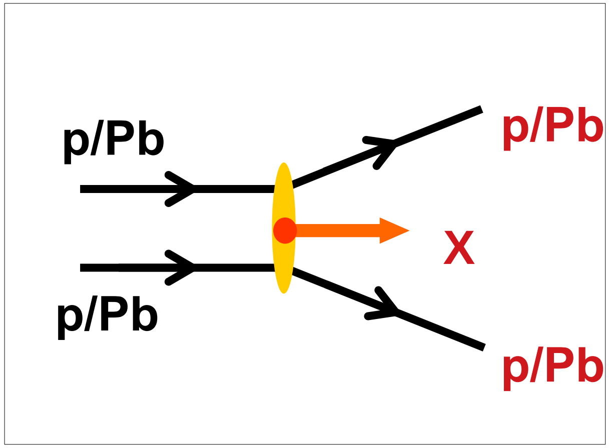
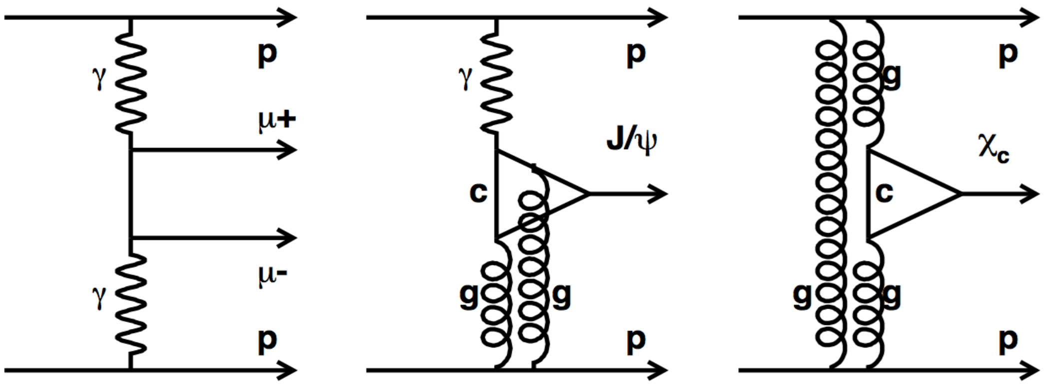
Exclusive production of vector mesons at LHCb

Lucas Meyer Garcia,
on behalf of the LHCb Collaboration

Central Exclusive Production (CEP)





- Elastic process: protons remain intact and an object X is produced exclusively
- For charmonia, cross-sections can be calculated in perturbative QCD
  - Constrains gluon PDF at low x values, tests pQCD predictions and probes the pomeron
- Low-background environment
  - Allows better understanding of the centrally produced object

Published analysis

Run 1

Central Exclusive Dimuon Production at $\sqrt{s} = 7$ TeV
LHCb-CONF-2011-022

Exclusive J/ψ and ψ(2S) production in pp collisions at $\sqrt{s} = 7$ TeV
J. Phys. G40 (2013) 045001

Updated measurements of exclusive J/ψ and ψ(2S) production cross-sections in pp collisions at $\sqrt{s} = 7$ TeV
J. Phys. G41 (2014) 055002

Observation of charmonium pairs produced exclusively in pp collisions
J. Phys. G41 (2014) 115002.

Measurement of the exclusive ϒ production cross-section at $\sqrt{s} = 7$ TeV and 8 TeV
JHEP 1509 (2015) 084

Run 2

Study of coherent J/ψ production in lead-lead collisions at $\sqrt{s_{NN}} = 5$ TeV with the LHCb experiment
LHCB-CONF-2018-003

Central exclusive production of J/ψ and ψ(2S) mesons in pp collisions at $\sqrt{s} = 13$ TeV
JHEP 10 (2018) 167

J/ψ photoproduction in Pb-Pb peripheral collisions at $\sqrt{s_{NN}} = 5$ TeV
PHYS. REV. C105 (2022) L032201

Study of coherent charmonium production in ultra-peripheral lead-lead collisions
LHCB-PAPER-2022-012

Published analysis

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J. Phys. G41 (2014) 055002

THIS TALK

Observation of charmonium pairs produced exclusively in pp collisions
J. Phys. G41 (2014) 115002.

pp Only!

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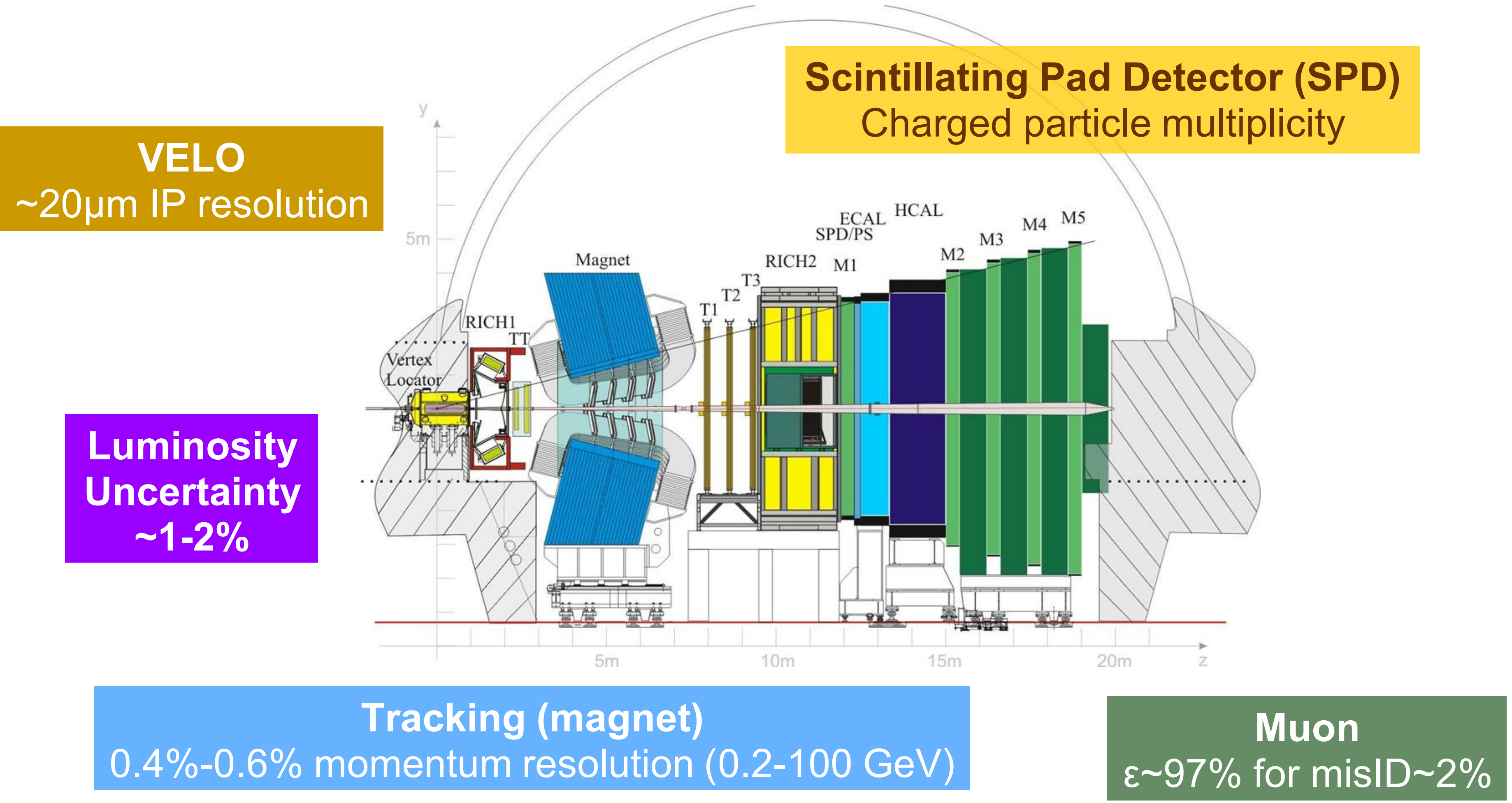
Xiaolin's Talk

Detector

LHCb is a single arm spectrometer fully instrumented in the forward region (2.0<η<5.0)

Designed for heavy flavour physics ↔ Exploited for general purpose physics

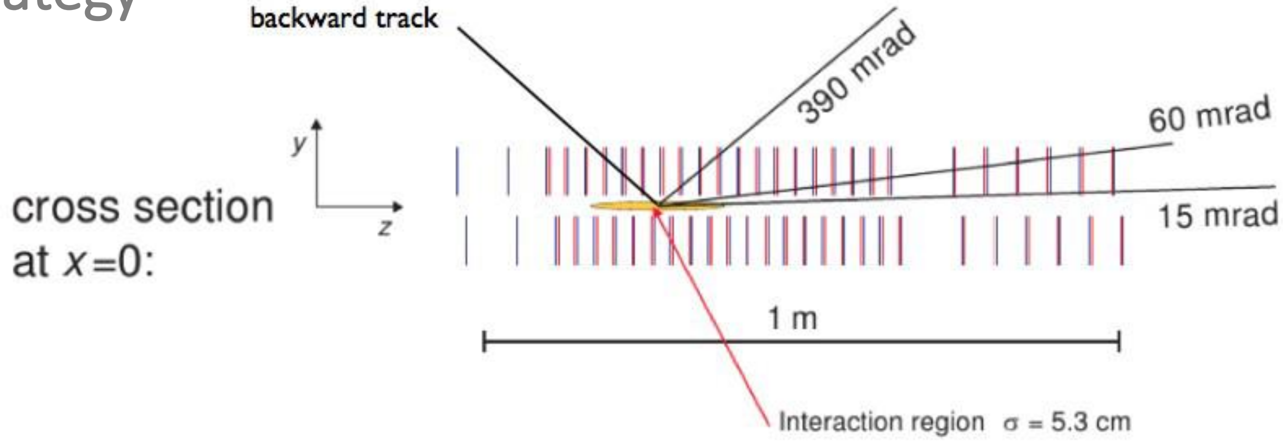
[Int. J. Mod. Phys. A 30, 1530022 (2015)]



