Production of Heavy Meson Molecules at the LHC

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SJTU

International Workshop on QCD Exotics

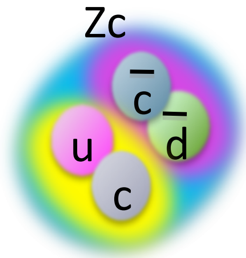
7-12 June 2015

Outline

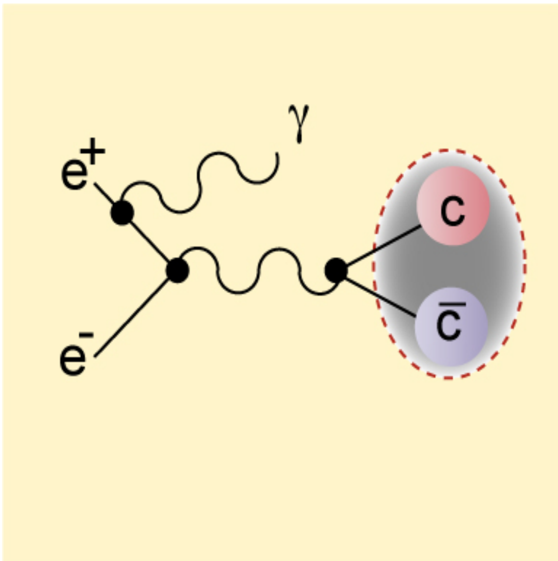
- Introduction
- Hadron Molecules
- Production at the LHC

  X(3872); X_b; Z_c/Z_b
- Summary

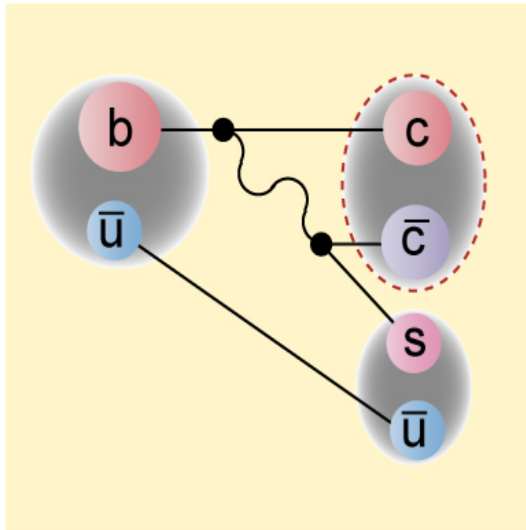
Z_c in e^+e^- and B decays



Many charged Zc have been discovered!
Some Z_c are found in e^+e^- ; some are in B decays



Zc(3900)
Zc(4020)



Zc(4430)
Zc(4200)

See Y.P. Guo's talk in this workshop *See P. Krokovny's talk in this workshop*

New production will be helpful !

Some Meson Molecule candidates

States	Constituent	J^{PC}	Mass(GeV)
X(3872)	DD^*	1^{++}	3.87169
X_b	BB^*	1^{++}	?
$Z^{\pm}_c(3900)$	DD^*	1^{+-}	3.8887
$Z^{\pm}_c(4020)$	D^*D^*	1^{+-}	4.0239
$Z^{\pm}_b(10610)$	BB^*	1^{+-}	10.6072
$Z^{\pm}_b(10650)$	B^*B^*	1^{+-}	10.6522
Ds(2317)	DK	0^{+}	2.3177

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X_b

- Counterpart of X(3872): $J^{PC}=1^{++}$; I=0; BB^* molecule?
- Heavy (~11 GeV): difficult to directly produce at e^+e^-

PHYSICAL REVIEW D **74,** 017504 (2006)

Searching for the bottom counterparts of $X(3872)$ and $Y(4260)$ via $\pi^+\pi^-\Upsilon$

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(Received 5 June 2006; published 27 July 2006)

The $X(3872)$ and $Y(4260)$, among a host of charmoniumlike mesons, have rather unusual properties: the former has very small total width, the latter has large rate into $\pi^+\pi^- J/\psi$ channel. It would not be easy to settle between the many suggested explanations for their composition. We point out that discovering the bottom counterparts should shed much light on the issue. The narrow state can be searched for at the Tevatron via $p\bar{p} \to \pi^+\pi^-\Upsilon + X$, but the LHC should be much more promising. The state with large overlap with Υ can be searched for at B factories via radiative return $e^+e^- \to \gamma_{\rm ISR} + \pi^+\pi^-\Upsilon$ on $\Upsilon(5S)$, or by $e^+e^- \to \pi^+\pi^-\Upsilon$ direct scan.

