Highlights from School

"Frontiers in Nuclear and Hadronic Physics"

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ALICE/SPbU/LUHEP Seminar

Abstract

The school is primarily addressed to Ph.D. students in theoretical physics, yet the lectures are also suitable for experimentalists. Participation of post-docs is also encouraged. The goal of the school is to provide an introduction to the basic concepts and tools in the fields of hadronic physics and high energy nuclear physics as well as to advanced research topics.

Topics

E. Swanson: QCD and Exotic hadron spectroscopy

A. Accardi: The partonic structure of protons and nuclei: from current facilities to the Electron-Ion Collider

J. Wambach: Meson propagation in nuclear matter

O. Philipsen: Lattice QCD at finite temperature

I. Karpenko: Relativistic hydrodynamics and its application to relativistic heavy ion collisions

A. Beraudo: Heavy quarks and hard probes in relativistic heavy ion collisions

K. Fukushima: Magnetic effects in relativistic heavy ion collisions

Lectures avaliable on YouTube:
https://www.youtube.com/channel/UCQsJ14ecgW8Ulcqis3HeZnw/playlists

Slides: http://www.ggi.fi.infn.it/index.php?page=talks.inc&idev=257

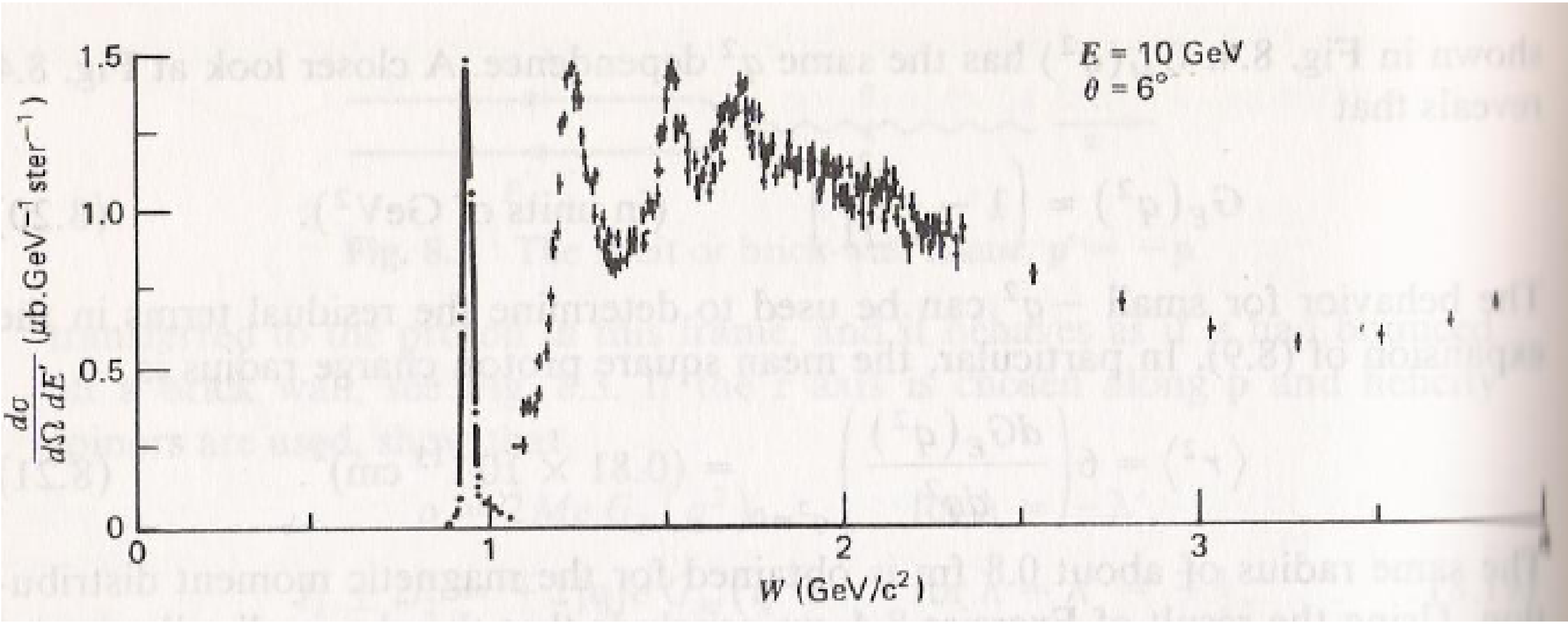
A. Accardi: The partonic structure of protons and nuclei: from current facilities to the Electron-Ion Collider:

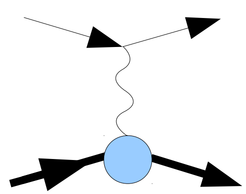
Parton Model, DIS,

Factorization Theorem

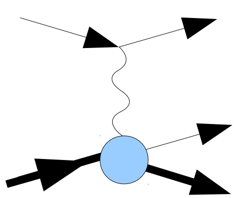
Global p.d.f. fits

Cross section

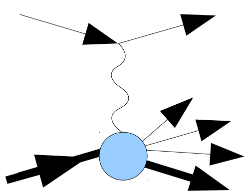




Elastic: W=M
(no energy to produce
any other particle)



Inelastic
(resonance region)
(W for only a few particles)

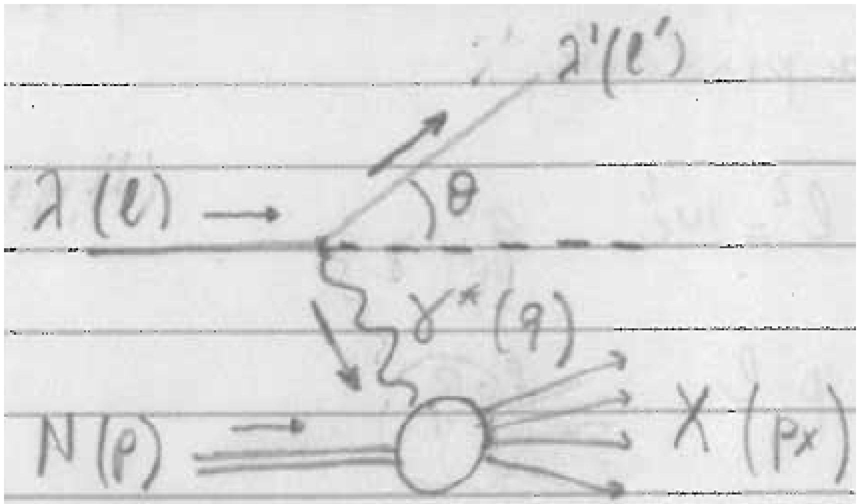


Deep inelastic
(large W, more particles)

$Q^2, W^2 \to \infty \quad x_B$ fixed

DIS

- **Inclusive lepton-hadron scattering:**



$$\lambda = e, \mu, \nu, \ldots$$

$$N = p, n, \ldots$$

$$q^\mu = \ell^\mu - \ell'^\mu$$ Virtual photon momentum

$$p_X^\mu = \sum_{i \in X} p_i^\mu$$ Hadronic final state momentum

$$Q^2 = -q^2$$
virtuality

$$x_B = \frac{q}{2p \cdot q}$$
Bjorken x

$$\nu = \frac{p \quad q}{\sqrt{p^2}}$$
beam energy loss *

$$y = \frac{p \cdot q}{p \cdot \ell}$$
inelasticity *

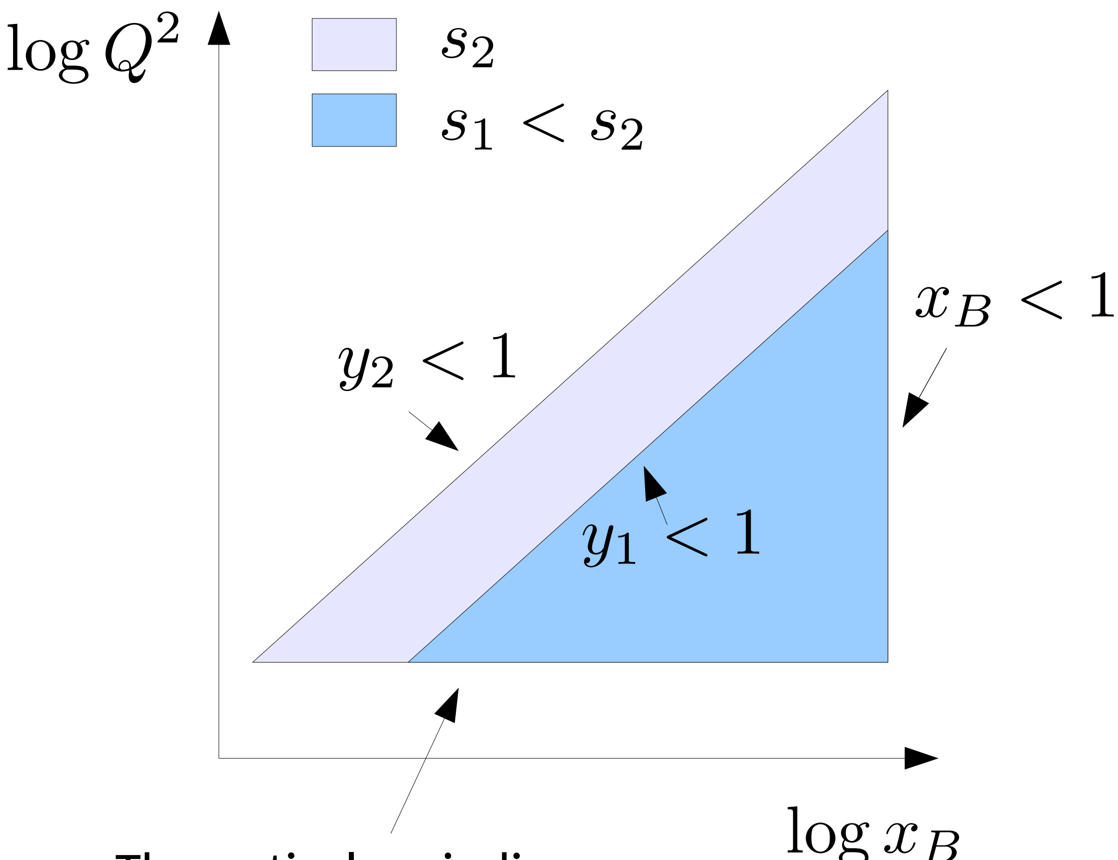
$$W^2 = (p + q)^2$$
(final state) invariant mass

$$s = (p + \ell)^2$$
center-of-mass energy

$$\nu = \frac{Q^2}{2M x_B} \qquad s - M^2 = \frac{Q^2}{2 x_B y} \qquad W^2 = M^2 + Q^2 \left(\frac{1}{x_B} - 1 \right)$$