Common strategy

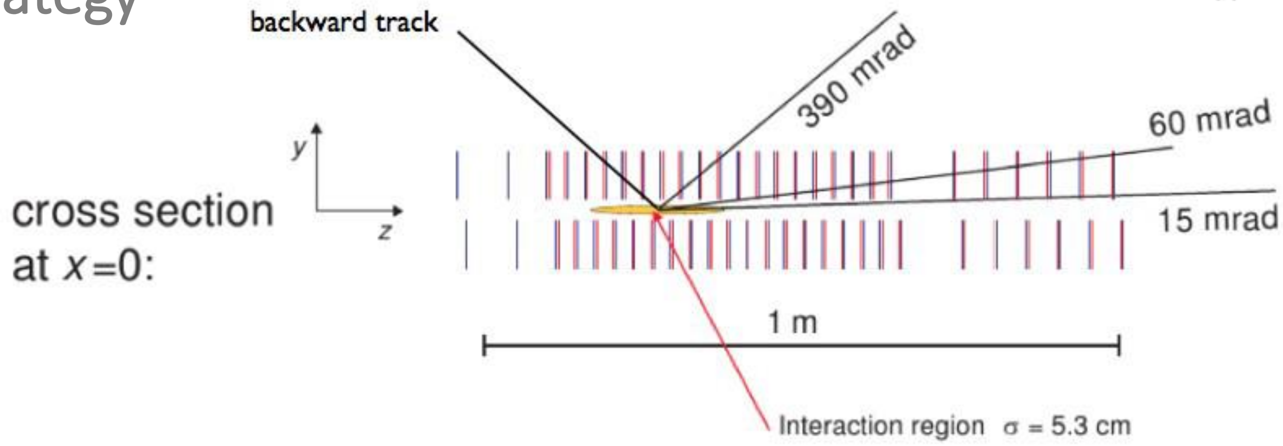
- LHCb cannot detect outgoing protons
  - Look for regions without particles (rapidity gaps)
- Trigger on low multiplicity events
  - Use information from SPD and/or tracking
- Select candidate, veto on aditional activity
  - Detector acceptance: $2.0 < \eta(\text{track}) < 5.0$
  - Veto backward tracks: $-1.5 < \eta < -3.5$ (+Herschel at Run 2)
- Background:
  - Non-resonant production
  - Resonant feed-down
  - Inelastic production

Common strategy

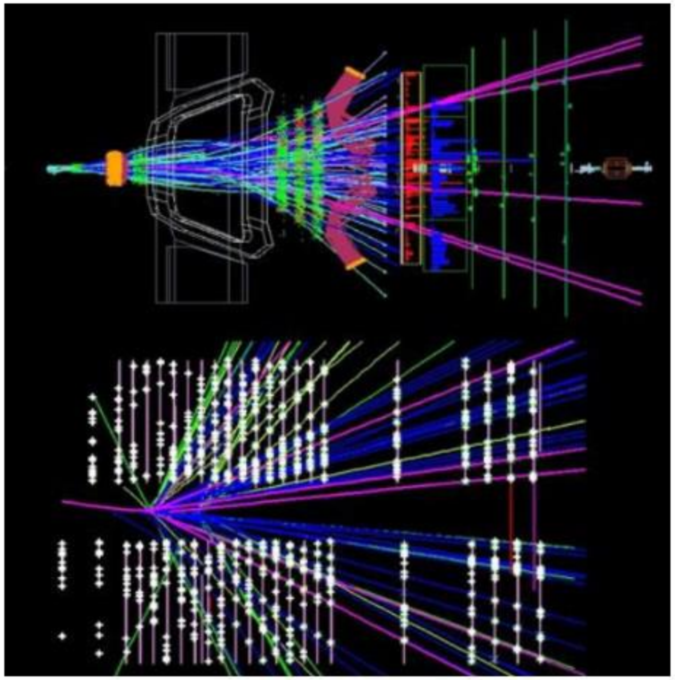


VELO
Surrounds the interaction point
No magnetic field
Reconstructs backward tracks (−3.5<η<−1.5)

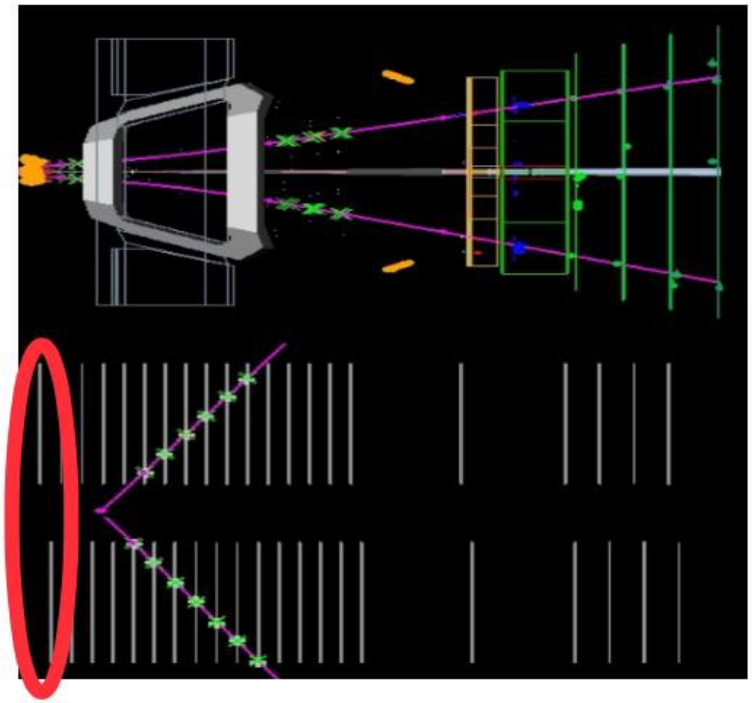
Common strategy

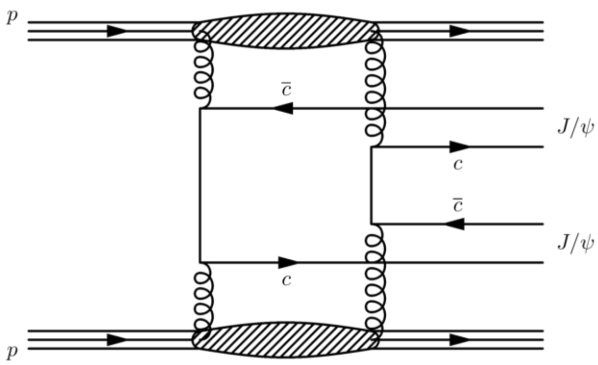


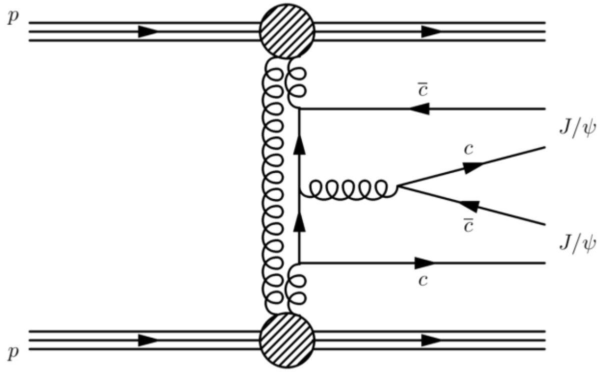
Typical Event



CEP-like event: 2muons







Combined dataset:

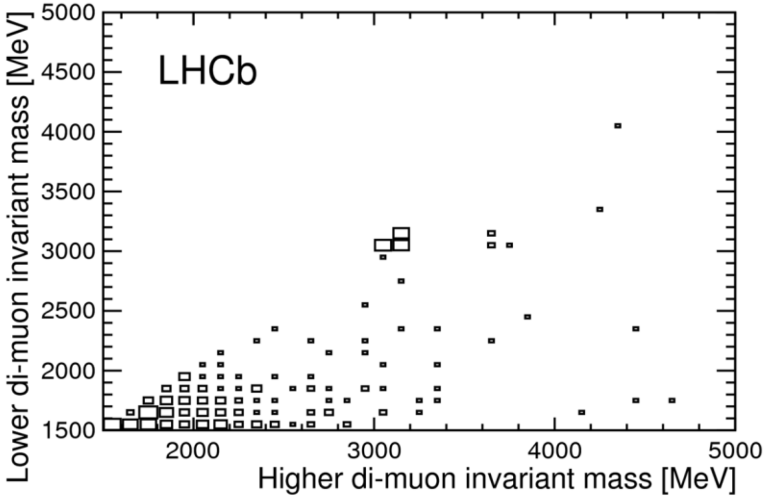
- 2011: $\sim 0.9\ fb^{-1}$ ($7\ TeV$)
- 2012: $\sim 2.0\ fb^{-1}$ ($8\ TeV$)

Trigger:

- 2 muons with $p_T > 400\ MeV$
- Less 10 hits at SPD

Candidate selection:

- Exactly 4 forward tracks, with at least 3 identified as muon



Candidates:
37 J/ψ - J/ψ
5 J/ψ - $\psi(2S)$

Exponential fit (up to $2500\ MeV$) extrapolated to estimate non-resonant background

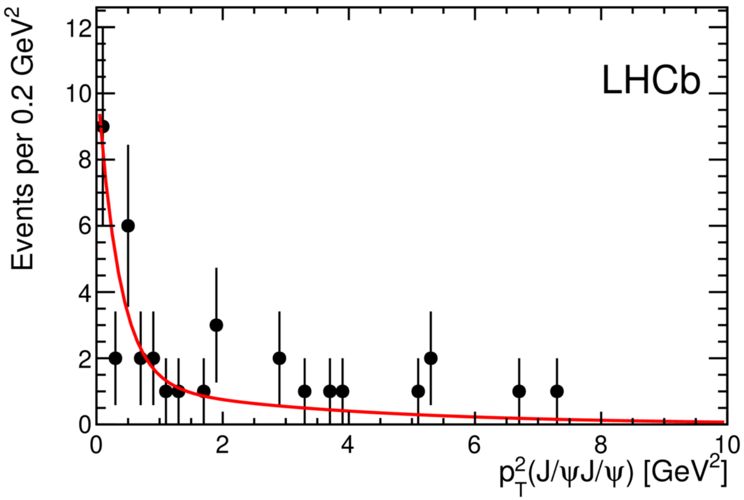
- 0.3 ± 0.1 background events for J/ψ
- 0.07 ± 0.02 background events for $\psi(2S)$

