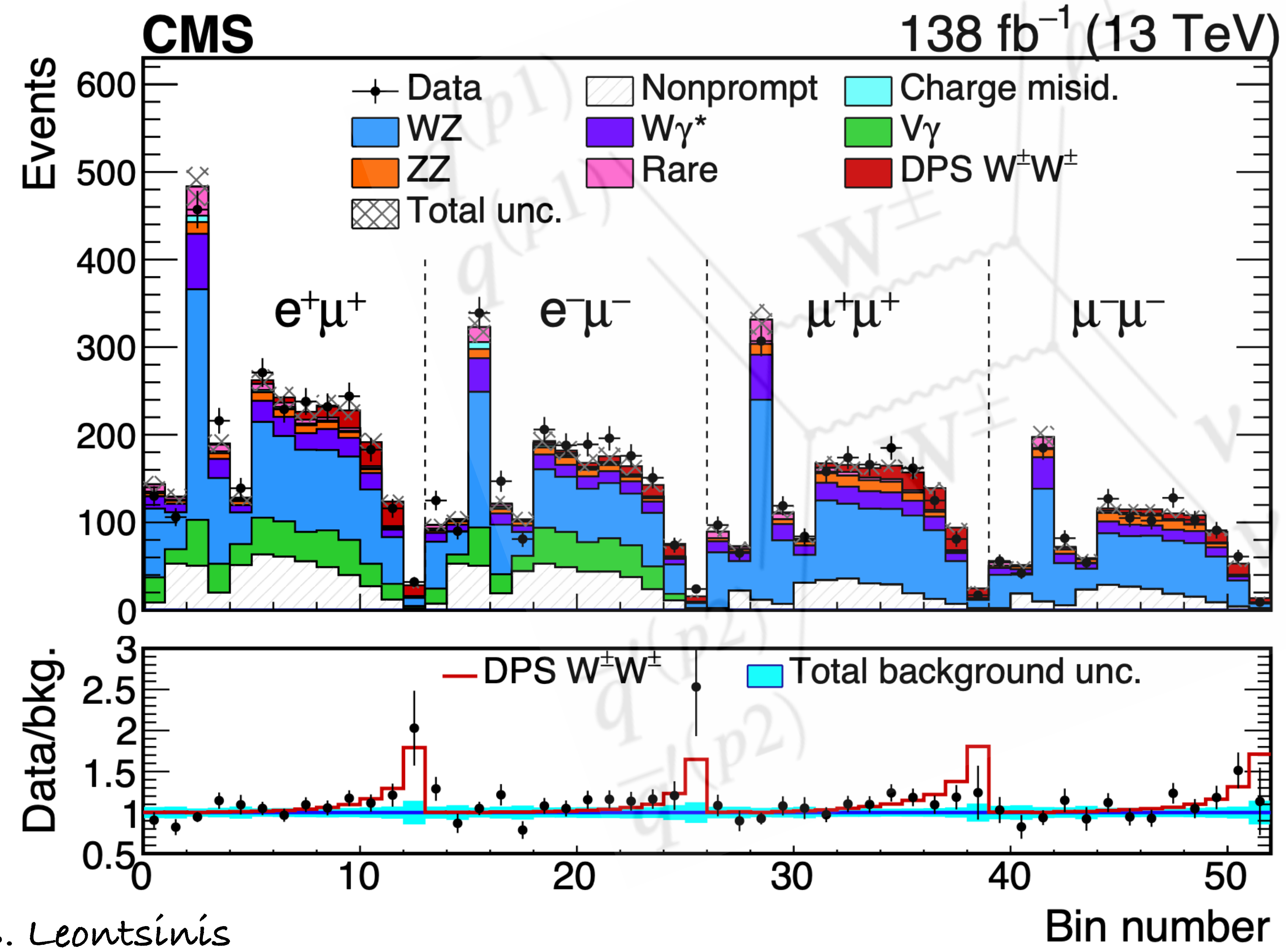
$$\sigma_{\mathrm{DPS}}^{pp\to\psi_1\,\psi_2+X} = \left(\frac{\mathfrak{m}}{2}\right)\frac{\sigma_{\mathrm{SPS}}^{pp\to\psi_1+X}\,\sigma_{\mathrm{SPS}}^{pp\to\psi_2+X}}{\sigma_{\mathrm{eff,DPS}}}$$

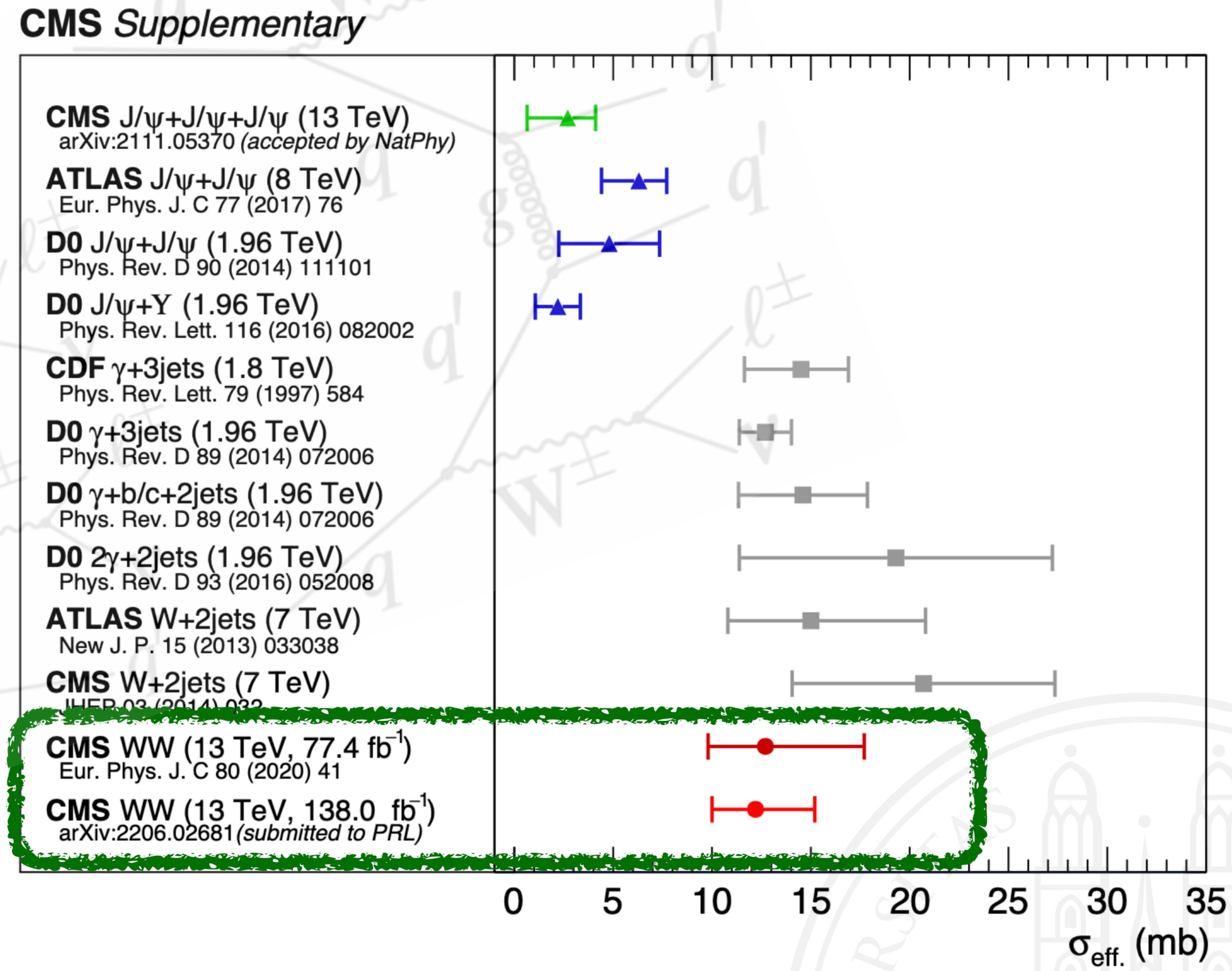
- $\sigma_{\mathrm{eff,DPS}}$ holds the effects of the transversity and is the parameter calculated from experiments
  - plenty of measurements the past decade
  - final states (so far) include jets, photons, EW bosons and quarkonia!

