Review of CHARM 2013 Conference

Birmingham HEP Seminar

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- CHARM 2013: The 6th International Workshop on Charm Physics
- Very interesting conference, many new results and much discussion!

Multiple sessions on broad range of topics within charm physics

- Exotic hadron spectroscopy
- Charmonium spectroscopy
- Open charm hadron spectroscopy
- Rare decays
- Charm hadron production
- Charm mixing
- CP violation in charm
- Future experiments and facilities

This review:

I'll cover the topics I found most interesting...

(They also happen to span the majority of what was presented...)

- XYZ Charm Hadrons
- Quarkonium production
- Rare Charm Decays
- The PANDA Experiment
- CP Violation in Charm

New $c\bar{c}$ Mesons above $D\bar{D}$ threshold

15 neutral $c\bar{c}$ mesons

5 charged $c\bar{c}$ mesons

TABLE I:

State	M (MeV)	Γ (MeV)	J^{PC}	Decay modes	1st observation
neutral $c\bar{c}$ mesons					
$X(3823)$	3823.1±1.9	< 24	$?^{?-}$	$\chi_{c1}\gamma$	Belle 2013
$\boldsymbol{X(3872)}$	3871.68±0.17	< 1.2	1^{++}	$J/\psi\,\pi^+\pi^-$, $J/\psi\,\pi^+\pi^-\pi^0$ $D^0\bar{D}^0\pi^0$, $D^0\bar{D}^0\gamma$ $J/\psi\,\gamma$, $\psi(2S)\,\gamma$	Belle 2003
$\boldsymbol{X(3915)}$	3917.5 ± 1.9	20±5	0^{++}	$J/\psi\,\omega$, $\gamma\gamma$	Belle 2004
$\boldsymbol{\chi_{c2}(2P)}$	3927.2 ± 2.6	24±6	2^{++}	$D\bar{D}$, $\gamma\gamma$	Belle 2005
$X(3940)$	3942^{+9}_{-8}	37^{+27}_{-17}	$?^{?+}$	$D^*\bar{D}$	Belle 2007
$\boldsymbol{G(3900)}$	3943 ± 21	52±11	1^{--}	$D\bar{D}$	*BABAR* 2007
$Y(4008)$	4008^{+121}_{-49}	226±97	1^{--}	$J/\psi\,\pi^+\pi^-$	Belle 2007
$\boldsymbol{Y(4140)}$	4144.5 ± 2.6	15^{+11}_{-7}	$?^{?+}$	$J/\psi\,\phi$	CDF 2009
$X(4160)$	4156^{+29}_{-25}	139^{+113}_{-65}	$?^{?+}$	$D^*\bar{D}^*$	Belle 2007
$\boldsymbol{Y(4260)}$	4263^{+8}_{-9}	95±14	1^{--}	$J/\psi\,\pi^+\pi^-$, $J/\psi\,\pi^0\pi^0$ $Z_c(3900)\,\pi$	*BABAR* 2005
$Y(4274)$	$4274.4^{+8.4}_{-6.7}$	32^{+22}_{-15}	$?^{?+}$	$J/\psi\,\phi$	CDF 2010
$X(4350)$	$4350.6^{+4.6}_{-5.1}$	$13.3^{+18.4}_{-10.0}$	$0/2^{++}$	$J/\psi\,\phi$, $\gamma\gamma$	Belle 2009
$\boldsymbol{Y(4360)}$	4361 ± 13	74±18	1^{--}	$\psi(2S)\,\pi^+\pi^-$	*BABAR* 2007
$X(4630)$	4634^{+9}_{-11}	92^{+41}_{-32}	1^{--}	$\Lambda_c^+\Lambda_c^-$	Belle 2007
$Y(4660)$	4664±12	48±15	1^{--}	$\psi(2S)\,\pi^+\pi^-$	Belle 2007
charged $c\bar{c}$ mesons					
$\boldsymbol{Z_c^+(3900)}$	3898 ± 5	51 ± 19	$?^{?-}$	$J/\psi\,\pi^+$	BESIII 2013
$Z_c^+(4020)$	4021.8 ± 2.7	5.7 ± 3.6	$?^{?-}$	$h_c(1P)\,\pi^+$, $D^*\bar{D}^*$	BESIII 2013
$Z_1^+(4050)$	4051^{+24}_{-43}	82^{+51}_{-55}	$?^{?+}$	$\chi_{c1}(1P)\,\pi^+$	Belle 2008
$Z_2^+(4250)$	4248^{+185}_{-45}	177^{+321}_{-72}	$?^{?+}$	$\chi_{c1}(1P)\,\pi^+$	Belle 2008
$Z^+(4430)$	4443^{+24}_{-18}	107^{+113}_{-71}	1^{+-}	$\psi(2S)\,\pi^+$	Belle 2007

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XYZ: Many new charm hadrons, none of them are understood!

New and recent results on the $X(3872)$ state

- The “classic” exotic hadron, over a decay old now...
- Confirmed by many experiments (B factories, Tevatron and LHC)
- We still don’t know what it is!
- Several new results could shed more light on this...
- Slides from Sebastian Neubert (CERN) and Changzheng Yuan (IHEP)

$X(3872) \to J/\psi\pi^+\pi^-$

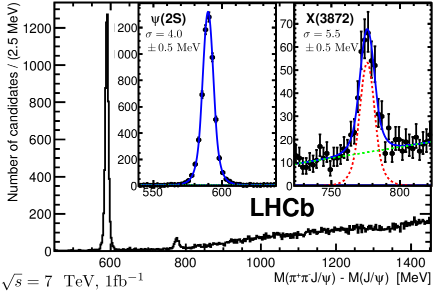
- Since its discovery a decade ago by Belle ↪ [PRL 91 262001] in $B^\pm \to J/\psi\pi\pi K^\pm$ the $X(3872)$ has been studied at a number of experiments
- The existence of the $X(3872)$ is now beyond doubt, but structure is still unclear:
  - Mass and decay mode disfavor $c\bar{c}$ state.
  - $C = +1 \quad \Leftarrow \quad X(3872) \to J/\psi\gamma$
    Belle ↪ [PRL 107 091803], *BABAR* ↪ [PRD 74 071101(R)]
  - CDF helicity angle measurement ↪ [PRL 98 132002] of inclusive $X(3872)$ excluded all J^{PC} except:
    - $J^{PC} = 2^{-+}$: Nearest in mass to $\eta_c(1^1D_2)$
    - $J^{PC} = 1^{++}$: $D^0\ D^*$ molecule, Tetra-quark
  - *BABAR* analysis of $X(3872) \to \omega J/\psi$ prefers 2^{-+} but does not exclude 1^{++} ↪ [PRD 82, 011101(R)]
  - Belle analysis of $X(3872) \to J/\psi\pi^+\pi^-$ prefers 1^{++} but does not exclude 2^{-+} ↪ [PRD 84 052004]

- New results from CMS and LHCb on $X(3872)$ production and J^{PC}

$B^{\pm} \to X(3872)K^{\pm}$ at LHCb

1 fb^{-1} @ 7 TeV: ↪ arXiv:1302.6269

- Selection: likelihood ratio classifier, $\left(\chi^2_{IP}(h), \chi^2_{IP}(B), \chi^2_{vtx}/ndf, \cos\theta_{\perp}(h, J/\psi)\right)$ signal/background shapes from MC, calibrated on $B^+ \to \psi(2S)K^+$ control channel



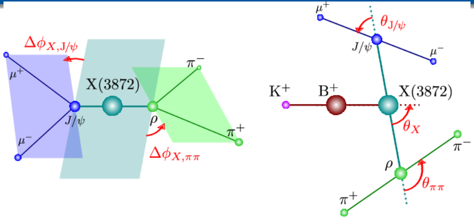
Yields:

- 5642 ± 76 $B^+ \to \psi(2S)K^+$
- 313 ± 26 $B^+ \to X(3872)K^+$

- Recent LHCb measurement of $X(3872)$ spin-parity using B decays

$X(3872)$ Angular Analysis

Exploit all angular correlations in the B decay → 5*D* decay model



- Only $\pi\pi$ P-wave contribution included
- Decay amplitude constructed in helicity formalism

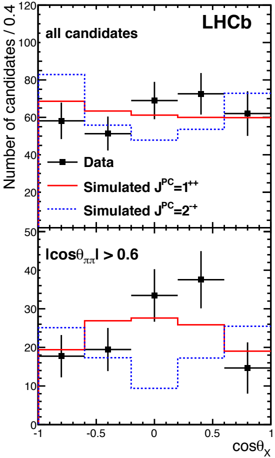
$$|\mathcal{M}(\Omega|J_X)|^2 = \sum_{\Delta\lambda_\mu=-1,+1} \Bigg| \sum_{\lambda_{J/\psi},\lambda_{\pi\pi}=-1,0,+1} A_{\lambda_{J/\psi},\lambda_{\pi\pi}} \times D^{J_X}_{0,\lambda_{J/\psi}-\lambda_{\pi\pi}}(\phi_X,\theta_X,-\phi_X) \times D^1_{\lambda_{\pi\pi},0}(\phi_{\pi\pi},\theta_{\pi\pi},-\phi_{\pi\pi}) \times D^1_{\lambda_{J/\psi},\Delta\lambda_\mu}(\phi_{J/\psi},\theta_{J/\psi},-\phi_{J/\psi}) \Bigg|^2$$

- Helicity couplings $A_{\lambda_{J/\psi},\lambda_{\pi\pi}}$ include one complex parameter α for $J^{PC}=2^{-+}$
  No free parameter for $J^{PC}=1^{++}$

- Full 5D angular analysis

$X(3872)$ angular correlations

5D fit using full information of B^+ decay chain



- How important are the angular correlations?
- Projections in $\cos\theta_X$ for all background-subtracted signal candidates (top) and background-subtracted signal candidates with $|\cos\theta_{\pi\pi}| > 0.6$ (bottom)
- Little discrimination between $J^{PC} = 1^{++}$ (red), $J^{PC} = 2^{-+}, \alpha = (0.671, 0.280)$ (blue) without using correlations!

- Data seem to support 1^{++} (red) bye eye...

Angular Analysis LogLikelihood

Background subtraction and acceptance correction

$$-2\ln\mathcal{L}(J_X) = -2s_w \sum_{i=1}^{N_{\text{data}}} w_i \frac{|\mathcal{M}(\Omega|J_X)|^2\epsilon(\Omega)}{I(J_X)}$$

- Normalization $I(J_X) = \int d\Omega|\mathcal{M}(\Omega|J_X)|^2\epsilon(\Omega)$

  Monte Carlo integration under the two hypothesis $J_X^{PC} = 1^{++}/2^{-+}$ with
- detector acceptance / selection efficiency $\epsilon(\Omega)$
- Background subtraction through sWeighting w_i (scale factor s_w)

Fitting the 2^{-+} hypothesis for helicity coupling

$$\alpha = (0.671 \pm 0.046, 0.280 \pm 0.046)$$

compatible with Belle result (0.64,0.27) $\hookrightarrow$ [PRD 84, 052004]

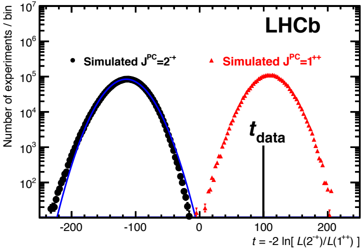
Test statistic to determine J^{PC}: $t = -2\ln[\mathcal{L}(2^{-+})/\mathcal{L}(1^{++})]$

- Use log ratio as test statistic

X(3872) 1^{++} vs 2^{-+} Hypotheses

LogLikelihood Ratio Test

- Likelihood ratio t
  - $t > 0$ implies $J^{PC} = 1^{++}$ favoured
  - $t < 0$ implies $J^{PC} = 2^{-+}$ favoured
- Compared to results for simulated $\mathrm{B}^{\pm} \to \mathrm{X}(3872)\mathrm{K}^{\pm}$ candidates



- $J^{PC} = 1^{++}$ compatible
- $J^{PC} = 2^{-+}$ rejected at $> 8\sigma$

- Fitting $J^{PC} = 1^{++}$ simulated events with 2^{-+} model for α yields consistent result

Sebastian Neubert | News on X,Y,Z States from Hadron Collider Experiments 9/22

- Data clearly favour 1^{++}, significant constraint on models!