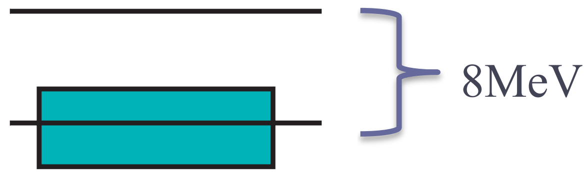
X_b

- Counterpart of X(3872): $J^{PC}=1^{++}$; I=0; BB^* molecule
- Heavy (~11 GeV): difficult to directly produce at electron-positron collider

- **X(3872):$M(D^+)+M(D^{*-})$=3879.87±0.17MeV**

  $M(D^0)+M(D^{*0})$=3871.8±0.17 MeV

  M(X(3872))=3871.69±0.17 MeV



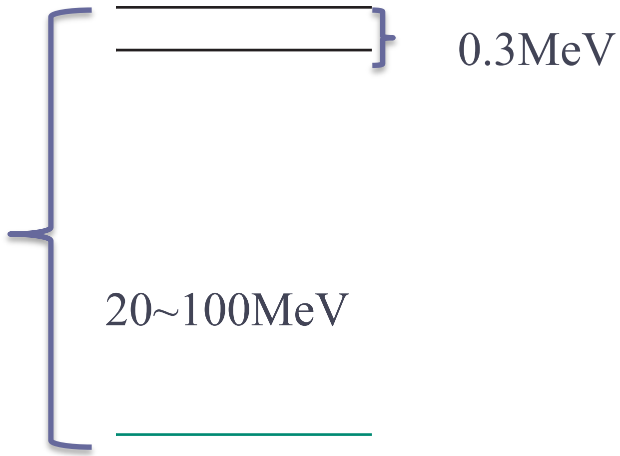
→ X(3872)→J/ψρ is large, isospin breaking

- **X_b: $M(B^0)+M(B^{*0})$=10604.8±0.57MeV**

  $M(B^+)+M(B^{*-})$=10604.5±0.57MeV

  $M(X_b)$=10504 MeV ***0911.2787***

  10580 MeV ***1303.6608***



→ X_b->Υρ may be suppressed by isospin.

X_b

- **Counterpart of X(3872):** $J^{PC}=1^{++}$; I=0; BB^* molecule
- **Heavy** (~11 GeV): difficult to directly produce at electron-positron collider

- **Xb: $M(X_b)$=10504 MeV** *0911.2787*

  10580 MeV *1303.6608*

$M(B^0)+M(B^{*0})$=10604.8±0.57MeV

$M(B^+)+M(B^{*-})$=10604.5±0.57MeV

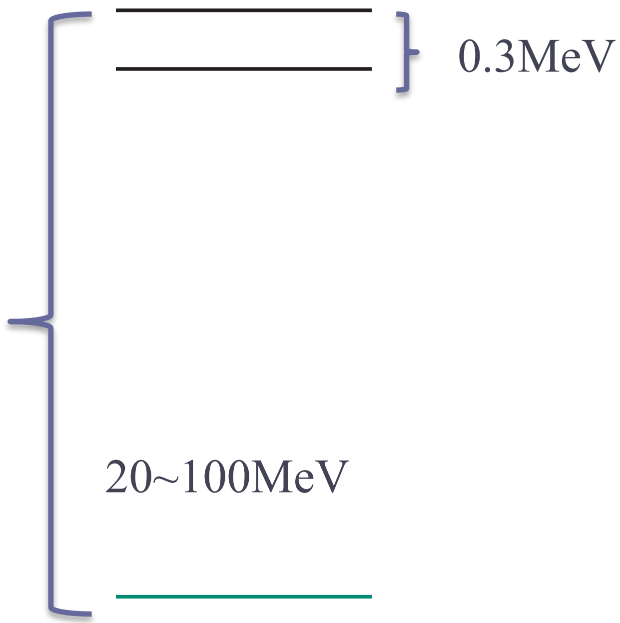
→ X_b->$\Upsilon\rho$ may be suppressed by isospin.