Kinematics

- **Kinematic plane – theoretical**
  - Pick x_B , Q^2, y as independent variables



$$y_i \approx \frac{Q^2}{x s_i}$$

$$s_2 > s_1$$

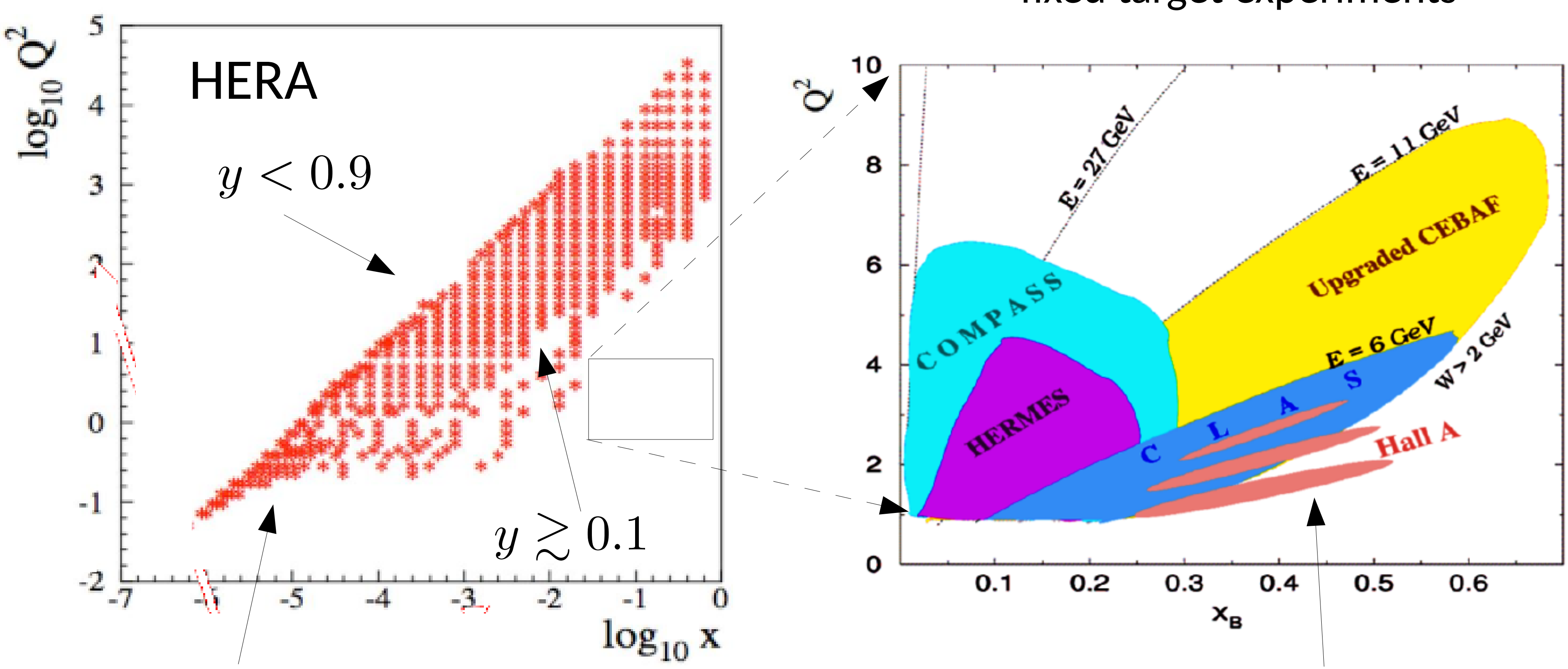
Theoretical prejudice:
can use pQCD only if Q^2 large "enough"

Kinematics

- **Kinematic plane – in practice**

e+p collider

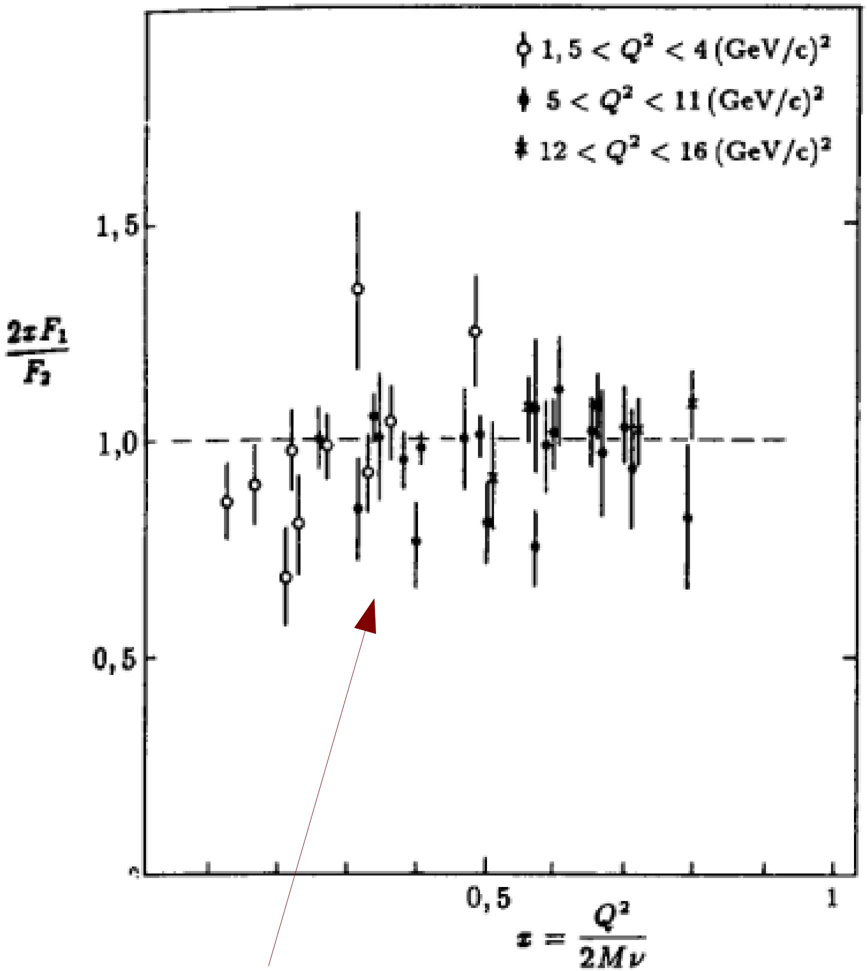
fixed target experiments



$\theta > \theta_{\rm min}$

Fixed-angle spectrometers

Experimental data



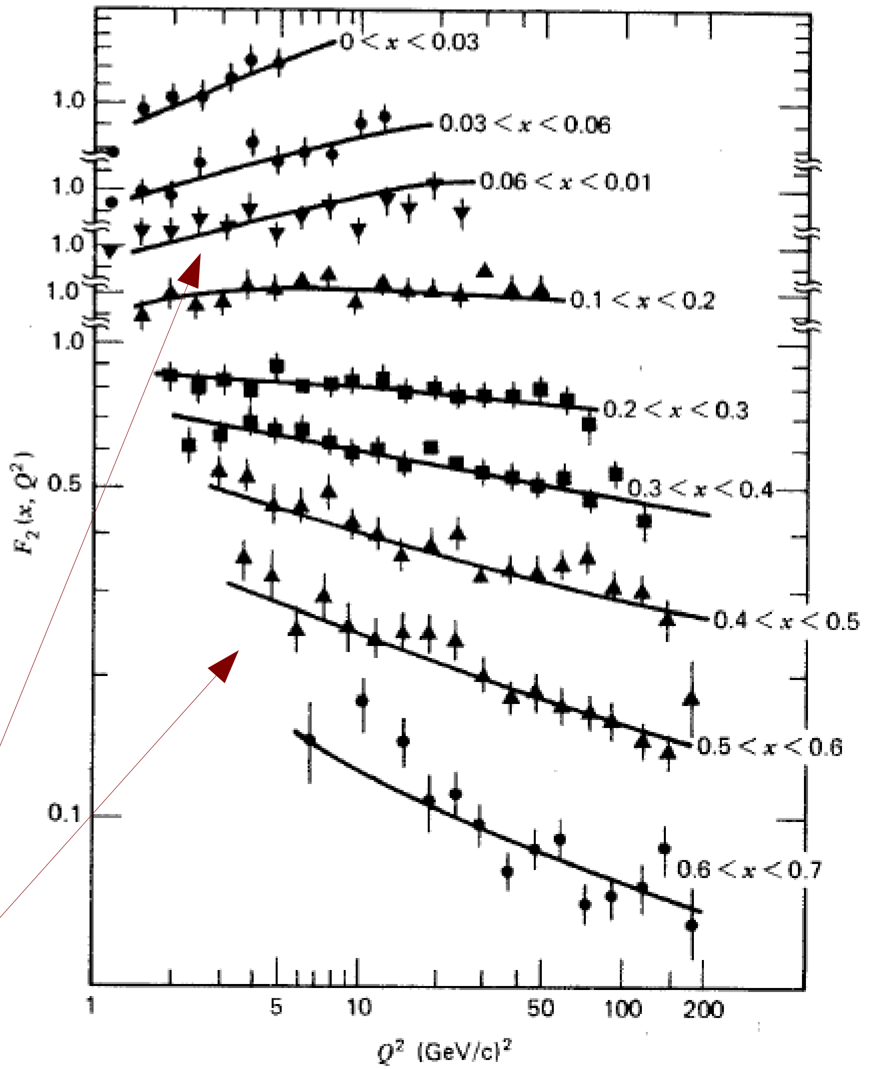


Fig. 10.10 Deviations from scaling. With increasing Q^2, the structure function $F_2(x, Q^2)$ increases at small x and decreases at large x. The data are from the CDHS counter experiment at CERN.