$\mathrm{X}(3872)$ Prompt Production Cross Section

- Significant fraction of $\mathrm{X}(3872)$ found in prompt production at CDF
- Triggered discussion on $D^{*0}\bar{D}^0$ molecule interpretation
  $\hookrightarrow$ [PRL 103 (2009) 162001]
- NRQCD factorization explains large production cross section through rescattering effects and allows to predict $d\sigma^{\text{prompt}}/dp_T$ in $\mathrm{p\,\overline{p}}$ and $\mathrm{p\,p}$ collisions
  $\hookrightarrow$ [PRD 81 (2010) 114018]
- Inclusive production cross section measured at LHCb
  $\hookrightarrow$ [EPJ C72 (2012) 1972]
- New: Differential prompt production cross section by CMS

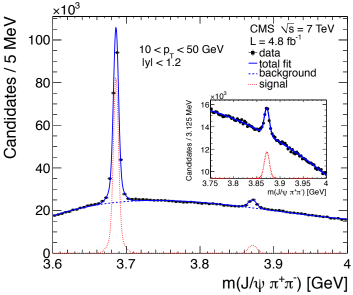
$X(3872)$ Production at CMS
in pp at $\sqrt{s} = 7$ TeV

Selection of $J/\psi\pi^+\pi^-$:

- 2011a(2011b) data taking periods, 4.8 fb^{-1} @ $\sqrt{s} = 7$ TeV
- Muons:

$$p_T(\mu) > \begin{cases} 4\,\text{GeV} & \text{if } |\eta(\mu)| < 1.2 \\ 3.3\,\text{GeV} & \text{if } 1.2 < |\eta(\mu)| < 2.4 \end{cases}$$

- J/ψ 2011a(2011b): $(|y(\mu\mu)| < 1.25)$ && $(p_T(\mu\mu) > 7(10)$ GeV$)$ && $(\Delta m J/\psi) < 75$ MeV$)$
- Correlation of $(\pi\pi)$ and J/ψ direction $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 0.55$
- $J/\psi\pi^+\pi^-$ candidates: $(|y| < 1.2)$ && $(10(13.5)$ GeV $< p_T < 50$ GeV$)$



- $\psi(2S)$ yield: $178\,540 \pm 850$
- $X(3872)$ yield: $11\,910 \pm 490$

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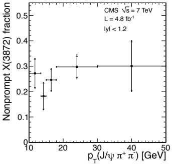
- Use relative $\psi(2S)$ vs. $X(3872)$ efficiencies to control systematics

$X(3872)$ Prompt Production

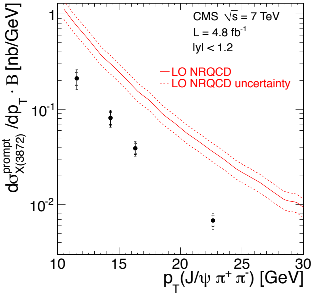
Differential cross section $d\sigma/dp_T$ at $\sqrt{s} = 7$ TeV

- Prompt/Non-Prompt ratio determined from a B-enriched sample with transverse decay-length $\ell_{xy} > 100\ \mu m$
- Efficiency of this cut as function of ℓ_{xy} from MC, xchecked on $\psi(2S)$



- Differential $\psi(2S)$ production cross section from ↪ [JHEP 02 (2012) 011]

Comparison with $D^{*0}\bar{D}^0$ molecule model from ↪ `arXiv:0911.2016`



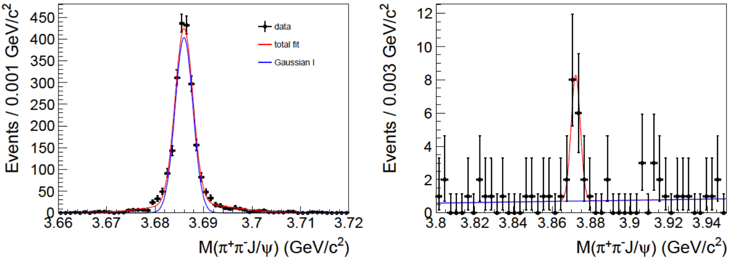
NRQCD curve from P. Artoisenet and E. Braaten

applied to CMS phase space

$\sigma^{\text{prompt}}(pp \to X(3872) + \text{any})\mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-) = 1.06 \pm 0.11 \pm 0.15\text{nb}$

- Data in clear disagreement with molecular model! (red line)

Observation of $e^+e^- \to \gamma X(3872)$



ISR ψ' signal is used for rate, mass, and mass resolution calibration.

N(ψ')=1242 ; Mass=3685.96±0.05 MeV; σ_M=1.84 ±0.06 MeV

BESIII preliminary

N(X(3872))=15.0±3.9 **5.3σ**

M(X(3872)) = 3872.1±0.8±0.3 MeV [PDG: 3871.68 ±0.17 MeV]

- **NEW:** Evidence for radiative decay $Y(4260) \to X(3872)\,\gamma$

Observation of $e^+e^- \to \gamma X(3872)$

$\sqrt{s}$ (GeV)	$\sigma^B[e^+e^- \to \gamma X(3872)] \cdot \mathcal{B}(X(3872) \to \pi^+\pi^- J/\psi)$ (pb)
4.009	< 0.13 at 90% C.L.
4.230	$0.32 \pm 0.15 \pm 0.02$
4.260	$0.35 \pm 0.12 \pm 0.02$
4.360	< 0.39 at 90% C.L.

It seems X(3872) is from Y(4260) decays. At 4.26 GeV,
$\sigma^B(e^+e^- \to \pi^+\pi^- J/\psi) = (62.9 \pm 1.9 \pm 3.7)$ pb,

$$\frac{\sigma[e^+e^- \to \gamma X(3872)] \cdot \mathcal{B}(X(3872) \to \pi^+\pi^- J/\psi)}{\sigma(e^+e^- \to \pi^+\pi^- J/\psi)} = (5.6 \pm 2.0) \times 10^{-3}$$

If we take $\mathcal{B}(X(3872) \to \pi^+\pi^- J/\psi) \sim 5\%$, (>2.6% in PDG)
$\frac{\sigma(e^+e^- \to \gamma X(3872))}{\sigma(e^+e^- \to \pi^+\pi^- J/\psi)} \sim 11.2\%$ Large transition ratio !

BESIII preliminary

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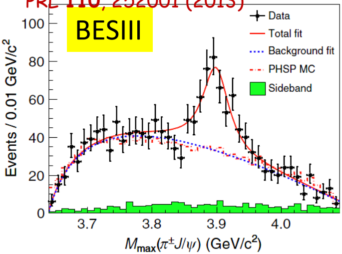
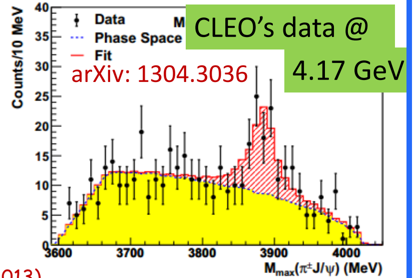
- Excess of $X(3872)\gamma$ events at $e^+e^- \to Y(4260)$ resonance

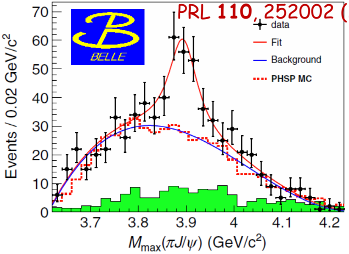
Observation of the $Z_c^{\pm}(3900)$ states

- The latest chapter in the *XYZ* story
- Two charged "charmonium-like" states
- Decays to $J/\psi\pi^{\pm}$, must contain at least 4 quarks!
- Slides from Zhiqing Liu (IHEP)

BESIII + Belle + CLEO's data







1. CLEO's data: M=3885$\pm$5 MeV, Γ=34$\pm$13 MeV.
2. Belle: M=(3894.5$\pm$6.6$\pm$4.5) MeV; Γ=(63$\pm$24$\pm$26) MeV.
3. BESIII: M=(3899.0$\pm$3.6$\pm$4.9) MeV; Γ=(46$\pm$10$\pm$20)MeV
4. Z_c(3900)=Z(3900)$^{\pm}$.

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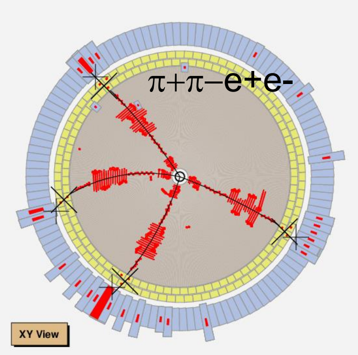
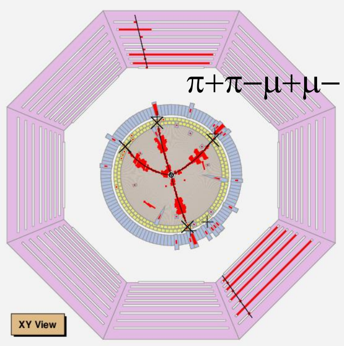
- Charged states recently observed by three experiments!

$Z_c(3900)$ from BESIII





1. Very simple and straightforward analysis.
2. The produced vector charmonium(like) state almost in rest frame.
3. Y(4260)→π+π−J/ψ, four charged track detected (π+π−e+e- & π+π−μ+μ−).

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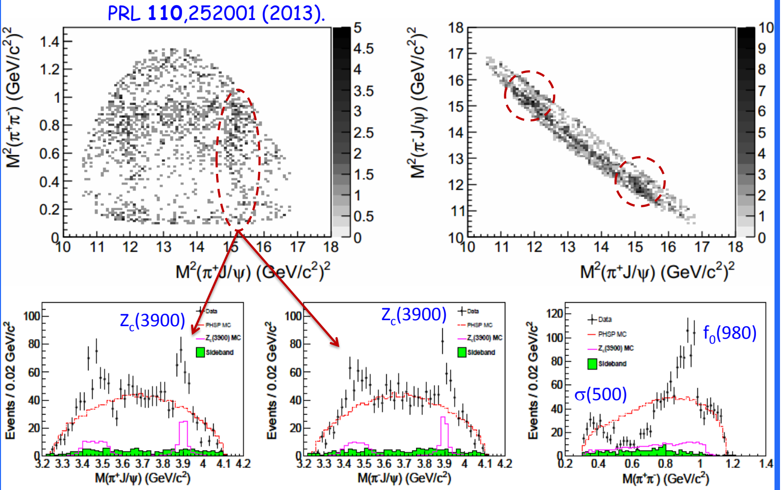
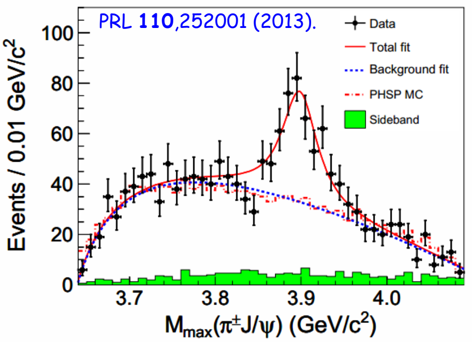
- BES perform Dalitz plot analysis of $Y(4260) \to J/\psi\pi^+\pi^-$ decays

$Z_c(3900)$ from BESIII



- Lower mass peaks in $M(J/\psi\pi^{\pm})$ are reflections of charge conjugate states



1. 1D fit to extract resonant parameters.
2. Divided Dalitz plot by diagonal line; Fit $M_{max}(\pi^{\pm}J/\psi)$ mass distribution.
3. S-Wave Breit Wigner; p*q phase space factor; efficiency applied.
4. $M=(3899.0\pm3.6\pm4.9)$MeV; $\Gamma=(46\pm10\pm20)$MeV.
5. Statistical significance: $>8\sigma$, discovery!

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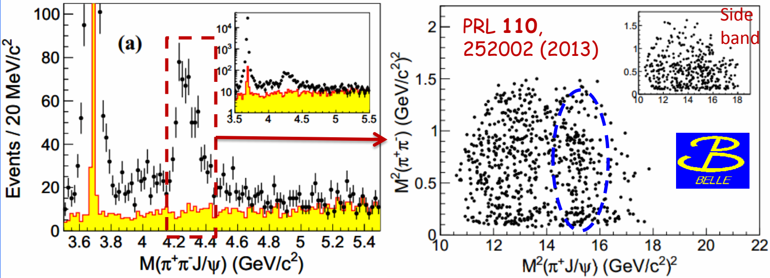
- Plot $M_{max.}(J/\psi\pi^{\pm})$ to combine $\pm$ state yields, clear structure!

Z(3900)$^{\pm}$ from Belle



1. Full Belle data sample used: Lum=967 fb^{-1}.
2. Study the $\pi^+\pi^-J/\psi$ using ISR photon non-tagged method.
3. Y(4260) was observed significantly, agree with BaBar.
4. 4.15<M($\pi^+\pi^-J/\psi$)<4.45 GeV to select Y(4260) events.
5. Dalitz plot shows structures in M($\pi^{\pm}J/\psi$) mass distribution.
6. J/ψ signal: [3.06,3.14]; sideband: [2.91,3.03]GeV & [3.17,3.29] GeV

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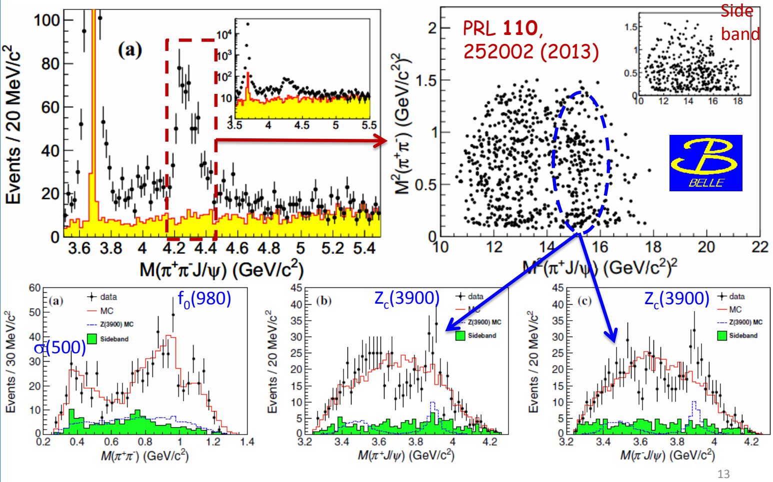
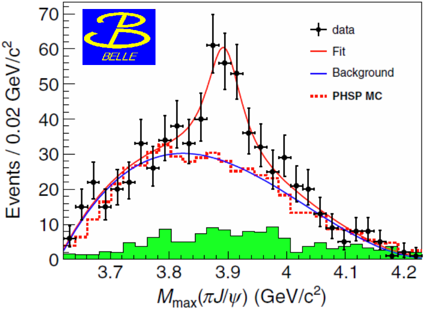
- Similar approach from Belle, same structre observed...

$Z(3900)^{\pm}$ from Belle



- Dalitz plots look almost identical, same structures and reflections

$Z(3900)^{\pm}$ from Belle



1. Belle observed 689 events, with 139 background in Y(4260) region.
2. Belle use the 1D fit strategy to $M_{max}(\pi^{\pm}J/\psi)$ distribution.
3. S-Wave BW, p*q phase space factor, efficiency applied.
4. $M=(3894.5\pm6.6\pm4.5)$ MeV; $\Gamma=(63\pm24\pm26)$ MeV.
5. Significance:5.2σ. Observation!

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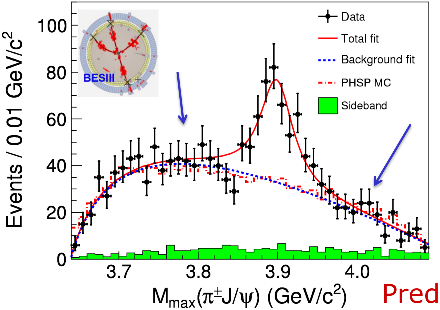
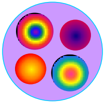
- Same clear peak in $M_{max.}(J/\psi\pi^{\pm})$

What is $Z_c(3900)$?