- **X_b->$\Upsilon\gamma$ or $\chi_b\pi\pi$, $\Upsilon\omega$.**

  F.K. Guo, U.Meissner, WW, 1402.6236

  G.Li, WW, 1402.6463

  M.Karliner, J. Rosner, 1410.7729



Hunting for the X_b via radiative decays

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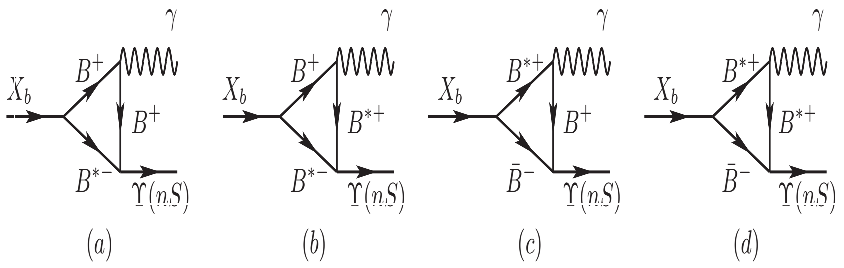
[a] Department of Physics, Qufu Normal University, Qufu 273165, People's Republic of China
[b] Helmholtz-Institut für Strahlen- und Kernphysik and Bethe Center for Theoretical Physics, Universität Bonn, D-53115 Bonn, Germany



$$\mathcal{F}(m_2, q_2^2) \equiv \left(\frac{\Lambda^2 - m_2^2}{\Lambda^2 - q_2^2}\right)^2$$

$$\mathcal{F}(m_2, q_2^2) \equiv \frac{\Lambda^2 - m_2^2}{\Lambda^2 - q_2^2}$$

	$X_b \to \gamma\Upsilon(1S)$		$X_b \to \gamma\Upsilon(2S)$		$X_b \to \gamma\Upsilon(3S)$	
Dipole Form Factor	$\alpha = 2.0$	$\alpha = 3.0$	$\alpha = 2.0$	$\alpha = 3.0$	$\alpha = 2.0$	$\alpha = 3.0$
$E_{X_b} = 1$ MeV	0.12	0.41	0.34	0.96	0.22	0.46
$E_{X_b} = 2$ MeV	0.19	0.62	0.42	1.18	0.28	0.57
$E_{X_b} = 5$ MeV	0.28	0.92	0.53	1.53	0.33	0.70
$E_{X_b} = 20$ MeV	0.36	1.20	0.66	1.96	0.30	0.66
Monopole Form Factor	$\alpha = 2.0$	$\alpha = 3.0$	$\alpha = 2.0$	$\alpha = 3.0$	$\alpha = 2.0$	$\alpha = 3.0$
$E_{X_b} = 1$ MeV	0.02	0.06	0.05	0.11	0.03	0.06
$E_{X_b} = 2$ MeV	0.04	0.08	0.07	0.16	0.04	0.08
$E_{X_b} = 5$ MeV	0.06	0.13	0.12	0.26	0.07	0.12
$E_{X_b} = 20$ MeV	0.13	0.30	0.26	0.56	0.12	0.22