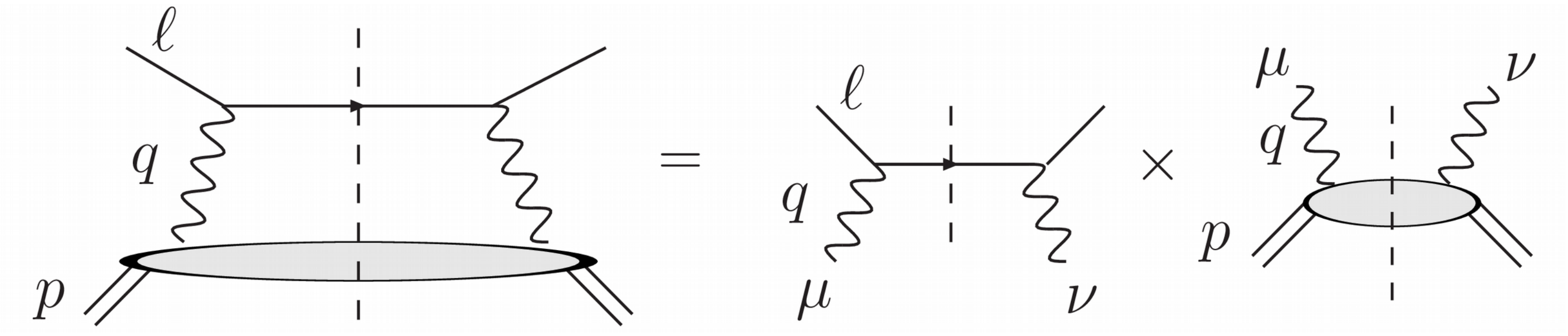
Charged partons have spn ½ (quarks!)

log(Q^2) scaling violations

Structure functions

- Leptonic and hadronic tensors – 1 photon exchange

$$d\sigma \propto L_{\mu\nu}(\ell, q) W^{\mu\nu}(p, q)$$



  – Electron is elementary: $L_{\mu\nu}$ can be calculated perturbatively

- Lorentz decomposition + gauge invariance = structure functions

$$W^{\mu\nu}(p, q) = \Big(-g^{\mu\nu} + \frac{q^\mu q^\nu}{q^2}\Big) F_1(x_B, Q^2)$$
$$+ \Big(p^\mu - \frac{p \cdot q}{q^2} q^\mu\Big)\Big(p^\nu - \frac{p \cdot q}{q^2} q^\nu\Big) F_2(x_B, Q^2)$$
$$+ i\varepsilon_{\mu\nu\alpha\beta} \frac{p^\alpha q^\beta}{2p \cdot q} F_3(x_B, Q^2)$$

$\neq 0$ only for $W^\pm$, Z^0 boson exchanges

Structure functions and cross section

- The cross section (for a γ exchange) reads

$$\frac{d\sigma}{dx dQ^2} = \frac{2\pi\alpha^2 y^2}{Q^4} L_{\mu\nu}(\ell, q) W^{\mu\nu}(p, q)$$

- Using

$$L_{\mu\nu} = 2\big(\ell_\mu \ell'_\nu + \ell'_\mu \ell'_\nu - \ell \cdot \ell' g_{\mu\nu}\big)$$

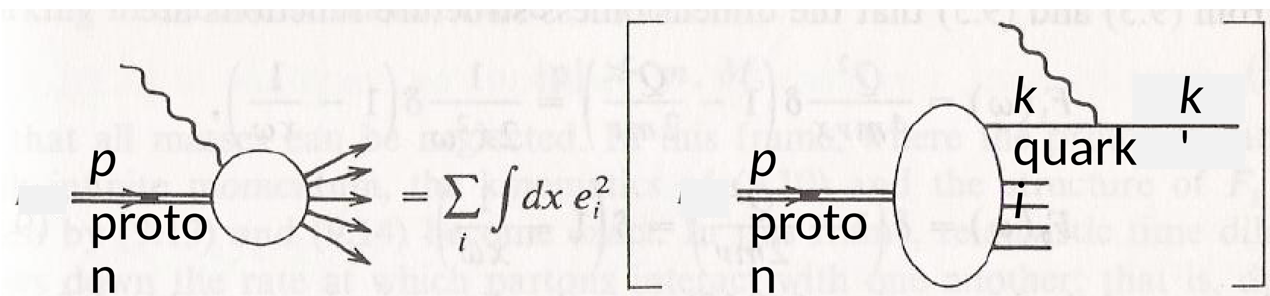
one obtains

$$\frac{d\sigma}{dx_B dQ^2} = \frac{4\pi\alpha^2}{x_B Q^4}\bigg\{\bigg(1 - y - x_B^2 y^2 \frac{M^2}{Q^2}\bigg) F_2(x_B, Q^2) + y^2 x_B F_1(x_B, Q^2) \mp \bigg(y - \frac{y^2}{2}\bigg) x_B F_3(x_B, Q^2)\bigg\}$$

Parton model (see [Feynman])

- We have evidence that a proton is a composite object made of spin ½ particles (and should also expect some radiated gluons)

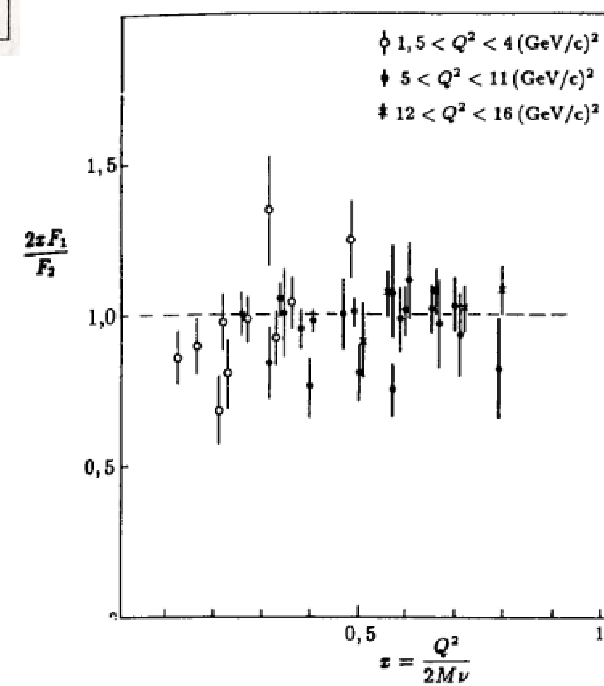
- At high-energy, expect a “probe” to interact with these point-like objects



- In DIS, the photon scatters on quasi-free quarks
  - Empirical evidence: $F_2 = 2x_B F_1$

- Seen by a high-energy probe,

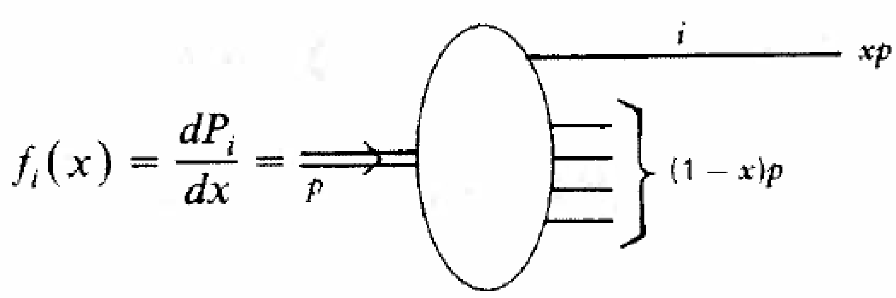
the nucleon seems a box of practically free “partons” sharing the proton’s momentum



Parton model (see [Feynman])

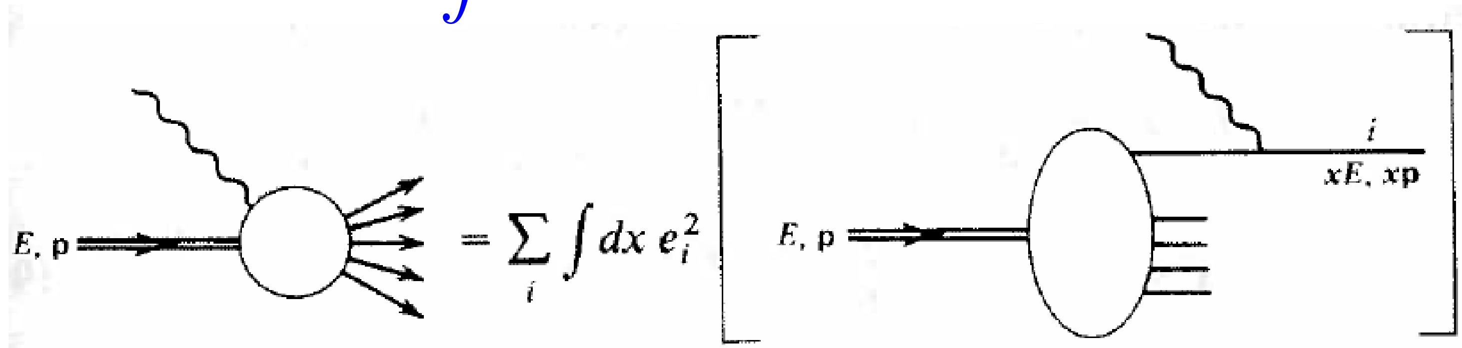
- Define a parton distribution

$f_i(x)dx =$ Probability of finding a parton *i* with momentum Fraction between *x* and *x+dx*