- Couples to $c\bar{c}$
- Has electric charge
- At least 4-quarks
- What is its nature?



- $\bar{D}D^*$ molecule?
- Tetraquark state?
- Cusp?
- Threshold effect?
- …

Predictions and more experimental information will be essential to understand its nature.

➔ A partner below/above Z_c?

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➔ Panel discussions on Monday

▶ Manifestly exotic! More properties needed to inform understanding...

Theoretical interpretation of the *XYZ* states

- <u>Many</u> ideas for what the *XYZ* states could be!
- No single model can describe all states!
- However, certain ideas seem to fit very well for some states...
- Slides from Eric Braaten (Ohio)

Models for *XYZ* Mesons

- conventional quarkonium ($Q\bar{Q}$)
- quarkonium hybrids ($Q\ \bar{Q}\ g$)
- quarkonium tetraquarks ($Q\ \bar{q}\ q\ \bar{Q}$)
  - compact tetraquark
  - meson molecule
  - diquark-onium
  - hadro-quarkonium

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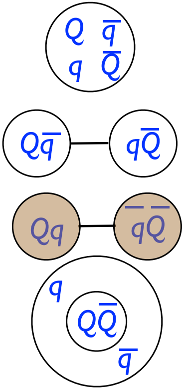
Models for *XYZ* Mesons

quarkonium tetraquarks

- compact tetraquark
- meson molecule
- diquark-onium
- hadro-quarkonium



- Born-Oppenheimer tetraquark! arXiv:1305.6905

▶

Models for *XYZ* Mesons

Conventional Quarkonium

$Q\ \bar{Q}$

- well-developed phenomenology
  based on potential models

- accurate <u>below</u> open-heavy-flavor threshold!
  how accurate <u>above</u>?

- spin-symmetry multiplets
  S-wave: $\{0^{-+}, 1^{--}\}$
  P-wave: $\{1^{+-}, (0,1,2)^{++}\}$
  D-wave: $\{2^{-+}, (0,1,2)^{--}\}$

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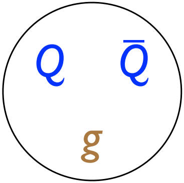
Models for *XYZ* Mesons



Quarkonium Hybrids

- small wave function for $Q\bar{Q}$ at the origin
  $Q\bar{Q}$ in color-octet state $\Longrightarrow$ repulsive potential

- suppression of decays into S-wave + S-wave mesons
  S-wave + P-wave preferred (if kinematically accessible)
  Close & Page 1995, Kou and Pene 2005

- constituent gluon picture

- Born-Oppenheimer picture

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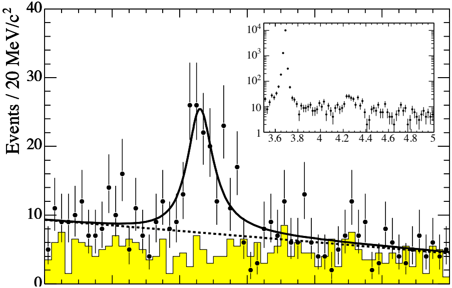
►

Models for *XYZ* Mesons

Charmonium Hybrid

Y(4260) Babar 2005

- *1*$^{--}$
- produced very weakly in e^+e^- annihilation
  $\Longrightarrow$ small wavefunction for $c\bar{c}$ at the origin
- not observed in S-wave + S-wave charm mesons



identify as
charmonium hybrid
Close and Page 2005

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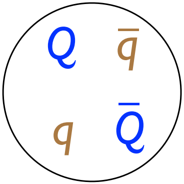
Models for *XYZ* Mesons

Compact Tetraquark



- spacially overlapping orbitals
- 2-body potentials only
  $\Longrightarrow$ fall-apart decays into meson+meson
  unless mass is below all meson pair thresholds
  Vijande, Valcarce, Richard
- 3-body and higher potentials?

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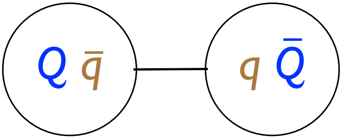
Models for *XYZ* Mesons

Meson Molecule



- constituents must be narrow
  - *S*-wave charm mesons: D, D^*, D_s, D_s^*
  - *P*-wave charm mesons: D_1, D_2^*, D_{s0}^*, D_{s1}, D_{s2}^*
- many *XYZ* mesons are near a charm-meson-pair threshold

Are *XYZ* mesons near thresholds just by coincidence?
25 nonstrange thresholds between 3770 and 5150 MeV!

Are charm mesons bound by their interactions?
π exchange between charm mesons Tornqvist 1993
isospin-0 bound states near threshold
$D^*\bar{D}$: $0^{-+}, 1^{++}$
$D^*\bar{D}^*$: $0^{++}, 0^{-+}, 1^{+-}, 2^{++}$

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Models for *XYZ* Mesons

Definitive Meson Molecule: *X(3872)*

X(3872)

- extremely close to threshold for $D^{*0}\,\bar{D}^0$

  below threshold by 0.3±0.4 MeV   Belle, CDF, LHCb
- quantum numbers 1^{++} LHCb

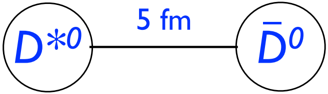
  $\Longrightarrow$ S-wave coupling to $D^{*0}\,\bar{D}^0$

must be loosely bound molecule

superposition of $D^{*0}\,\bar{D}^0$ and $D^0\,\bar{D}^{*0}$

rms separation of charm mesons: 5 fm

(if binding energy is 0.3 MeV)



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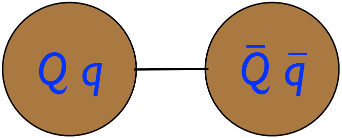
Models for *XYZ* Mesons

Diquark-Onium



- diquark Qq: color anti-triplet, spin 0 or 1

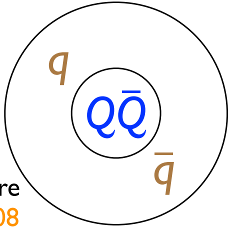
- for q = u,d only
  degenerate isospin-0 and isospin-1 multiplets
  quantum numbers: $0^{++}, 0^{++}, 0^{++}, 0^{++}$
  $1^{+-}, 1^{+-}, 1^{++}, 1^{++}$
  $2^{++}, 2^{++}$

- include q = s
  orbital excitations?
  radial excitations?

proliferation of predicted states!

Models for *XYZ* Mesons

Hadro-Quarkonium



- light quarks bound to color-singlet $Q\bar{Q}$ core
  Dubynskiy & Voloshin 2008
- or light meson bound to quarkonium
- motivation: many *XYZ* mesons observed
  though single hadronic transition
  to specific charmonium and light meson

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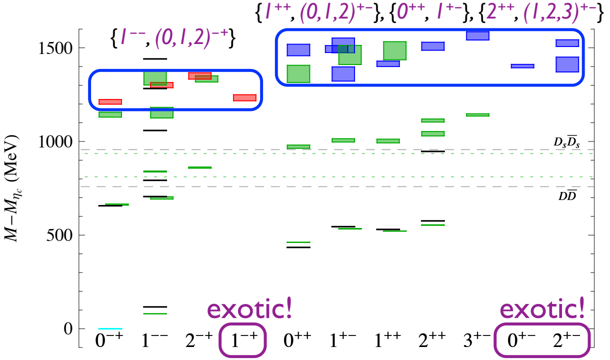
►

Lattice QCD for charmonium

Hadron Spectrum Collaboration 2012

charmonium hybrid candidates
fill out 4 spin-symmetry multiplets



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►

Conclusions

discoveries of neutral *XYZ* mesons

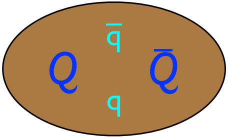
bottomonium tetraquarks Z_b, Z_b'

charmonium tetraquarks Z_c, Z_c'

have revealed a serious gap in our understanding of the QCD spectrum

none of the proposed models for the *XYZ* mesons has yet presented a compelling pattern

new proposal: Born-Oppenheimer hybrids and tetraquarks



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►

Charmonium Production at the LHC

- Important window on QCD
- Several new results from LHC experiments

Quarkonium Production Theory Review

- Still no firm understanding of quarkonium production and polarisation in hadroproduction
- NRQCD factorisation seems best candidate so far...
- Slides from Mathias Butenschön (Vienna))

Production and Decay Rates of Heavy Quarkonia

Heavy Quarkonia: Bound states of heavy quark and antiquark.

The classic approach: Color-singlet model

- Calculate cross section for heavy quark pair in physical **color singlet** (=color neutral) state. In case of J/ψ: $c\bar{c}[^3S_1^{[1]}]$
- Multiply by quarkonium wave function at origin
- Leftover IR singularities in case of *P* wave quarkonia
- Mid 90's: Strong disagreement with Tevatron data apparent

Nonrelativistic QCD (NRQCD):

- Rigorous effective field theory: Bodwin, Braaten, Lepage (1995)
- Based on **factorization of soft and hard scales** (Scale hierarchy: $Mv^2, Mv \ll \Lambda_{QCD} \ll M$)
- Not proven yet. Large part of talk: **Tests of NRQCD factorization**

Further approaches: k_T factorization, Color Evaporation Model

J/ψ Production with NRQCD

Factorization theorem: $\sigma_{J/\psi} = \sum_n \sigma_{c\bar{c}[n]} \cdot \langle O^{J/\psi}[n] \rangle$

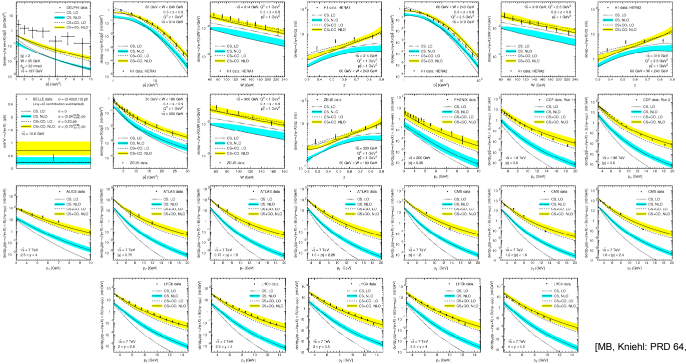
- ***n***: Every possible Fock state, including **color-octet** (CO) states.
- $\boldsymbol{\sigma_{c\bar{c}[n]}}$: Production rate of $c\bar{c}[n]$, calculated in perturbative QCD
- $\boldsymbol{\langle O^{J/\psi}[n] \rangle}$: Long distance matrix elements (LDMEs): describe $c\bar{c}[n] \rightarrow J/\psi$, universal, extracted from experiment.

Scaling rules: LDMEs scale with definite power of v ($v^2 \approx 0.2$):

scaling	v^3	v^7 ("CO states")	v^{11}
n	$^3S_1^{[1]}$	$^1S_0^{[8]}$, $^3S_1^{[8]}$, $^3P_J^{[8]}$	...

- **Double expansion** in v and α_s
- Leading term in v ($n = {}^3S_1^{[1]}$) equals **color-singlet model**.

Global Fit to Unpolarized Data

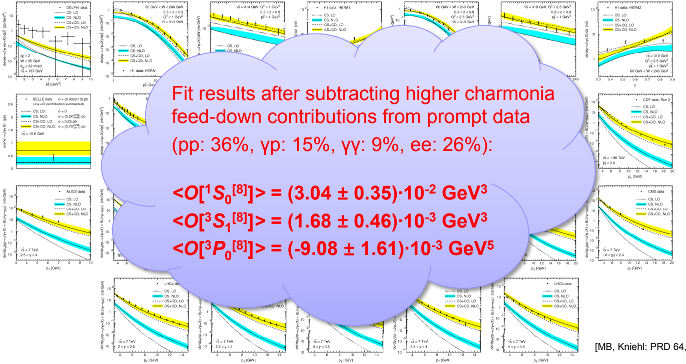


[MB, Kniehl: PRD 64, 051501R]

$<\mathcal{O}[{}^1S_0^{[8]}]> = (4.97 \pm 0.44)\cdot 10^{-2}\ \mathrm{GeV}^3$ $<\mathcal{O}[{}^3S_1^{[8]}]> = (2.24 \pm 0.59)\cdot 10^{-3}\ \mathrm{GeV}^3$

$<\mathcal{O}[{}^3P_0^{[8]}]> = (-1.61 \pm 0.20)\cdot 10^{-2}\ \mathrm{GeV}^5$

Global Fit to Unpolarized Data



Fit results after subtracting higher charmonia feed-down contributions from prompt data (pp: 36%, γp: 15%, γγ: 9%, ee: 26%):

$\langle O[^1S_0^{[8]}]\rangle = (3.04 \pm 0.35)\cdot 10^{-2}$ GeV^3

$\langle O[^3S_1^{[8]}]\rangle = (1.68 \pm 0.46)\cdot 10^{-3}$ GeV^3

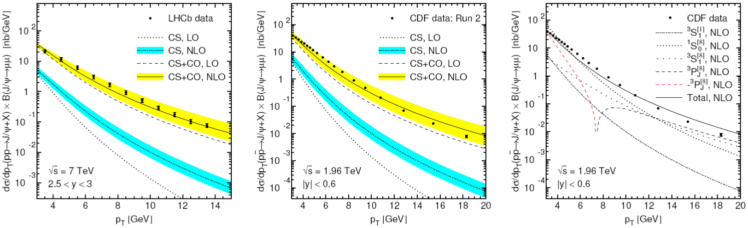
$\langle O[^3P_0^{[8]}]\rangle = (-9.08 \pm 1.61)\cdot 10^{-3}$ GeV^5

[MB, Kniehl: PRD 64, 051501R]

$\langle O[^1S_0^{[8]}]\rangle = (4.97 \pm 0.44)\cdot 10^{-2}$ GeV^3 $\langle O[^3S_1^{[8]}]\rangle = (2.24 \pm 0.59)\cdot 10^{-3}$ GeV^3

$\langle O[^3P_0^{[8]}]\rangle = (-1.61 \pm 0.20)\cdot 10^{-2}$ GeV^5

In Detail: Hadroproduction (LHC, Tevatron)

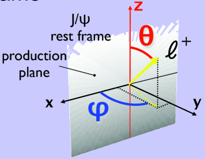


- Color singlet model **far below** data. **CS+CO** describes data **well**.
- $^3P_J^{[8]}$ short distance cross section **negative** at $p_T > 7$ GeV.
- But: Short distance cross sections and LDMEs **unphysical**
  ➡ No problem!
- Hadroproduction data below $p_T = 3$ GeV excluded from our fit.
- Observation: Change s or rapidity y just **rescaling** of cross sections: CO LDMEs describing RHIC or Tevatron must also describe LHC!