Recent Double Parton Scattering Measurements

Same sign WW production with **CMS** arXiv:2206.02681

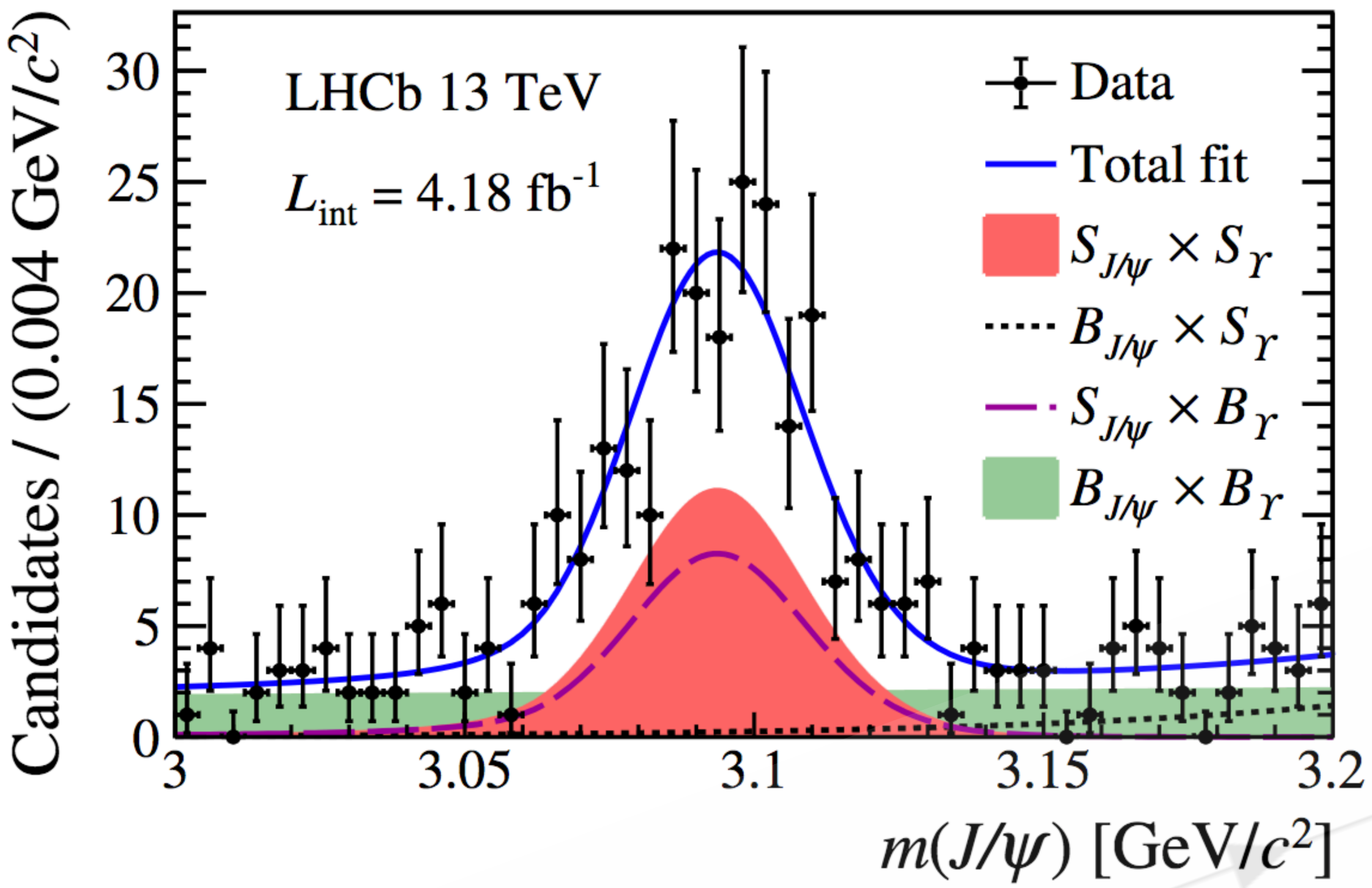


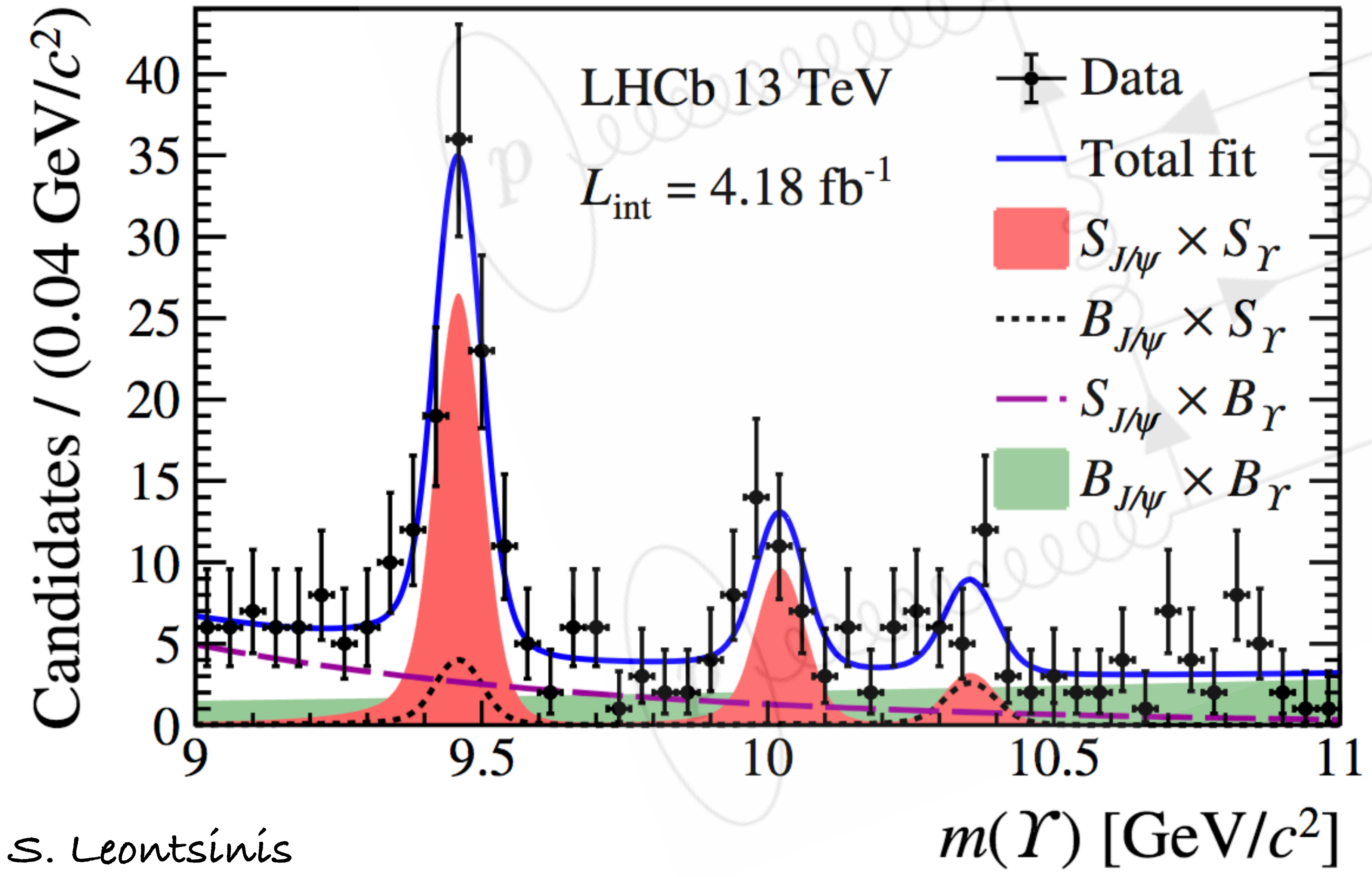




J/ψ+Υ production with **LHCb**

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	—	$1.7\,\sigma$

$$\sigma(J/\psi\text{-}\Upsilon(1S)) = 133 \pm 22 \pm 7 \pm 3\,\text{pb}$$

$$\sigma(J/\psi\text{-}\Upsilon(2S)) = 76 \pm 21 \pm 4 \pm 7\,\text{pb}$$

J/ψ+Y production with **LHCb**

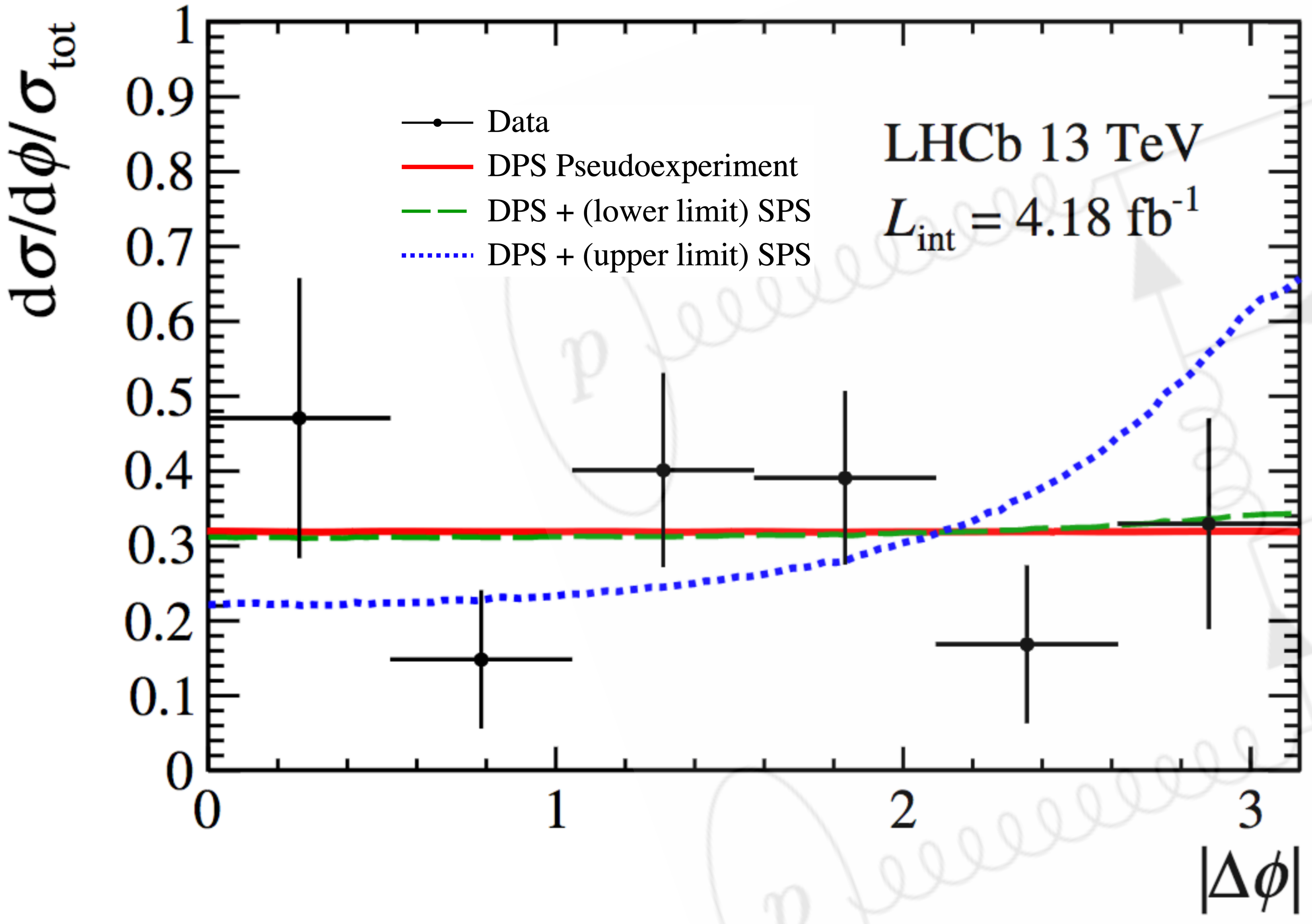