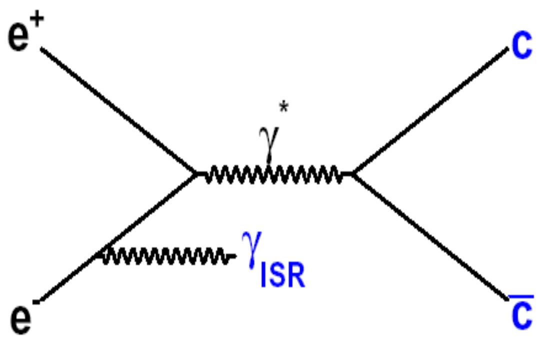
Predicted partial width in unit of keV

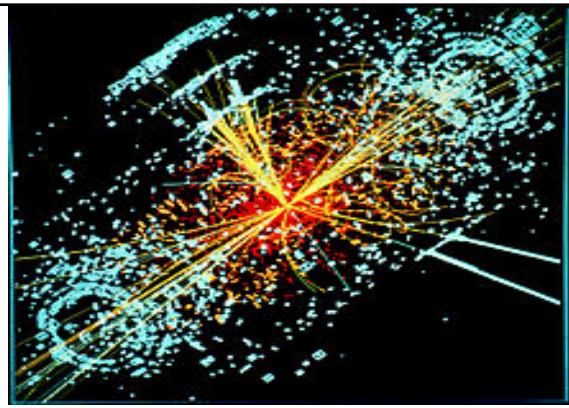
X(3872): $\Gamma_{tot} < 1.2$ MeV
If similar for X_b, BR~10^{-3}

Belle, 1408.0504

Lepton Collider vs Hadron Collider

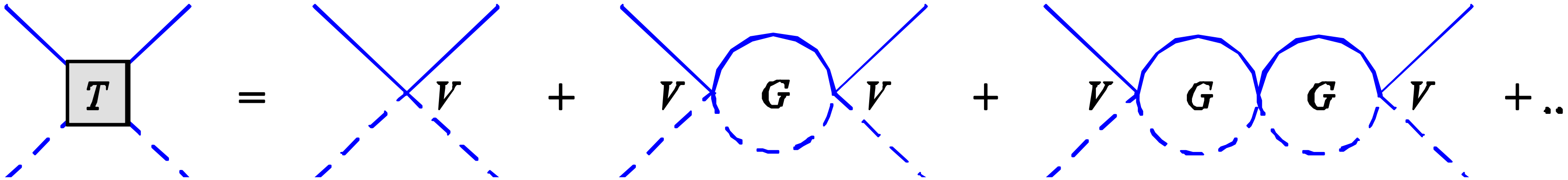
Lepton collider (Belle, BES)	Hadron Collider (LHC, Tevatron)
Clean background	Complicated background
E<11GeV Can not produce Heavy	High Collision Energy Heavy Meson produced
Produce 1^{--} Others are from 1^{--}	Arbitrary Quantum Numbers





See K. Yi's talk in this workshop

Hadron Molecules in unitarized approach

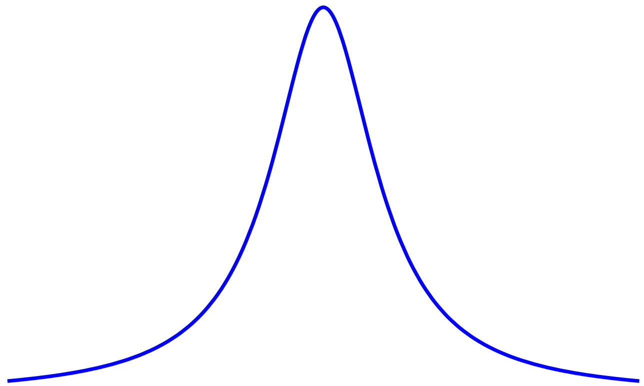


Summing all order contributions:

V+ VGV + VGVGV+…. = V(s)/(1-GV)

$$1\text{-}GV=0$$

$$s=s_0$$



Chiral Perturbation Theory

π's Goldstone Bosons
of the spontaneous
chiral symmetry breaking
$SU(3)_L \times SU(3)_R \to SU(3)_V$

⟷ QCD degrees of freedom
at **low energies << $4\pi f_\pi$~1 GeV**

ChPT is the low energy EFFECTIVE THEORY OF QCD
most general **low-energy expansion**
of a pion lagrangian with the QCD symmetries

Leading order parameters: $\mathbf{f_\pi}$ $\mathbf{m_\pi}$

At higher orders, QCD
dynamics encoded in **Low Energy Constants**
determined from experiment

$\mathbf{L_1, \ldots . L_{10}}$

leading $1/N_c$ behavior known from QCD !!!