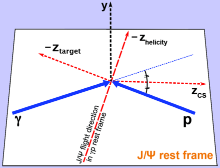
J/ψ Polarization

- **Angular distribution** of decay lepton l^+ in *J/ψ* rest frame
  ➡ Polarization observables ***λ***, ***μ***, ***ν***:

$$\frac{d\Gamma(J/\psi \to l^+ l^-)}{d\cos\theta\, d\phi} \propto 1 + \lambda \cos^2\theta + \mu \sin(2\theta)\cos\phi + \frac{\nu}{2}\sin^2\theta\cos(2\phi)$$



- Depends on choice of **coordinate system:**
  - Helicity frame: z axis $\parallel -(\vec{p}_\gamma + \vec{p}_p)$
  - Collins-Soper frame: z axis $\parallel \vec{p}_\gamma/|\vec{p}_\gamma| - \vec{p}_p/|\vec{p}_p|$
  - Target frame: z axis $\parallel -\vec{p}_p$

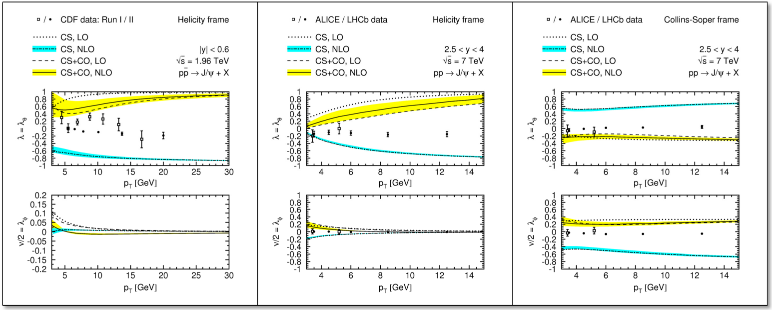


- **In Calculation:** Plug in explicit expressions for $c\bar{c}[n]$ spin polarization vectors according to

$$\lambda = \frac{d\sigma_{11} - d\sigma_{00}}{d\sigma_{11} + d\sigma_{00}}, \quad \mu = \frac{\sqrt{2}\mathrm{Re}\, d\sigma_{10}}{d\sigma_{11} + d\sigma_{00}}, \quad \nu = \frac{2 d\sigma_{1,-1}}{d\sigma_{11} + d\sigma_{00}}$$

- We use the CO LDME set with feed-down contributions subtracted.

J/ψ Polarization in Hadroproduction



[MB, Kniehl: PRL 108, 172002]

- **Helicity frame**: NRQCD predicts strong **transverse** polarization at high p_T.
- **Collins-Soper frame**: NRQCD predicts slightly longitudinal J/ψ.
- **Disagreement** with CDF Run II data, and with new ALICE and LHCb data.
  ➡ **Challenge to LDME universality!**

Overview: Three J/ψ Production Works

AGREEMENT:
Can NOT describe e^+e^-, γp, pp yield and pp polarization with same LDMEs.

	e^+e^- yield:	γp yield:	pp yield:	CDF polariz.:

Butenschön, K...

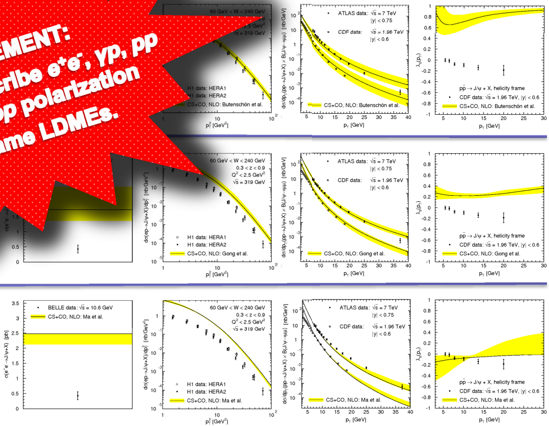
$\langle O_8^{J/\psi}(^1S_0)\rangle$ ...
$\langle O_8^{J/\psi}(^3S_1)\rangle$ ...
$\langle O_8^{J/\psi}(^3P_0)\rangle = -$ ...

Gong, W...
H.-F. Zh...

$\langle O_8^{J/\psi}(^1S_0)\rangle$ ...
$\langle O_8^{J/\psi}(^3S_1)\rangle = -0.0046$ GeV ...
$\langle O_8^{J/\psi}(^3P_0)\rangle = -0.0214$ GeV^5 ... 0.0095 ...
$\langle O_8^{\chi_0}(^3S_1)\rangle = 0.$ ... eV^3

Chao, Ma, Shao, K. Wang, Y.-J. Zhang:

$\langle O_8^{J/\psi}(^1S_0)\rangle = 0.089$ GeV^3
$\langle O_8^{J/\psi}(^3S_1)\rangle = 0.003$ GeV^3
$\langle O_8^{J/\psi}(^3P_0)\rangle = 0.0126$ GeV^5



M. Butenschön Theory of Charmonium Production **15/21**

LDME Universality Problem: Possible Ways Out

If LDMEs not universal ⟶ Problem!

BUT IT MAY WELL BE THAT…

- Velocity (v) expansion converges only slowly (Wait for future calculations.)
- NRQCD factorization does only hold for exclusive production
  (All tests performed for inclusive processes.)
- NRQCD factorization does only hold for $p_T \gg M_{onium}$
  (HERA data only up to $p_T = 10$ GeV. Wait for future *ep* collider.)
- NRQCD factorization does only hold for unpolarized production
  (Orbital and spin angular momentum might decouple strictly only in spin-averaged observables.)

- After all: Ongoing effort to prove NRQCD factorization to all orders!
- Also: Ongoing effort to resum large logarithms p_T/M_{onium}!

k_T Factorization Approach

Apply k_T factorization to quarkonium production:

- **Idea:** Scales of quarkonium production much smaller than collision energy:

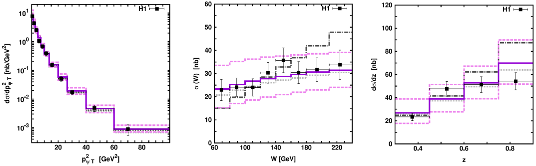
  $$p_T, m_c \ll \sqrt{s}$$

  ➡ Longitudinal parton momentum fractions x small, **transverse parton momenta k_T** should not be neglected.
- Use **off shell** matrix elements with k_T dependence entering via

  $$\varepsilon^\mu(k_T) = k_T^\mu / |\vec{k}_T| \,.$$
- Usually just LO matrix elements used.
- Fold with k_T dependent, **unintegrated PDFs**.
- **Various prescriptions** for deriving uPDFs from usual PDFs in DGLAP, BFKL or “CCFM” approach.
- Monte Carlo program **CASCADE** simulates initial state gluon radiation within k_T factorization framework [Jung, Salam (2001)].

k_T Factorization Approach: Results (1)

- Baranov, Lipatov, Zotov (2011); Baranov, Lipatov, Zotov (2012): **Color Singlet Model** predictions for various uPDFs:



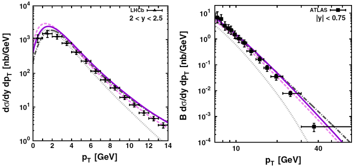


TABLE I. The polarization parameters of prompt J/ψ mesons calculated in the kinematical region of CMS and ATLAS measurements [27,28]. The CCFM A0 gluon density is used.

Source	λ_θ (HX)	λ_ϕ (HX)	$\lambda_{\theta\phi}$ (HX)	λ_θ (CS)	λ_ϕ (CS)	$\lambda_{\theta\phi}$ (CS)
Direct	−0.15	−0.09	0.01	0.20	−0.22	−0.01
Feed-down	0.19	0.14	0.00	0.35	0.09	0.00
Total	−0.07	−0.03	0.01	0.24	−0.14	−0.01

➡ **No room** and no need for **color octet** contributions.

Summary

- 40 years after J/ψ discovery:
  Still no successful description of charmonium production!
- Traditional color singlet model:
  - Can successfully describe only e^+e^- data
  - Theoretically incomplete due to uncancelled IR divergences
- NRQCD factorization based on solid effective field theory approach, but
  - Factorization theorem not yet proven (IR safe to all orders?)
  - Current NLO analyses in combination with recent polarization measurements cast doubt on LDME universality.
- Possible ways out:
  - NRQCD factorization may not hold in all kinematic regions / for all observables
  - Resummation of large logrithms p_T^2/m_c^2 (large p_T resummation)
  - Apply k_T dependent PDFs.

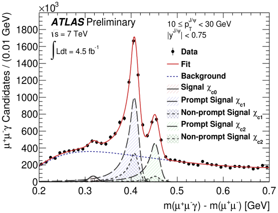
New ATLAS Charmonium Production Results

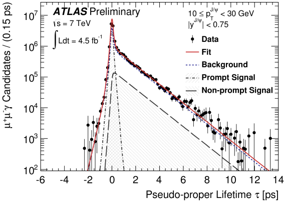
- New results on χ_c production ($\leftarrow$ Birmingham involvement!)
- New results on $\psi(2S)$ production
- Slides from Lee Alison (Lancaster)

χ_c decay to $J/\psi\gamma$ production measurement

Poster by Andy Chisholm

ATLAS-CONF-2013-095





- Using 4.46 fb^{-1} at 7 TeV (2011)
- A triplet state with large radiative branching fraction into $J/\psi\gamma$
  - $J/\psi \rightarrow \mu^+\mu^-$
    - Using di-muons in the barrel region only, $|y| < 0.75$
  - Photon reconstructed from $\gamma \rightarrow e^+e^-$ conversions in ID (provides necessary resolution)
    - Soft photons typically < 5 GeV
- χ_{c1} and χ_{c2} have easily identifiable and well separated signal peaks
  - χ_{c0} is not measured, as inclusive yield too low for reliable measurements

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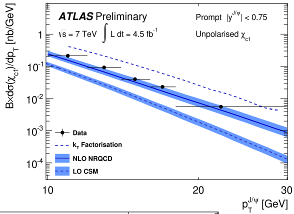
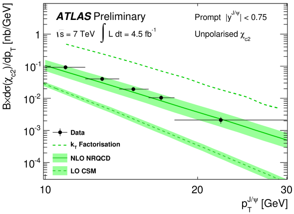
- Use photon conversions to reconstruct $\chi_c \rightarrow J/\psi\gamma$, clear χ_{cJ} signals!

$\chi_{c1,2}$ prompt cross-section

ATLAS-CONF-2013-095

- Prompt cross-sections are measured as a function J/ψ p_T
  - In the region J/ψ |y| < 0.75
  - Assuming unpolarised production
- Compared to 3 theoretical models:
  - NLO NRQCD
    - Good agreement to data
  - k_T factorisation
    - Predicts a larger cross-section than the one measured
  - LO CSM
    - Underestimates the data





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- Measurements separated in to prompt and non-prompt (*b* hadron decay)

$\chi_{c1,2}$ non-prompt cross-section

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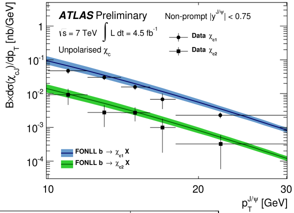
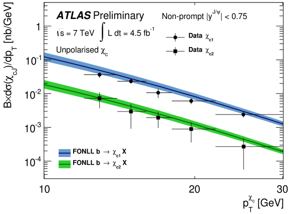
- Non-prompt cross-sections are measured as a function of both J/ψ p_T and χ_c p_T
  - In the region J/ψ |y| < 0.75
  - Assuming unpolarised production
- Compared to
  - FONLL
    - Good agreement with data





χ_c cross-section ratios

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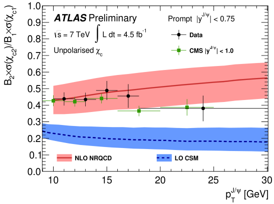
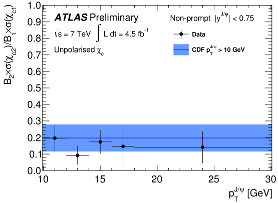
- Prompt cross-section ratio χ_{c2}/χ_{c1} is a well known puzzle, as there is a lot more χ_{c1} than χ_{c2}
  - Compared to CMS result
  - NLO NRQCD
    - General good agreement with data
  - LO CSM
    - Underestimates the data
- Non-prompt cross-section ratio χ_{c2}/χ_{c1} is expect to be around 0.191
  - Compared to CDF result





CMS Collaboration, Eur.Phys.J. C72 (2012) 2251
CDF Collaboration, Phys.Rev.Lett. 98 (2007) 232001

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- Prompt cross section ratio sensitive to production mechanism

χ_c fractions

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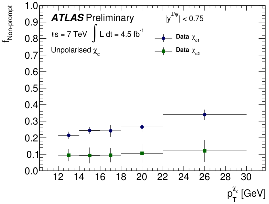

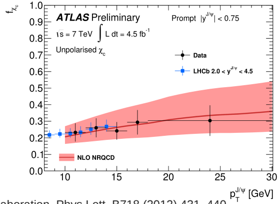

LHCb Collaboration, Phys.Lett. B718 (2012) 431–440

- The non-prompt fraction measurement, shows that the production of $\chi_{c1,2}$ is mostly prompt
  - This is opposite to what is seen in J/ψ and ψ(2S)
  - First time measured at the LHC
- Fraction of prompt J/ψ produced in χ_c decays is the sum of χ_{c1} & χ_{c2} (Without χ_{c0} it is still a good approximation)
  - This provides an estimate of the contribution to prompt J/ψ ~25%
- Measure of the Br($B^+ \rightarrow \chi_{c1} K^+$) was also preformed (see backup)

