Measurements of particle production, soft-QCD and double parton scattering at LHCb

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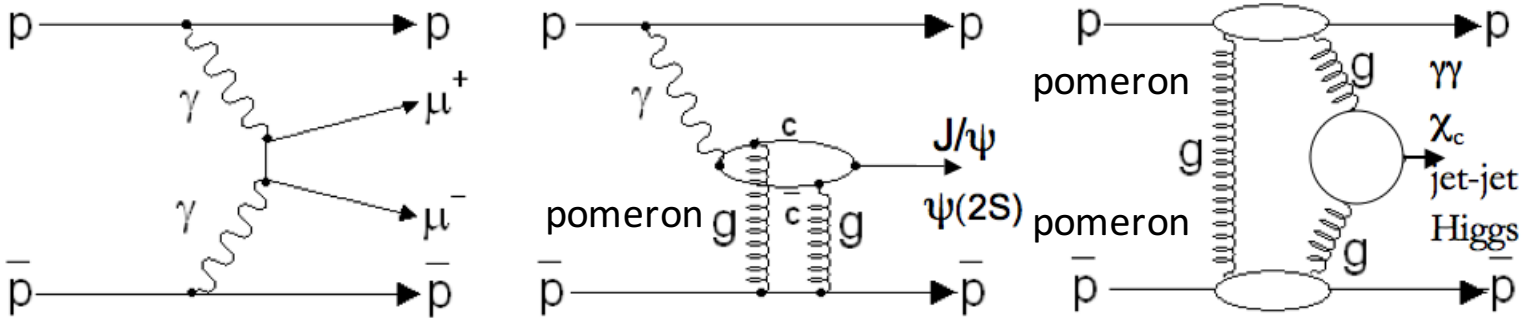
Soft QCD

- Soft QCD is of high importance at LHC
  - ✓High energy pp collisions dominated by soft partonic collisions
  - ✓Soft interactions usually present in the remains of hard scattering events
  - ✓Can't be calculated perturbatively; need to rely on phenomenological models

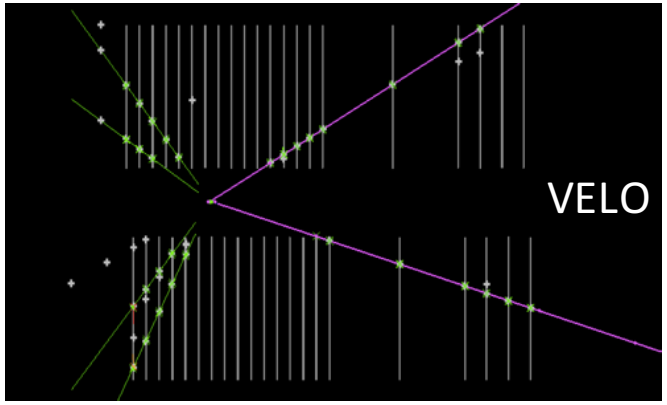
- A wide range of topics, e.g.
  - ✓Minimum bias
    - Measurement of charged particle multiplicities and densities in pp collisions at $\sqrt{s} = 7$ TeV in the forward region [EPJC (2014) 74:2888]
  - ✓Underlying event
    - Measurement of the forward energy flow in pp collisions at $\sqrt{s} = 7$ TeV [EPJC (2013) 73:2421]
  - ✓Inelastic cross-section
    - Measurement of the inelastic pp cross-section at a centre-of-mass energy of $\sqrt{s} = 7$ TeV [JHEP 1502 (2015) 129]
  - ✓Central exclusive production (CEP)
    - Measurements of exclusive J/ψ and $\psi(2S)$ production cross-sections in pp collisions at $\sqrt{s} = 7$ TeV [JPG: NPP 41 (2014) 055002]
    - Observation of charmonium pairs produced exclusively in pp collisions [JPG: NPP 41 (2014) 115002]
    - Central exclusive production of J/ψ and $\psi(2S)$ mesons in pp collisions at $\sqrt{s} = 13$ TeV (Inclusive production presented yesterday by *Patrick Spradlin*) [CERN-LHCb-CONF-2016-007]

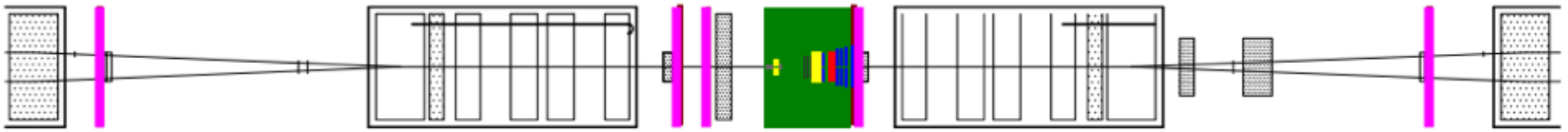
CEP at LHCb

- $p + p \to p + X + p$: X well isolated in rapidity



- LHCb detector: a single-arm forward region spectrometer covering $2 < \eta < 5$
  - ✓Rapidity range complementary to other experiments
  - ✓Dedicated CEP trigger lines
  - ✓Low pile-up environment
  - ✓VELO has backward coverage $-3.5 < \eta < -1.5$
  - ✓ **HERSCHEL**: new high rapidity shower counters in RunII; can largely reduce non-CEP backgrounds!

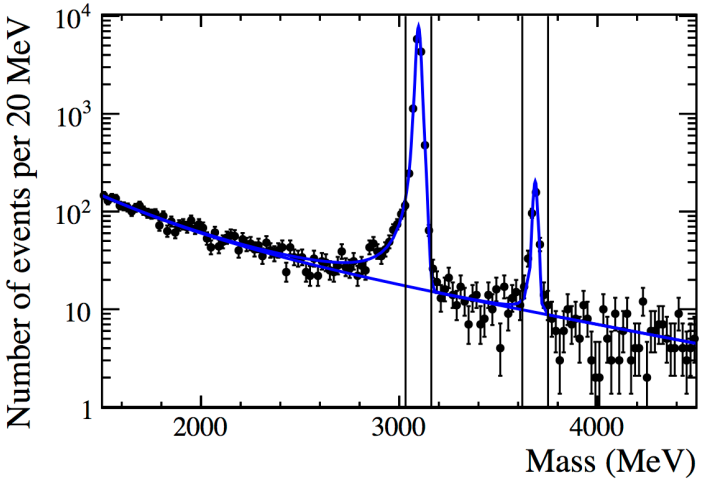




Exclusive J/ψ and $\psi(2S)$ @ 13 TeV

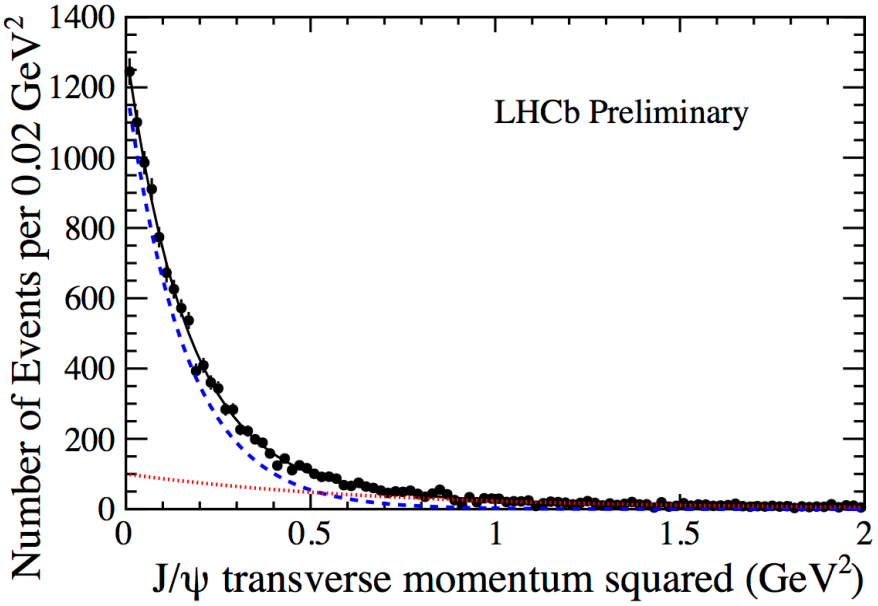
- Using 204 pb^{-1} data at $\sqrt{s} = 13$ TeV
- Events with
  1) additional VELO tracks **or**
  2) neutral energy > 200 MeV **or**
  3) significant deposits in HERSCHEL