⚠ ChPT limited to low energies

Heavy Meson χPT

$$\mathscr{L}_{\rm LO} = -i\mathrm{Tr}[\bar{H}_a v_\mu D^\mu_{ba} H_b] + g_\pi \mathrm{Tr}[\bar{H}_a H_b \gamma_\nu \gamma_5] u^\nu_{ba} + \frac{\lambda}{m_Q}\mathrm{Tr}[\bar{H}_a \sigma_{\mu\nu} H_a \sigma^{\mu\nu}] \quad ($$

$$H = \frac{1+\not{v}}{2}\left[\not{V} + iP\gamma_5\right], \quad \bar{H} = \gamma^0 H^\dagger \gamma^0,$$

- Heavy Meson pair: DD^*, BB^*
- Heavy Meson +Pseudo-Scalar: DK
- Two Pseudo-Scalar

Heavy Meson χPT

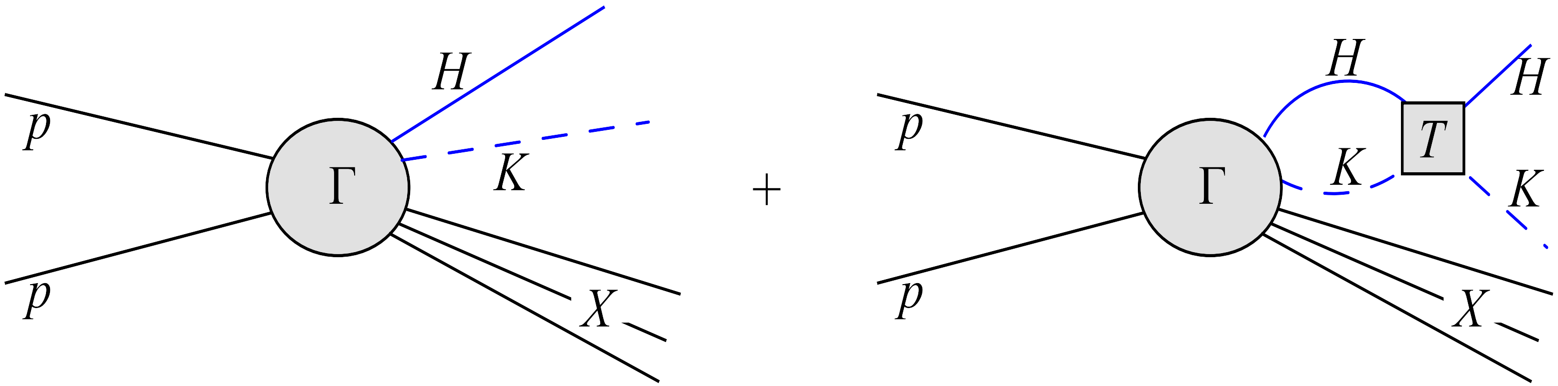
$$\mathscr{L}_{\rm LO} = -i\mathrm{Tr}[\bar{H}_a v_\mu D^\mu_{ba} H_b] + g_\pi \mathrm{Tr}[\bar{H}_a H_b \gamma_\nu \gamma_5] u^\nu_{ba} + \frac{\lambda}{m_Q}\mathrm{Tr}[\bar{H}_a \sigma_{\mu\nu} H_a \sigma^{\mu\nu}]$$

$$H = \frac{1+\not{v}}{2}\left[\not{V} + iP\gamma_5\right], \quad \bar{H} = \gamma^0 H^\dagger \gamma^0,$$

- Heavy Meson pair: DD^*, BB^*
- Heavy Meson +Pseudo-Scalar:
- Two Pseudo-Scalar

States	Constituent
X (3872)	DD^*
X_b	BB^*
$Z^\pm_c$ (3900)	DD^*
$Z^\pm_c$ (4020)	D^*D^*
$Z^\pm_b$ (10610)	BB^*
$Z^\pm_b$(10650)	B^*B^*
Ds (2317)	DK