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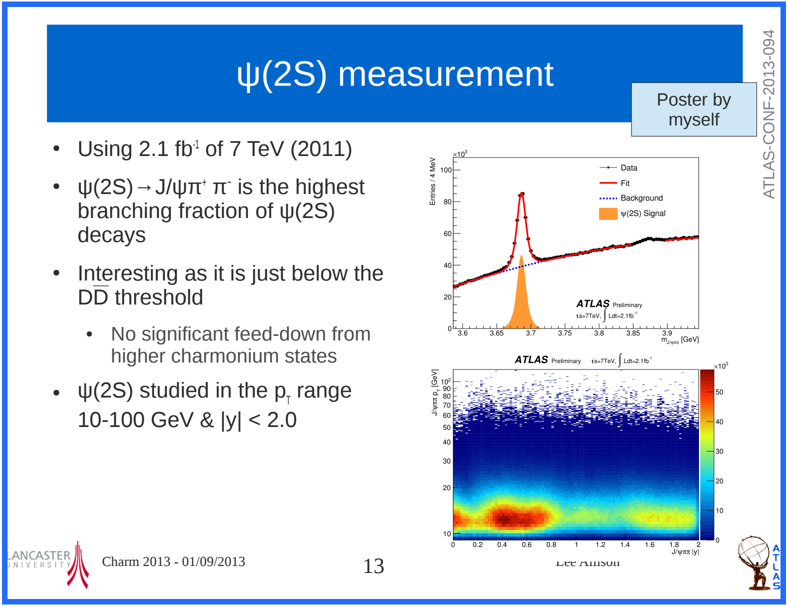
- Measurements show $\sim 25\%$ of prompt J/ψ produced in χ_c decays



- $\psi(2S)$ is a clean probe of the production mechanism - no significant feed-down

ψ(2S) Yields

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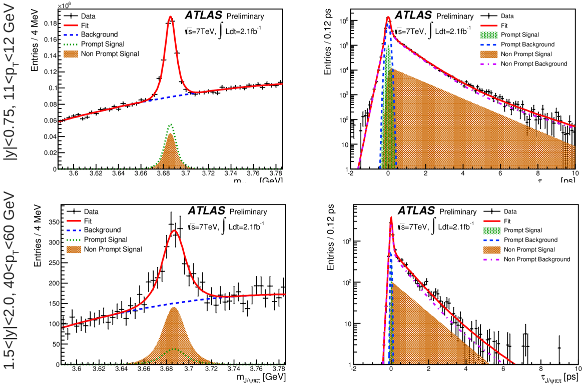

- The analysis had to take into account the additional acceptance and efficiency correction
- A result of using pions as-well as muons

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- Same 2D mass-lifetime fit approach as χ_c measurement

ψ(2S) cross-Section compared to existing results

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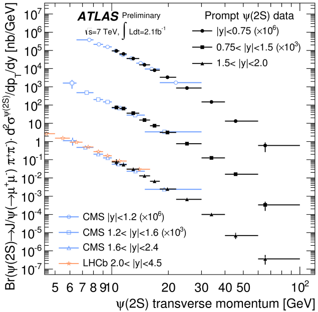
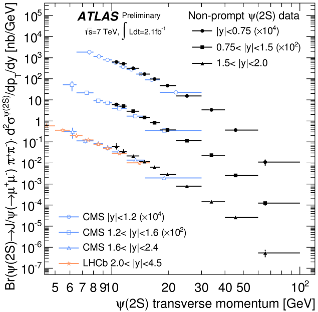


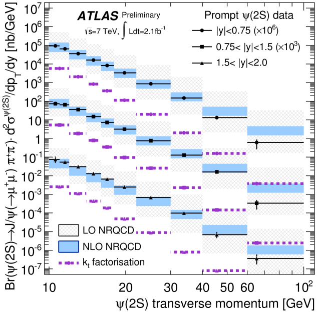
Where CMS & LHCb use the ψ(2S)→μμ

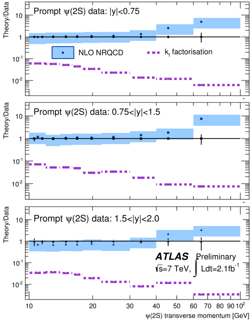


- Good agreement with existing LHC result
- Extends on existing results

ψ(2S) prompt cross-section compared to theory

ATLAS-CONF-2013-094





- LO & NLO NRQCD (NLO NRQCD has good agreement with data, except for the highest p_T region)
- k_T factoriastion (Clearly underestimates data)

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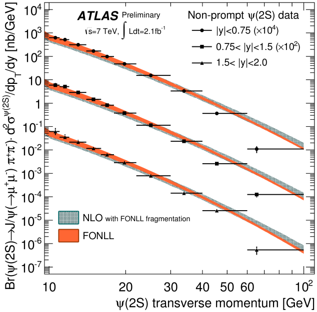
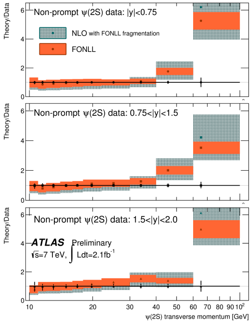
- Good agreement with NRQCD predictions

ψ(2S) non-prompt cross-section compared to theory

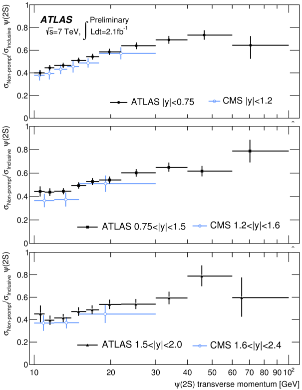
ATLAS-CONF-2013-094





- NLO & FONLL (Both describing the data reasonably well at low p_T, but starts to diverge at higher p_T)

ψ(2S) non-prompt fraction



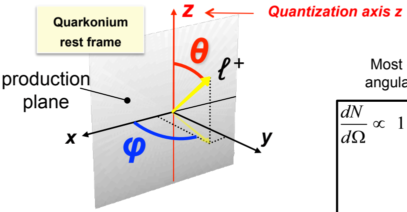
- The non-prompt fraction is a useful measurement as some of the systematic effects cancel out
- The results show that there is no significant dependence on rapidity
- The majority of events at higher p_T are non-prompt.

ATLAS-CONF-2013-094

Recent CMS Quarkmonium Polarisation Results

- Recent results on ψ and Υ polarisation
- Rigorous test NRQCD predictions
- Un-expected result
- Slides from Linlin Zhang (Peking)

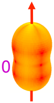
Quarkonium polarization: variables and frames



Most general observable angular decay distribution:

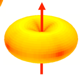
$$\frac{dN}{d\Omega} \propto 1 + \lambda_\theta \cos^2\theta + \lambda_\varphi \sin^2\theta \cos 2\varphi + \lambda_{\theta\varphi} \sin 2\theta \cos\varphi$$

$\lambda_\theta = +1$
$\lambda_\varphi = \lambda_{\theta\varphi} = 0$



$J_z = \pm 1 \rightarrow$ λ_θ **= +1** : **"transverse"** polarization

$\lambda_\theta = -1$
$\lambda_\varphi = \lambda_{\theta\varphi} = 0$

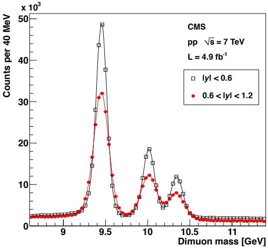


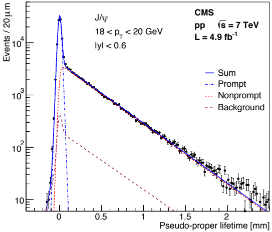
$J_z = 0 \rightarrow$ λ_θ **= -1** : **"longitudinal"** pol.

- CMS measured λ_ϑ, λ_φ, $\lambda_{\vartheta\varphi}$ and $\tilde{\lambda}$ in three frames (HX, CS, PX)
- Data collected in 2011 using dimuon trigger with $L_{\text{int}} = 4.9\,\text{fb}^{-1}$
- As a function of dimuon p_{T}

  J/ψ: $14 < p_{\text{T}} < 70$ GeV (10 bins)
  $\psi(2S)$: $14 < p_{\text{T}} < 50$ GeV (4 bins)
  $\Upsilon(nS)$: $10 < p_{\text{T}} < 50$ GeV (5 bins)
- And dimuon rapidity $|y|$

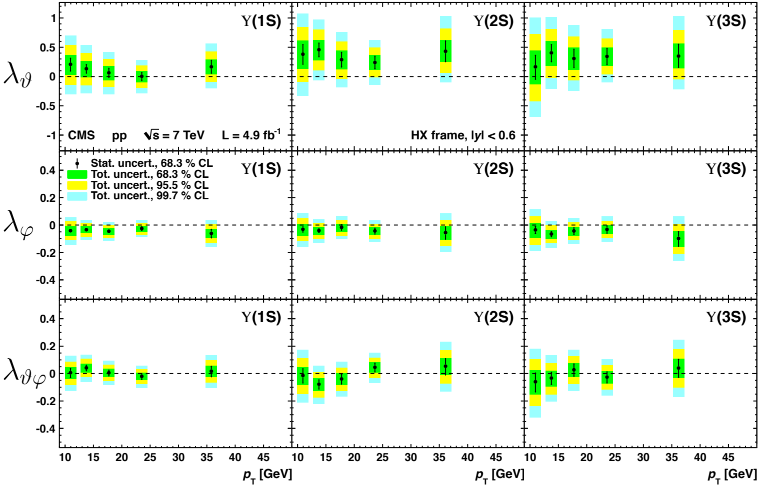
  $\text{J}/\psi, \Upsilon(nS) : |y| < 1.2$ (2 bins)
  $\psi(2S) : |y| < 1.5$ (3 bins)
- For J/ψ and $\psi(2S)$, non-prompt components need to be taken into account





- High statistics data sample, very good $m(\mu^+\mu^-)$ resolution

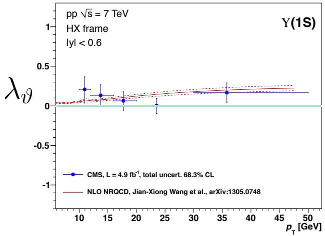
$\Upsilon(nS)$ polarization in the HX frame, $|y| < 0.6$

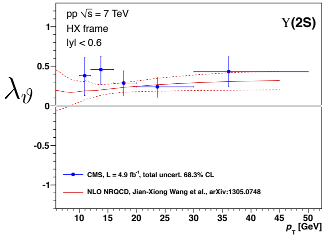


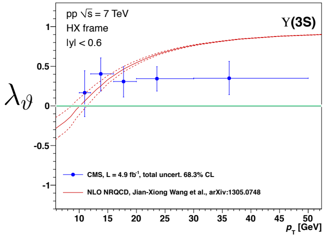
Quarkonium Production and Polarization at CMS | Linlin ZHANG (PKU) | 12 / 16

- All Λ consistent with zero, Υ production is ∼unpolarised

$\Upsilon(nS)$: Comparison to NLO NRQCD







- Color octet matrix elements are fit to hadroproduction data only
- Theory calculations account for feed-down contributions to $\Upsilon(1S)$ and $\Upsilon(2S)$ states
- Calculations for $\Upsilon(3S)$ may change once including feed-down from $\chi_b(3P)$

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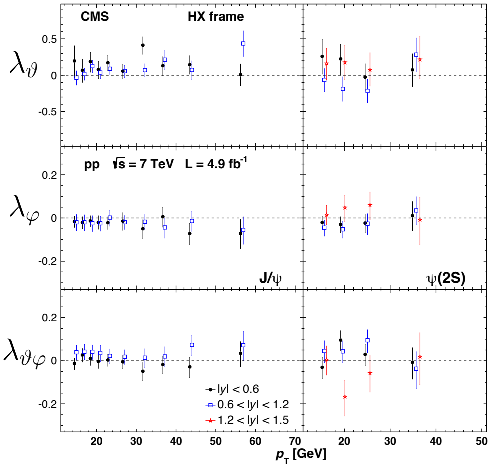
- Feed-down dilutes polarisation, now also true for $\Upsilon(3S)$ with $\chi_b(3P)$ discovery

Prompt $\psi(nS)$ polarization in the HX frame

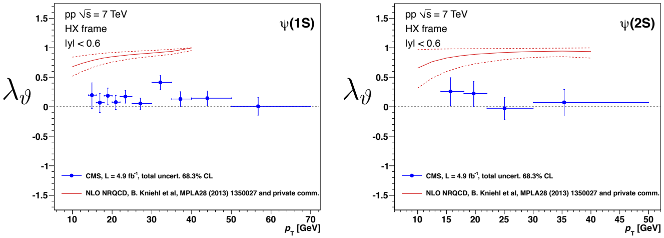


- No signs of strong polarizations
- The $\psi(2S)$ is not affected by feed-down from heavier quarkonia $\rightarrow$ easier comparison to theory

Error bars show total uncertainties at 68.3% CL

- Same story for ψ, no feed-down for $\psi(2S)$ but still no polarisation!

$\psi(nS)$: Comparison to NLO NRQCD



- CMS results disagree with existing NLO NRQCD calculations
- Calculations use a global fit of color octet matrix elements to photo- as well as hadroproduction data
- Theory predictions are for the polarization of the directly produced J/ψ's, not accounting for the feed-down from decays of P-wave states

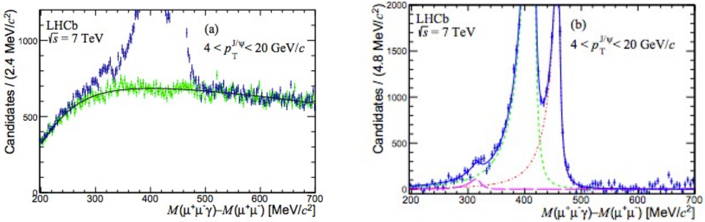
- χ_c contribution must be an important factor!