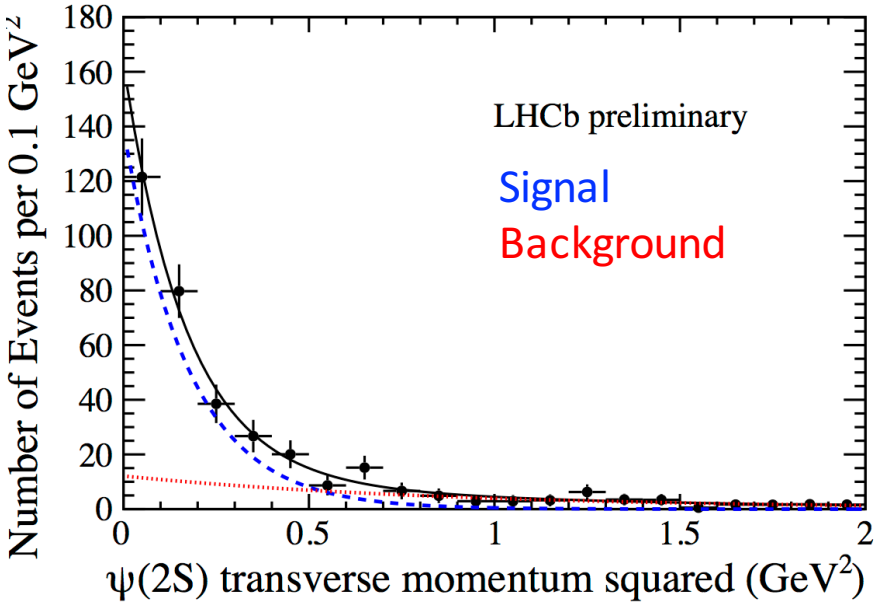
  are removed



- With HERSCHEL, roughly halves the background events!

[CERN-LHCb-CONF-2016-007]





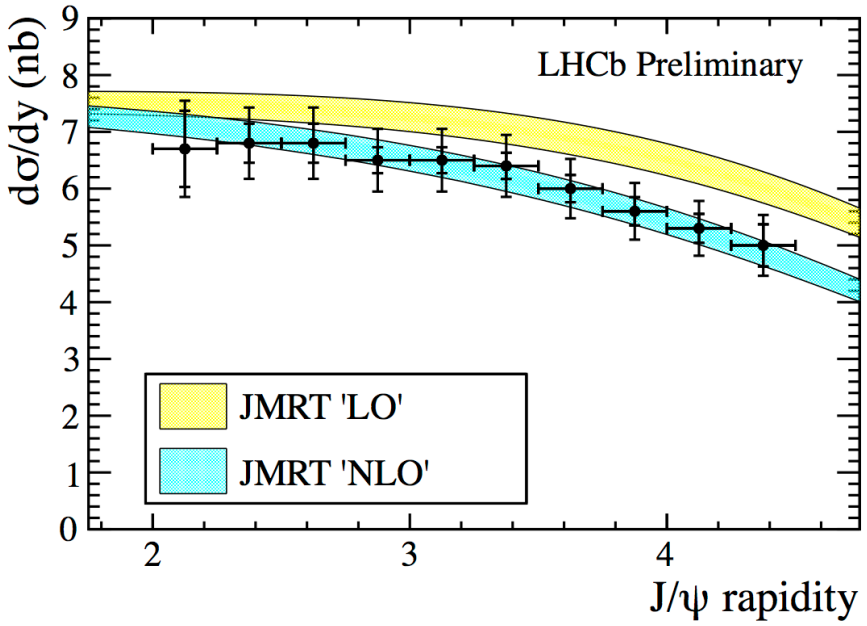
Cross-sections

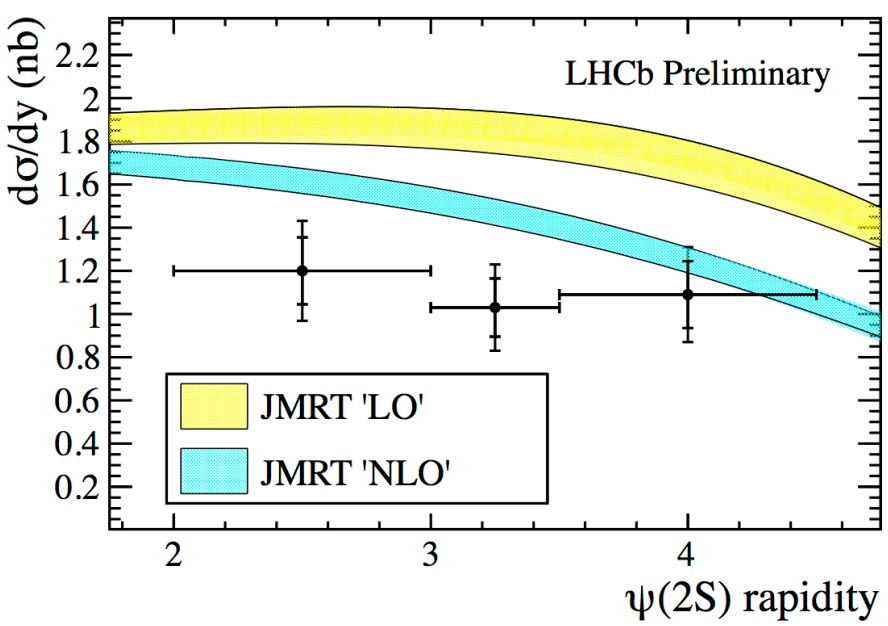
- Total cross-sections

$$\sigma_{J/\psi\to\mu^+\mu^-}\left(2.0<\eta_{\mu^+},\eta_{\mu^-}<4.5\right)=407\pm8(\text{stat})\pm24(\text{syst})\pm16(\text{lumi})\ \text{pb}$$

$$\sigma_{\psi(2S)\to\mu^+\mu^-}\left(2.0<\eta_{\mu^+},\eta_{\mu^-}<4.5\right)=9.4\pm0.9(\text{stat})\pm0.6(\text{syst})\pm0.4(\text{lumi})\ \text{pb}$$

- Differential cross-sections with respect to rapidity
  - ✓Better agreement with JMRT NLO predictions





[CERN-LHCb-CONF-2016-007]

Photo-production cross-section

➢Relation with the photo-production cross-section $\sigma_{\gamma p\to\psi p}$

$$\sigma_{pp\to pXp} = r(W_+)k_+\frac{dn}{dk_+}\sigma_{\gamma p\to\psi p}(W^+) + r(W_-)k_-\frac{dn}{dk_-}\sigma_{\gamma p\to\psi p}(W^-)$$

✓$r(W_\pm)$: gap survival factor; taken from previous studies

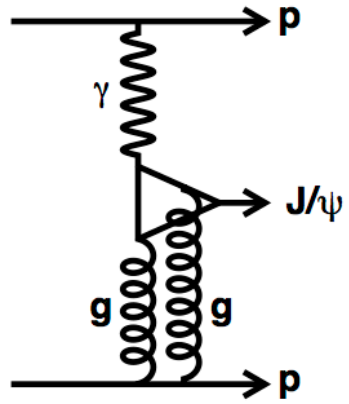
✓$k_\pm$: photon energy, $= m_\psi/2\times e^{\pm|y|}$