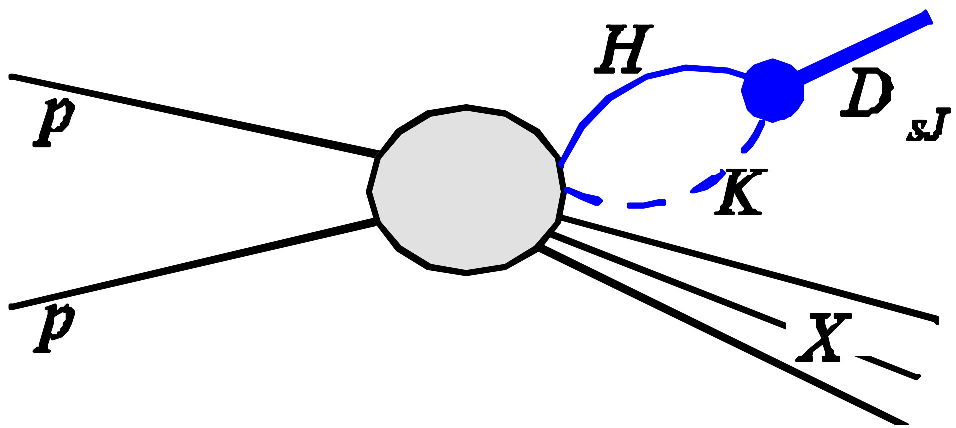
Production at LHC



Γ+ ΓGV + ΓGVGV+…. = Γ /(1-GV)

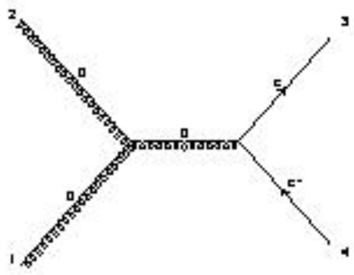
Γ is tree-level amplitude.