JHEP 08 (2023) 093

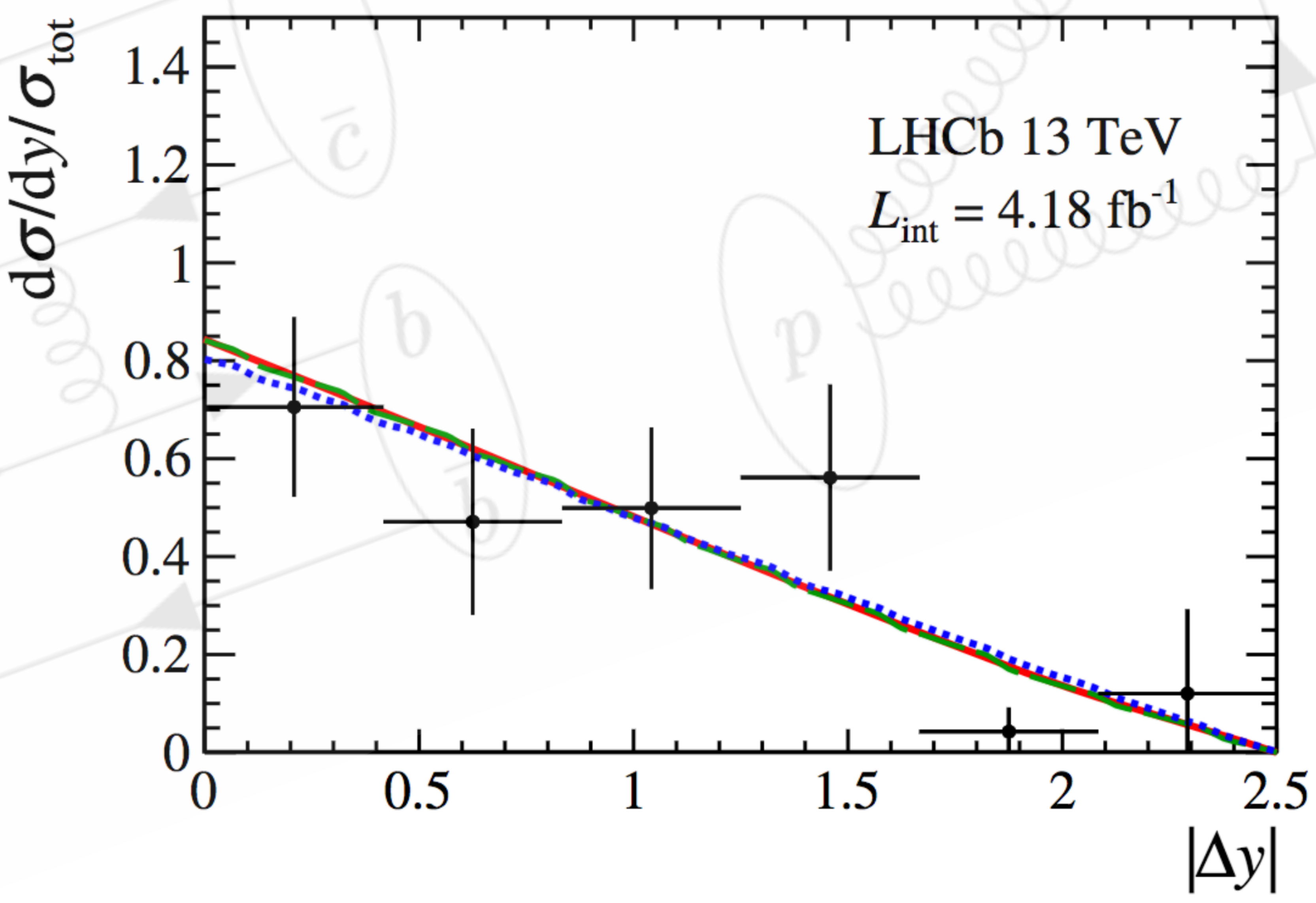
- $\sigma_{SPS}\left(J/\psi + Y(1S)\right) = 20^{+52}_{-15}$ pb PRL 117 (2016) 062001
- $\sigma_{SPS}\left(J/\psi + Y(2S)\right) = 8^{+22}_{-6}$ pb

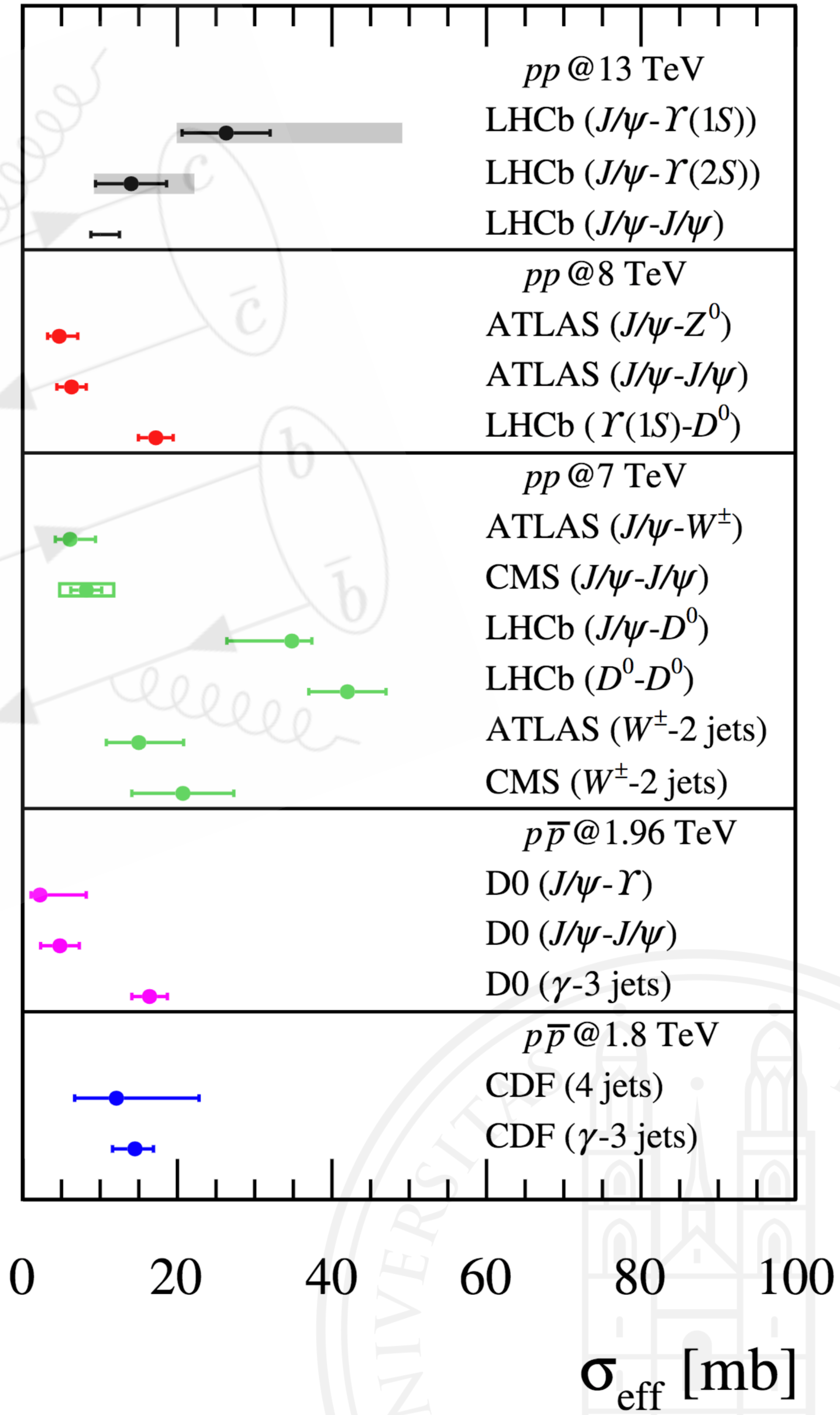
$$\sigma_{DPS}(J/\psi\text{-}\Upsilon) = \frac{\sigma(J/\psi)\times\sigma(\Upsilon)}{\sigma_{eff}}$$

$$\sigma_{eff}(J/\psi\text{-}\Upsilon(1S)) = 26 \pm 5 \pm 2^{+22}_{-3}\ \text{mb}$$

$$\sigma_{eff}(J/\psi\text{-}\Upsilon(2S)) = 14 \pm 5 \pm 1^{+7}_{-1}\ \text{mb},$$