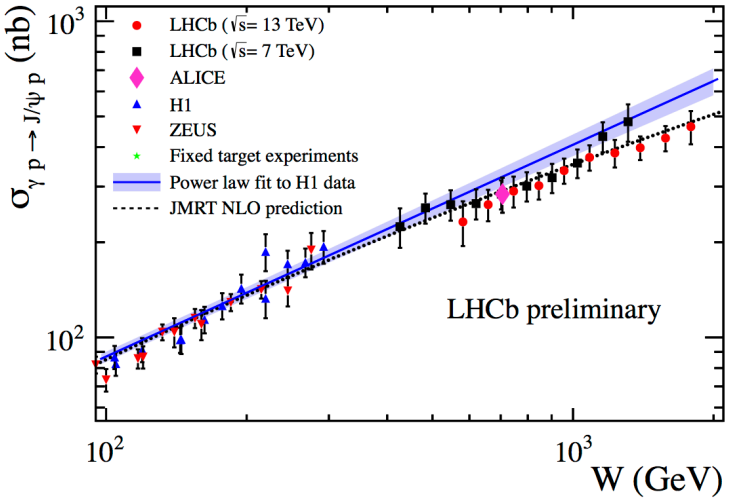
✓$\frac{dn}{dk_\pm}$: photon flux; taken from previous studies

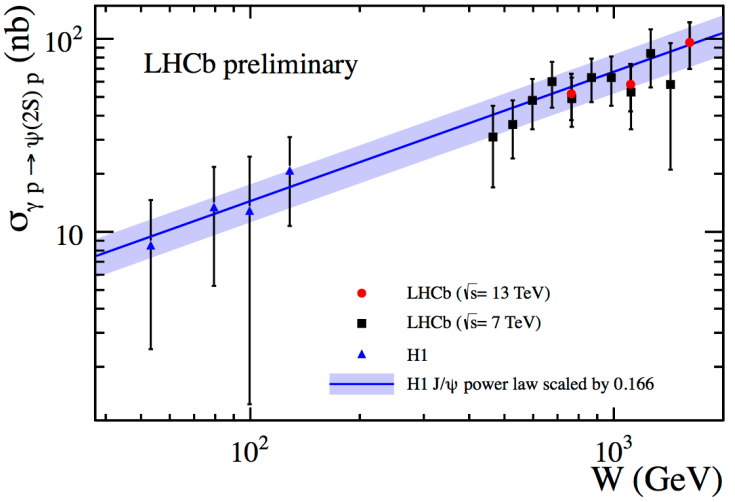
✓$W_\pm$: center-of-mass energy of the photon-proton system;

$$W_\pm = \sqrt{m_\psi \times e^{\pm|y|}\times\sqrt{s}}$$

can explore $W = 2$ TeV with $\sqrt{s} = 13$ TeV data; the highest energy so far!



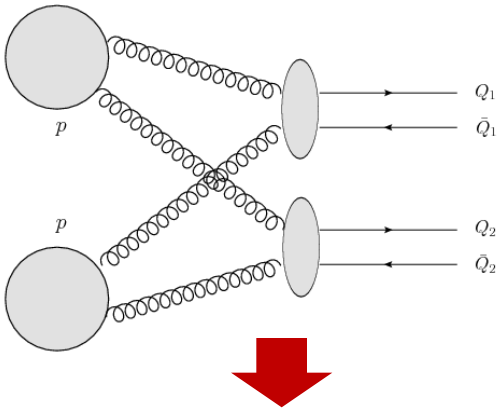




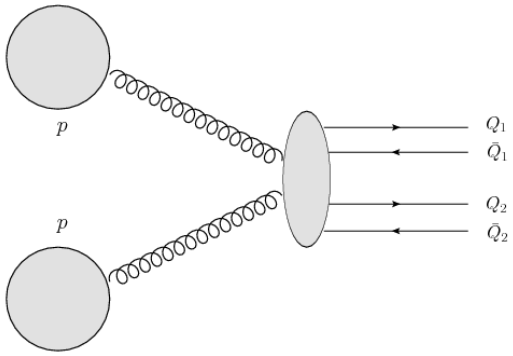
[CERN-LHCb-CONF-2016-007]

Double parton scattering

Double-parton scattering (DPS)



Single-parton scattering (SPS)



- ✓ Provide information on parton transverse profile & correlations in proton
- ✓ Help understand background in searches for new physics ($Z + b\bar{b}$, W^+W^+ etc.)

- ➢ Assumption 1: factorization of transverse & longitudinal components of partons
- ➢ Assumption 2: no correlation between two partons

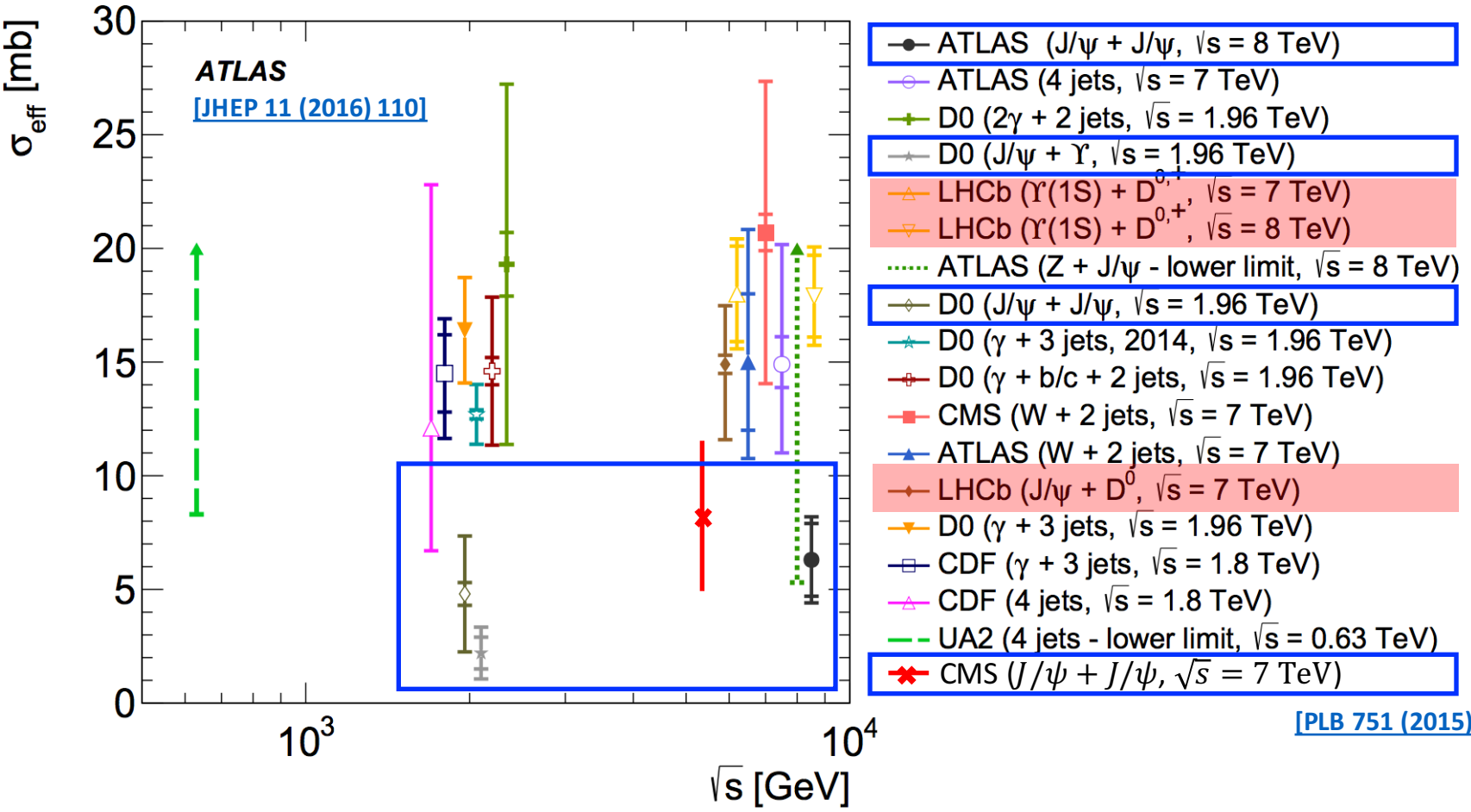
⇒ Pocket formula

$$\sigma_{Q_1Q_2} = \frac{1}{1+\delta_{Q_1Q_2}} \frac{\sigma_{Q_1}\sigma_{Q_2}}{\sigma_{\text{eff}}}$$