- Hard processes (e.g. a DIS cross section) should be **“factorized”**

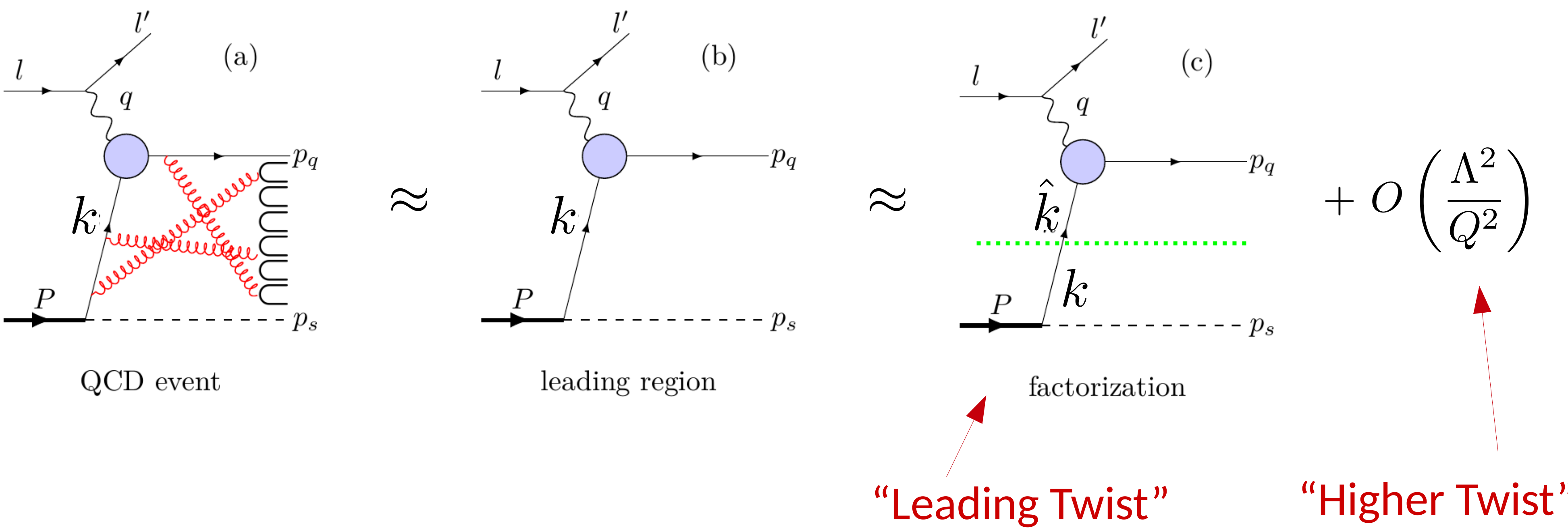
$$\sigma(p,q) = \sum_i \int dx\, f_i(x)\hat{\sigma}^i(xp,q) = \sum_i f_i \otimes \hat{\sigma}^i$$



Collinear factorization*

see, Accardi, Qiu, JHEP 2008 (simple)
Qiu, PRD 1990 (coll. expansion and HT)
Collins' book (full proof)

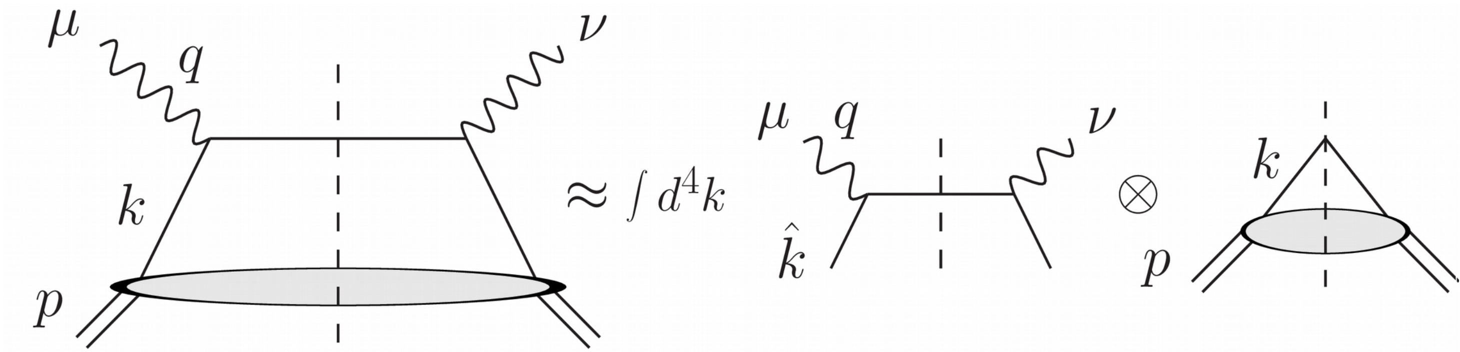
- General idea:
  - Identify "leading regions" in the integrals involved in the calculation
  - Expand around the parton's largest momentum component



*Note: will consider $M^2/Q^2 \ll 1$ for simplicity (but check the exercises)

Collinear factorization

- The hadronic tensor factorizes (see handwritten notes for details):



$$W^{\mu\nu}(p,q) = \int \frac{dx}{x} \widehat{W}_q^{\mu\nu}(\hat{k},q) q(x)$$

$$q(x) = \int \frac{dz^-}{2\pi} e^{ixp^+z^-} \langle p|\overline{\psi}(z^- n)\frac{\gamma^+}{2}\psi(0)|p\rangle$$

For M/Q → 0

$$F_1(x_B,Q^2) = \sum_q \int_{x_B}^1 \frac{dx}{x} \hat{F}_1^q\Big(\frac{x_B}{x}, Q^2\Big) q(x)$$

$$= \hat{x}_q$$

$$F_2(x_B,Q^2) = \sum_q \int_{x_B}^1 dx\, \hat{F}_2^q\Big(\frac{x_B}{x}, Q^2\Big) q(x)$$

Global PDF fits

data

- DIS: p, d
- p+p(pbar) $\rightarrow l^+l^-$, $W^\pm$, Z
- p+p(pbar) $\rightarrow$ jets, γ+jet

theory

- pQCD at NLO
- Factorization & universality
- Large-x, low-Q^2, nuclear corr.

fits

- Parametrize PDF at Q_0, evolve to Q
- Minimize χ^2

PDFs

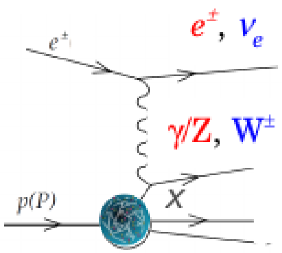
$F_2(n)$

W, Z / W',Z', Higgs

(or any other "hard" observable)

The 3 work horses: DIS, DY, and jets

Deep Inelastic Scattering:



ep data: quarks and gluon at small x (F_L), flavour separation (CC)

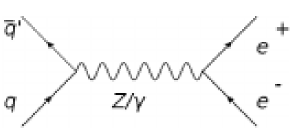
jets → gluons (moderate x) and α_s

heavy quarks → gluons, tests of heavy quark schemes, mass determination

fixed target data: higher x

neutrino DIS: flavour decomposition, x>0.01

Drell-Yan production:

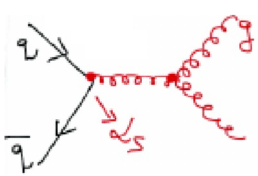


different PDF combinations (low/mid/high x), deuterium target – $\bar{u}/\bar{d}$ asymmetry

W/Z ratio, asymmetries → quark flavour separation

V+ heavy flavour → sensitivity to s quark

Inclusive jets, dijets and ratios:



high x gluon, α_s

Isolated photon → gluon at medium and high x

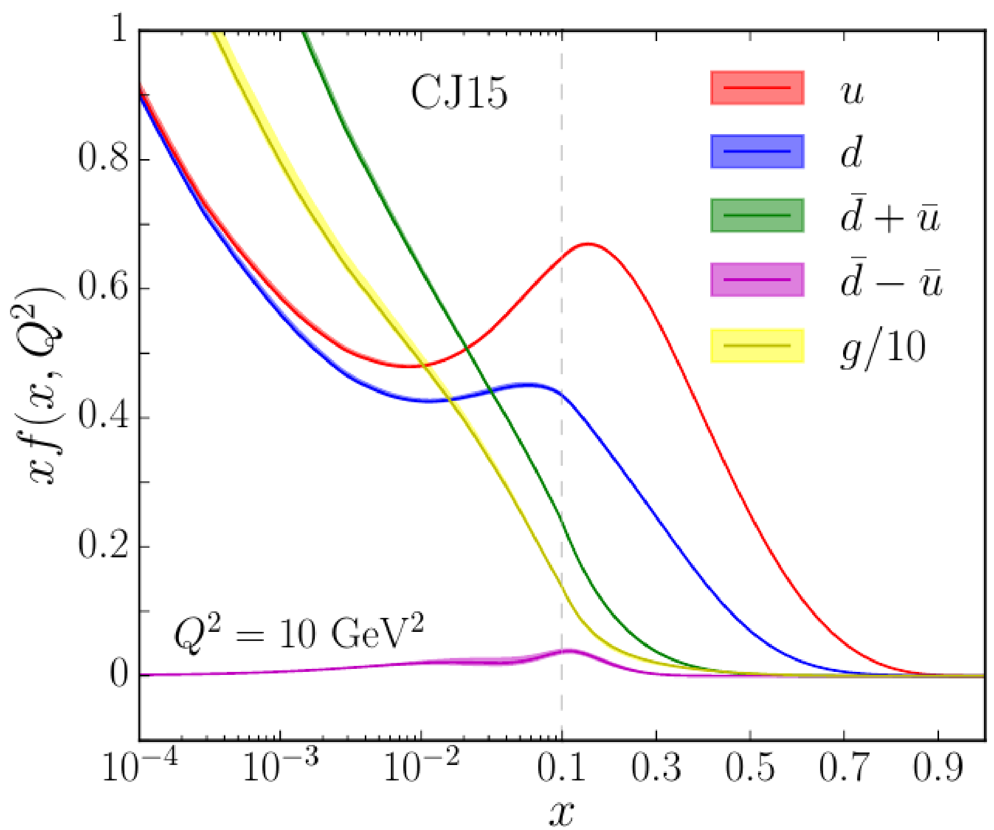
ttbar, single top:

gluon at high x, u and d quarks, α_s

Example: the CJ15 PDFs

Accardi, Owens, Melnitchouk, arXiv:1602.03154

"CTEQ-JLab"



- Hessian error analysis
  - Correlated errors where available
- Error bands displayed for

$$\Delta\chi^2 = 2.71$$

(90% confidence level
in a perfect, Gaussian world)

- NLO fit gives $\chi^2/\mathrm{datum} = 1.04$
- LO fit much worse – cannot accommodate Q^2 dependence of data

Topics

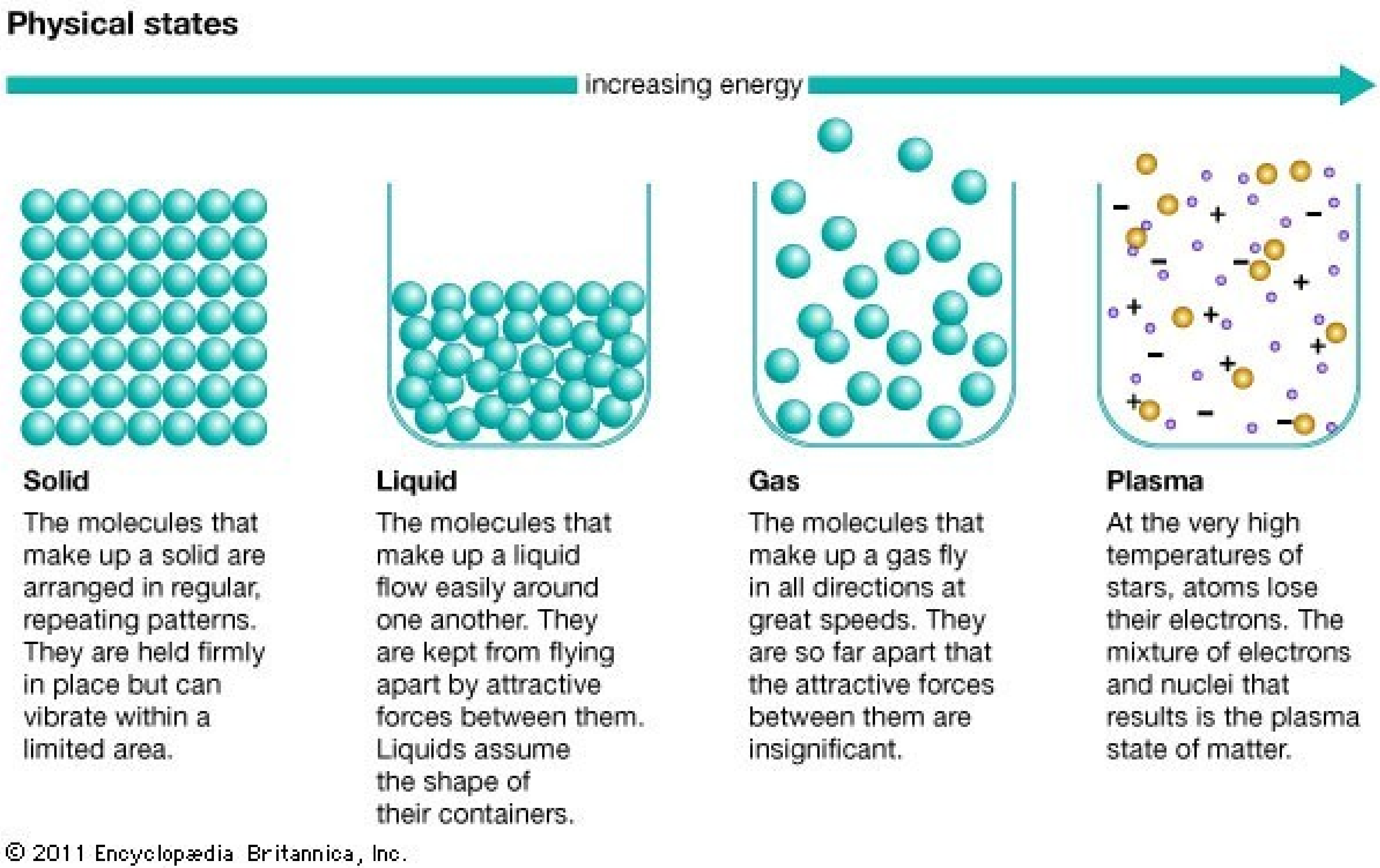
J. Wambach: Meson propagation in nuclear matter