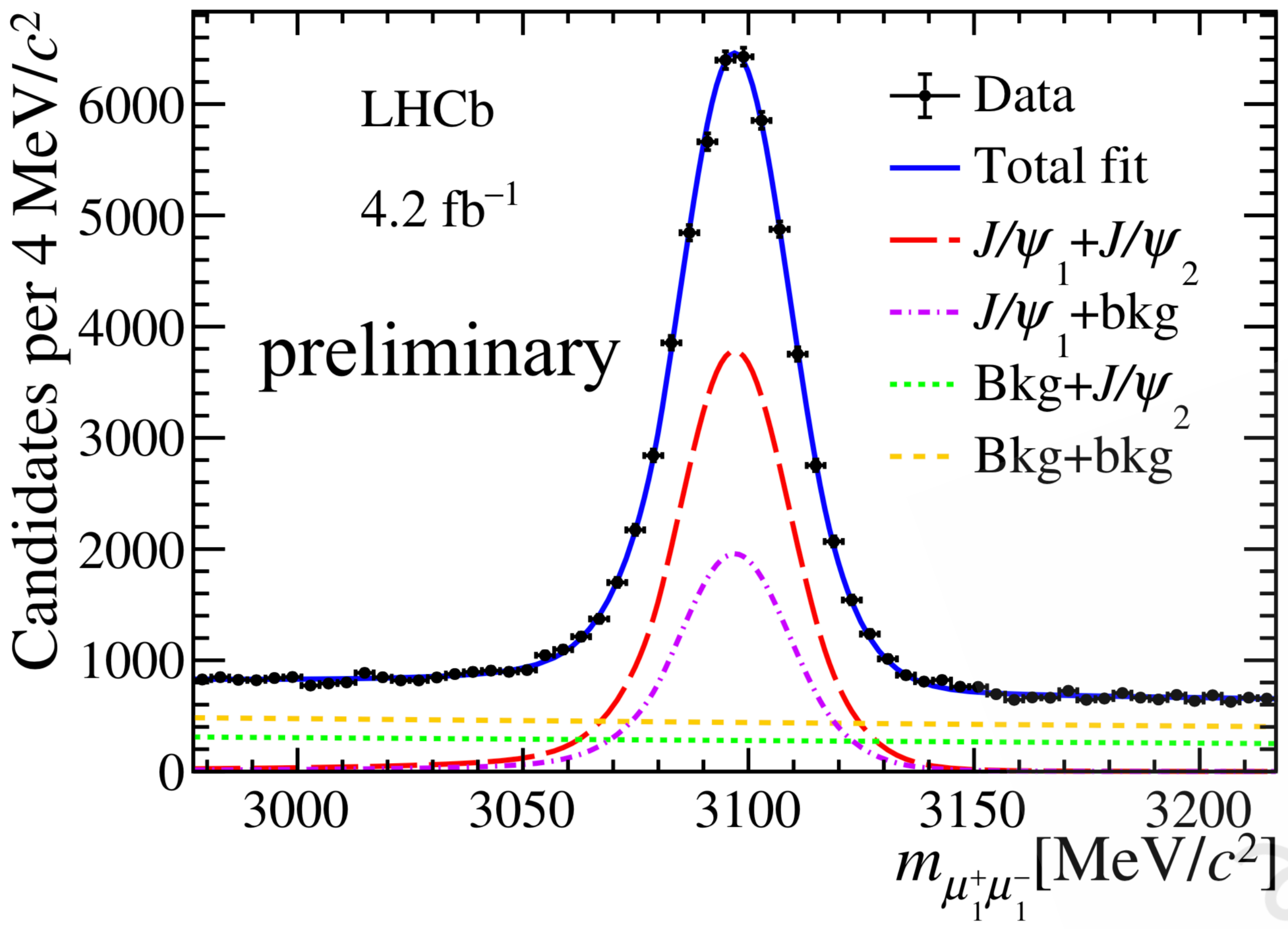


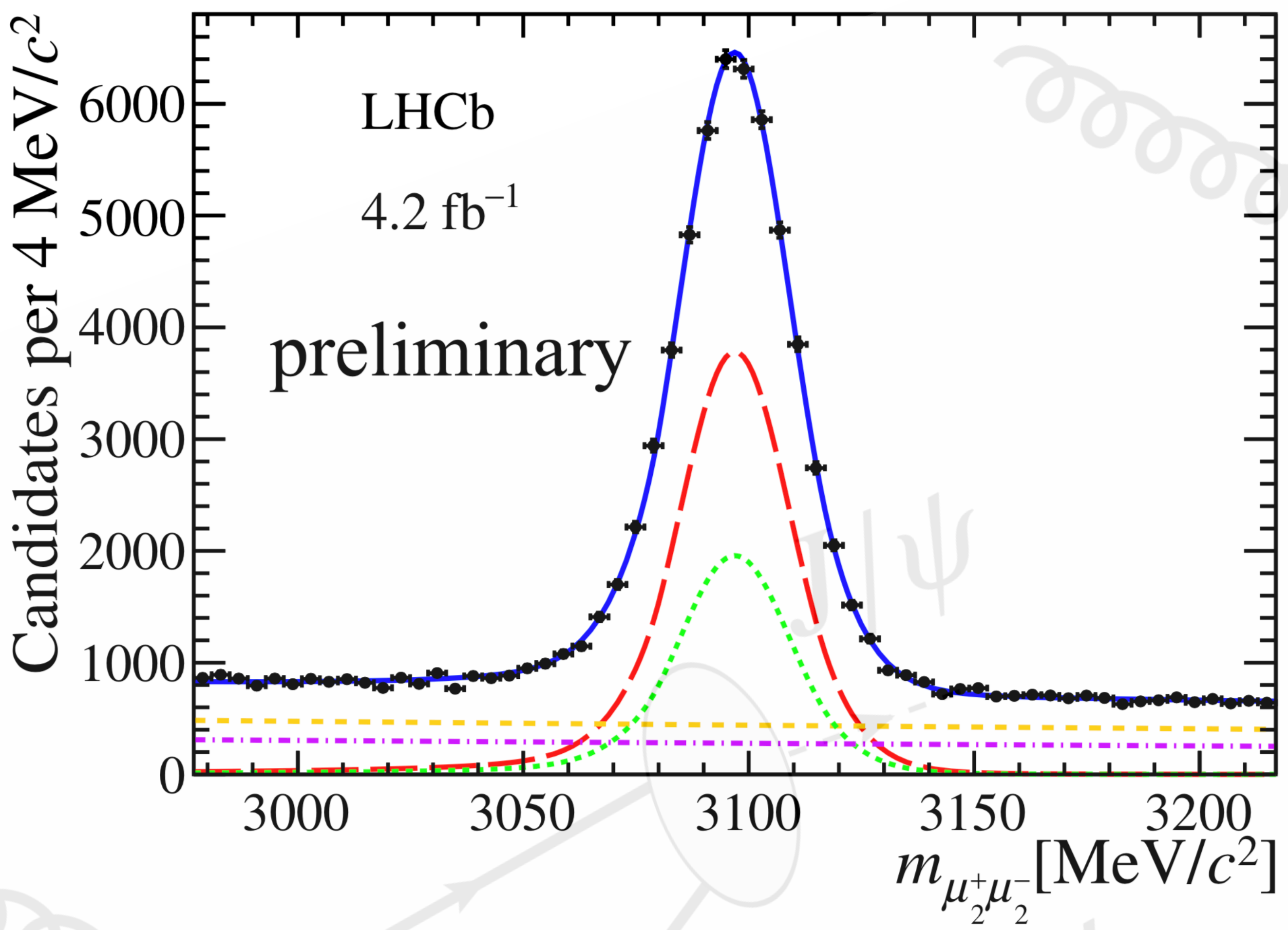


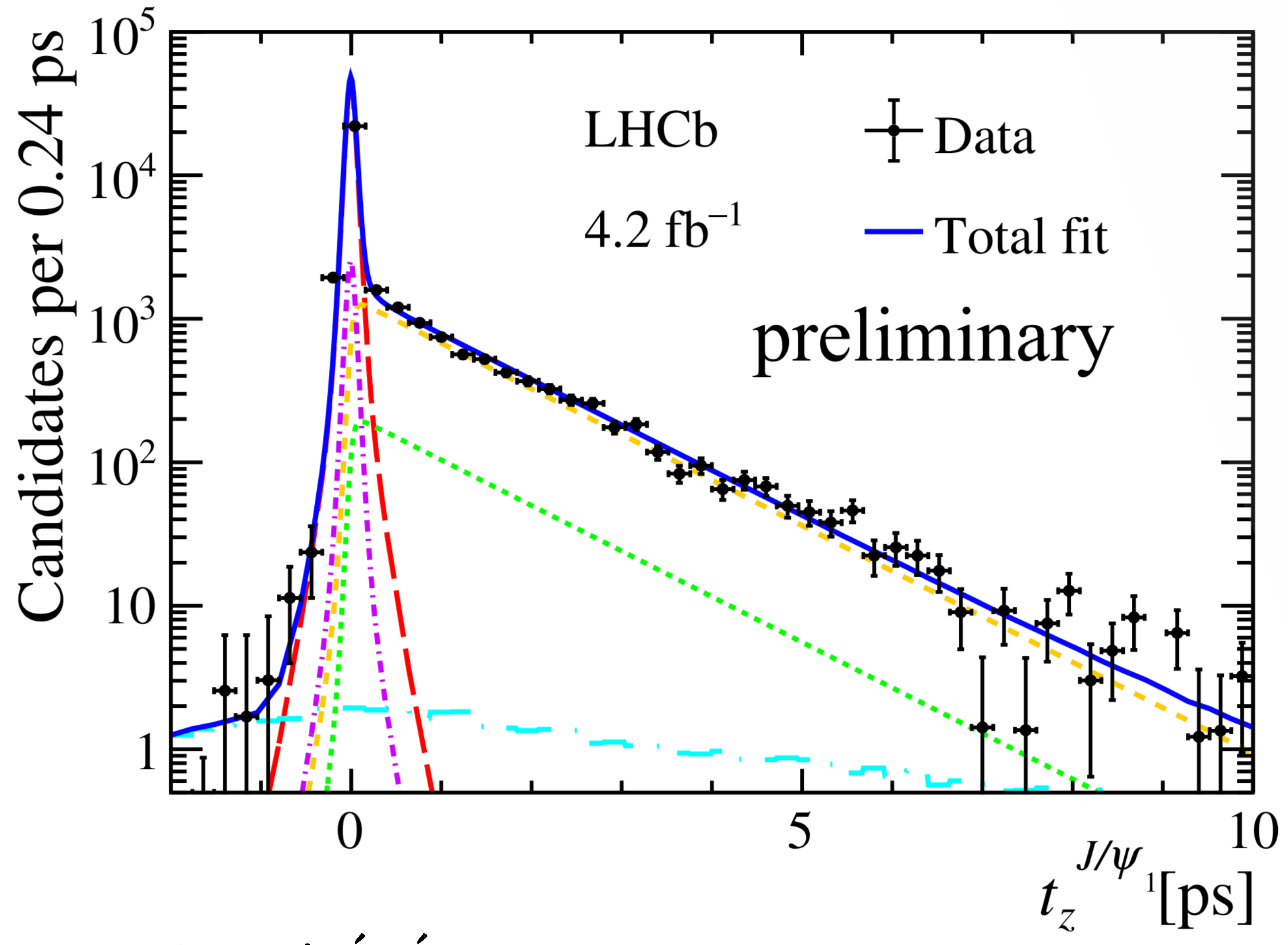


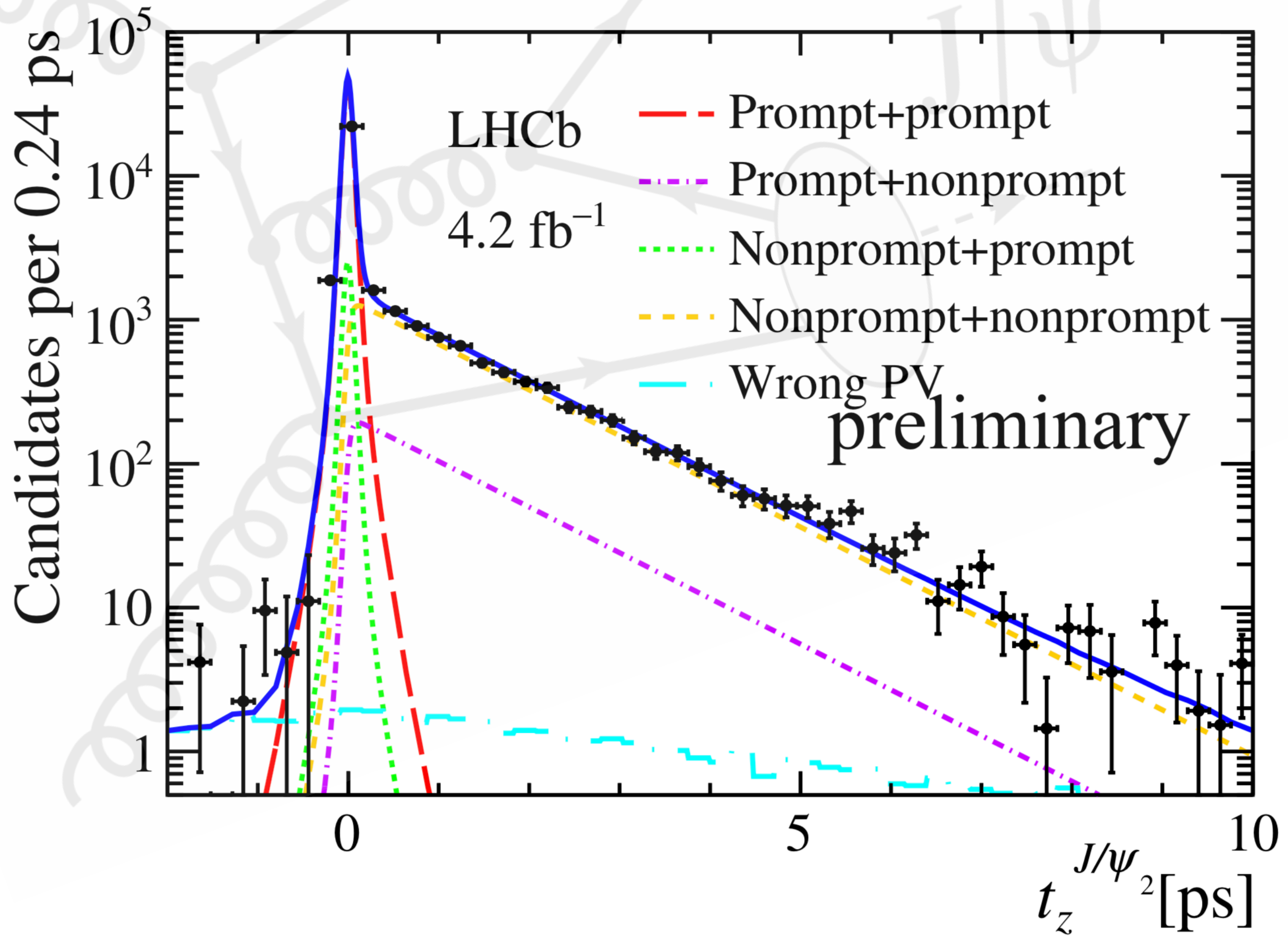
J/ψ pair production with **LHCb** LHCb-PAPER-2023-022