- ✓ Under the naive assumptions, σ_{eff} is thought to be universal, i.e. independent of process and energy

Effective cross-section summary

- General purpose of DPS measurements: measure σ_{eff}
  - ✓ validate its universality or probe the dependence on process and energy



[PLB 751 (2015) 479]

J/ψ pair @ 13 TeV

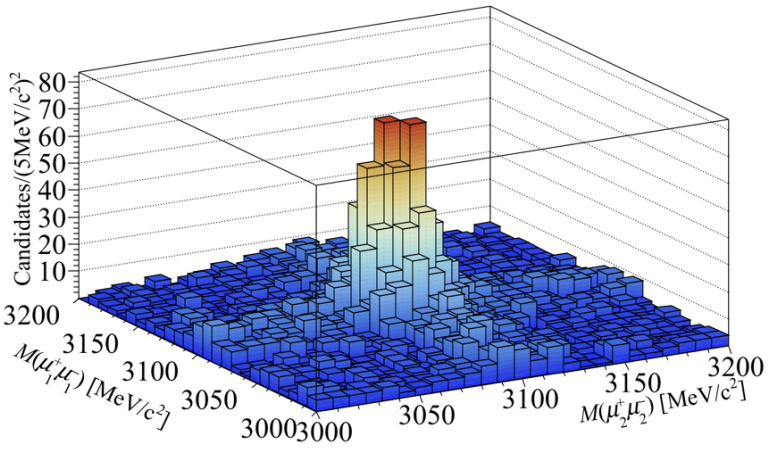
- Data sample: pp collision data at $\sqrt{s} = 13$ TeV corresponding to 279 pb^{-1}
- Fiducial region: both J/ψ mesons $p_{\text{T}} < 10\ \text{GeV}/c$, $2.0 < y < 4.5$

- The master relation

$$\sigma = \frac{N^{cor}}{L_{\text{int}} \times \mathcal{B}^2(J/\psi \to \mu^+\mu^-)}$$

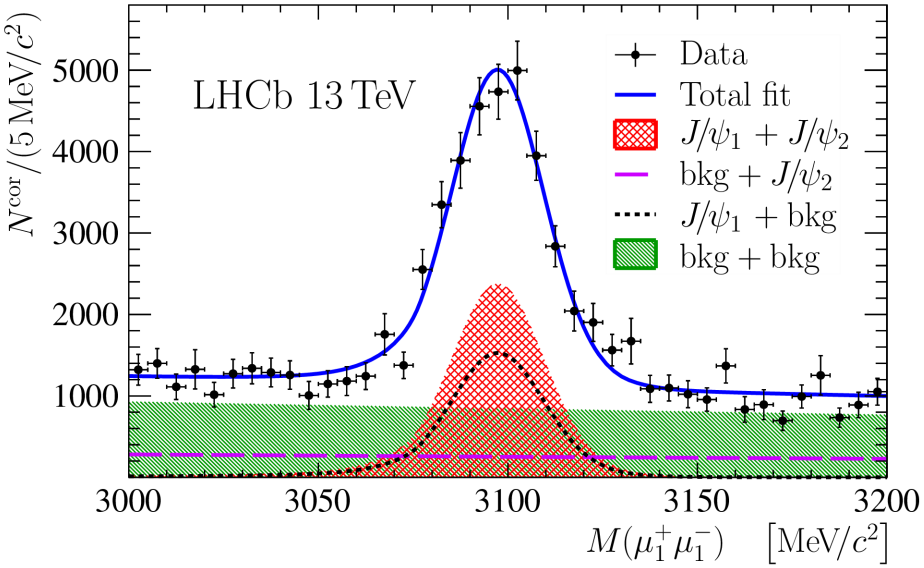
  - ✓ N^{cor}: signal yield after per-event efficiency correction
  - ✓ Efficiencies estimated using data & simulation

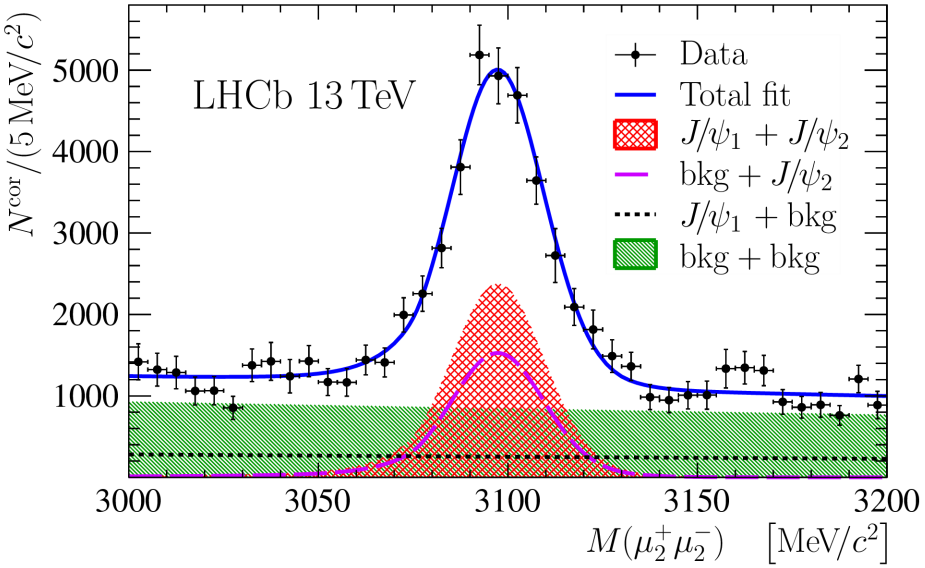
- Trigger targeted at selecting high quality muons
- Simple cuts applied
  - ✓ Identified muons with good track quality;
    $p_{\text{T}} > 0.65\ \text{GeV}/c$; $6 < p < 200\ \text{GeV}/c$;
    $2 < \eta < 5$;
    good quality dimuon vertex
  - ✓ Four muons to come from the same PV
  - ✓ Duplicate tracks and multiple candidates removed



Cross-section

- Signal yield obtained from simultaneous fit to the efficiency-corrected 2D $\left(M(\mu_1^+\mu_1^-), M(\mu_2^+\mu_2^-)\right)$ distribution





[arXiv: 1612.07451]

- Residual from-b component subtracted afterwards
  - ✓ The contribution determined using simulation together with $\sigma(pp \to b\bar{b})$ and $\sigma(\text{prompt}\, J/\psi)$ from J/ψ production measurement [JHEP 10 (2015) 172]

- Result:

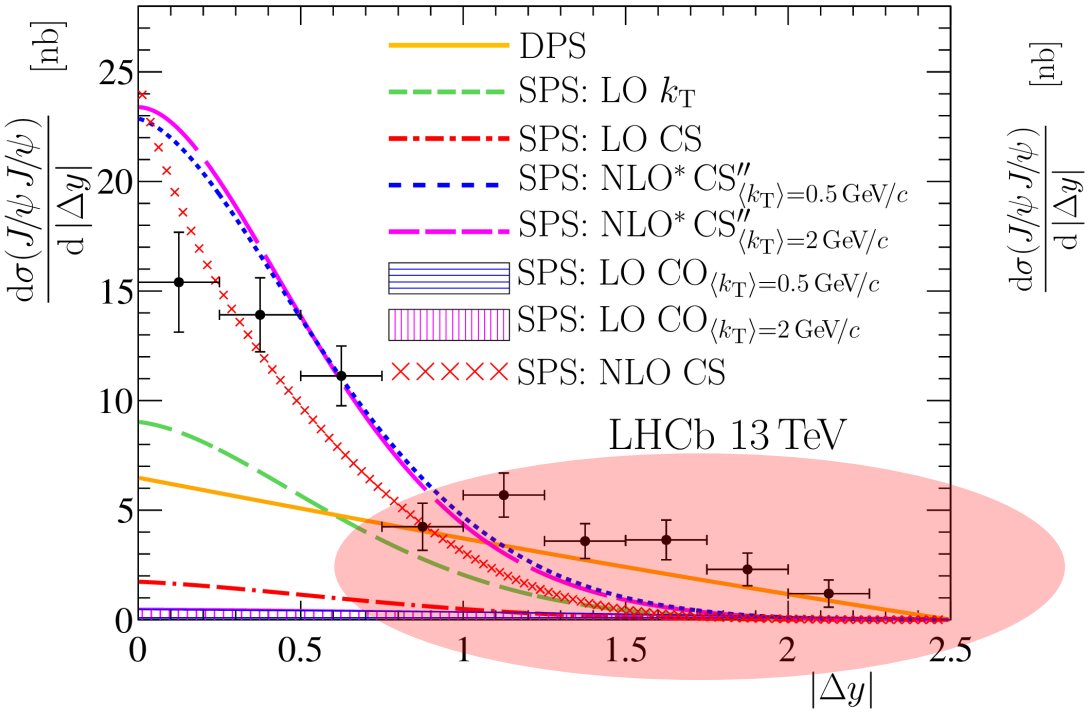
$$\sigma(J/\psi J/\psi) = 15.2 \pm 1.0(\text{stat}) \pm 0.9(\text{syst})\ \text{nb}$$

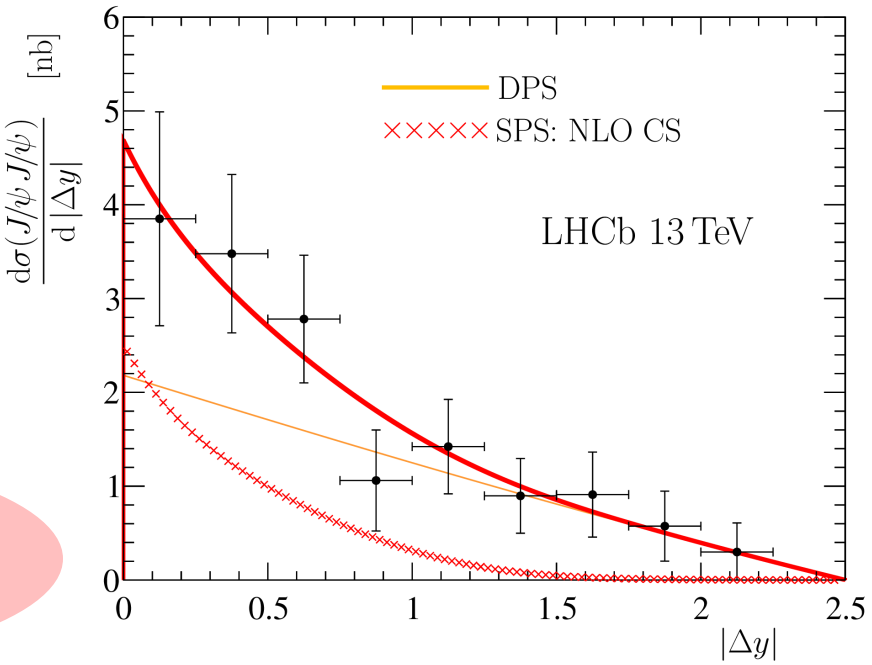
Comparison to theory

- Differential cross-sections of different variables compared to theory predictions
  - ✓ Most significant indication of DPS comes from $|\Delta y|$
  - ✓ DPS contribution essential for the region $|\Delta y| > 1.5$

- Template DPS+SPS fits performed for different variables using various models

$$\frac{\mathrm{d}\sigma}{\mathrm{d}v} = \sigma_{\mathrm{DPS}} F_{\mathrm{DPS}}(v) + \sigma_{\mathrm{SPS}} F_{\mathrm{SPS}}(v)$$





[arXiv: 1612.07451]

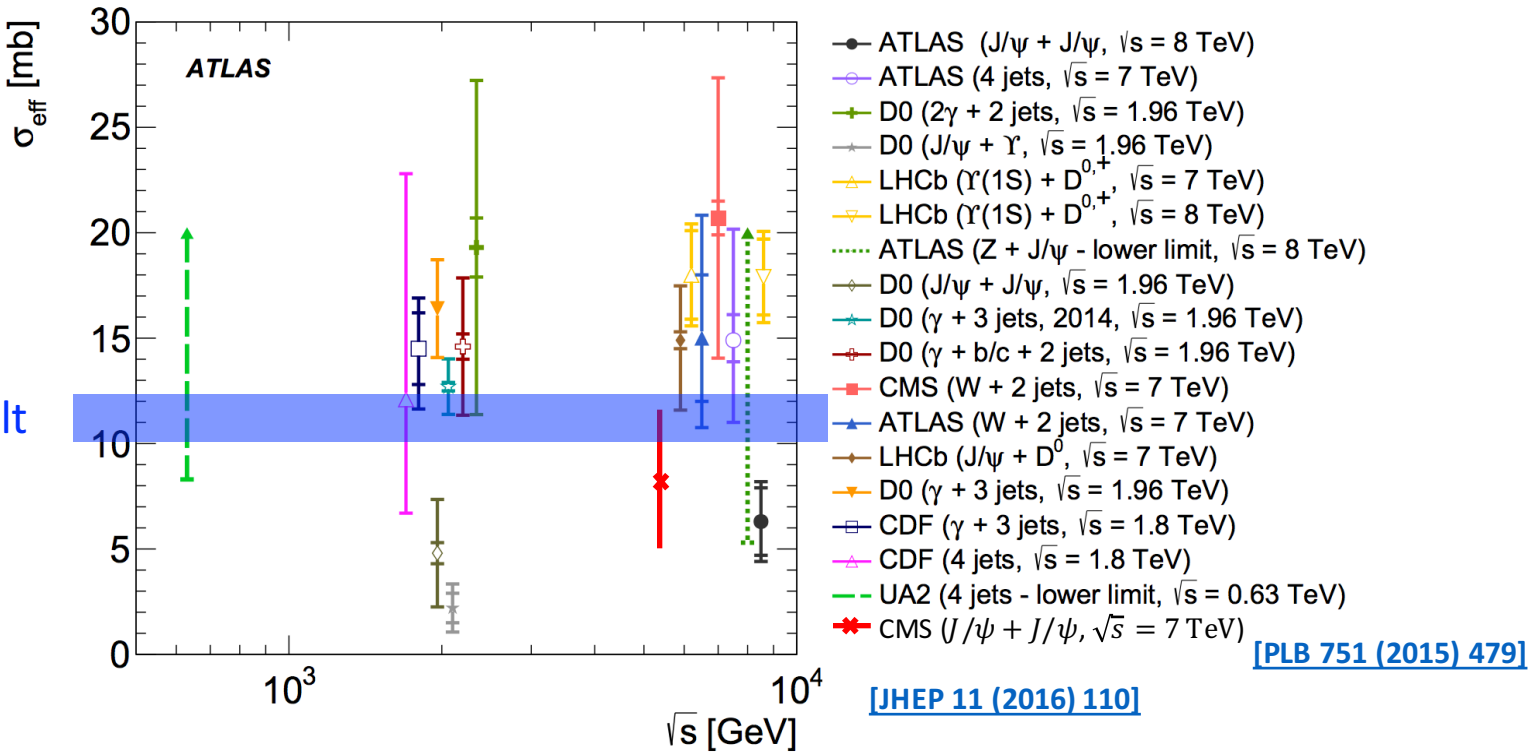
Effective cross-section

- Determined using $\sigma_{\text{eff}} = \frac{1}{2}\frac{\sigma(J/\psi)^2}{\sigma_{\text{DPS}}}$; lying between 10.0~12.5 mb