Phase Diagram of QCD Matter

Functional Renormalization Group

Mesons evolution

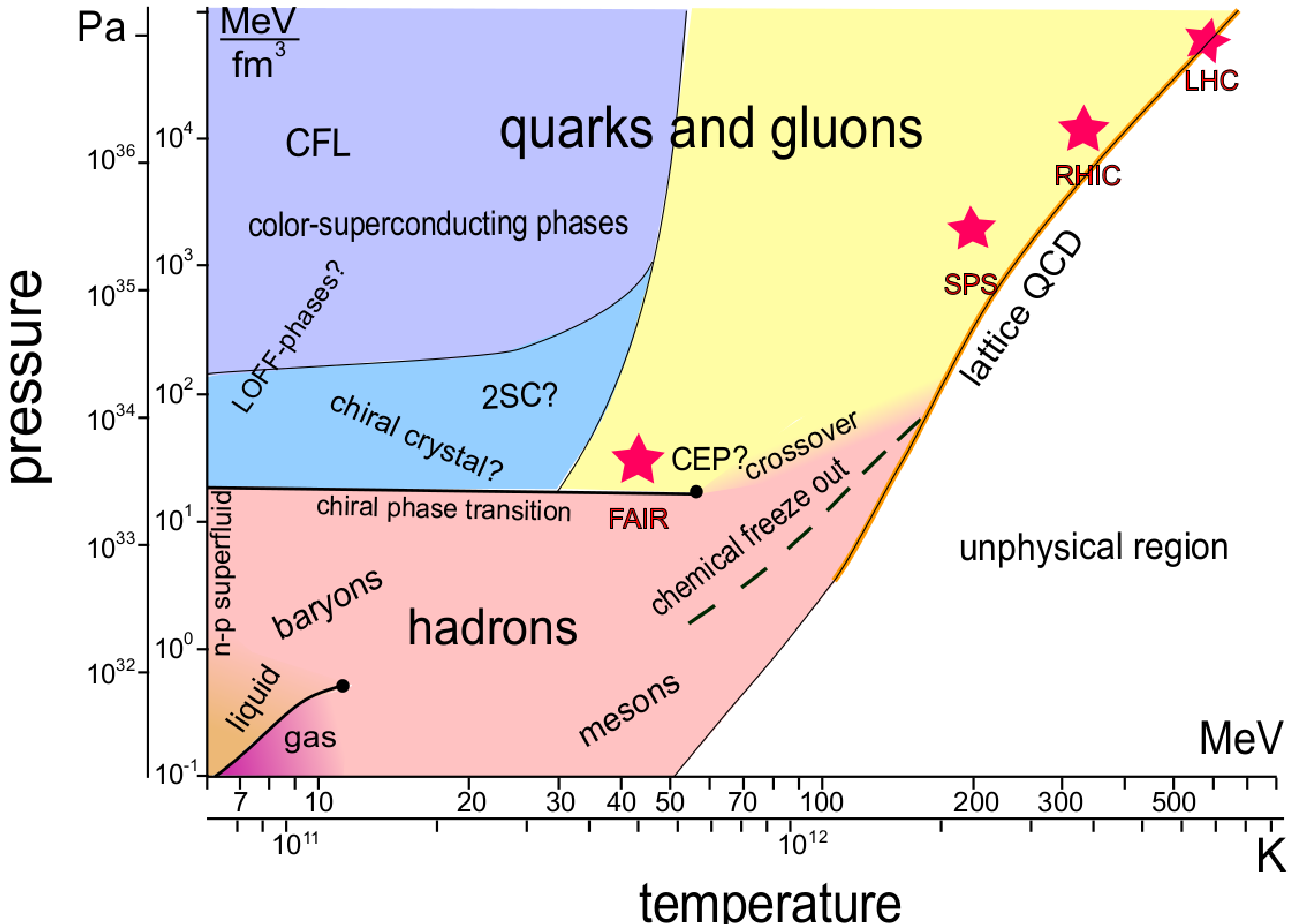
States of Matter



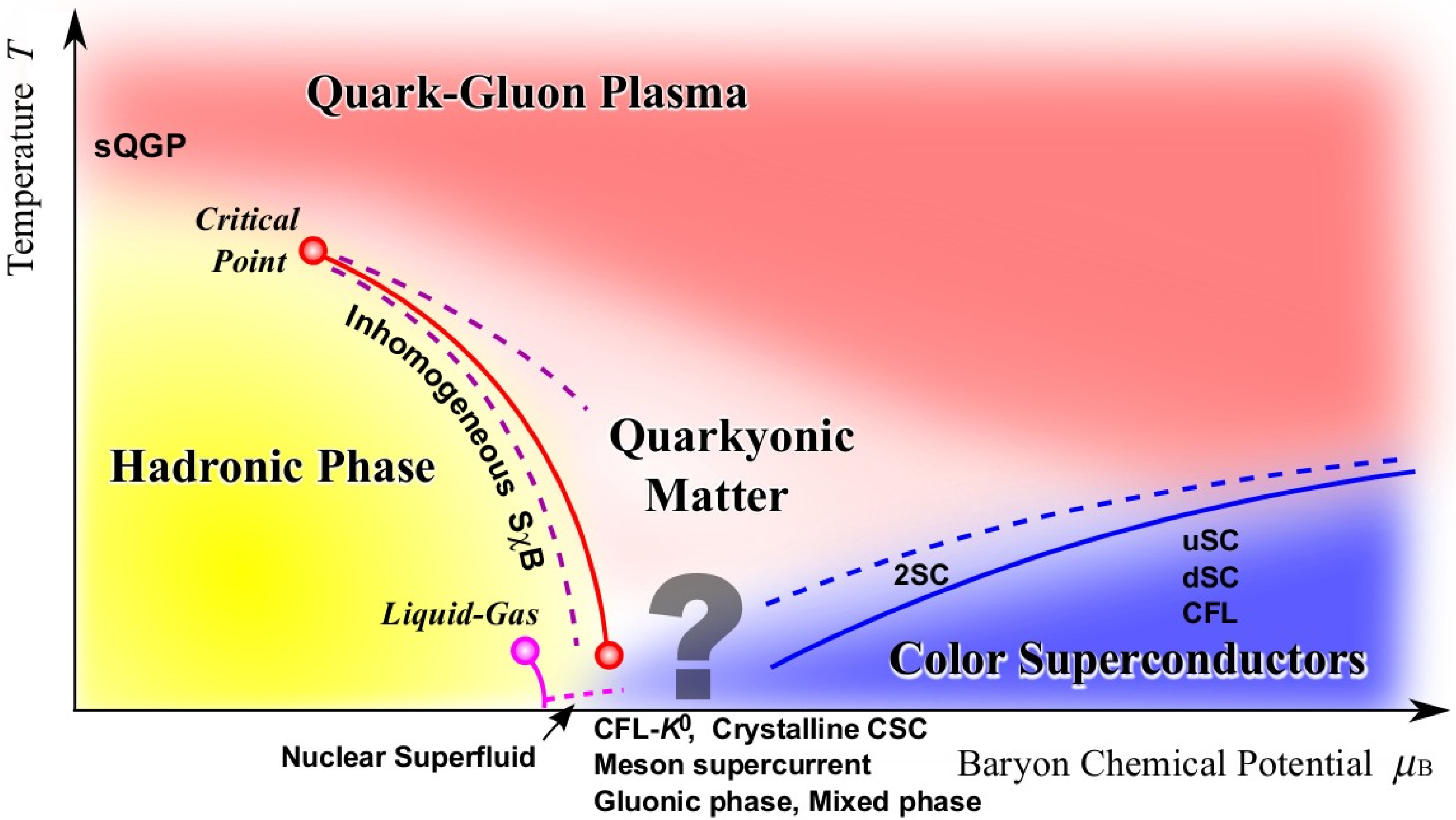
Symmetries of QCD and Breaking Pattern

symmetry	vacuum	high T	low T, high μ	order parameter	consequences
(local) color $SU(3)$	unbroken	unbroken	broken	diquark condensate	color superconductivity
$Z(3)$ center symmetry	unbroken	broken	broken	Polyakov loop	confinement/ deconfinement
scale invariance	anomaly			gluon condensate	scale (Λ_{QCD}), running coupling
chiral symmetry $U_L(N_f) \times U_R(N_f) = U_V(1) \times SU_V(N_f) \times SU_A(N_f) \times U_A(1)$					
$U_V(1)$	unbroken	unbroken	unbroken	—	baryon number conservation
flavor $SU_V(N_f)$	unbroken	unbroken	unbroken	—	multiplets
chiral $SU_A(N_f)$	broken	unbroken	broken	quark condensate	Goldstone bosons, no degenerate states with opposite parity
$U_A(1)$	anomaly			topological susceptibility	violation of intrinsic parity