Recent LHCb Quarkmonium Results

- Recent results on relative χ_{c1} and χ_{c2} production
- Recent results on J/ψ polarisation
- Study of J/ψ production in pA collisions
- Exclusive charmonium production
- Slides from Denis Derkach (Oxford)

Background estimation and integrated results

We fix the shape of the background distribution to the "fake" photons: the energy for them is set to twice that of e^+ or e^-. We than subtract this distribution and then perform the fit to the data using Crystal Ball functions to describe the χ_c signal



We measure

$$\sigma(\chi_{c0})/\sigma(\chi_{c2}) = 1.19 \pm 0.27\,(\text{stat}) \pm 0.29\,(\text{syst}) \pm 0.16\,(p_T\,\text{model}) \pm 0.09\,(\mathcal{B})$$

the uncertainties are: statistical, systematics, p_t modeling, branching fraction.

This gives the first evidence of χ_{c0} production at the hadron collider at 4.3σ significance

For comparison, we obtain

$$\sigma(\chi_{c2})/\sigma(\chi_{c1}) = 0.787 \pm 0.014\,(\text{stat}) \pm 0.034\,(\text{syst}) \pm 0.051\,(p_T\,\text{model}) \pm 0.047\,(\mathcal{B})$$

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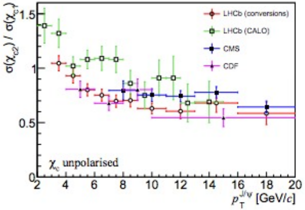
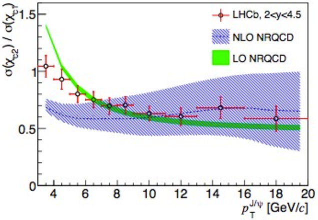
- χ_c ratio (arXiv:1307.4285): First measurement of $\sigma(\chi_{c0})/\sigma(\chi_{c2})$

Results in transverse momentum bins

To compare to theory, we also measure $\sigma(\chi_{c1})/\sigma(\chi_{c2})$ as a function of transverse momentum.





NLO NRQCD: PRD 83, 111503(R) (2011)
LO NRQCD: arXiv:1305.2389

The statistical and systematic uncertainties are not correlated to our previous analysis.

the uncertainties are: statistical, systematics, branching fraction and unknown polarisation

$p_T^{J/\psi}$ [GeV/c]	$\sigma(\chi_{c2})/\sigma(\chi_{c1})$
$3-4$	$1.037 \pm 0.033(\text{stat}) \pm 0.060(\text{syst}) \pm 0.062\ (\mathcal{B})\ ^{+0.10}_{-0.03}(\text{pol})$
$4-5$	$0.923 \pm 0.029(\text{stat}) \pm 0.060(\text{syst}) \pm 0.055\ (\mathcal{B})\ ^{+0.05}_{-0.02}(\text{pol})$
$5-6$	$0.795 \pm 0.028(\text{stat}) \pm 0.048(\text{syst}) \pm 0.048\ (\mathcal{B})\ ^{+0.03}_{-0.03}(\text{pol})$
$6-7$	$0.746 \pm 0.032(\text{stat}) \pm 0.044(\text{syst}) \pm 0.045\ (\mathcal{B})\ ^{+0.05}_{-0.05}(\text{pol})$
$7-8$	$0.692 \pm 0.039(\text{stat}) \pm 0.040(\text{syst}) \pm 0.042\ (\mathcal{B})\ ^{+0.08}_{-0.08}(\text{pol})$
$8-9$	$0.699 \pm 0.044(\text{stat}) \pm 0.041(\text{syst}) \pm 0.042\ (\mathcal{B})\ ^{+0.08}_{-0.10}(\text{pol})$
$9-11$	$0.625 \pm 0.035(\text{stat}) \pm 0.036(\text{syst}) \pm 0.038\ (\mathcal{B})\ ^{+0.11}_{-0.09}(\text{pol})$
$11-13$	$0.600 \pm 0.057(\text{stat}) \pm 0.036(\text{syst}) \pm 0.036\ (\mathcal{B})\ ^{+0.13}_{-0.13}(\text{pol})$
$13-16$	$0.675 \pm 0.067(\text{stat}) \pm 0.051(\text{syst}) \pm 0.040\ (\mathcal{B})\ ^{+0.15}_{-0.15}(\text{pol})$
$16-20$	$0.581 \pm 0.096(\text{stat}) \pm 0.038(\text{syst}) \pm 0.035\ (\mathcal{B})\ ^{+0.15}_{-0.15}(\text{pol})$

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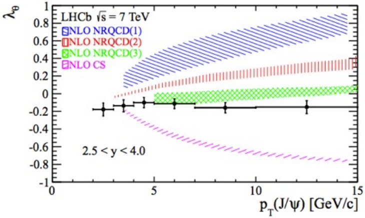
- Some discrepancy between new and old (calo.) LHCb results at low p_T...

Results

We obtain the following results in the Helicity frame:



NLO CS and NRQCD 1: Nucl. Phys. Proc. Suppl. B222-224 (2012) 151
NLO NRQCD 2: Phys. Rev. Lett. 110 (2013) 042002
NLO NRQCD 3: Phys. Rev. Lett. 108 (2012) 242004,

In addition, we update the cross-section results:

$$\sigma_{\text{prompt}}(2 < y < 4.5, 2 < p_{\text{T}} < 14\,\text{GeV}/c) = 4.88 \pm 0.01 \pm 0.27 \pm 0.12\ \mu\text{b}$$

$$\sigma_{\text{prompt}}(2 < y < 4.5, p_{\text{T}} < 14\,\text{GeV}/c) = 9.46 \pm 0.04 \pm 0.53\,^{+0.86}_{-1.10}\ \mu\text{b}$$

Previously, results had high systematic uncertainty due to the unknown polarisation up to 20%)

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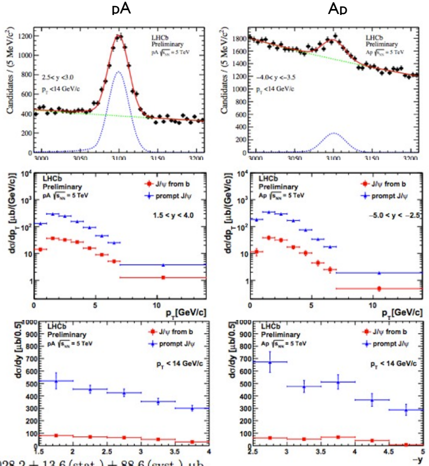
- J/ψ polarisation (arXiv:1307.6379): Again, no strong polarisation!

The analysis was performed using data collected in September 2012. A particular benefit of LHCb detector is again its coverage in rapidity.

The full study of production is performed, we extract the differetial cross-section and the full cross-section.



$$\sigma_{\mathrm{Ap}}(\text{prompt } J/\psi; p_{\mathrm{T}} < 14 \text{ GeV}/c, -5.0 < y < -2.5)$$
$$= 1141.9 \pm 49.8\,(\text{stat.}) \pm 98.4\,(\text{syst.})\ \mu\text{b},$$
$$\sigma_{\mathrm{Ap}}(J/\psi \text{ from } b; p_{\mathrm{T}} < 14 \text{ GeV}/c, -5.0 < y < -2.5)$$
$$= 119.7 \pm 8.3\,(\text{stat.}) \pm 10.0\,(\text{syst.})\ \mu\text{b}.$$

$$\sigma_{\mathrm{pA}}(\text{prompt } J/\psi; p_{\mathrm{T}} < 14 \text{ GeV}/c, 1.5 < y < 4.0) = 1028.2 \pm 13.6\,(\text{stat.}) \pm 88.6\,(\text{syst.})\ \mu\text{b},$$
$$\sigma_{\mathrm{pA}}(J/\psi \text{ from } b; p_{\mathrm{T}} < 14 \text{ GeV}/c, 1.5 < y < 4.0) = 150.1 \pm 4.2\,(\text{stat.}) \pm 12.6\,(\text{syst.})\ \mu\text{b}.$$

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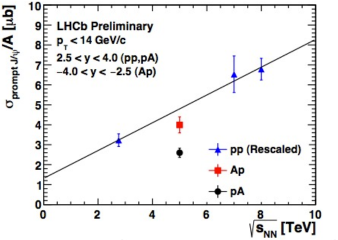
- J/ψ production in pA collisions (LHCb-CONF-2013-008)

Summary of Quarkonia Inclusive Measurements

LHCb has performed a set of analyses on quarkonia production and polarisation.

The production cross-section have got a well pronounced dependence of energy.

More results to come.



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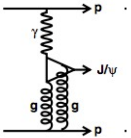
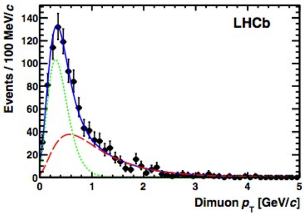
- Evidence for production supression in pA w.r.t pp!

Exclusive production

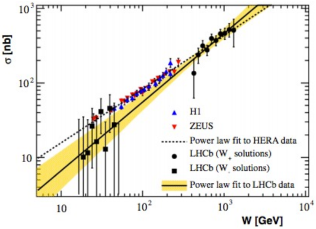




We reconstruct only events with exactly two tracks. DiMuon transverse momentum is used to discriminate between signal and inelastic background component. Signal distribution is estimated with SuperChic event generator.

We obtain:

$$\sigma_{pp\to J/\psi(\to\mu^+\mu^-)}(2.0 < \eta_{\mu^\pm} < 4.5) = 307 \pm 21 \pm 36\ \text{pb},$$
$$\sigma_{pp\to \psi(2S)(\to\mu^+\mu^-)}(2.0 < \eta_{\mu^\pm} < 4.5) = 7.8 \pm 1.3 \pm 1.0\ \text{pb},$$



Moreover we were able to estimate the dependence of the J/Psi production on the centre-of-mass energy of the photon-proton system, W. The results are compatible to that of H1 and Zeus

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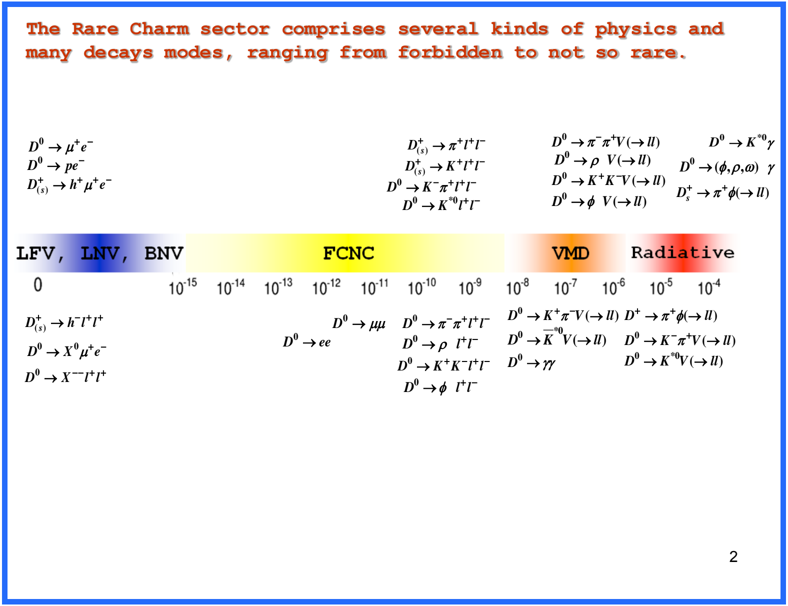
- Observation of exclusive J/ψ production (J. Phys. G 40 045001)

Rare Charm Hadron Decays

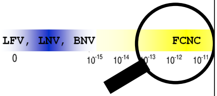
- Slides from Benoit Viaud (LAL/IN2P3/CNRS)



- Many possible decays, from the not so rare to the ridiculous!

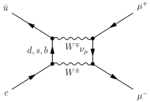
Flavor Changing Neutral Currents

Very rare due a strong GIM suppression



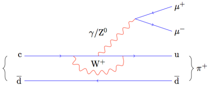
$D^+_{(s)} \to \pi^+ l^+ l^-$ $D^+_{(s)} \to K^+ l^+ l^-$
$D^0 \to \rho\ l^+ l^-$ $D^0 \to \pi^- \pi^+ l^+ l^-$
$D^0 \to \phi\ l^+ l^-$ $D^0 \to K^+ K^- l^+ l^-$
$D^0 \to K^{*0} l^+ l^-$ $D^0 \to K^- \pi^+ l^+ l^-$
$D^0 \to ll$ $D^0 \to \gamma\gamma$

Ex: $D^0 \to \mu^+\mu^-$



$B_{SM} \sim 10^{-18}$ [1]

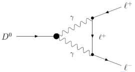
$D \to h(h')\mu^+\mu^-$



$\sim 10^{-12}$-10^{-9} [2,3]

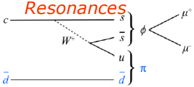
Dominated by Long Distance, via intermediate states.

2-photon



$B_{SM} < 6.\ 10^{-11}$ [1]

Resonances

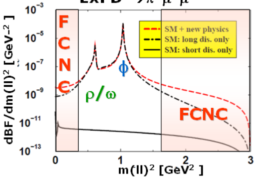


$\sim 10^{-8}$ to 10^{-5} [3,4]

NP might change the picture, making the SD contribution measurable
BF at 10^{-9} / 10^{-8} level ?

In multibody decays, avoid the LD contribution by measuring BF far from the m(μμ) resonant regions

Ex: $D^+ \to \pi^+\mu^+\mu^-$



[1] G. Burdman et al. PR D66, 014009 (2002)
[2] G. Buchalla et al. EPJC57,309(2008),
[3] S. Fajfer et al, PRD64 (2001) 114009,
Phys.Rev. D73 (2006) 054026, PRD76 (2007),074010
[4] L.Cappiello et al. arXiv:1209.4235v1

4

- The usual motivation: "New Physics" $\otimes$ "Loops" $=$ Surprise!