Variable	LO k_T	NLO* CS″ $\langle k_T \rangle = 2\,\text{GeV}/c$	NLO* CS″ $\langle k_T \rangle = 0.5\,\text{GeV}/c$	NLO CS
$p_T(J/\psi\,J/\psi)$	11.3 ± 0.6	10.1 ± 6.5	10.9 ± 1.2	—
$y(J/\psi\,J/\psi)$	—	11.9 ± 7.5	10.0 ± 5.0	—
$m(J/\psi\,J/\psi)$	10.6 ± 1.1	10.2 ± 1.0		10.4 ± 1.0
$\lvert\Delta y\rvert$	12.5 ± 4.1	12.2 ± 3.7	12.4 ± 3.9	11.2 ± 2.9

[arXiv: 1612.07451]

Our result



[PLB 751 (2015) 479]

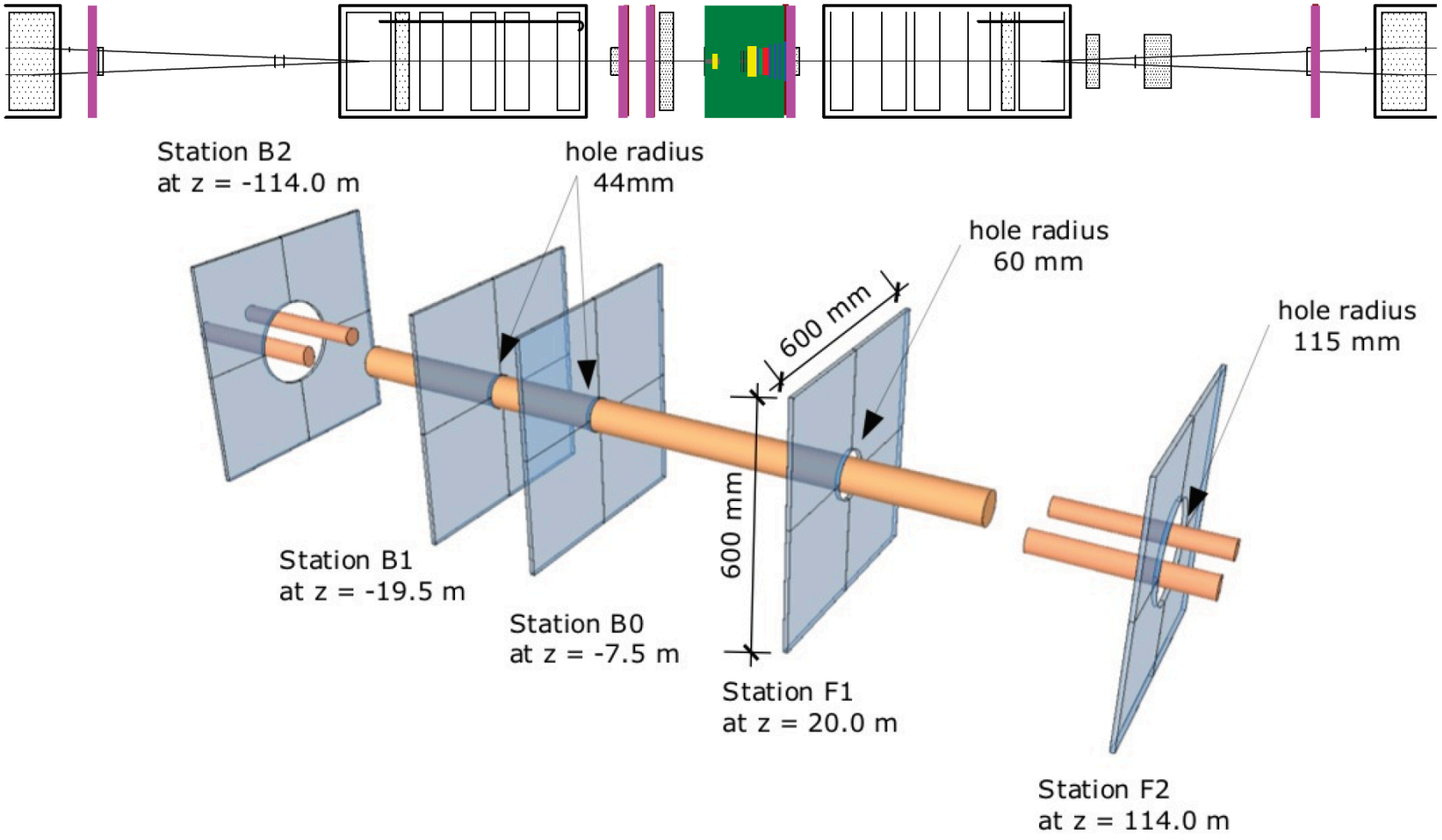
[JHEP 11 (2016) 110]

Summary and prospect

- Soft QCD actively studied at LHCb
  - ✓Central exclusive J/ψ and $\psi(2S)$ production at $\sqrt{s} = 13$ TeV measured
    - Good agreement with JMRT NLO predictions
- DPS processes explored at LHCb
  - ✓J/ψ pair production at $\sqrt{s} = 13$ TeV measured
    - Differential cross-sections show evidence for DPS contribution
    - σ_{eff} determined using SPS+DPS template fits
- Prospects
  - ✓Inelastic pp cross-section at 5 and 13 TeV & forward energy flow at 13 TeV to be expected soon!
  - ✓More CEP processes to be measured using RunII data
  - ✓Measure the $J/\psi/\Upsilon$ + open charm processes with RunII data
  - ✓New DPS channels to search for: $\Upsilon + J/\psi$, $2\times\Upsilon$ etc.
  - ✓Triple-parton scattering?