Feed-down from J/ψ ψ(2S) to J/ψ J/ψ estimated from simulation

- Normalize simulation to match J/ψ ψ(2S) yield
- 2.9 ± 2.0 background events

Inelastic background estimated only for J/ψ J/ψ

- Describe di-meson p_T^2 with sum of 2 exponentials (elastic and inelastic)



$$f_{\mathrm{el}} b_s \exp\left(-b_s p_{\mathrm{T}}^2\right) + (1 - f_{\mathrm{el}}) b_b \exp\left(-b_b p_{\mathrm{T}}^2\right).$$

Elastic fraction: 0.42 ± 0.17

Charmonium pairs

J. PHYS. G41 (2014) 115002

Cross-sections are quoted without proton dissociation correction

Limits are caculated with 90% CL

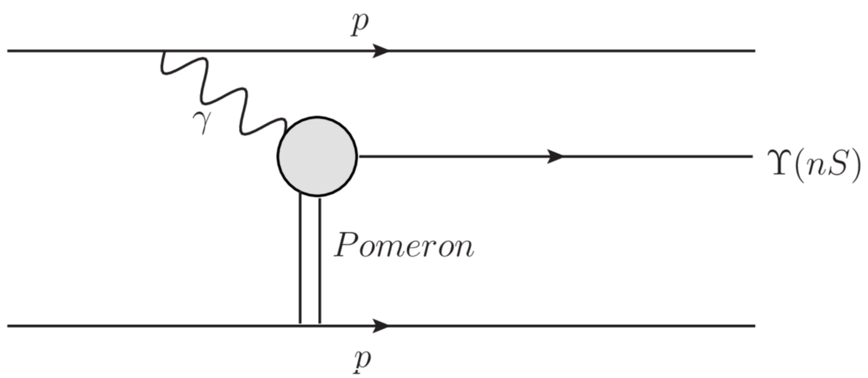
$$
\begin{aligned}
\sigma^{J/\psi\, J/\psi} &= 58 \pm 10(\text{stat}) \pm 6(\text{syst})\,\text{pb},\\
\sigma^{J/\psi\, \psi(2S)} &= 63^{+27}_{-18}(\text{stat}) \pm 10(\text{syst})\,\text{pb},\\
\sigma^{\psi(2S)\psi(2S)} &< 237\,\text{pb},\\
\sigma^{\chi_{c0}\chi_{c0}} &< 69\,\text{nb},\\
\sigma^{\chi_{c1}\chi_{c1}} &< 45\,\text{pb},\\
\sigma^{\chi_{c2}\chi_{c2}} &< 141\,\text{pb},
\end{aligned}
$$

$$\frac{\sigma(J/\psi\,\psi(2S))}{\sigma(J/\psi\,J/\psi)} = 1.1^{+0.5}_{-0.4}$$

$$\frac{\sigma(\psi(2S))}{\sigma(J/\psi)} = 0.17 \pm 0.02$$

$$\sigma^{J/\psi\, J/\psi}/\sigma^{J/\psi}|_{\text{exclusive}} = (2.1 \pm 0.8) \times 10^{-3}$$

$$\sigma^{J/\psi\, J/\psi}/\sigma^{J/\psi}|_{\text{inclusive}} = (5.1 \pm 1.0 \pm 0.6^{+1.2}_{-1.0}) \times 10^{-4}$$



Combined dataset:

- 2011: $\sim 0.9\ fb^{-1}$ (7 TeV)
- 2012: $\sim 2.0\ fb^{-1}$ (8 TeV)

Trigger:

- 2 muons with p_T > 400 MeV
- Less 10 hits at SPD

Candidate selection:

- Exactly 2 forward tracks, both identified as muons
- $p^2_{T(\Upsilon)} < 2\ GeV^2$
- $M_\Upsilon \in [9\ GeV, 20\ GeV]$

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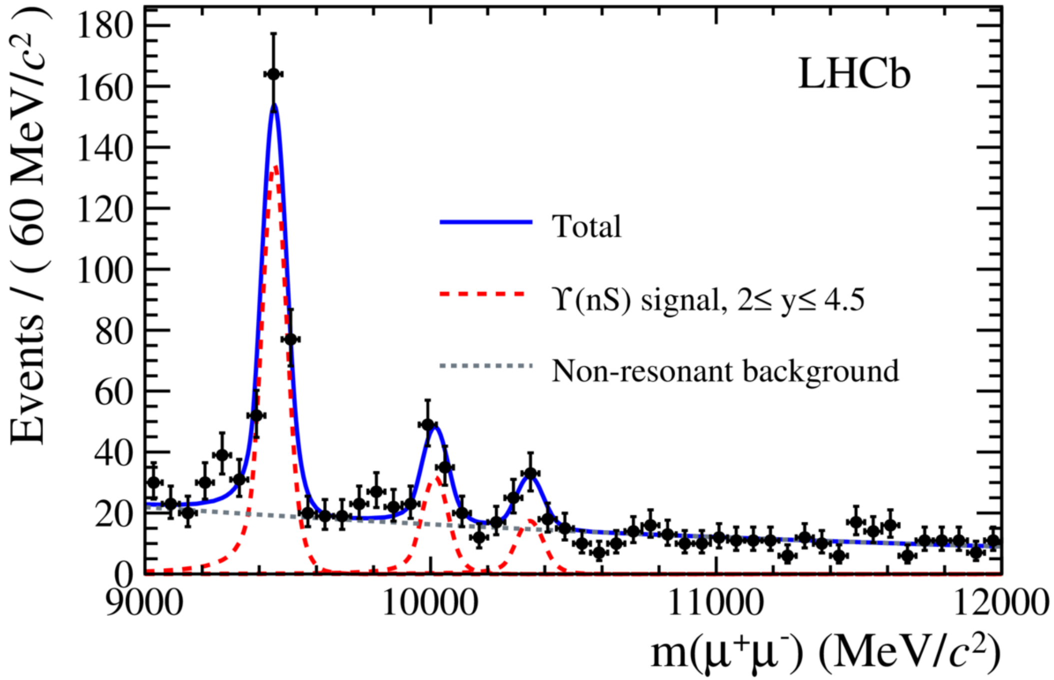


1901 selected candidates

Non-resonant background separated via mass fit.

- Resonances modeled with double-sided Crystal Ball functions.
- Non-resonant modeled with exponential function.
- Takes input from data and simulation (Only 6 free parameters)

Feed-down background from χ_b decays estimated from simulation and data.

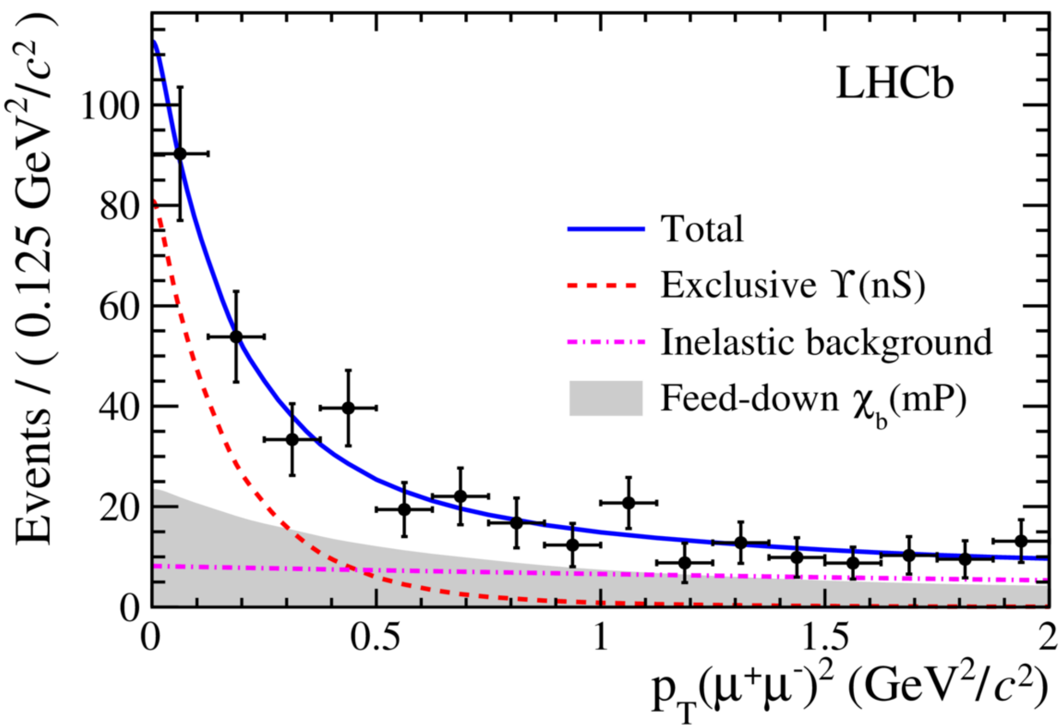
Background fraction: 39%

Proton dissociation background extracted from fit to p_T^2 of dimuons.