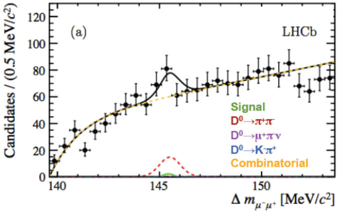
$D^0 \to \mu\mu$ at LHCb

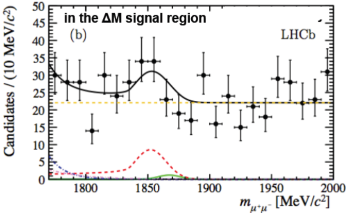
1 fb^{-1} of pp collisions @ $\sqrt{s}$=7TeV

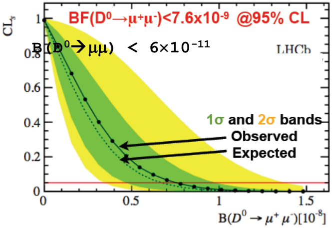
arXiv:1305.5059

Phys. Lett. B 725 (2013) 15-24

No significant signal.







$BF(D^0 \to \mu\mu) < 6.2\ (7.6)\cdot 10^{-9}$ @ 90% (95%) CL

➔ **Best limit !**

Belle: $\mathcal{B}\left(D^0 \to \mu^+\mu^-\right) < 1.4\cdot 10^{-7}$ @90% CL

CDF: $\mathcal{B}\left(D^0 \to \mu^+\mu^-\right) < 2.1\cdot 10^{-7}$ @90% CL

CMS: $B\left(D^0 \to \mu^+\mu^-\right) < 5.4\times 10^{-7}$ @90% CL

➔ **Still: ~100× SM, ~10× higher NP predictions**

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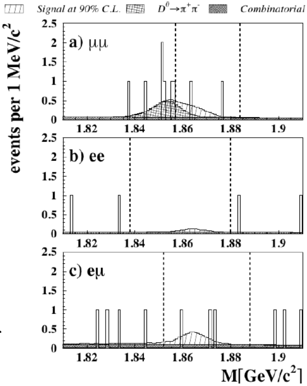
- Don't be fooled by the bump!

$D^0 \to ll$ at Belle

[Phys.Rev. D81 (2010) 091102]

	$D^0 \to \mu^+\mu^-$	$D^0 \to e^+e^-$	$D^0 \to e^\pm\mu^\mp$
N_{bkg}	3.1 ± 0.1	1.7 ± 0.2	2.6 ± 0.2
N	2	0	3
$\epsilon_{\ell\ell}[\%]$	7.02 ± 0.34	5.27 ± 0.32	6.24 ± 0.27
$\epsilon_{\pi\pi}[\%]$	12.42 ± 0.10	10.74 ± 0.09	11.22 ± 0.09
$f[10^{-8}]$	$4.84(1 \pm 5.3\%)$	$6.47(1 \pm 6.4\%)$	$5.48(1 \pm 4.8\%)$
UL $[10^{-7}]$	1.4	0.79	2.6



Data driven methods are used to minimize the systematics.

-$D^0 \to K^-\pi^+$ to measure $\pi \to l$ misID rate;

-$B \to J/\psi(\mu\mu)X$ to correct the MC PID eff.

Single event sensitivity is~$5(1\pm5\%)10^{-8}$

In the end, negligible effect on the upper limits.

u.l @ 90% CL

$$\mathcal{B}(D^0 \to \mu^+\mu^-) < 1.4 \cdot 10^{-7}$$
$$\mathcal{B}(D^0 \to e^+e^-) < 7.9 \cdot 10^{-8}$$
$$\mathcal{B}(D^0 \to e^\pm\mu^\mp) < 2.6 \cdot 10^{-7}$$

World Best !

Babar's 90% limit (see back-up)

$$\mathcal{B}\left(D^0 \to e^+e^-\right) < 1.7 \cdot 10^{-7}$$

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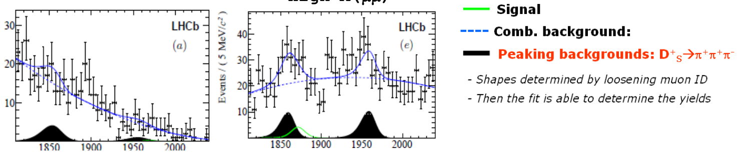
$D^+_{(s)} \to \pi^+\mu^+\mu^-$ at LHCb

1 fb^{-1} of pp collisions @ $\sqrt{s}$=7TeV
arXiv:1304.6365, Phys. Lett. B 724 (2013) 203-212

No signal found in FCNC regions !



Limits 90(95%) C.L.: few $10^{-8}(10^{-7})$ for $D^+(D_s)$

Region	$B(D^+ \to \pi^+\mu^+\mu^-)$	$B(D_S \to \pi^+\mu^+\mu^-)$
Low M(μμ)	2.0 (2.5) $\times 10^{-8}$	6.9 (7.7) $\times 10^{-8}$
High M(μμ)	2.6 (2.9) $\times 10^{-8}$	16.0 (18.6) $\times 10^{-8}$
Total	7.3 (8.3) $\times 10^{-8}$	41.0 (47.7) $\times 10^{-8}$

World best.

~50-100 times better than Babar and D0 (see back-up)

Still above the largest NP values ($O(10^{-8})$).

For more detail on this analysis:
Ed Greening's talk, Parrallel 1c
"Rare decays and facilities"
Monday at 9:00.

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$D^0 \to \pi^+\pi^-\mu^+\mu^-$ at LHCb

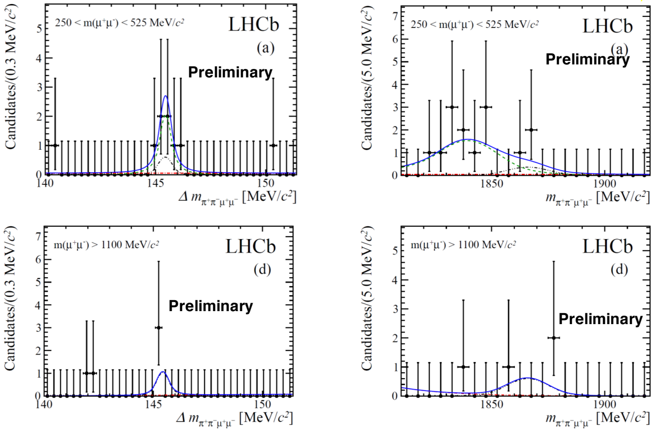
1 fb^{-1} of pp collisions @ $\sqrt{s}$=7TeV

[LHCb-PAPER-2013-50]

NEW !

No significant signal found

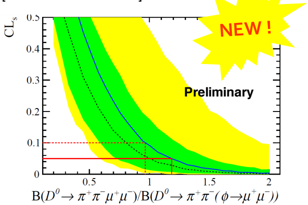
- Signal
- $D^0 \to \pi\pi\pi\pi$
- Comb.Bkg.



19

$D^0 \to \pi^+\pi^-\mu^+\mu^-$ at LHCb

1 fb^{-1} of pp collisions @ $\sqrt{s}$=7TeV
[LHCb-PAPER-2013-50]



Ratio of branching fractions

Upper limit	Bin	90%	95%
$\dfrac{\mathcal{B}(D^0\to\pi^+\pi^-\mu^+\mu^-)}{\mathcal{B}(D^0\to\pi^+\pi^-(\phi\to\mu^+\mu^-))}$	low-$m(\mu^+\mu^-)$	0.41	0.51
	high-$m(\mu^+\mu^-)$	0.17	0.21
	Total	0.96	1.19

Translated into an absolute BF using

$B(D^0\to\pi^+\pi^-\phi(\mu^+\mu^-)) = B(D^0\to\pi^+\pi^-\phi(KK)) \times B(\phi\to\mu\mu)/B(\phi\to KK) = (5.2\pm1.1)\times10^{-7}$

From CLEO-c $D^0\to K^+K^-\pi^+\pi^-$ amplitude analysis [Phys.Rev. D85, 122002(2012)]

Limits 90(95%) C.L.: few 10^{-7} => World Best !

Upper limit	Bin	90% [$\times10^{-7}$]	95% [$\times10^{-7}$]
	low-$m(\mu^+\mu^-)$	2.3	2.9
$\mathcal{B}(D^0\to\pi^+\pi^-\mu^+\mu^-)$	high-$m(\mu^+\mu^-)$	1.0	1.2
	Total	5.5	6.7

~100 times better than E791 and CLEO (back-up)

Still 1 or 2 orders of magnitude above NP predictions.

20

$D^0 \rightarrow \gamma\gamma$ at Babar

470.5 fb^{-1} of e+e- collisions at Y(4S)

PRD85(2012)091107(R)

In the SM: ~4.10^{-8} (Long distance). MSSM: up to 6.10^{-6}.

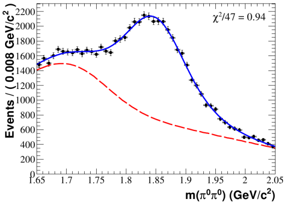
Use a D^* tag and normalize to $D^0 \rightarrow K_s \pi^0$.

Selection tuned on MC. Based on standard kinematics and inv. mass cuts. Also:

- Bkg from QED rejected by $N_{charged}$ & $N_{neutral}$ > 4.
- π^0 veto against main bkg: $D^0 \rightarrow \pi^0\pi^0$ (main bkg).

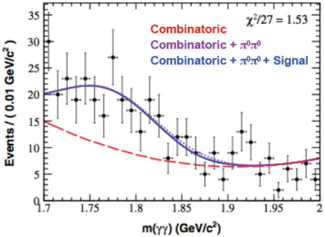
Reject γ's that can be used for a π^0

Same analysis applied to $D^0 \rightarrow \pi^0\pi^0$



$$B\left(D^0 \rightarrow \pi^0\pi^0\right) = \left(8.4 \pm 0.1 \pm 0.3\right) \times 10^{-4}$$

No significant signal.



$$B\left(D^0 \rightarrow \gamma\gamma\right) < 2.2 \times 10^{-6} \quad @90\% \quad C.L.$$

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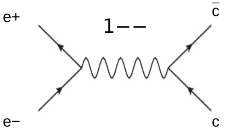
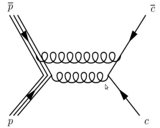
The PANDA Experiment

- New facility to study the XYZ states via hadroproduction
- Fixed target experiment at GSI, Darmstadt
- Slides from Soeren Lange (Giessen)

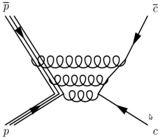
Charmonium in $\bar{p}p$ annihilation

- 2 mechanisms:
  Formation $\bar{p}p \rightarrow X_{c\bar{c}}$
  Production $\bar{p}p \rightarrow X_{c\bar{c}}$ + meson(s) @ higher $\sqrt{s}$
- In e+e− formation only $J^{PC}=1^{--}$,
  in $\bar{p}p$ formation any (non-exotic) quantum number





2 gluons: 0−+, 0++, 2++, ...

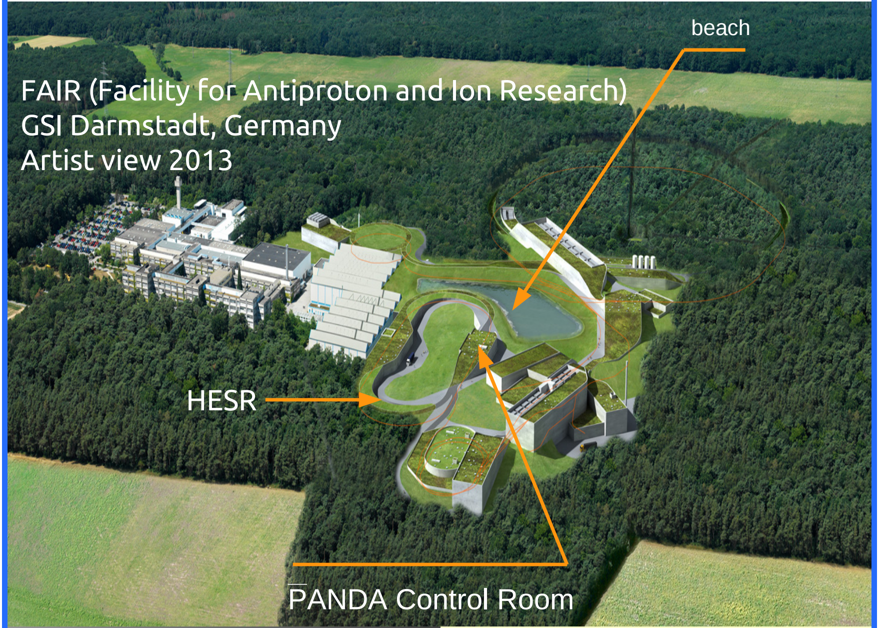


3 gluons: 1−−, 1+−, ...