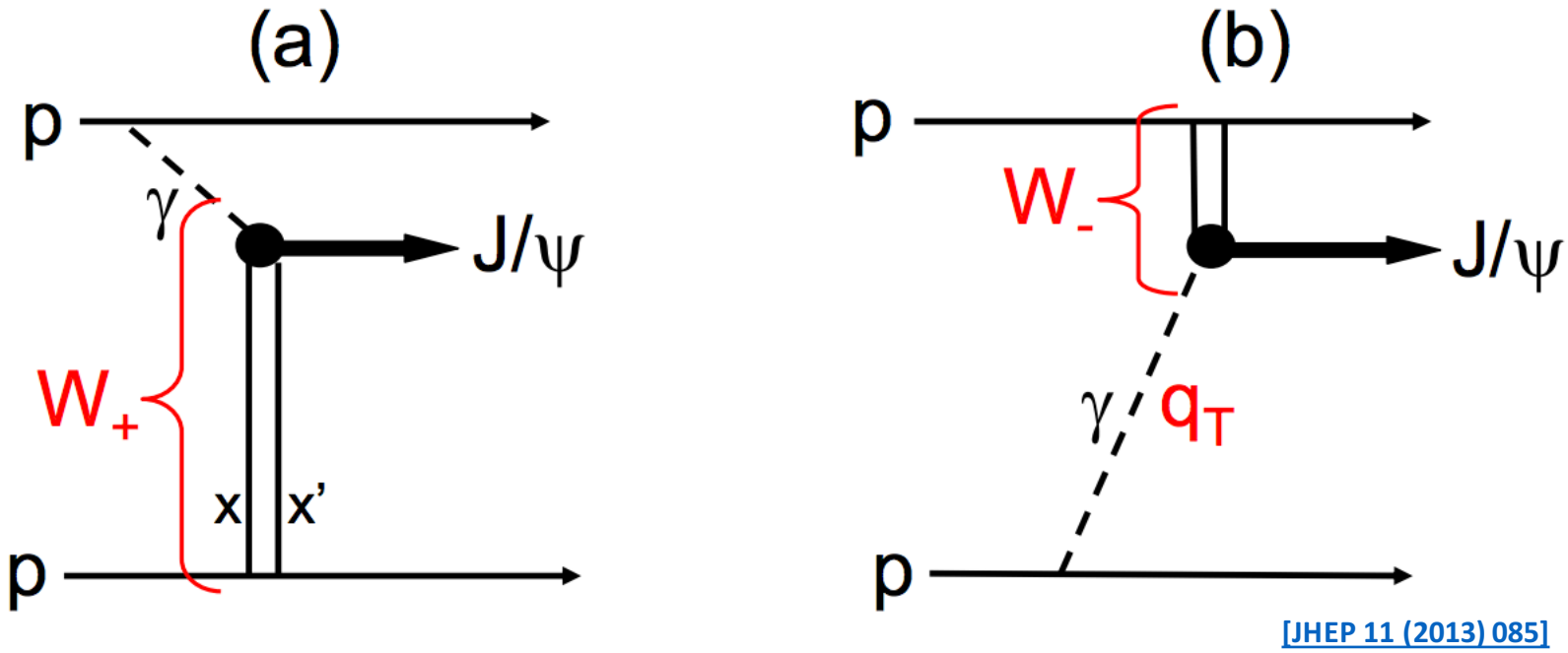
Backup

Herschel



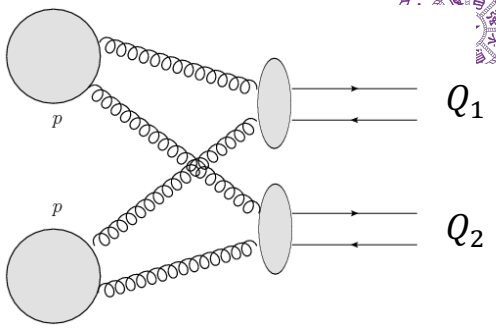
VELO&Herschel: $-10 < \eta < -5, -3.5 < \eta < -1.5, 1.5 < \eta < 10$

Photo-production cross-section



[JHEP 11 (2013) 085]

DPS formula



$$\sigma_{Q_1Q_2} = \frac{1}{1+\delta_{Q_1Q_2}} \sum_{i,j,k,l} \int dx_1 dx_2 dx_1' dx_2' d^2\mathbf{b}_1 d^2\mathbf{b}_2 d^2\mathbf{b}$$

$$\times \Gamma_{ij}(x_1, x_2, \mathbf{b}_1, \mathbf{b}_2)\, \hat{\sigma}_{ik}^{Q_1}(x_1, x_1')\, \hat{\sigma}_{jl}^{Q_2}(x_2, x_2')\, \Gamma_{kl}(x_1', x_2', \mathbf{b}_1 - \mathbf{b}, \mathbf{b}_2 - \mathbf{b}),$$

Generalized double parton PDF

SPS parton-level cross-section

- Assumption 1: factorization of transverse & longitudinal components

$$\Gamma_{ij}(x_1, x_2, \boldsymbol{b}_1, \boldsymbol{b}_2) = D_{ij}(x_1, x_2) T_{ij}(\boldsymbol{b}_1, \boldsymbol{b}_2)$$

- Assumption 2: no correlation

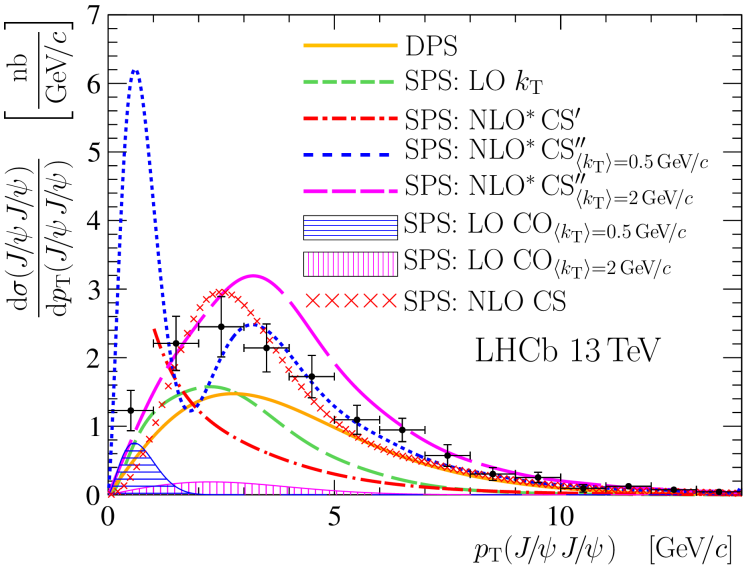
$$D_{ij}(x_1, x_2) = f_i(x_1) f_j(x_2), \qquad T_{ij}(\boldsymbol{b}_1, \boldsymbol{b}_2) = T_i(\boldsymbol{b}_1) T_j(\boldsymbol{b}_2)$$

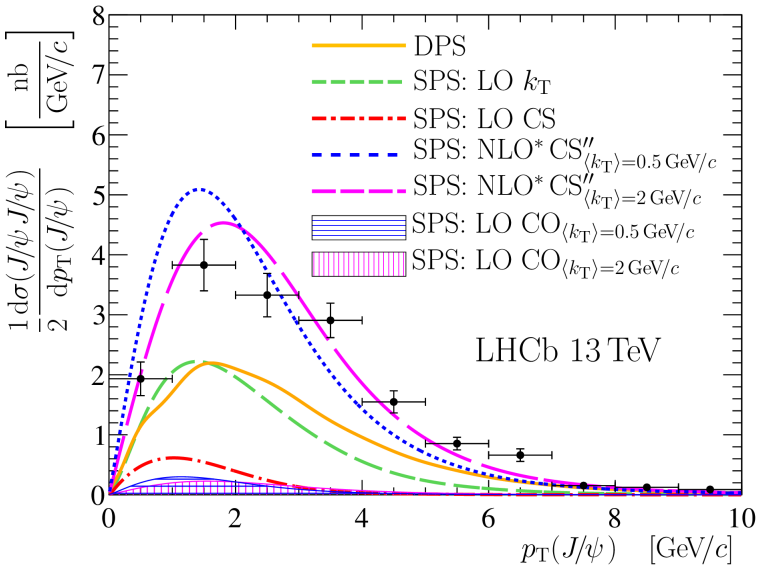
⇒ Pocket formula

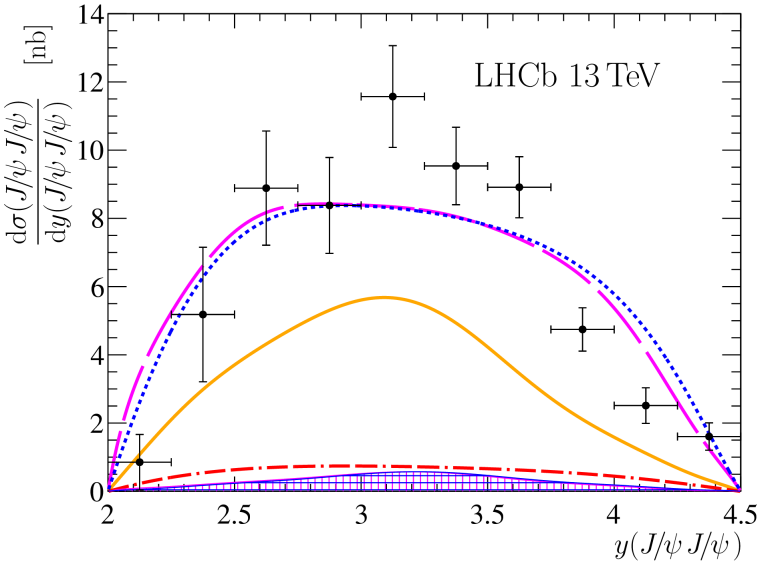
$$\sigma_{Q_1Q_2} = \frac{1}{1+\delta_{Q_1Q_2}} \frac{\sigma_{Q_1}\sigma_{Q_2}}{\sigma_{\text{eff}}}$$