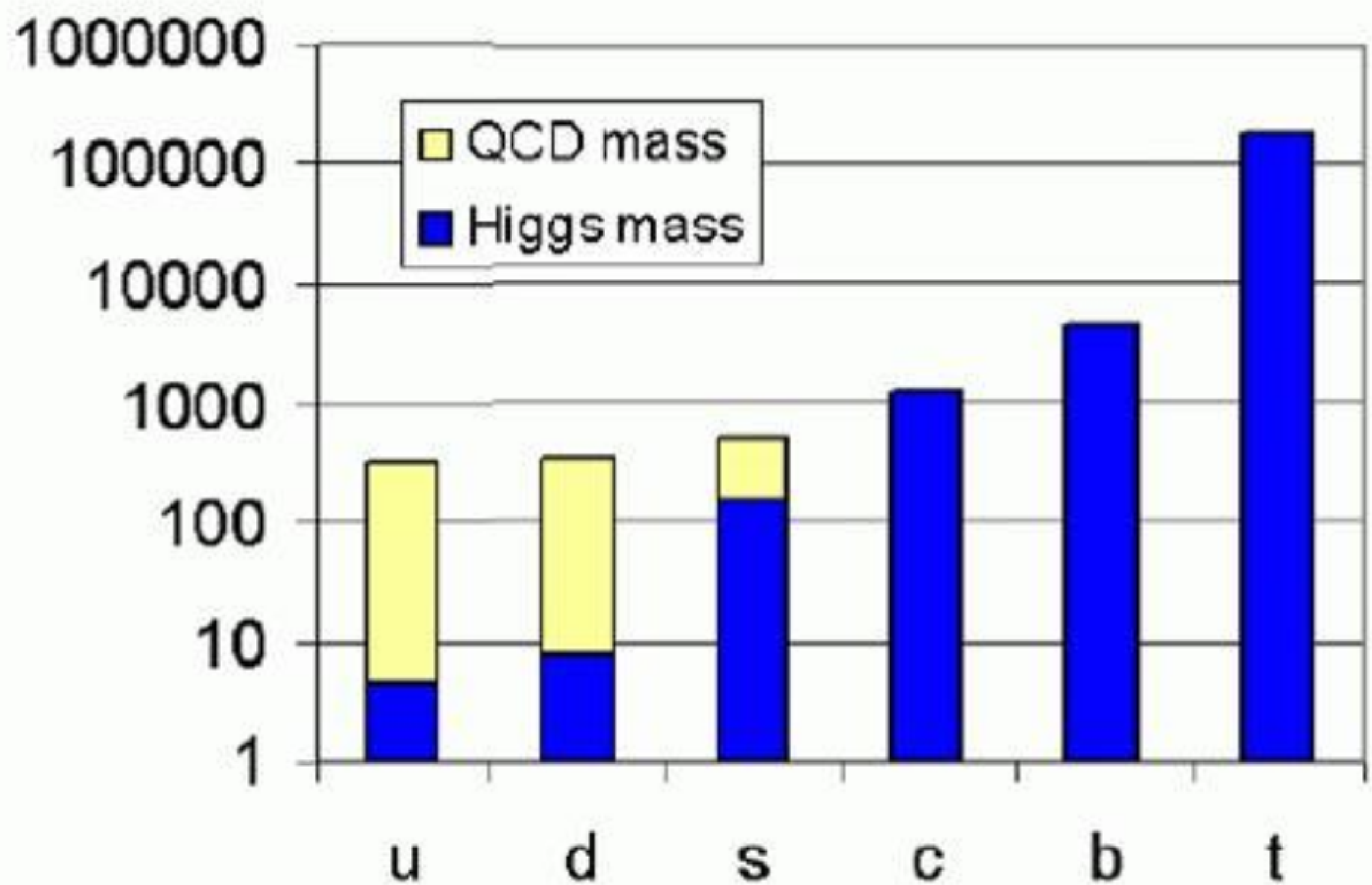
Phase Diagram of QCD Matter



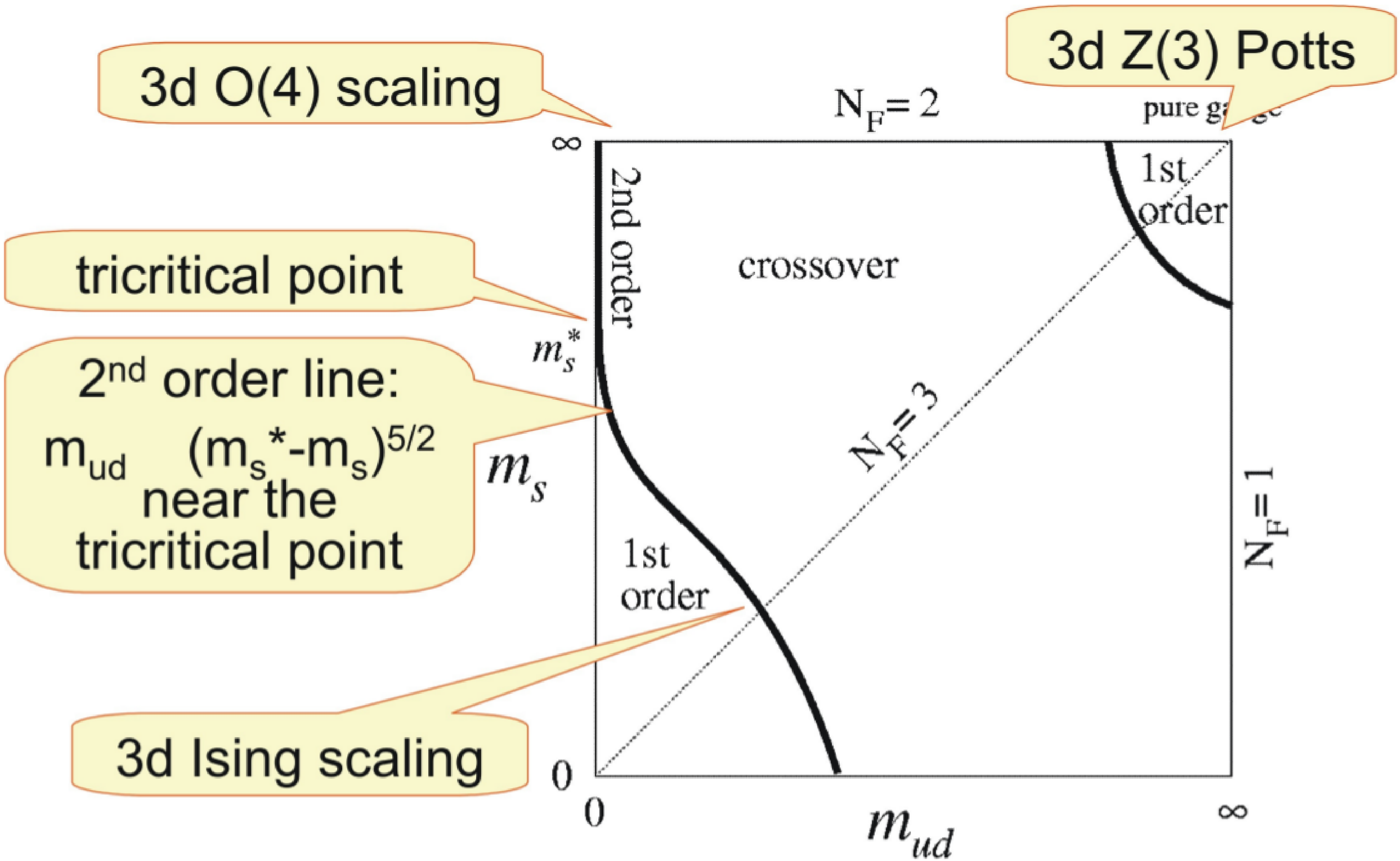
Phase Diagram of QCD Matter



Generation of Mass in QCD



'Columbia' Plot



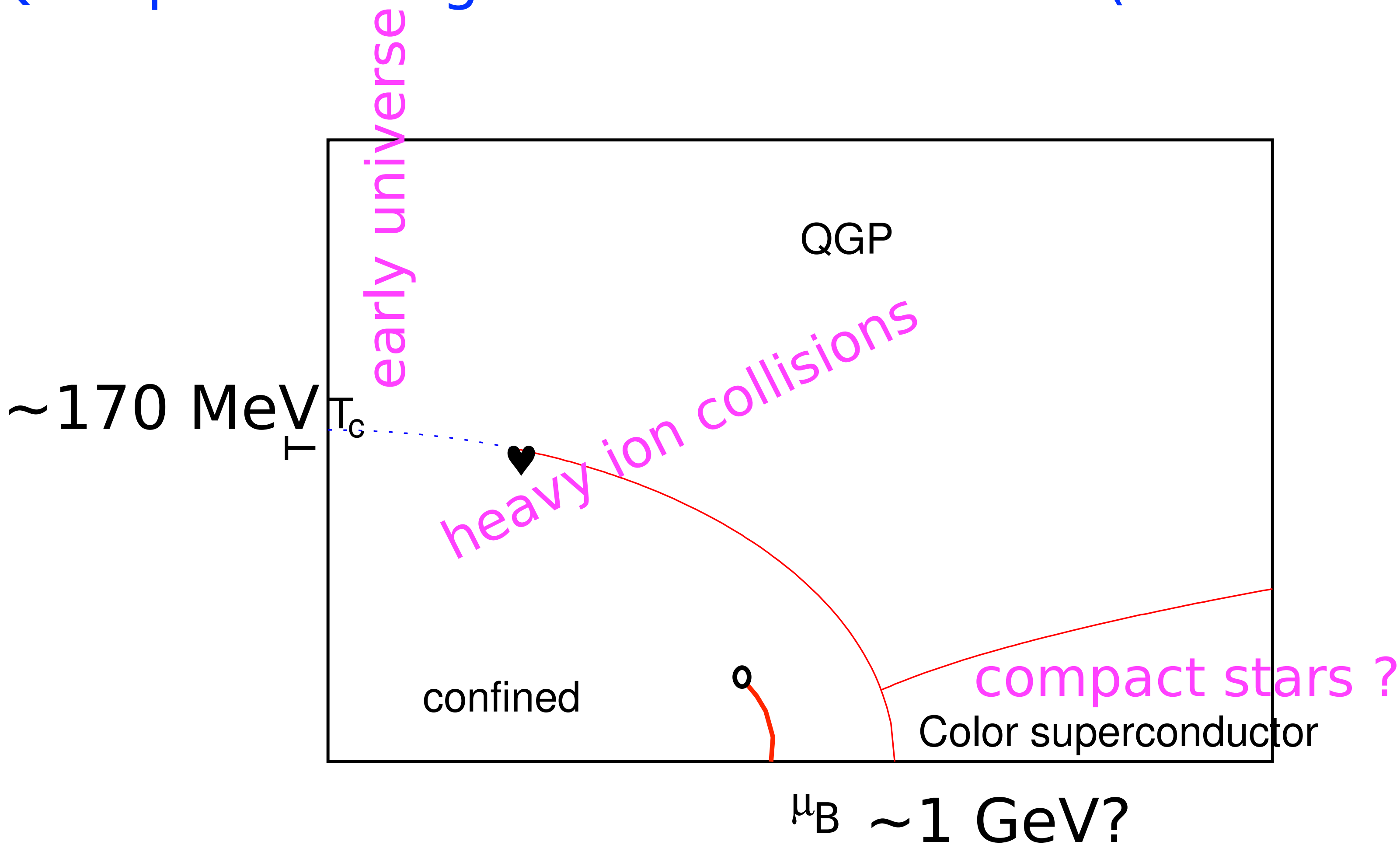
Topics

O. Philipsen: Lattice QCD at finite temperature

QCD at zero and finite temperature

The lattice formulation

QCD phase diagram: theorist's view (science fiction)

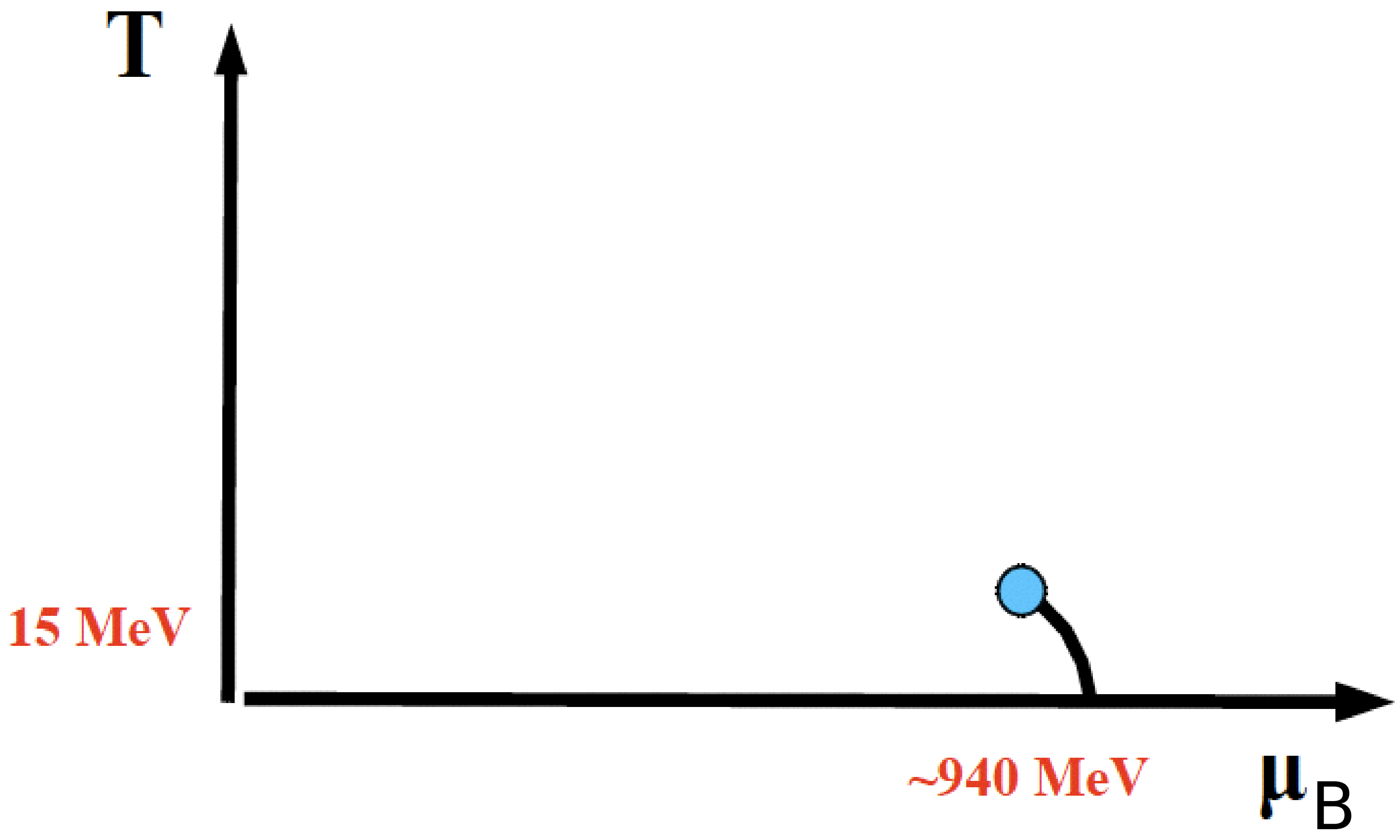


Until 2001: no finite density lattice calculations, sign proble

Expectation based on simplifying models (NJL, linear sigma

Check this from first principles QCD!