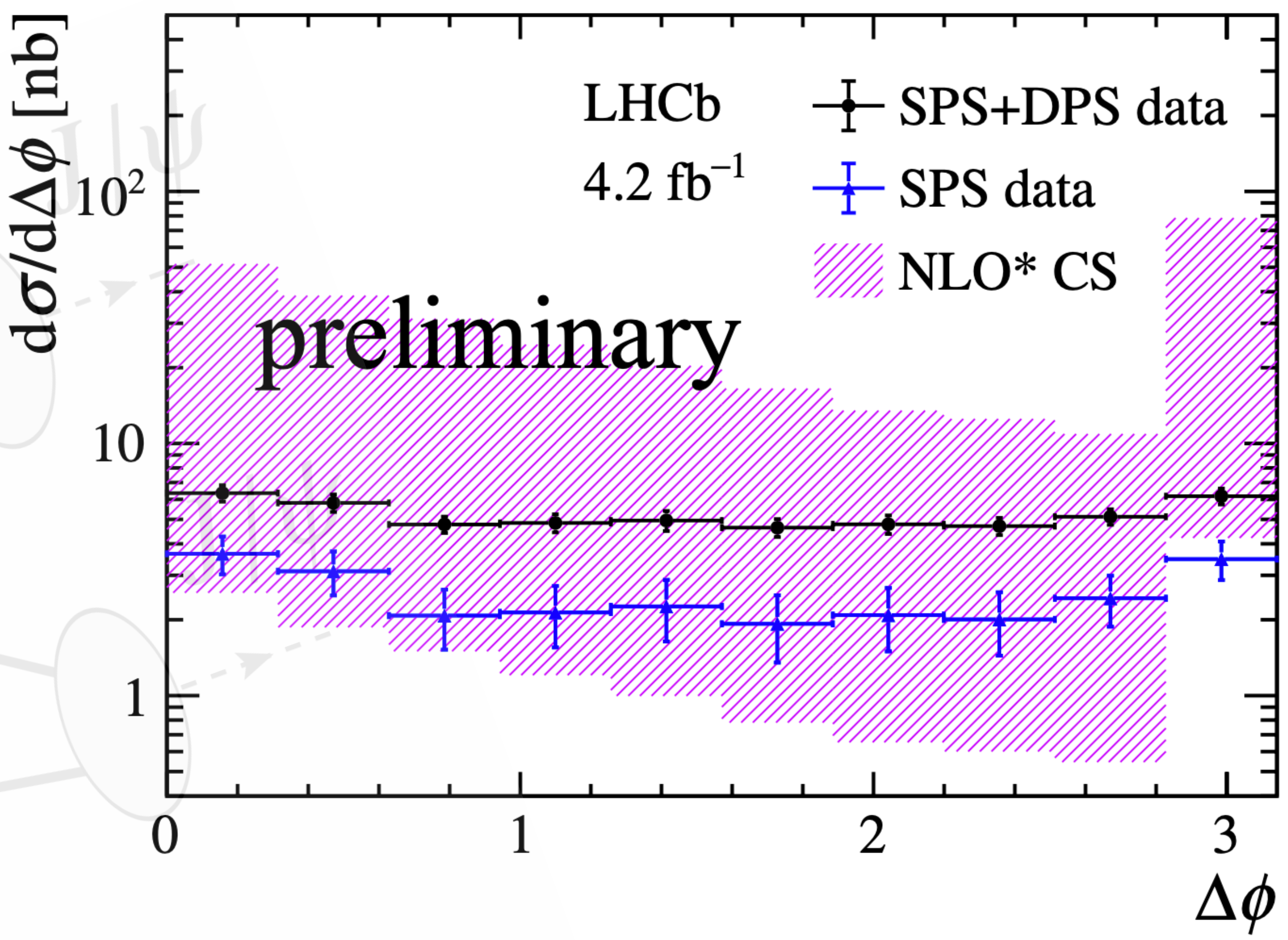
- $N\left(\mathrm{J}/\psi + \mathrm{J}/\psi\right) = (2.187 \pm 0.020) \times 10^4$
- $\sigma\left(\mathrm{J}/\psi + \mathrm{J}/\psi\right) = 16.36 \pm 0.28\,(\mathrm{stat}) \ \pm 0.88\,(\mathrm{syst})\,\mathrm{nb}$