S. Lange (Giessen) $\bar{P}$ANDA 3

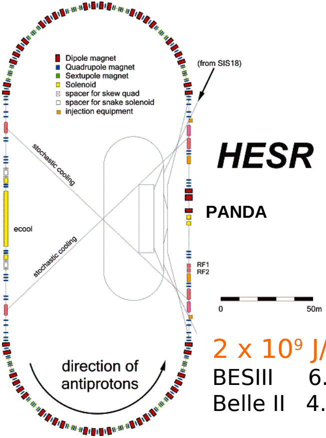
- Can produce any J^{PC} along and more high J states than e^+e^- and B decays


FAIR (Facility for Antiproton and Ion Research)
GSI Darmstadt, Germany
Artist view 2010


beach
FAIR (Facility for Antiproton and Ion Research)
GSI Darmstadt, Germany
Artist view 2013
HESR
$\overline{\text{P}}$ANDA Control Room

HESR (High Energy Storage Ring)

for Anti-Protons



- High intensity mode
  - stochastic cooling, $p \geq 3.8$ GeV/c
  - $\mathcal{L} = 2 \times 10^{32}\ \mathrm{cm^{-2}\,s^{-1}}$
  - $10^{11}\ \bar{p}$
  - $\delta p/p = 2 \times 10^{-4}$
- High resolution mode
  - e^- cooling, $1.5 \leq p \leq 8.9$ GeV/c
  - $\mathcal{L} = 2 \times 10^{31}\ \mathrm{cm^{-2}\,s^{-1}}$
  - $10^{10}\ \bar{p}$
  - $\delta p/p = 4 \times 10^{-5}$

2×10^9 J/ψ per year

BESIII 6.4×10^9

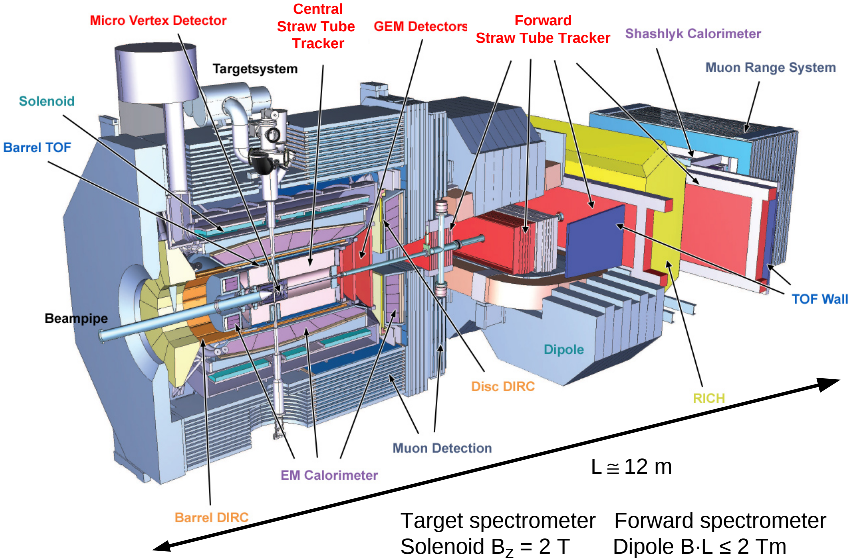
Belle II 4.0×10^9

Targets

- frozen H_2 pellets
- cluster jet

S. Lange (Giessen) $\bar{\text{P}}$ANDA 6

- $\bar{p}$ beam on Hydrogen target, capable of high luminosity and resolution



Target spectrometer	Forward spectrometer
Solenoid $B_z = 2$ T	Dipole $B \cdot L \leq 2$ Tm
helix tracks	parabola tracks

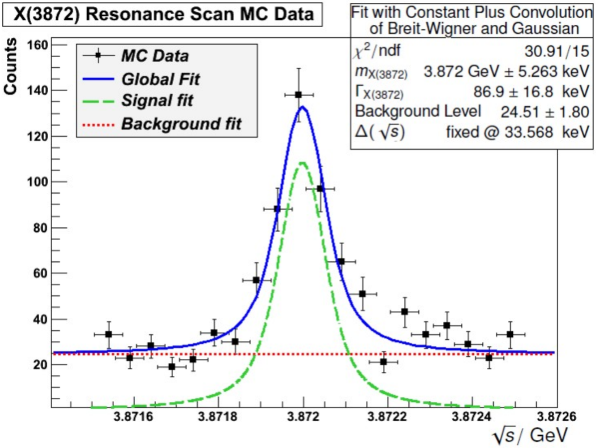
→ Talk by Kai Brinkmann, Monday 10:00, Session 1c

Advantages of $\overline{\text{P}}$ANDA

- Charmonium(-like) states with high masses
  beam momentum $p \leq 15$ GeV/c → $m_{c\bar{c}} \leq 5.5$ GeV
- Charmonium(-like) states with high quantum numbers
  (suppressed by angular barrier in *B* decays or radiative decays)
- High statistics
  assume $\sigma_{\bar{p}p \to X(3872)} = 50$ nb → 4.3 x 10^5 events per 1 day
  in high luminosity mode
- Beam momentum resolution ≥66 keV
  in high resolution mode
  → resonance scan in FORMATION $\bar{p}p \to X(3872)$
  → measure width $\Gamma_{X(3872)}$

S. Lange (Giessen) $\overline{\text{P}}$ANDA 9

- Unique access to properties un-measureable at the *B* factories and LHC



Natural width of 100 keV can be reproduced (within the error bars)

S. Lange (Giessen) $\bar{\text{P}}$ANDA 11

- Could measure $X(3872)$ width with precision of $\mathcal{O}(10\,\text{keV})$!

Challenges for $\overline{\text{P}}$ANDA

- Fixed target
  - high boost $\beta_{cms} \geq 0.8$
  - many tracks and photons in forward acceptance $\vartheta \leq 30^o$
  - with high $p_z \leq 10$ GeV/c and high $E_\gamma \leq 10$ GeV
- High background from hadronic reactions
  - $S/\sqrt{(S+B)} \sim 10^{-6}$
  - S and B have identical signatures
    → hardware trigger not possible
    → self-triggered electronics
    free streaming data
    ≤20 MHz interaction rate
    → data bandwidth $\mathcal{O}$(200 GB/s)
    → complete realtime event reconstruction
    (e.g. invariant mass)

S. Lange (Giessen) $\overline{\text{P}}$ANDA 12

- Propose to run experiment without trigger!

Summary

$\overline{\text{P}}$ANDA ≥2018

- Unprecedented antiproton beam momentum resolution by cooling
- High statistics for XYZ states, but high background
- Search for yet unobserved states (high mass, high J^{PC})
- Search for rare decays of XYZ
- New techniques for signal extraction (e.g. recoil mass)
- New techniques for suppression of background (e.g. radiative cascade)

Thank you.

- Will hopefully shed more light on the XYZ states!

CP Violation in Charm

- Updated HFAG world averages for CPV in Charm sector
- Slides from Silvia Borghi (Manchester), Matt Charles (Oxford) and Alexander Lenz (Durham)

Simplified/popularised summary for the press

Ancient knowledge:

There is no CPV in the charm system

LHCb: 1112.0938 - 175 citations

There is CPV in the charm system

Theoretical (re)considerations

This is a clear indication of NP

NP = New Physics vs. NP = Non-perturbative QCD

LHCb: 1303.2614 - 15 citations

What we actually meant: there is no CPV in the charm system

Theorists: **Experimentalists have to work harder!**

2013, Manchester — A. Lenz, September 3rd 2013 - p. 5

- CP violation in Charm is a tricky business...

CP violation in charm

- CP-violating asymmetries in the charm sector provide a unique probe for physics beyond the Standard Model (SM)
- In the SM CP violation is expected to be small
- New Physics can enhance CP violating observables
- CP violation contributions:
  - In decay: amplitudes for a process and its conjugate differ: $\left|\frac{\bar{A}_{\bar{f}}}{A_f}\right|^{\pm 2} \approx 1 \pm A_d$

    ➔ direct CP violation $a_{CP}^{dir} \approx -\frac{1}{2} A_d$
  - In mixing: rate of $\overline{D^0} \rightarrow D^0$ and $D^0 \rightarrow \overline{D^0}$ differ: $\left|\frac{q}{p}\right|^{\pm 2} \approx 1 \pm A_m$
  - In interference between mixing and decay diagrams $\lambda_f = \frac{q}{p}\left|\frac{\bar{A}_f}{A_f}\right| e^{i\phi}$

    ➔ indirect CP violation $a_{CP}^{ind} = -\frac{A_m}{2} y \cos\phi + x \sin\phi$

A_m: *CPV from mixing*
A_d: *from direct CPV*

x,y: mixing parameters
ϕ: weak phase

CP violation

- 3 types of CP violation:
  - In decay: amplitudes for a process and its conjugate differ
  - In mixing: rate of $D^0 \to \overline{D}^0$ and $\overline{D}^0 \to D^0$ differ
  - In interference between mixing and decay diagrams

Direct

Indirect

- In the SM, indirect CP violation in charm is expected to be very small and universal between CP eigenstates
  - Perhaps $O(10^{-3})$ for CPV parameters => $O(10^{-5})$ for observables like A_Γ
- Direct CP violation can be larger in SM, very dependent on final state (therefore we must search wherever we can)
  - Negligible in Cabibbo-favoured modes (SM tree dominates everything)
  - In generic singly-Cabibbo-suppressed modes: up to $O(10^{-3})$ plausible
- Both can be enhanced by NP, in principle up to O(%)

Bianco, Fabbri, Benson & Bigi, Riv. Nuovo. Cim 26N7 (2003)
Grossman, Kagan & Nir, PRD 75, 036008 (2007)
Bigi, arXiv:0907.2950

Bobrowski, Lenz, Riedl & Rorhwild, JHEP 03 009 (2010)
Bigi, Blanke, Buras & Recksiegel, JHEP 0907 097 (2009)

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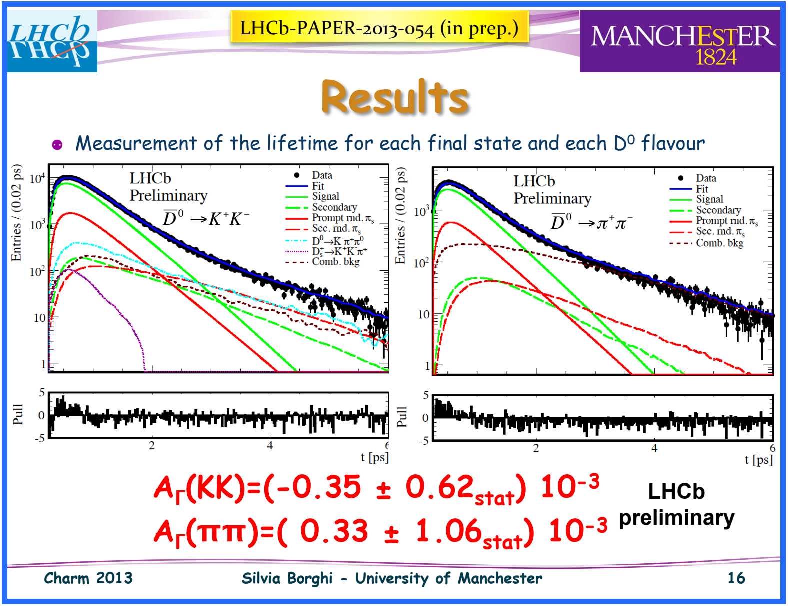
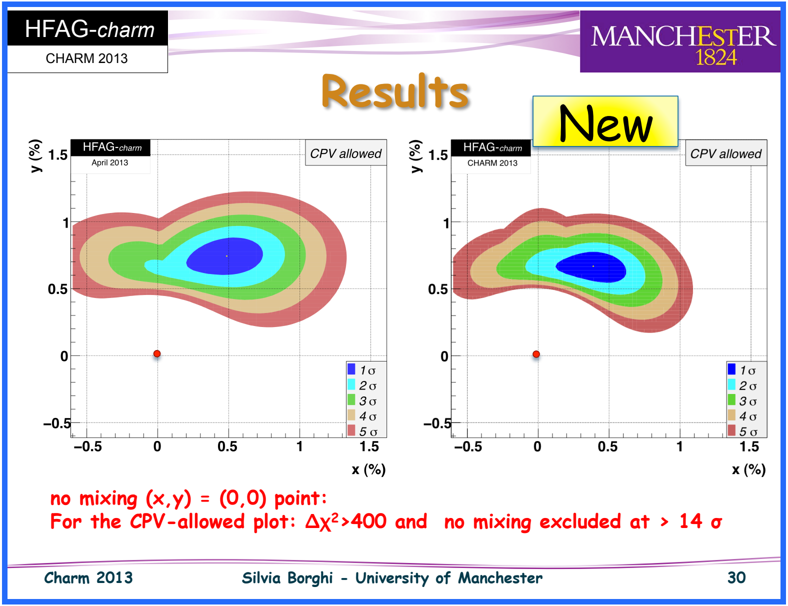
CPV in charm not yet discovered

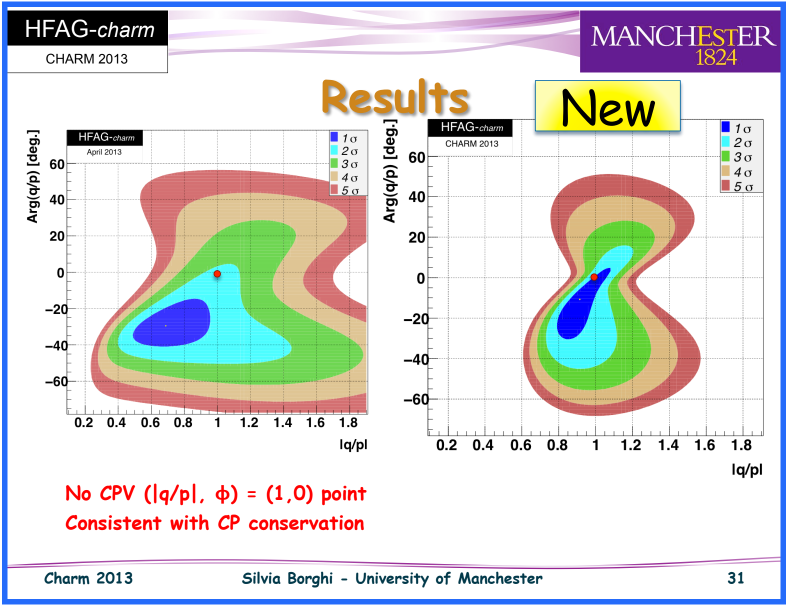
7



- New ΔA_{CP} (mixing and decays) result from LHCb



- New HFAG Charm mixing average, firmly established...



- New HFAG indirect CP violation average, now consistent with zero :-(

Conclusion

- Many new results in the charm during last year
- Mixing well established, no mixing hypothesis excluded at >14 σ
- Search of indirect CP violation still compatible with zero
  - Updated measurements at B factories
  - First measurement of A_Γ with a precision $<10^{-3}$ at LHCb
  - No difference observed for the 2 CP eigenstates
  - ➡ Results consistent with no CP violation at 2.0% C.L.
- Charm is exciting place where to look for hints of New Physics
- Other new results will appear
  - soon from many other channels with the full data set collected by LHCb
    … and a bit later from Belle II and LHCb upgrade

Charm 2013 Silvia Borghi - University of Manchester 32

- Back to where we were before 2011...

Conclusion

- Many interesting results!
- Hopefully many more for CHARM 2015 in Detroit (WSU)
- All slides can be found online:

http://indico.hep.manchester.ac.uk/conferenceDisplay.py?confId=4022