Non-resonant contribution subtracted via sPlot technique

Signal shape obtained from simulation

Background fraction: 28%



CEP Υ(nS)

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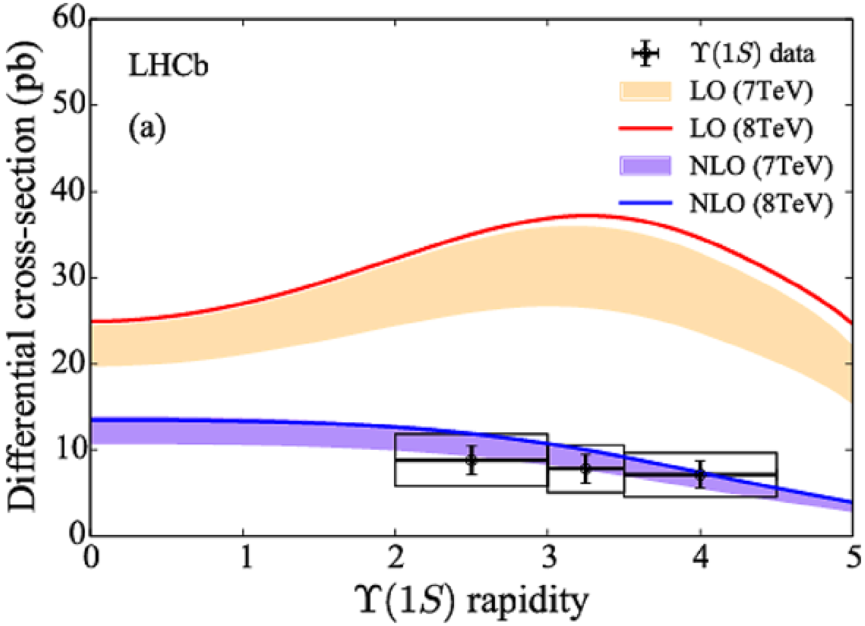
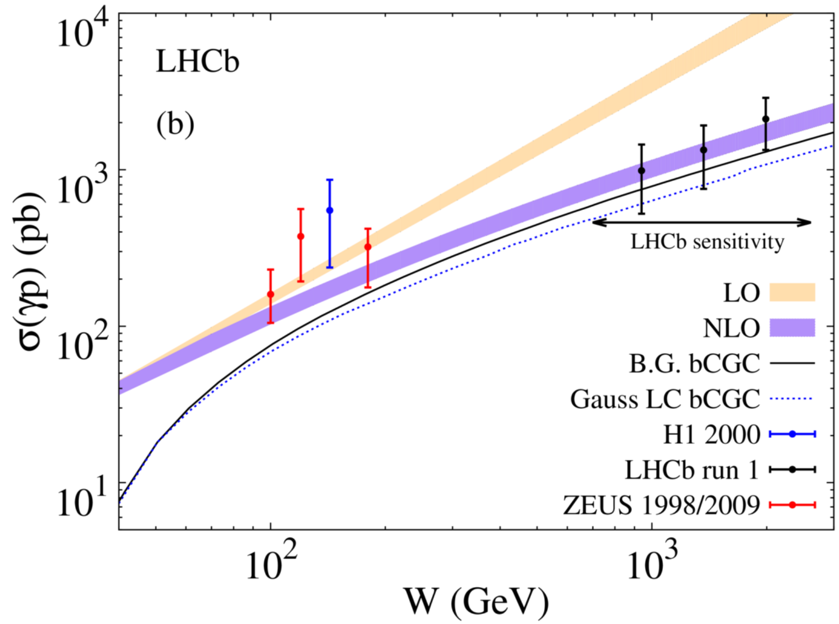
$$\sigma(pp \to p\Upsilon(1S)p) = 9.0 \pm 2.1 \pm 1.7 \text{ pb},$$
$$\sigma(pp \to p\Upsilon(2S)p) = 1.3 \pm 0.8 \pm 0.3 \text{ pb, and}$$
$$\sigma(pp \to p\Upsilon(3S)p) < 3.4 \text{ pb at the 95\% confidence level}$$



Rapidity dependence in agreement with NLO prediction.



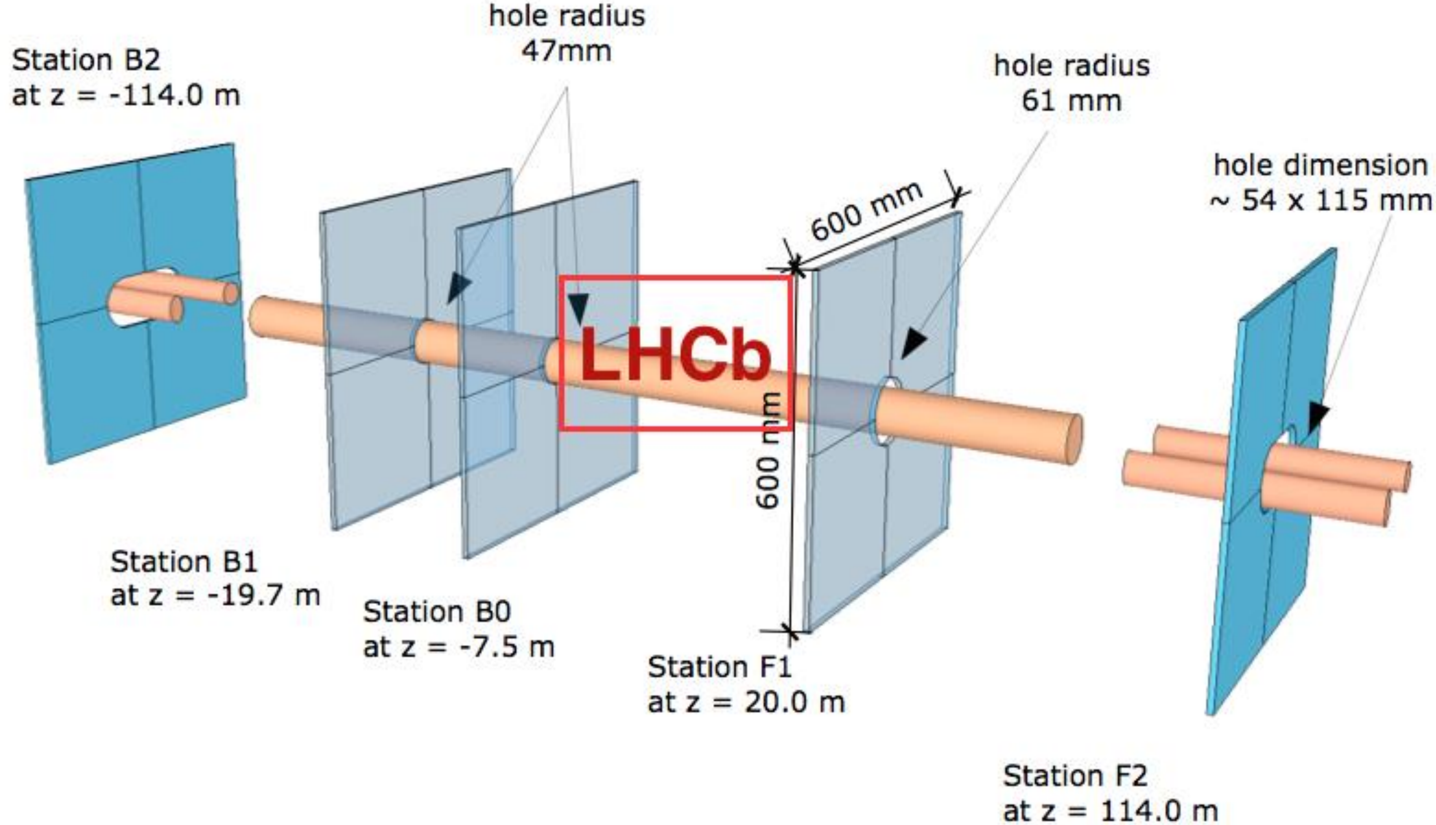
Photon-proton cross-section in agreement with NLO and CGC predictions.

LO & NLO: JHEP 1311 (2013) 085
bGCG: Phys. Lett. B742 (2015) 172

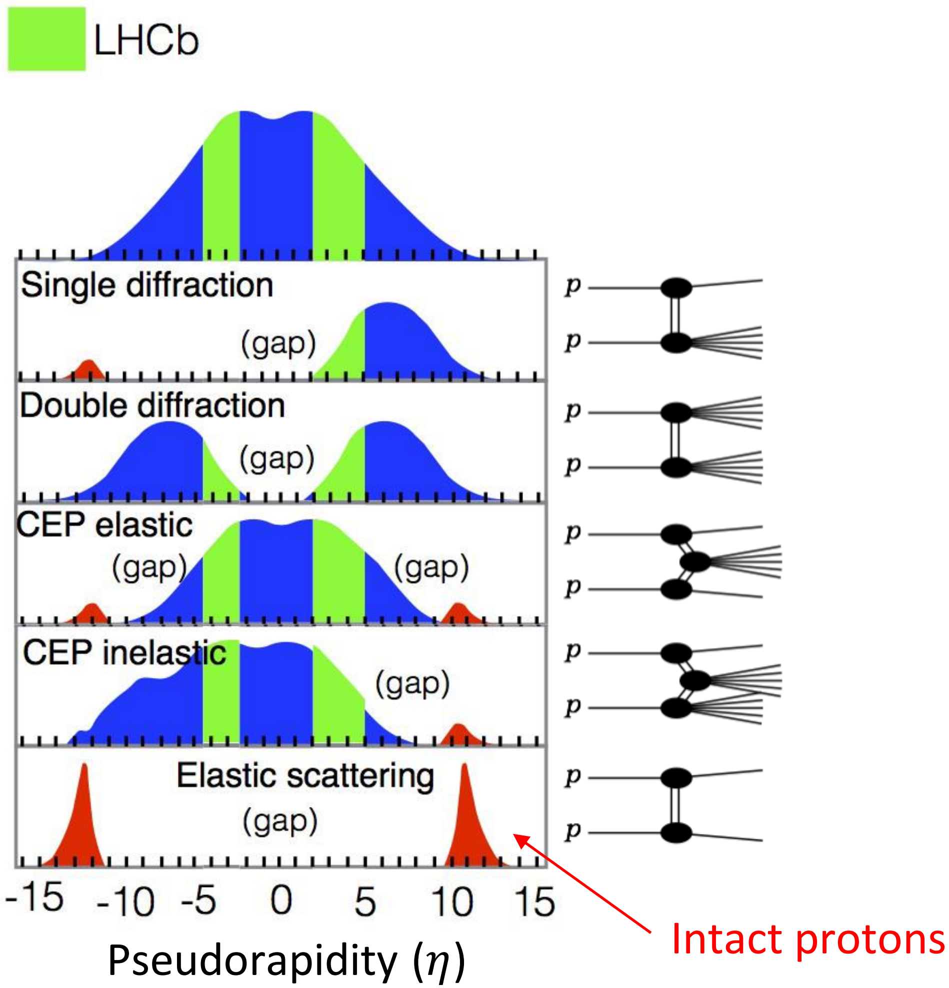
The HeRSCheL detector

JINST 13 (2018) P04017

High **R**apidity **S**hower **C**ounters for **L**HCb – **HeRSCheL**
- Installed at the end of 2014 → increase pseudorapidity coverage
- 5 stations with 4 scintillators with PMT
- Able to detect forward particle showers and veto events with these