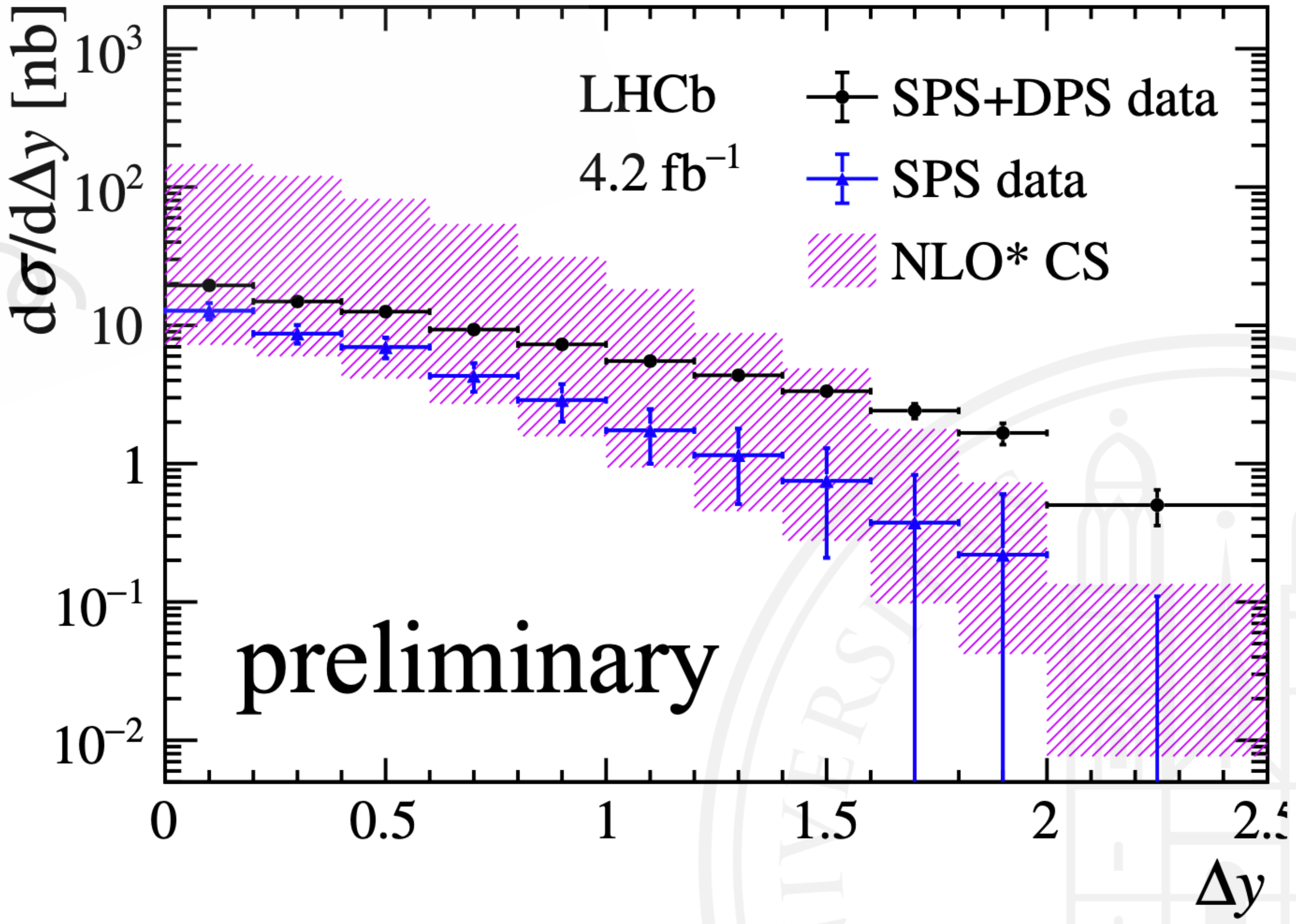








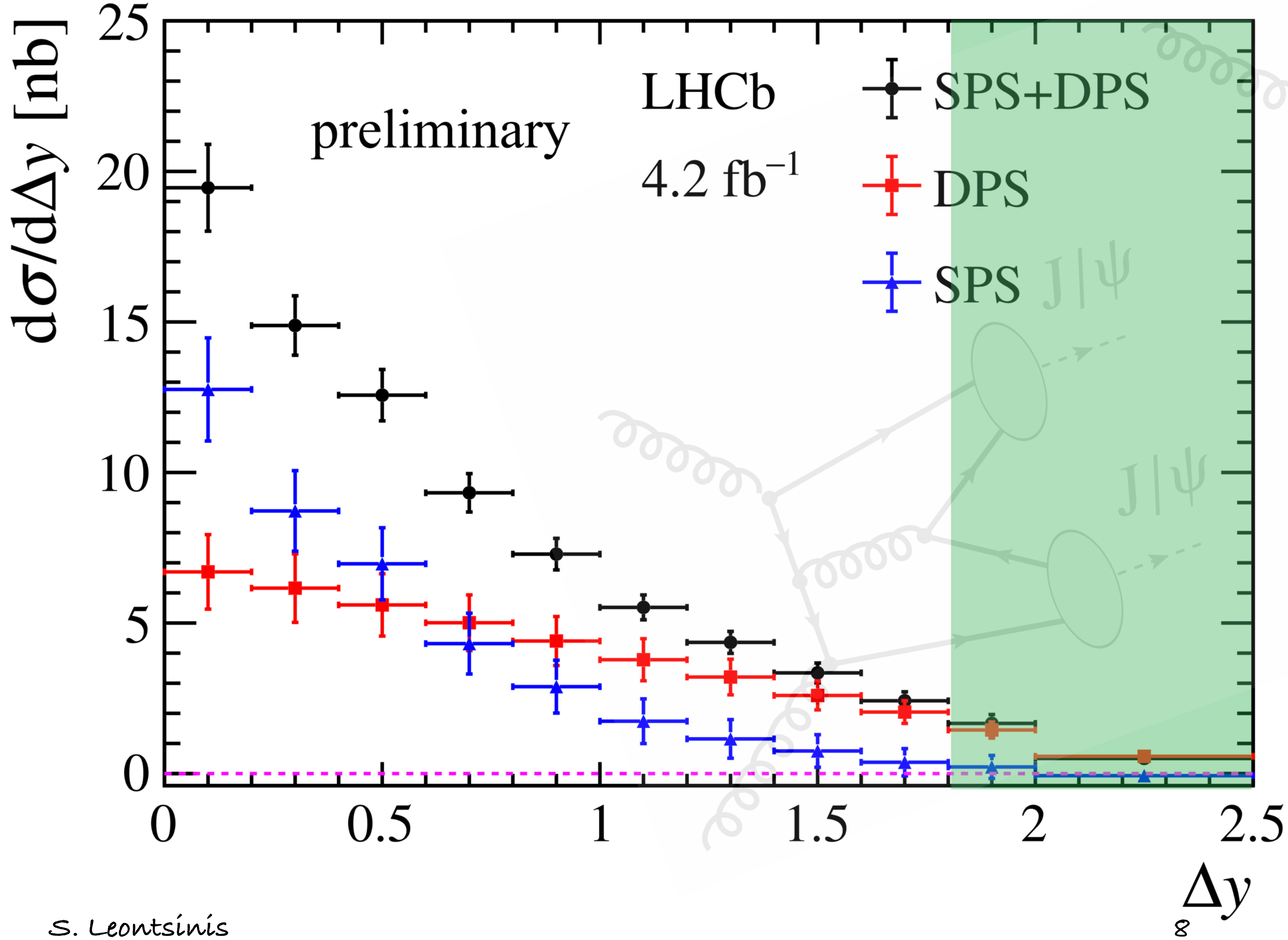




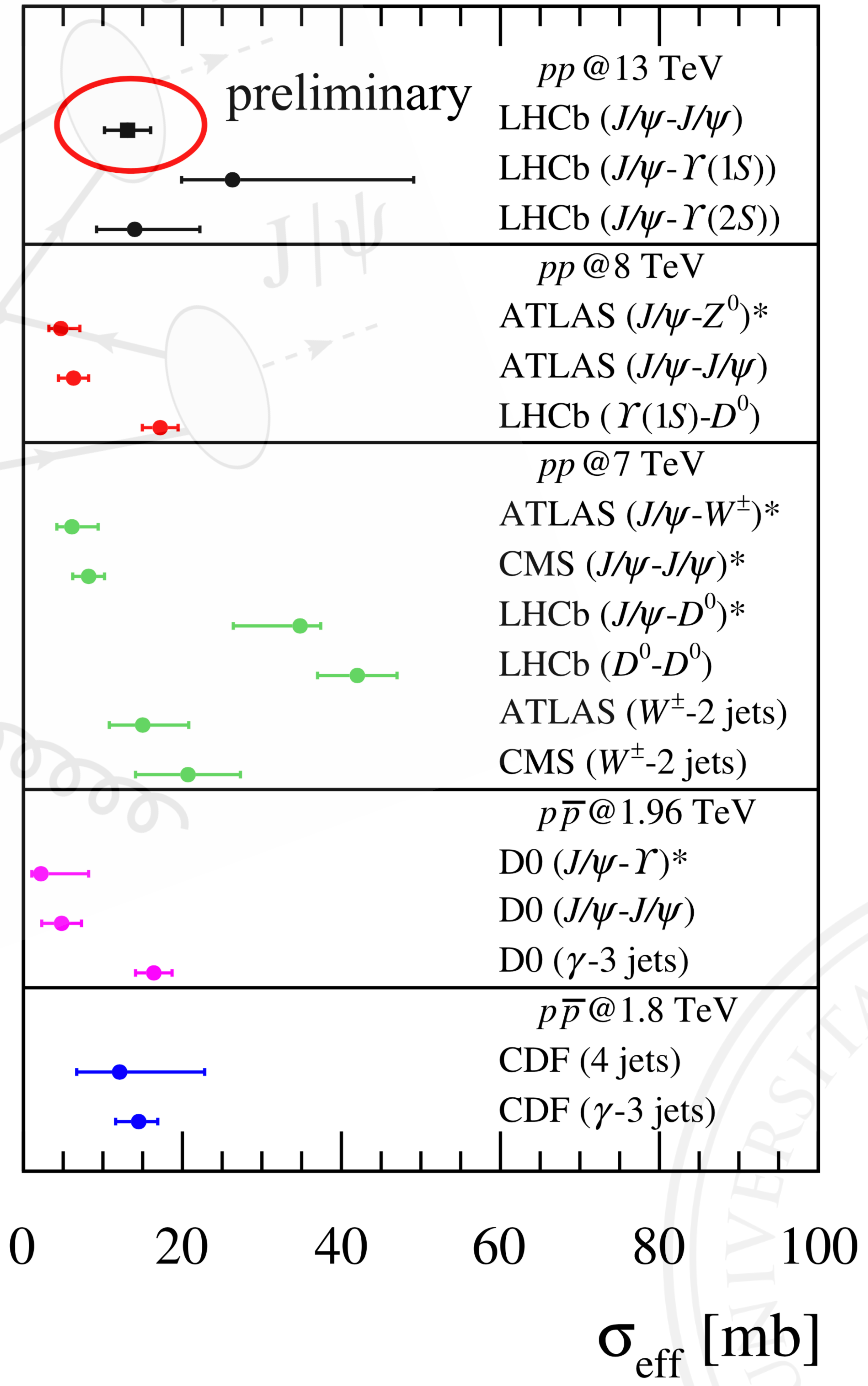
Recent Double Parton Scattering Measurements

J/ψ pair production with **LHCb** — LHCb-PAPER-2023-022

- $\sigma\left(J/\psi + J/\psi\right)_{DPS} = 8.6 \pm 1.2\,(\text{stat}) \pm 1.0\,(\text{syst})\,\text{nb}$
- $\sigma\left(J/\psi + J/\psi\right)_{SPS} = 7.9 \pm 1.2\,(\text{stat}) \pm 1.1\,(\text{syst})\,\text{nb}$