1-GV＝0



MC Event Generator

- Herwig/Pythia: simulate production rates of constituents, Γ



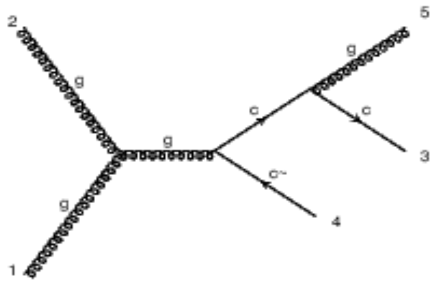


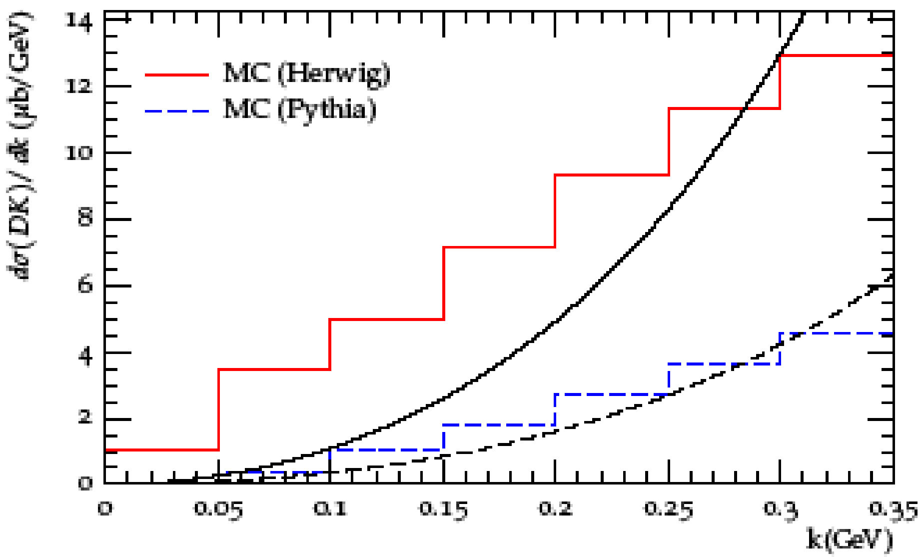
diagram 2 QCD=3, QED=0

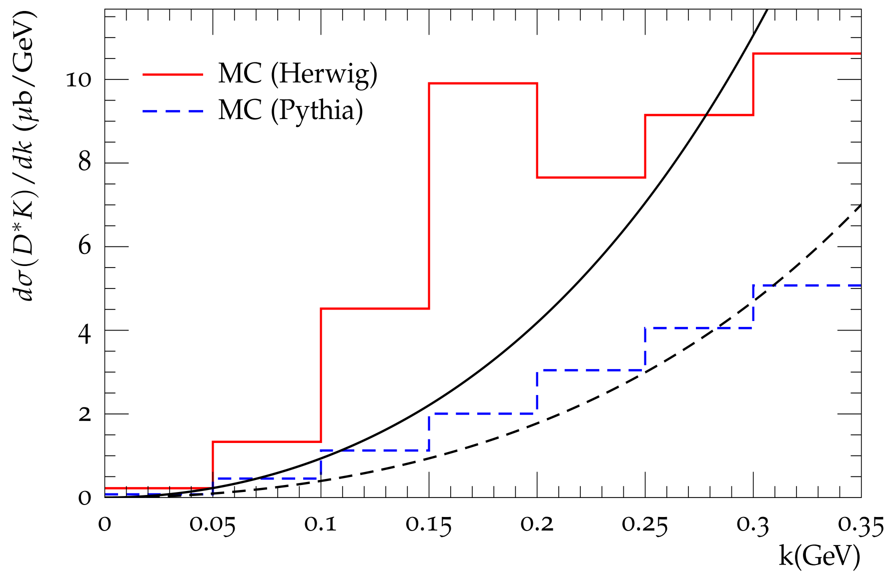
- For charmonium/bottomonium-like states, heavy quarks move together, and a third parton is requested. 2→ 3 process: use Madgraph

- Use Rivet to analyze hadronic events

EFT vs data: X(3872)

F.K. Guo, U.G. Meissner, WW, Z.Yang 1403.4032





Histograms: MC event generators Curves: fit according to EFT.

F.K. Guo, U.G. Meissner, WW, Z.Yang 1402.6236

$\sigma(pp/p\bar{p} \to X(3872))$	Ref. [16]	Ref. [18]	$\Lambda = 0.5$ GeV	$\Lambda = 1$ GeV	Experiment
Tevatron	< 0.085	1.5–23	10(7)	47(33)	37–115 [43]
LHC7	–	45–100 [a]	16(7)	72(32)	13–39 [6]

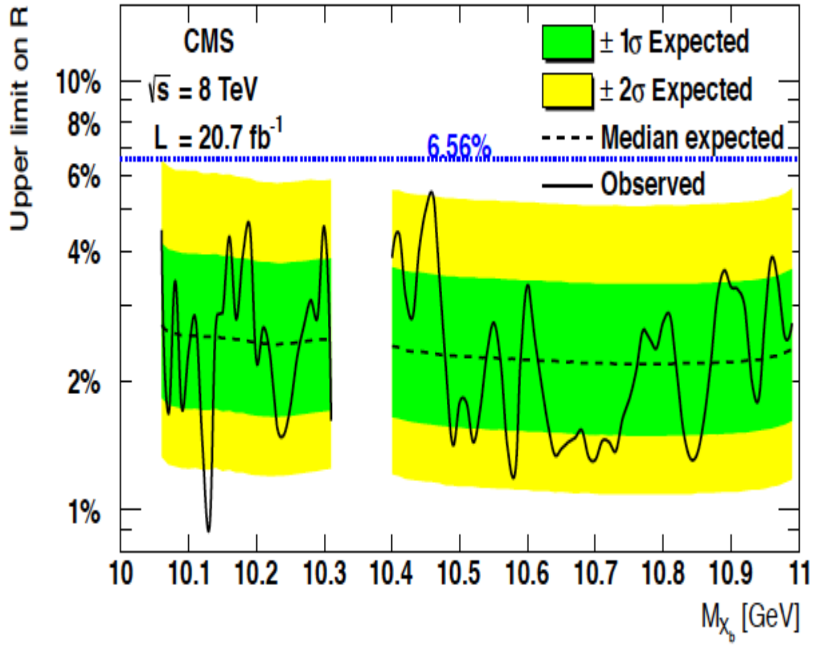
CDF： hep-ex/0409052

CMS： 1302.3968

16. C. Bignamini, B. Grinstein, F. Piccinini, A.D. Polosa, C. Sabelli, Phys. Rev. Lett. **103**, 162001 (2009). arXiv:0906.0882 [hep-ph]
18. P. Artoisenet, E. Braaten, Phys. Rev. D **81**, 114018 (2010). arXiv:0911.2016 [hep-ph]