JINST 13 (2018) P04017



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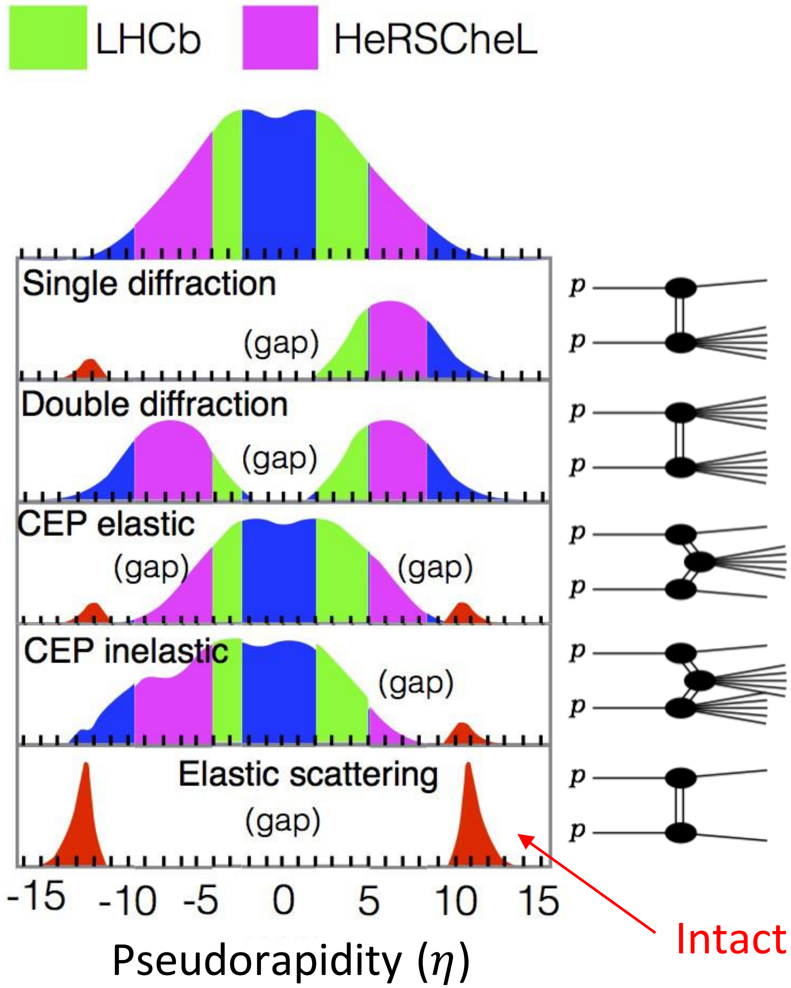
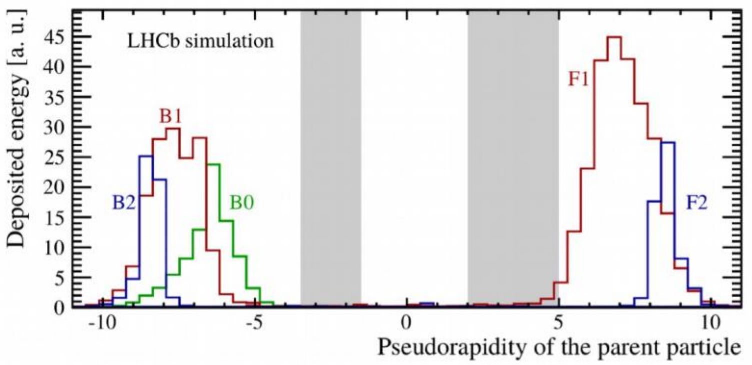
JINST 13 (2018) P04017



Intact protons



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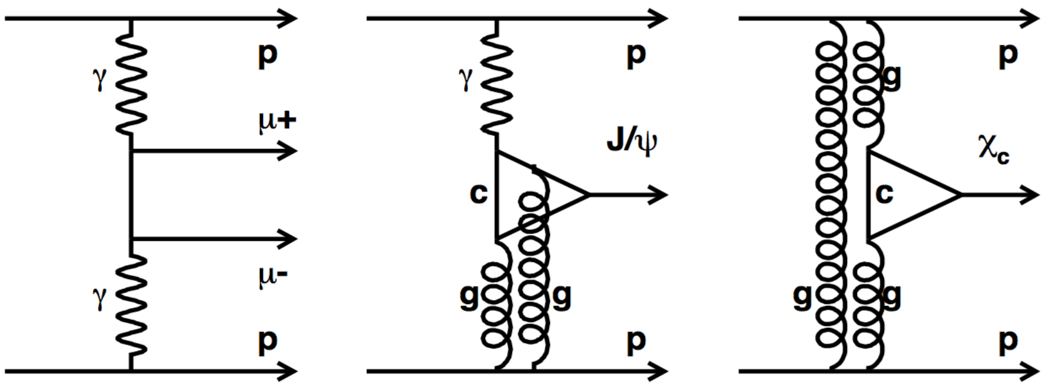

Combined dataset:
- ≈204 /pb (2015)

Trigger:
- 2 muons with $p_T > 400\ MeV$
- Less than 30 hits at SPD

Candidate selection:
- Exactly 2 reconstructed muons ($2 < \eta < 4.5$)
- $p^2_{T(J/\psi)} < 0.8\ GeV^2$
- Mass window
- Herschel cut: $\log(\chi^2_{HRC}) < 3.5$

J/ψ and ψ(2S) at 13 TeV

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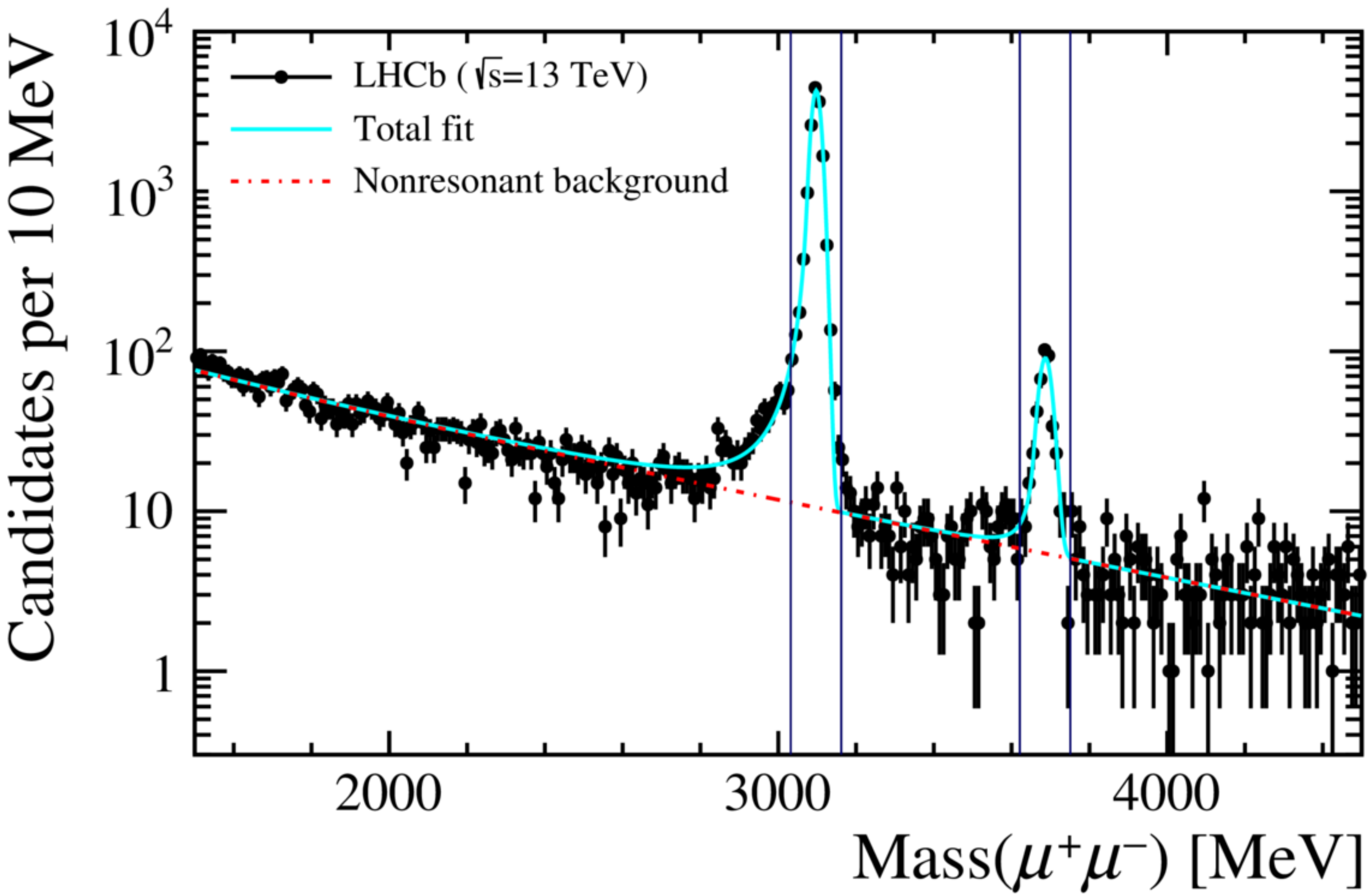
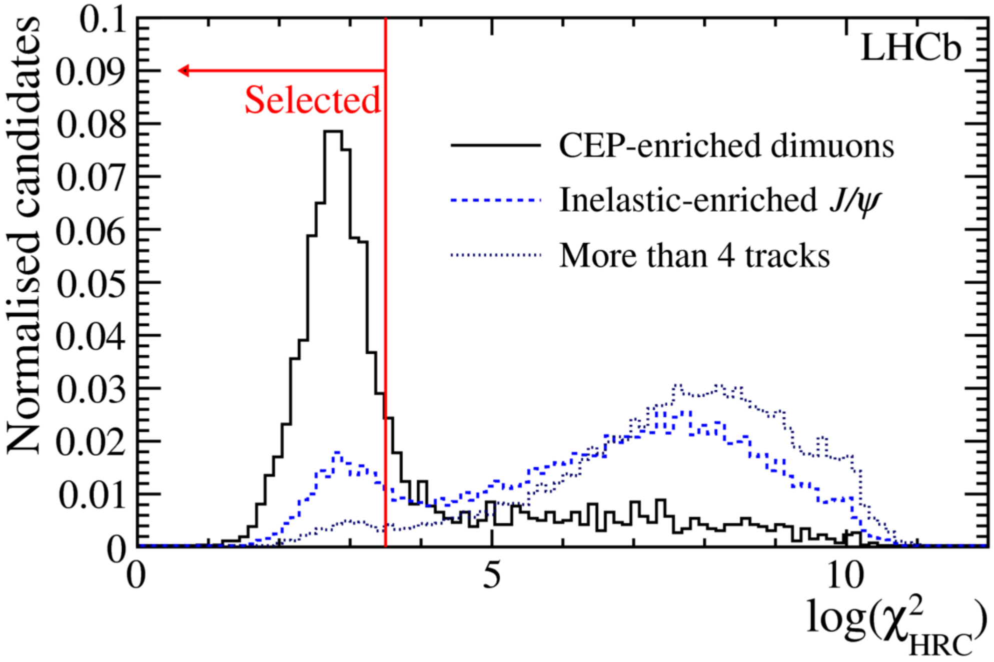