- $\sigma_{eff} = 13.1 \pm 1.8\,(\text{stat}) \pm 2.3\,(\text{syst})\,\text{mb}$

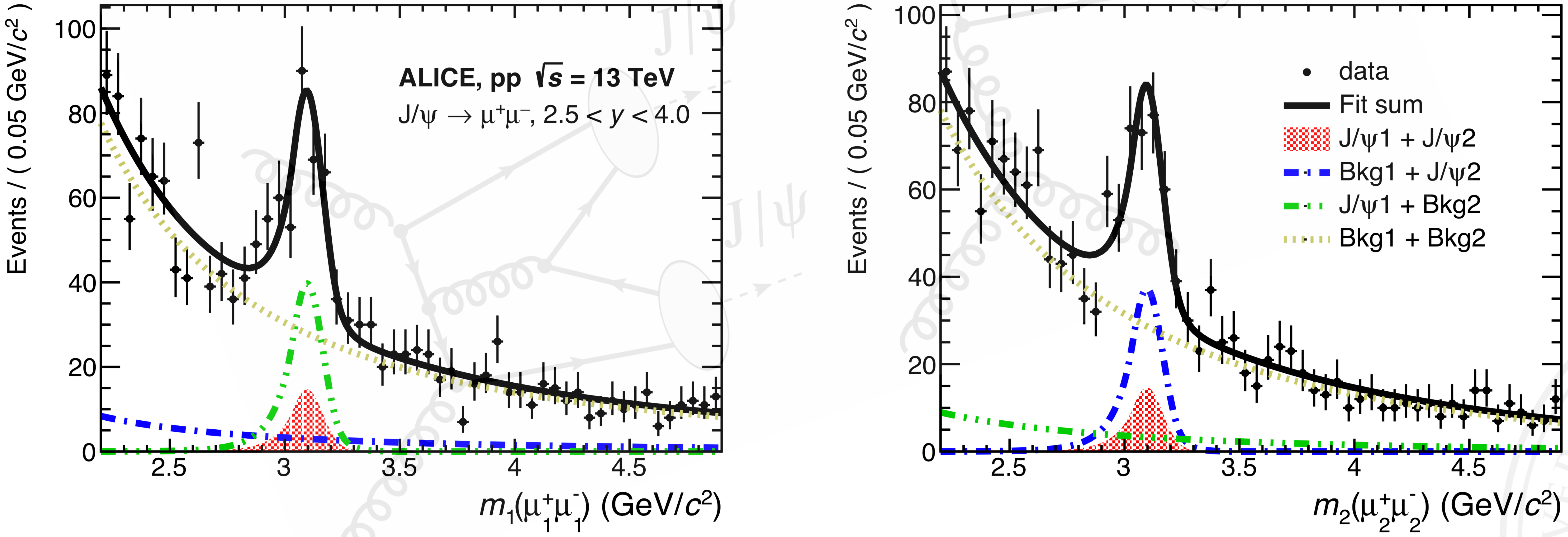


J/ψ pair production with **ALICE**

arXiv:2303.13431

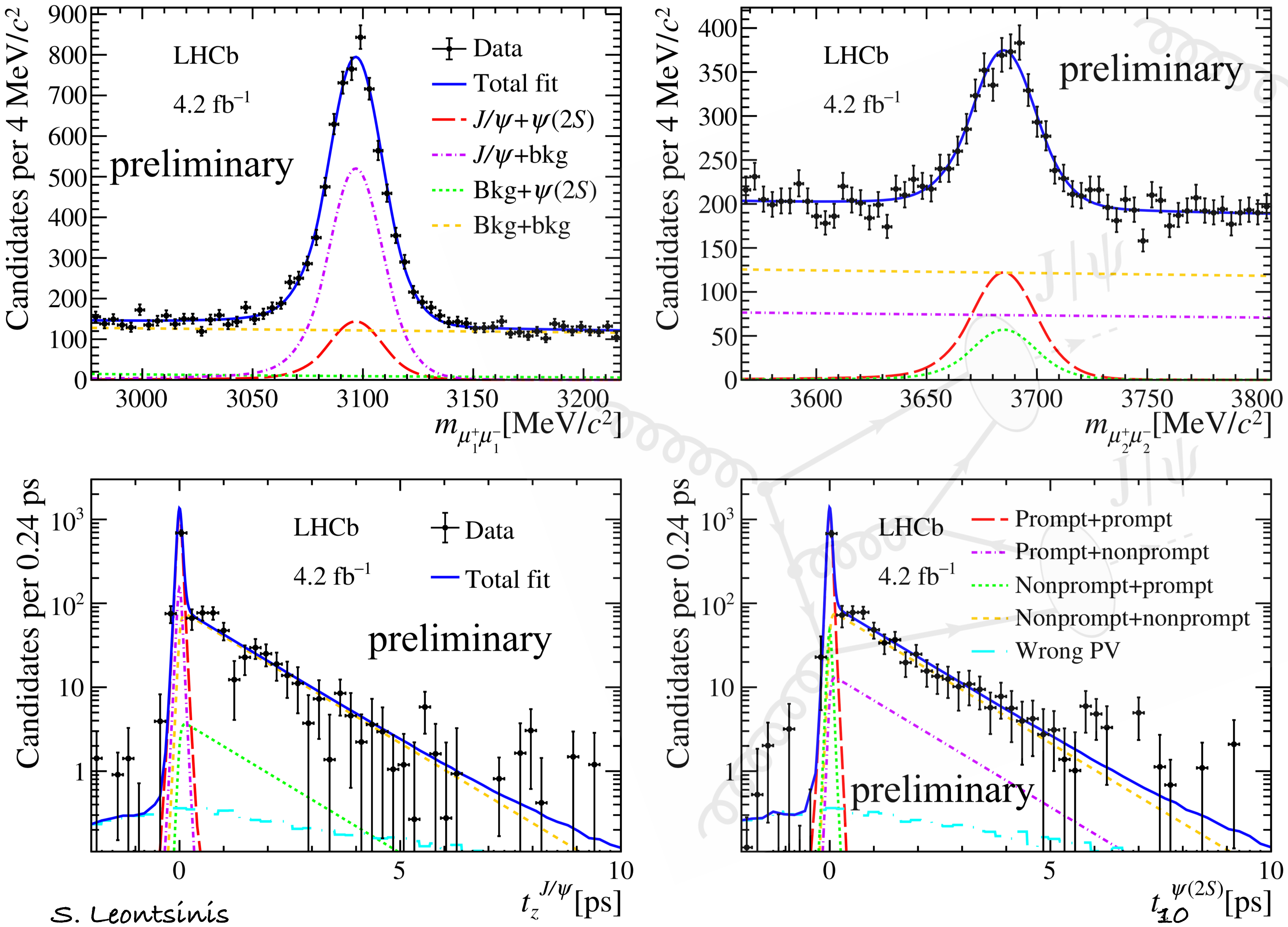
- $N\left(J/\psi + J/\psi\right) = 59.3 \pm 13.5\,(\text{stat}) \pm 4.4\,(\text{syst})$
- $\sigma\left(J/\psi + J/\psi\right) = 10.3 \pm 2.3\,(\text{stat}) \pm 1.3\,(\text{syst})\,\text{nb}$
- $\sigma_{\text{prompt}}\left(J/\psi + J/\psi\right) = 7.3 \pm 1.7\,(\text{stat})\,^{+1.9}_{-2.1}\,(\text{syst})\,\text{nb}$
- $\sigma_{\text{non-prompt}}\left(J/\psi + J/\psi\right) = 2.97 \pm 0.09\,(\text{stat})\,^{+0.68}_{-0.76}\,(\text{syst})\,\text{nb}$

Assuming all di-J/ψ events are DPS
DPS effective cross section from
prompt: $\sigma_{\text{eff}} = 6.7 \pm 1.4\,(\text{stat}) \pm 1.1\,(\text{syst})\,\text{mb}$
non-prompt: $\sigma_{\text{eff}} = 6.7 \pm 1.6\,(\text{stat}) \pm 2.7\,(\text{syst})\,\text{mb}$



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

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

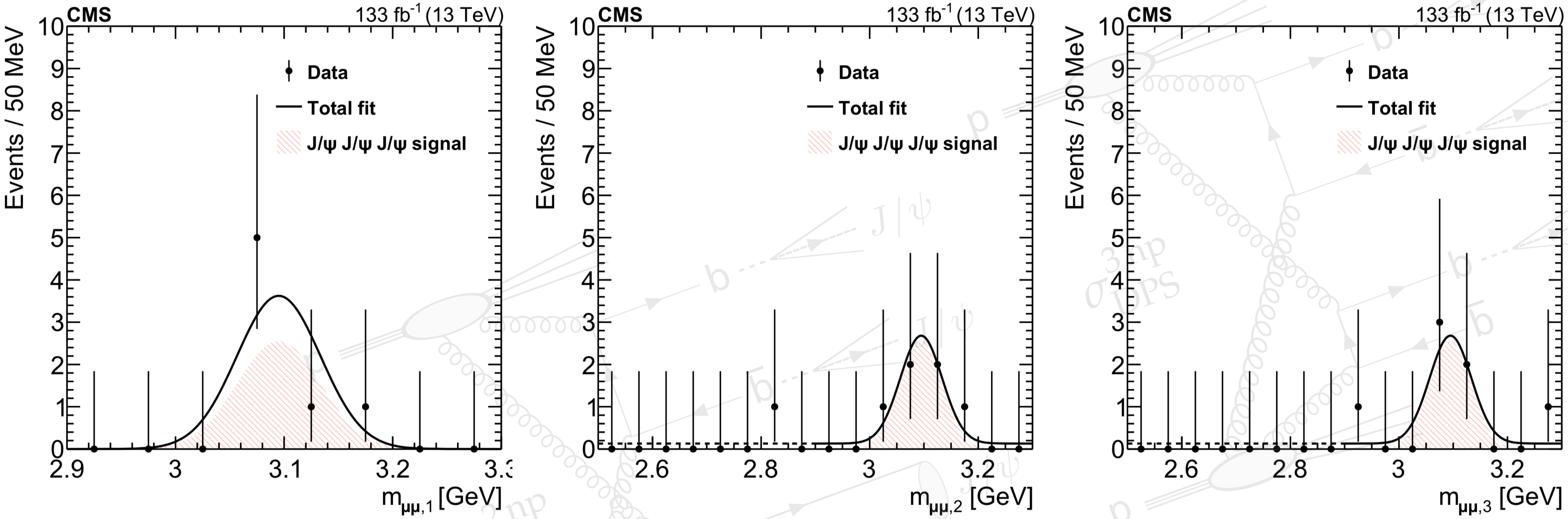


Lower limit on

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

Triple J/ψ meson production with **CMS** NP 19 (2023) 338

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



- Assuming that
  - generalised triple PDF can factorise into longitudinal & transverse components
  - longitudinal triple PDF is the product of 3 single PDFs (ignoring parton correlations in colour, momentum, etc)
- calculate the inverse of the cube of the transverse pp overlap reaching $\sigma_{\text{eff, TPS}} = (0.82 \pm 0.11) \times \sigma_{\text{eff, DPS}}$