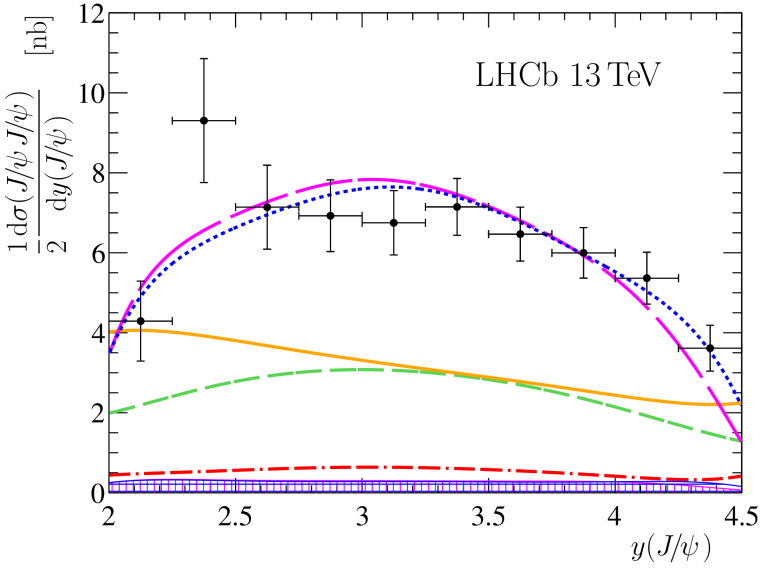
✓ $\sigma_{\text{eff}} = \left[\int d^2\boldsymbol{b} F(\boldsymbol{b})^2\right], F(\boldsymbol{b}) = \int T(\boldsymbol{b}_i) T(\boldsymbol{b}_i - \boldsymbol{b}) d^2\boldsymbol{b}_i$

Differential cross-sections (I)



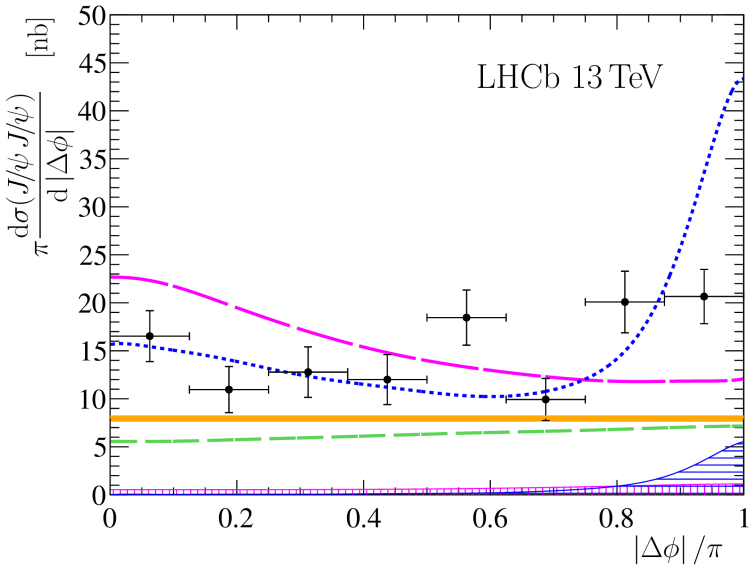


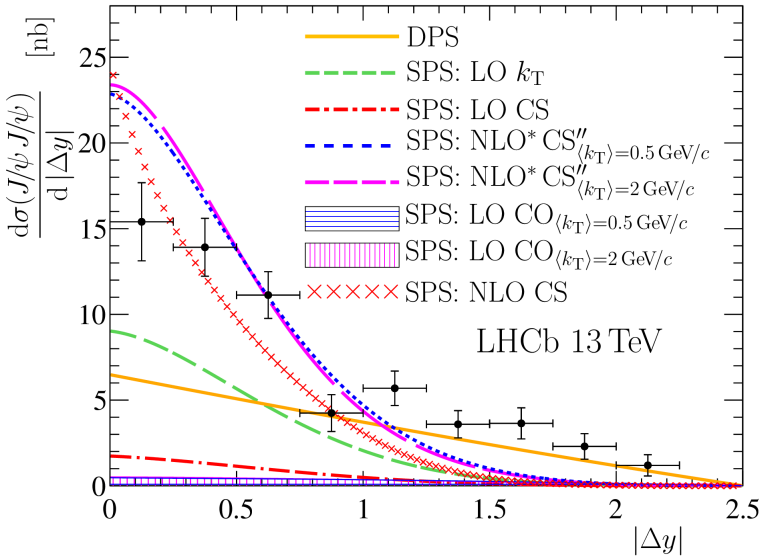


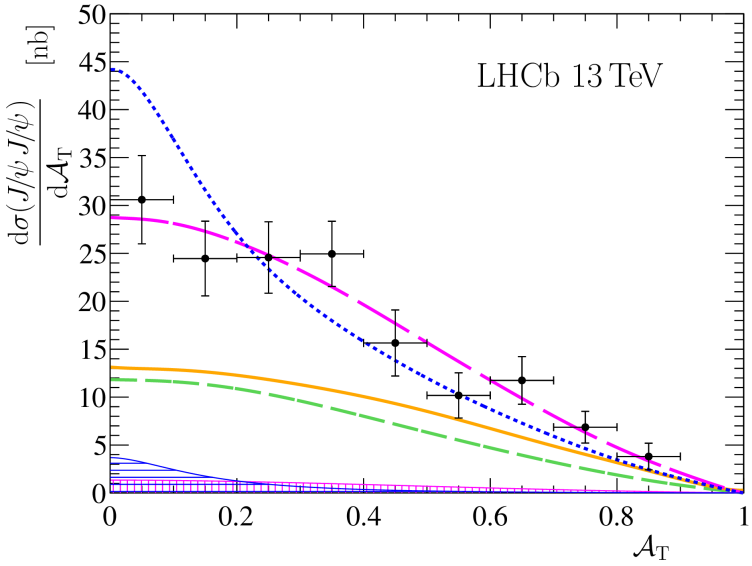


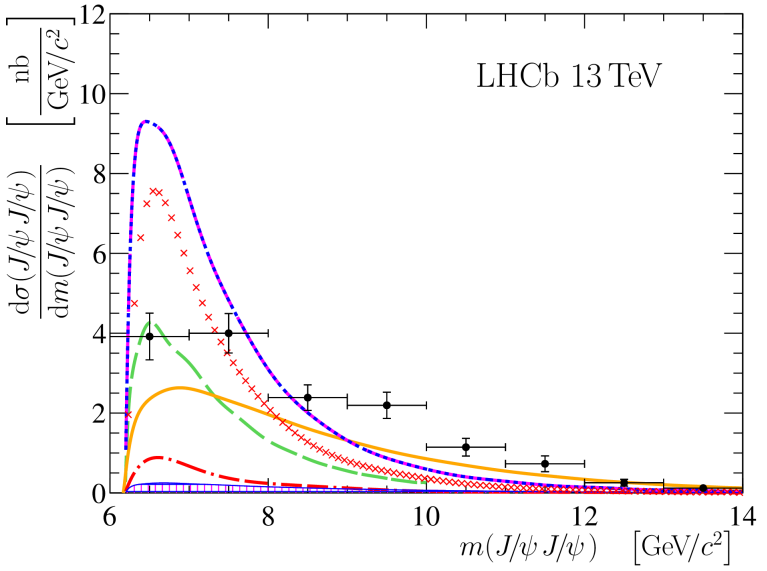
[arXiv:1612.07451]

Differential cross-sections (II)









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