14753 J/ψ candidates
440 $\psi(2S)$ candidates

JHEP 10 (2018) 167

The HeRSCheL response is described using a variable χ^2_{HRC} that quantifies the activity above noise, taking account of correlations between the counters.



Clear discrimination observed for:

CEP-enriched dimuons: $p^2_{T(J/\psi)} < 0.01\ GeV^2$

More than four tracks

Inelastic-enriched J/ψ: $p^2_{T(J/\psi)} > 1\ GeV^2$

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Non-resonant background estimated from fit to mass distribution.

- Resonances modeled with CrystalBall functions
- Non-resonant modeled with sum of exponential functions
- Background fraction: 0.9% (16.1%) for J/ψ ($\psi(2S)$)

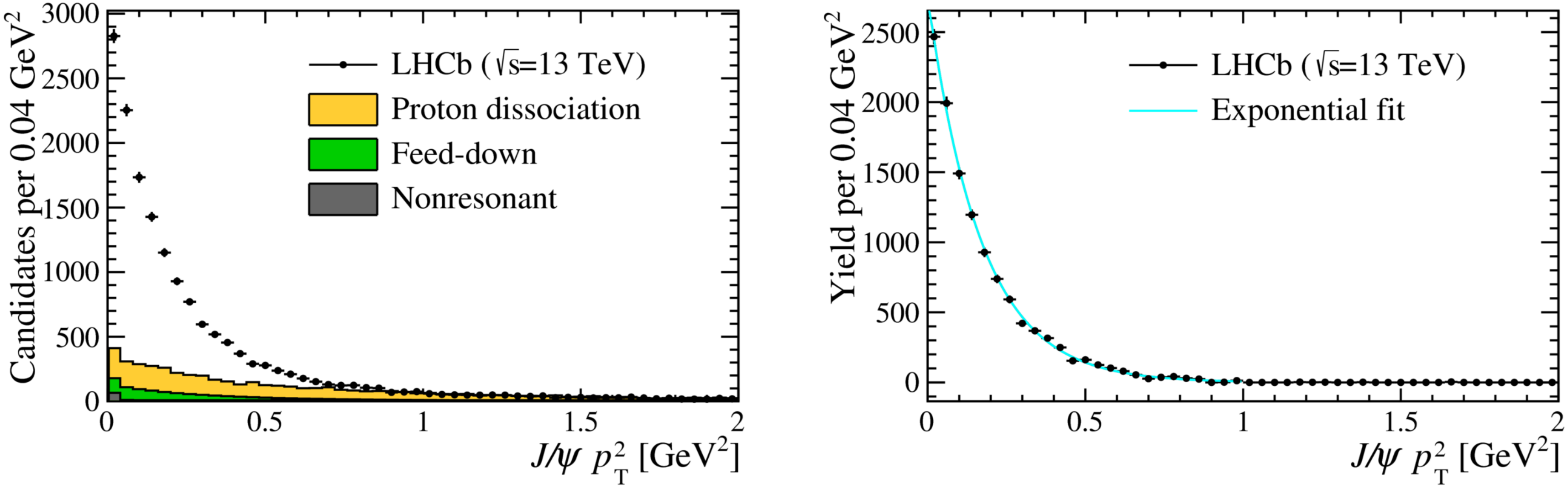
Feed-down background estimated from simulation and data.

- Considered only for J/ψ
- Combined background fraction: 0.6%

Proton dissociation background extracted from fit to p_T^2 of dimuons.

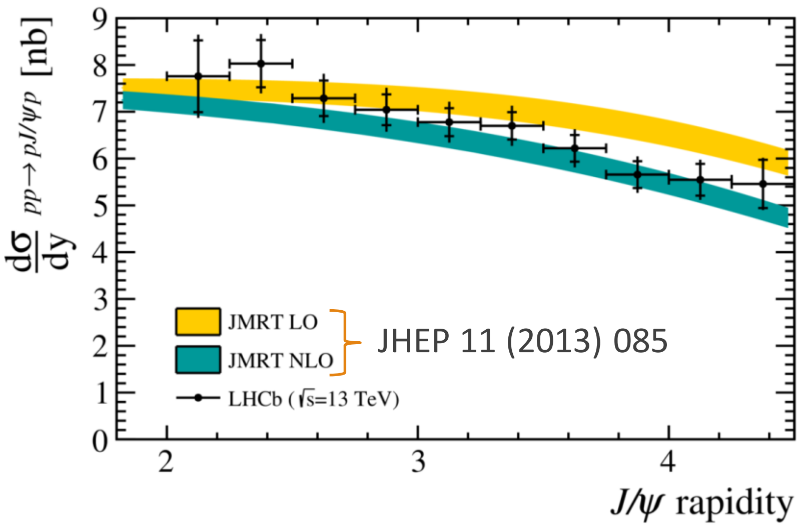
Based on HeRSCheL information

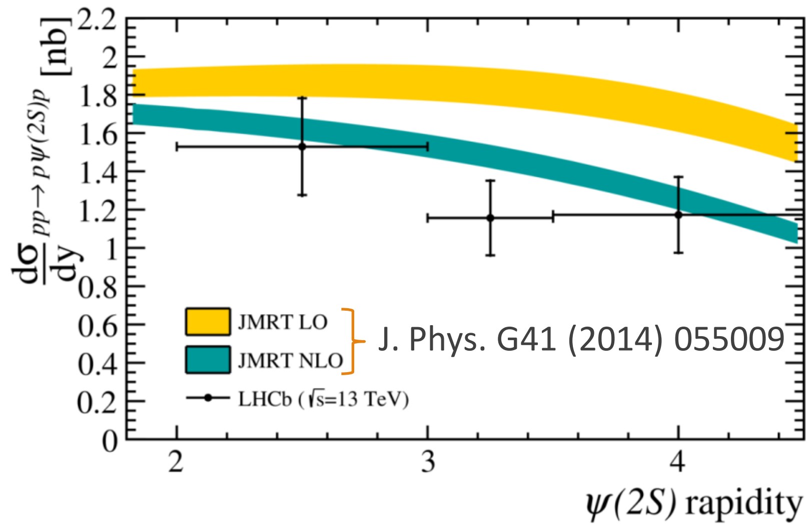
17.5% (11%)for J/ψ ($\psi(2S)$)



Lower feed-down and inelastic background thanks to HeRSCheL!