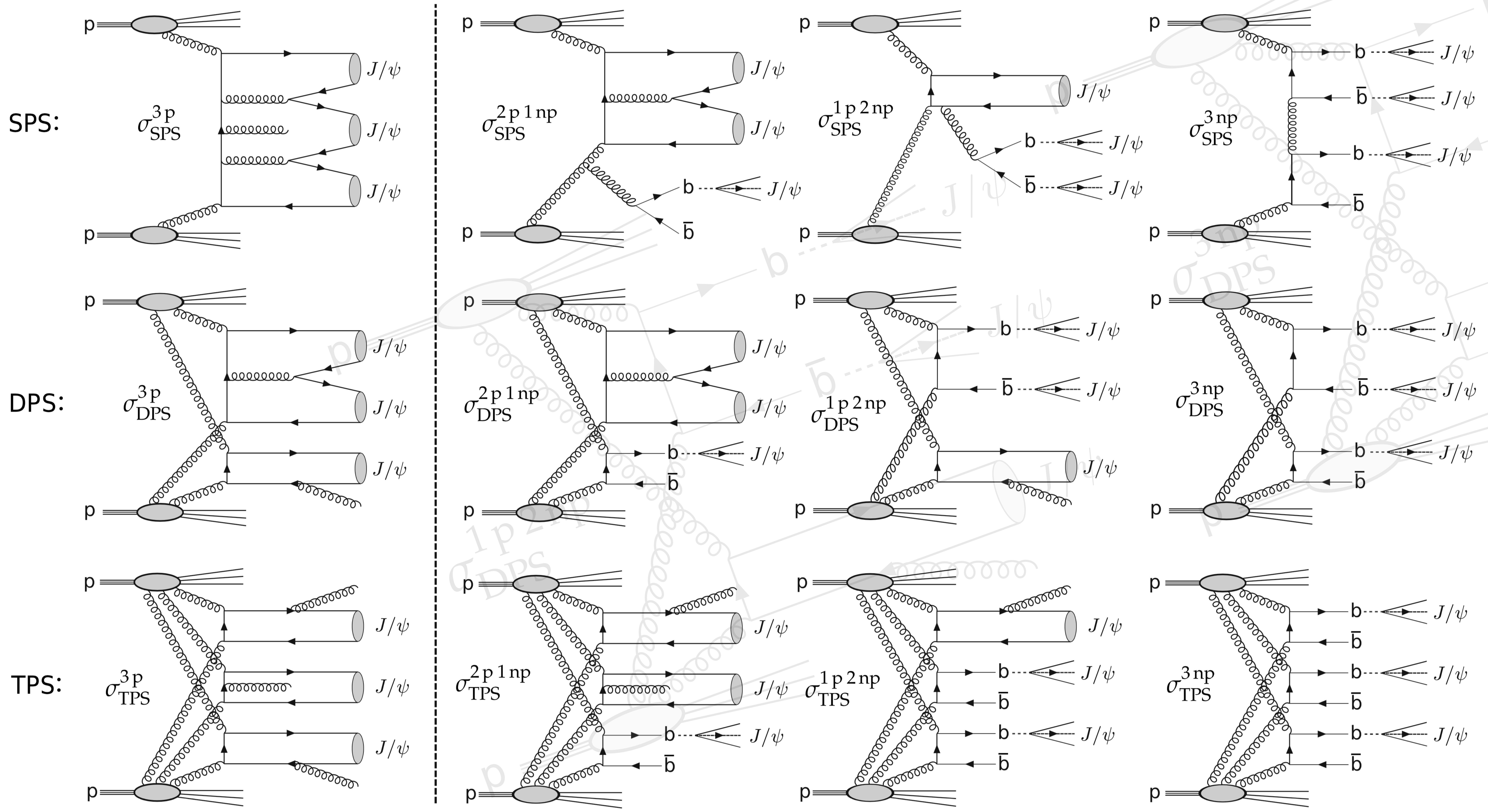
Recent Double Parton Scattering Measurements

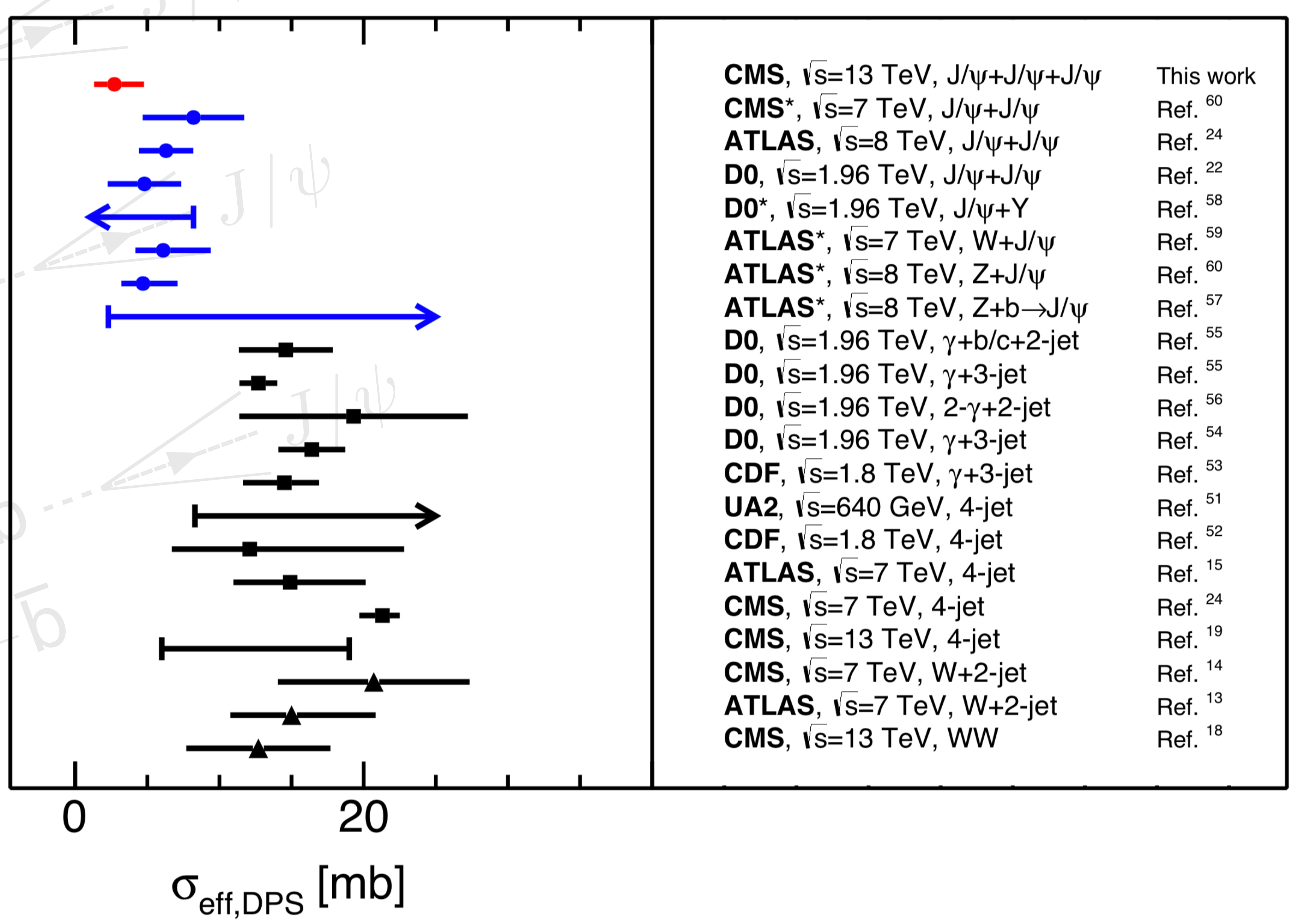
Triple J/ψ meson production with **CMS** <u>NP 19 (2023) 338</u>

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

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

Pure prompt production: Nonprompt contributions:





Remarks

- Status in 2019

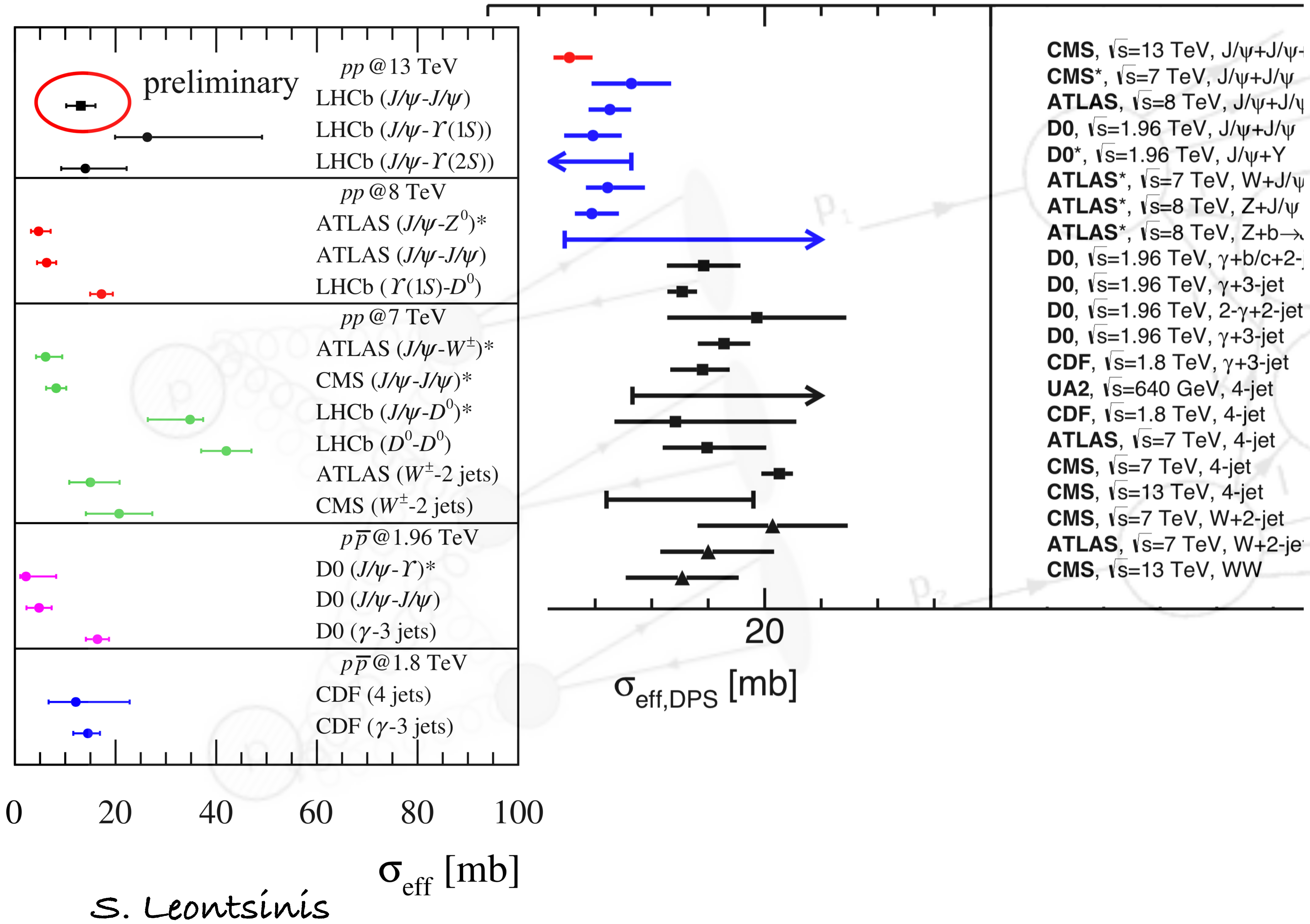
Observables	Experiments	CSM	CEM	NRQCD	Interest
$J/\psi + J/\psi$	LHCb, CMS, ATLAS, D0, NA3	NLO, NNLO*	NLO	LO	Test of the CSM; DPS; Gluon TMDs;
$J/\psi + \psi(2S)$ or $J/\psi + \chi_c$	–	LO	NLO	LO	DPS vs SPS;
$J/\psi + \Upsilon$	D0	LO	NLO	LO	Test of the CSM; DPS;
$\Upsilon + \Upsilon$	CMS	NLO (?)	NLO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

Recent Double Parton Scattering Measurements

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
- 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

end