EFT vs data: X_b

- **Counterpart of X(3872): $J^{PC}=1^{++}$;I=0; BB^* molecule**
- **Very heavy (11 GeV): difficult to directly produce at electron-positron collider**
- CMS made an attempt:
  Phys.Lett. B727 (2013) 57-76



$$\frac{\sigma(pp \to X_b \to \Upsilon(1S)\pi^+\pi^-)}{\sigma(pp \to \Upsilon(2S) \to \Upsilon(1S)\pi^+\pi^-)} < (0.009, 0.054)\ ,$$

$$\sigma(pp \to X_b)\mathcal{B}(X_b \to \Upsilon(1S)\pi^+\pi^-) < (0.18, 1.11)\ \text{nb.}$$

ATLAS:Phys.Lett.B740(2015)199

EFT vs data: X_b

Integrated cross sections (in units of nb) for the $pp/\bar{p} \to X_b$

X_b	$E_{X_b} = 1$ MeV	$E_{X_b} = 2$ MeV	$E_{X_b} = 5$ MeV
Tevatron	0.04(0.09)	0.06(0.13)	0.09(0.2)
LHC 7	0.77(1.5)	1.1(2.2)	1.7(3.5)
LHCb 7	0.12(0.24)	0.18(0.34)	0.28(0.54)
LHC 8	0.9(1.8)	1.3(2.5)	2.(4.)
LHCb 8	0.15(0.31)	0.21(0.43)	0.33(0.68)
LHC 14	1.6(3.4)	2.2(4.8)	3.6(7.5)
LHCb 14	0.32(0.64)	0.46(0.91)	0.72(1.4)

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1402.6236

X_b decays into $\Upsilon\pi^+\pi^-$ violates isospin → tiny BR.

One may look at $\Upsilon\gamma$, $\Upsilon\pi^+\pi^-\pi^0$, $\chi_b\pi^+\pi^-$.

Radiative decays width are about 1 keV

EFT vs data: Z_b/Z_c

TABLE II: Integrated normalized cross sections (in units of nb) for the reactions $pp/\bar{p} \to Z_b(10610), Z_b(10650), Z_c(3900)$, and $Z_c(4020)$ at the LHC and the Tevatron. Results are obtained using Herwig (Pythia). The rapidity range $|y| < 2.5$ has been assumed for the LHC experiments (ATLAS and CMS) at 7, 8 and 14 TeV, respectively, for the Tevatron experiments (CDF and D0) at 1.96 TeV, we use $|y| < 0.6$; the rapidity range $2.0 < y < 4.5$ is used for LHCb.

	$Z_b(10610)$	$Z_b(10650)$	$Z_c(3900)$	$Z_c(4020)$
Tevatron	0.26(0.47)	0.06(0.17)	11(13)	1.7(2.0)
LHC 7	4.8(8.0)	1.2(3.0)	187(211)	29(31)
LHCb 7	0.76(1.3)	0.18(0.47)	33(39)	5.5(5.8)
LHC 8	5.9(9.5)	1.4(3.5)	220(240)	34(36)
LHCb 8	0.9(1.4)	0.22(0.56)	40(48)	6.3(6.9)
LHC 14	11(17)	2.6(6.5)	382(423)	61(63)
LHCb 14	1.9(3.0)	0.52(1.2)	84(88)	14(14)

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$p_T > 5$ GeV

$22 fb^{-1}$
→10^9 events

EFT vs data: Z_c

Z_c decays into $J/\psi\ \pi^+$. To estimate background

$$\sigma(pp \to \psi\pi^{\pm} + anything) < \sigma(pp \to \psi + anything).$$

ATLAS data on pp→J/ψ: Nucl. Phys. B 850, 387 (2011)

$$\sigma(pp \to \psi(\to \mu^+\mu^-) + anything) = (81^{+27}_{-22})\ \mathrm{nb},$$

With 22fb^{-1} data, the signal/background ratio is estimated:

$$\frac{S}{\sqrt{B}} \sim \frac{200 \times 22 \times 10^6 \times 10\% \times 5.9\%}{\sqrt{81 \times 22 \times 10^6}} \sim 600,$$

Different cuts may be applied.

The experimental prospect seems very promising!

Summary

- Hadron Exotics is a fast-developing branch.

- Factorization for production:

  MC Event generators & EFT

- More exotics are to be (re)-discovered at LHC.

Thank you for your attention!