J/ψ and ψ(2S) at 13 TeV





NLO shows better agreement than LO

$$\sigma_{J/\psi\to\mu^+\mu^-}(2<\eta<4.5) = 399\pm16\pm10\pm16 \text{ pb},$$
$$\sigma_{\psi(2S)\to\mu^+\mu^-}(2<\eta<4.5) = 10.2\pm1.0\pm0.3\pm0.4 \text{ pb}.$$

J/ψ and ψ(2S) at 13 TeV

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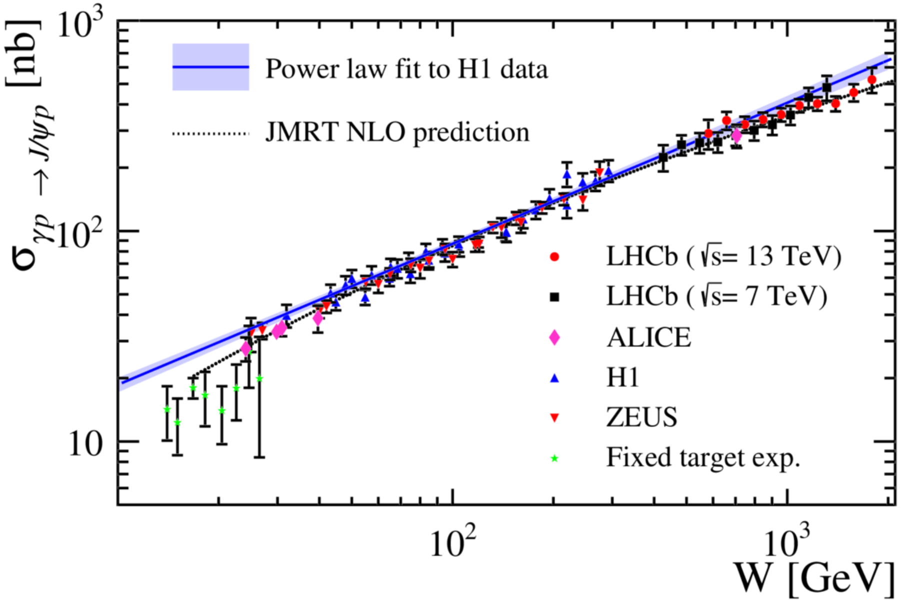
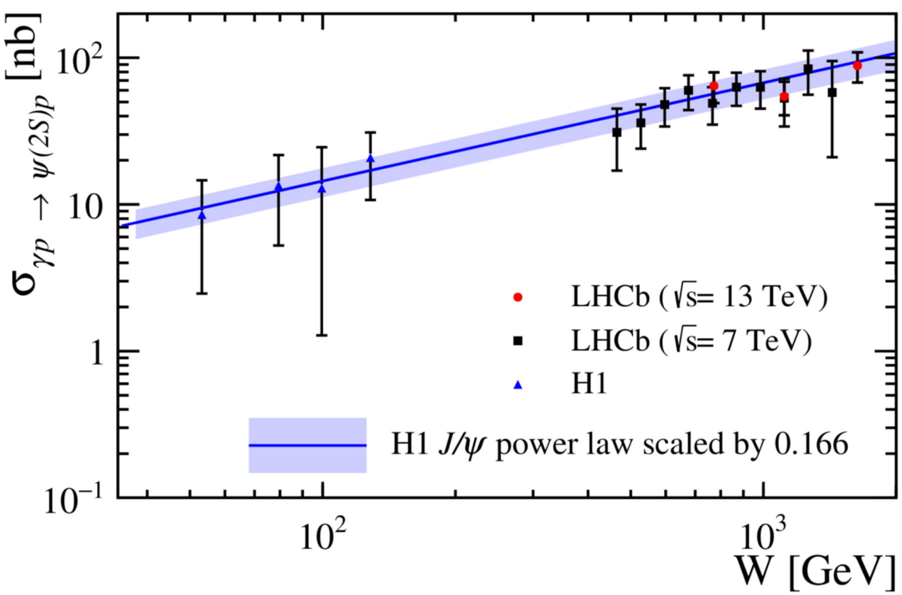
$$\sigma_{pp\to p\psi p} = r(W_+)k_+\frac{\mathrm{d}n}{\mathrm{d}k_+}\sigma_{\gamma p\to\psi p}(W_+) + r(W_-)k_-\frac{\mathrm{d}n}{\mathrm{d}k_-}\sigma_{\gamma p\to\psi p}(W_-)$$

r is the gap survival factor, $k_\pm \equiv M_\psi/2e^{\pm y}$ is the photon energy,

$\mathrm{d}n/\mathrm{d}k_\pm$ is the photon flux and $W_\pm^2 = 2k_\pm\sqrt{s}$ is the invariant mass of the photon-proton system

Assuming HERA result for W_-, one can obtain $\sigma(W_+)$:





More CEP!

Analysis in advanced stage:

- Update of CEP J/ψ and $\psi(2S)$ measurement with full Run 2 data
- Update of $\Upsilon(\boldsymbol{nS})$ CEP measurement
- Studies of exclusive $\phi\ \phi$ and $J/\psi\ \phi$ production

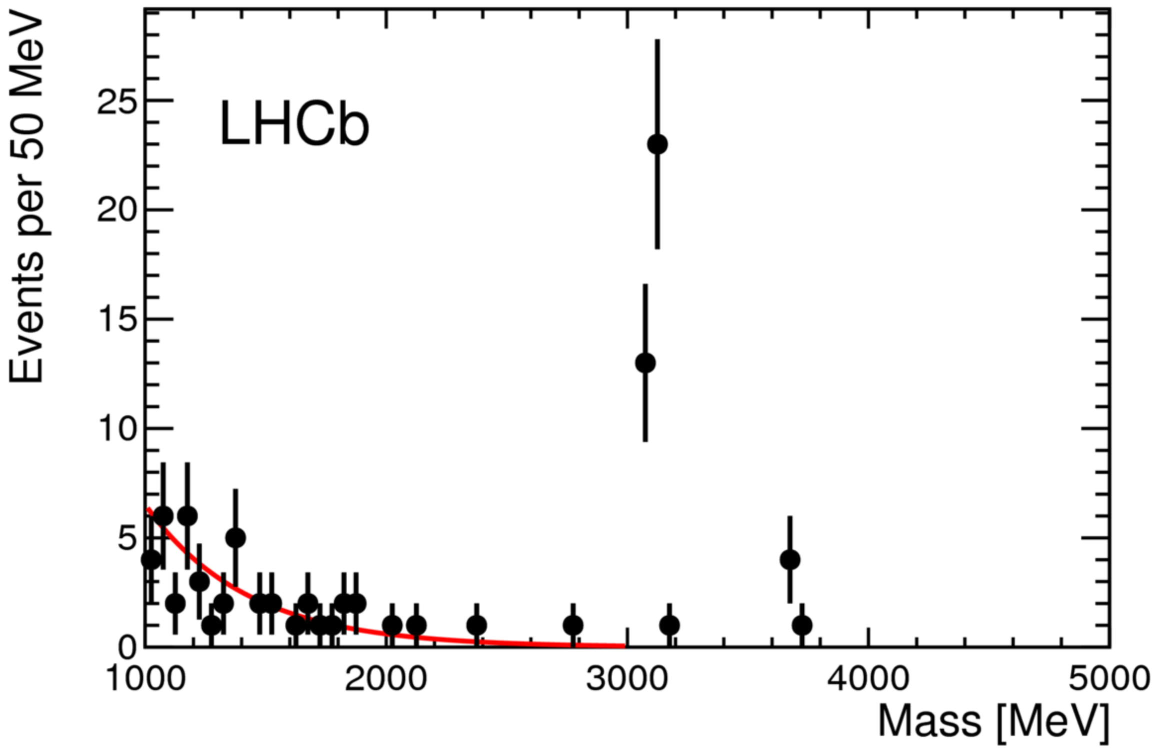
Summary

- Extensive CEP program at LHCb
  - Some results from pp data were shown
  - New studies coming soon
- Important tests of QCD in the forward region
- Studies are also conducted on PbPb colisions
  - See Xiaolin's talk for latest results

Thank you!

Backup

J. PHYS. G41 (2014) 115002



Mass of the second pair when the first pair has a mass consistent with J/ψ or $\psi(2S)$

Exponential fit (up to $2500\ MeV$) extrapolated to estimate non-resonant background

0.3 ± 0.1 background events for J/ψ

0.07 ± 0.02 background events for $\psi(2S)$

Feed-down from J/ψ ψ(2S) to J/ψ J/ψ estimated from simulation

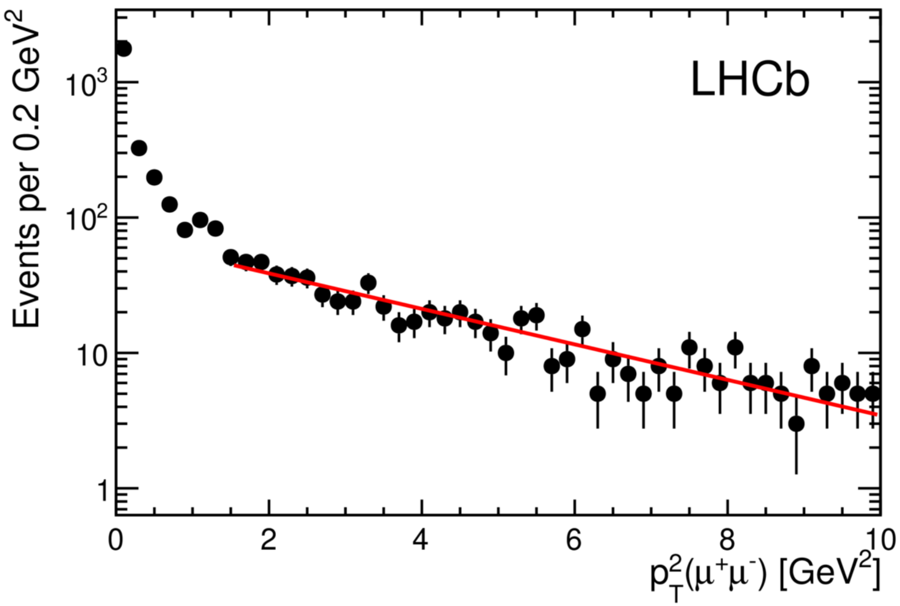
Normalize simulation to match J/ψ ψ(2S) yield

2.9 ± 2.0 background events

Inelastic background estimated only for J/ψ J/ψ

Describe di-meson p_T^2 with sum of 2 exponentials (elastic and inelastic)

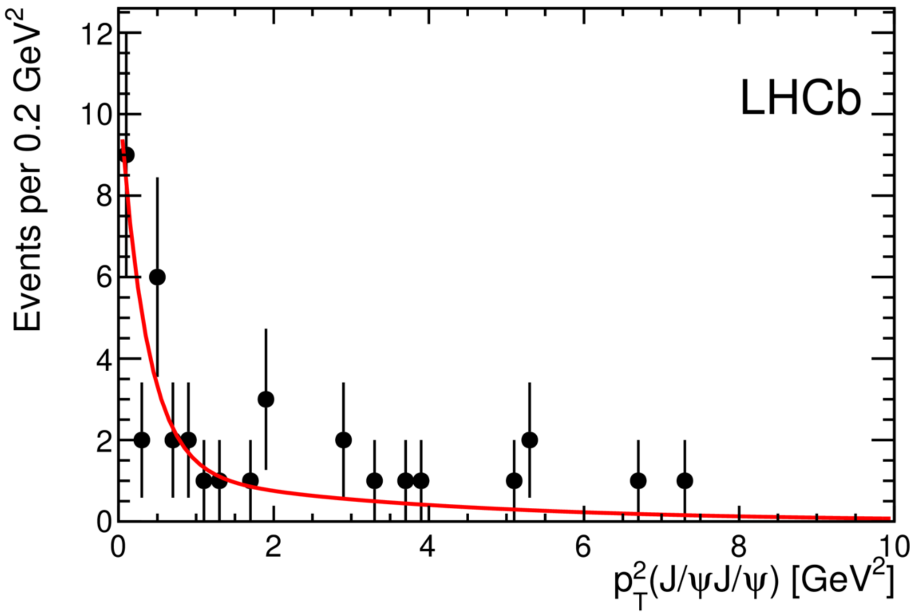
Slope of inelastic exponential obtained from fit to p_T^2 of exclusive dimuons with mass within [6, 9] GeV



J. PHYS. G41 (2014) 115002

Fit di-meson p_T^2 with fixed slope on background exponential to estimate elastic fraction

$$f_{\rm el} b_s \exp\left(-b_s p_{\rm T}^2\right) + (1 - f_{\rm el}) b_b \exp\left(-b_b p_{\rm T}^2\right)$$



Elastic fraction: 0.42 ± 0.17

J/ψ and ψ(2S) at 13 TeV

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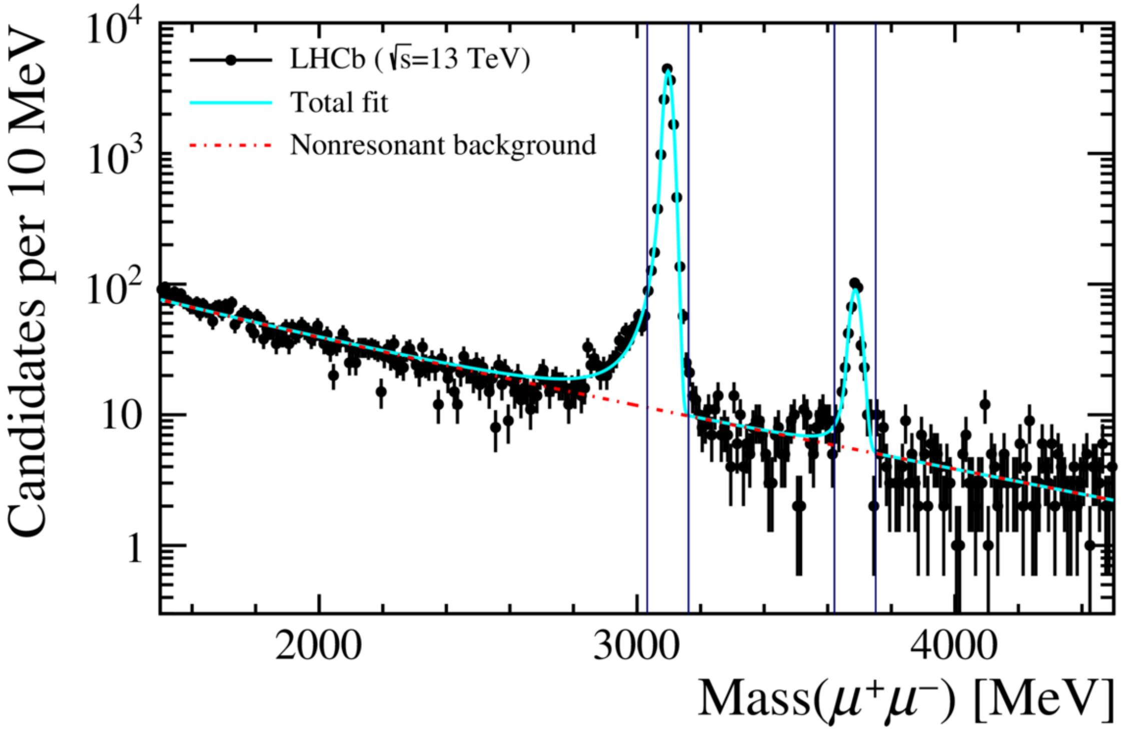

14753 J/ψ candidates
440 $\psi(2S)$ candidates

Reconstruction and selection efficiencies estimated from data driven methods

Fraction of single interaction beam crossings: (36.52 ± 0.03) %

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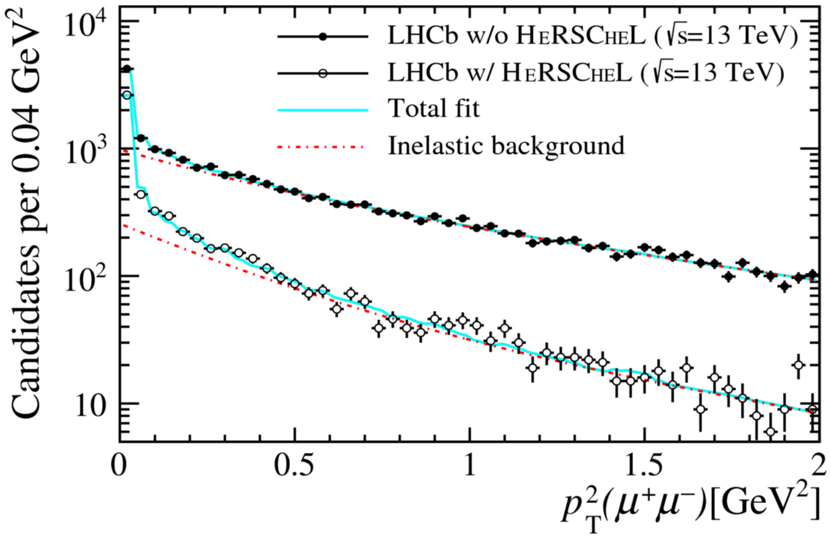
HeRSCheL efficiency estimated from fit to p_T^2 of non-resonant dimuons.

- Signal shape obtained from simulation
- Background modeled as sum of two exponentials



J/ψ and ψ(2S) at 13 TeV

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New Technique:

$N_{HRC} = \varepsilon N_{sig} + \beta(p_T) N_{bkg}$

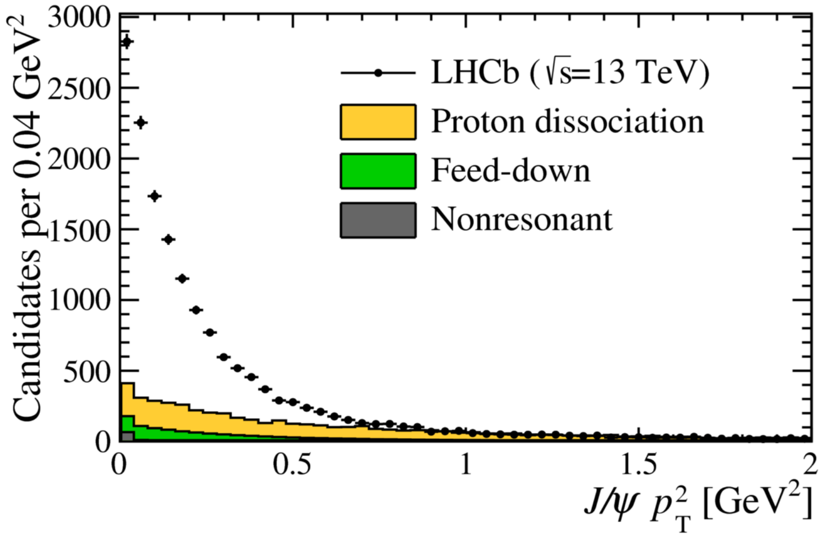
$N_{anti\text{-}HRC} = [1-\varepsilon] N_{sig} + [1-\beta(p_T)]\, N_{bkg}$

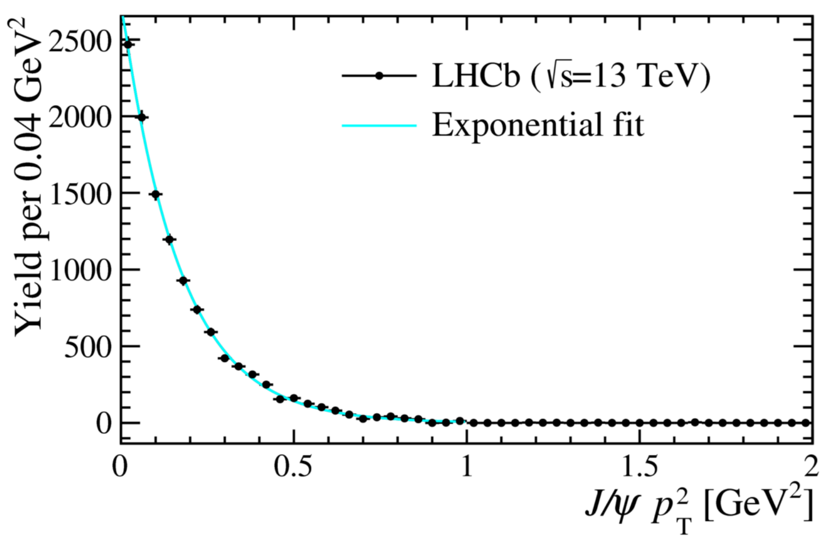
ε known from QED sample

Pure bkg sample obtained

Subtract bkg from total => Signal derived

$$\beta = S_{\bar{H}} - ((1-\epsilon_H)/\epsilon_H) S_H$$





J/ψ and ψ(2S) at 13 TeV

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