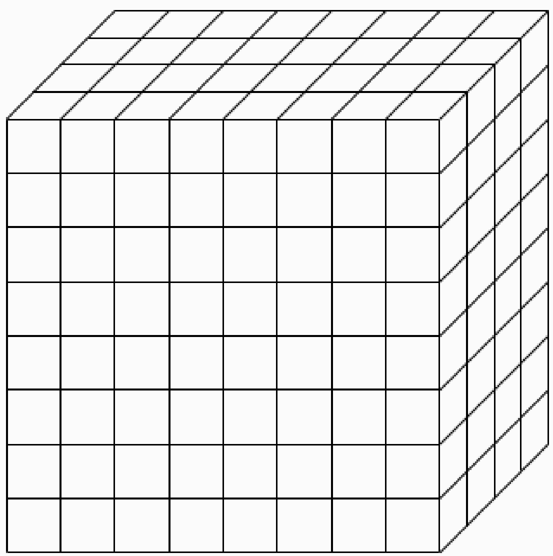
The QCD phase diagram established by experiment:



Nuclear liquid gas transition
with critical end point

Lattice formulation of Euclidean QFT's

$\mathbb{R}^4 \;\longrightarrow\; x = \{x_\mu \,|\, \mu = 1,\ldots,4\} \in a\mathbb{Z}^4 \qquad a \;:\;$ lattice spacing (or constant)



- $\phi(x)$: living on the lattice sites only
- partial derivatives $\longrightarrow$ finite differences:

$$\partial_\mu \phi \quad\longrightarrow\quad \triangle_\mu^{(*)}\phi(x) = \frac{\pm\phi(x \pm a\hat{\mu}) \mp \phi(x)}{a}$$

$\Rightarrow$ forward & backward lattice derivatives

Rotation symmetry:

$SO(4) \longrightarrow D_h^4$

$$\int \mathrm{d}^4x \quad\longrightarrow\quad \sum_x a^4 \qquad\qquad \mathcal{D}\phi \longrightarrow \prod_x \mathrm{d}\phi(x) \equiv \mathcal{D}[\phi]$$

(infinite-dimensional) integration measure well defined on discrete system!

➡ finite numbers on finite lattice!

Lattice action:

$$S = \sum_x a^4 \left\{ \frac{1}{2} \sum_{\mu=1}^{4} [\triangle_\mu \phi(x)]^2 + \frac{m_0^2}{2} \phi^2(x) + \frac{g_0}{4!} \phi^4(x) \right\}$$

$$\text{Fourier transform}: \quad \tilde{\phi}(p) = \sum_x a^4 \mathrm{e}^{-ipx} \phi(x) \quad \text{periodic}$$

$\Rightarrow$ restrict momenta to Brillouin zone $-\pi/a < p_\mu \leq \pi/a$

inverse Fourier transform:

$$\phi(x) = \int_{-\pi/a}^{\pi/a} \frac{\mathrm{d}^4 p}{(2\pi)^4} \, \mathrm{e}^{ipx} \, \tilde{\phi}(p) \quad \Leftrightarrow \quad \text{ultraviolet cutoff } |p_\mu| \leq \frac{\pi}{a}$$

$\Rightarrow$ field theories on a lattice are naturally regularized

finite volume $V = L^3 L_t$

boundary cond. (periodic)

coordinates $\quad x_\mu = a n_\mu\,,\ n_\mu = 0, 1, 2, \ldots L_\mu - 1$

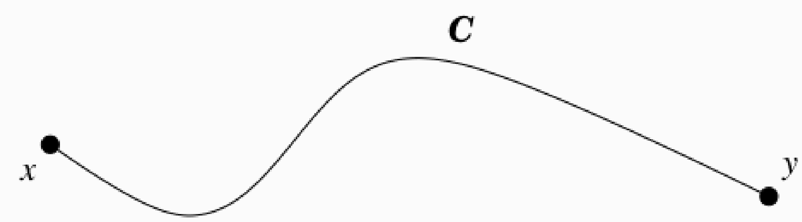
momenta $\quad p_\mu = \dfrac{2\pi}{a L_\mu} \times l_\mu\,,\ l_\mu = 0, 1, 2, \ldots L_\mu - 1$

momentum integrations $\quad \displaystyle\int \frac{\mathrm{d}^4 p}{(2\pi)^4} \rightarrow \frac{1}{a^4 V} \sum_{l_\mu}$

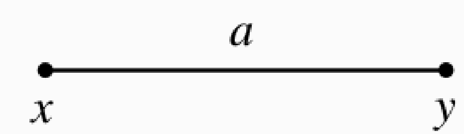
SU(N) gauge theory on a lattice

Gauge fields: cf. continuum parallel transport

$\psi(y) = \mathcal{P}\exp\left[\mathrm{i}g\int_x^y dz_\mu A_\mu(z)\right]\psi(x)$



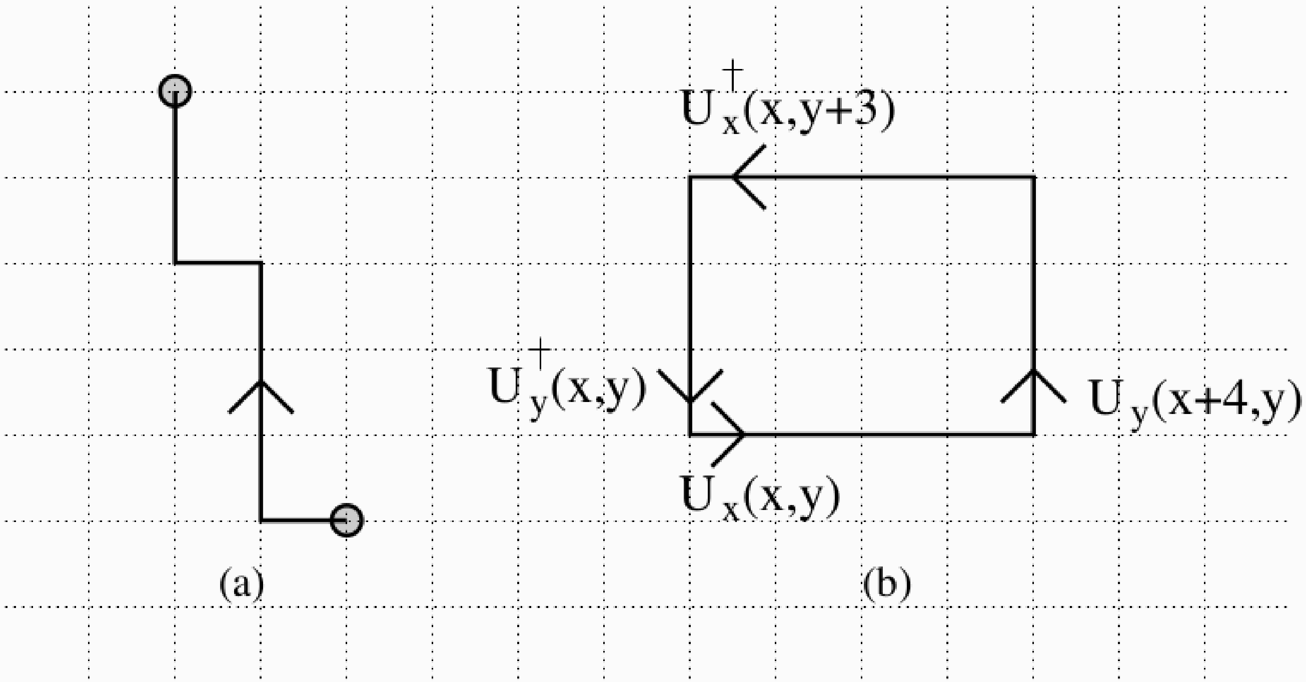
Links=parallel transp. by a: $U_\mu(x) = \mathrm{e}^{-\mathrm{i}agA_\mu(x)}$



Gauge trafo: $\psi^g(x) = g(x)\psi(x)$, $U_\mu^g(x) = g(x)U_\mu(x)g^\dagger(x+\hat{\mu})$

Covariant derivative: $D_\mu\psi(x) \to a^{-1}\left(U_\mu(x)\psi(x+\hat{\mu}) - \psi(x)\right) + O(a)$

Two kinds of gauge invariant objects $\longrightarrow$ observables



transforms adjoint:

$$U_C^g(x) = g(x)U_C(x)g^{-1}(x)$$

$$\Rightarrow \quad \mathrm{Tr}U_C^g = \mathrm{Tr}U_C(x)$$

Discretisation respects gauge invariance, independent of a!

smallest loop: "plaquette" $U_\mathrm{p}(x) \equiv U^\dagger(x,\nu)U^\dagger(x+a\hat{\nu},\mu)U(x+a\hat{\mu},\nu)U(x,\mu)$

$$\square \to 1 + ia^2 gF_{\mu\nu} - \frac{a^4 g^2}{2}F_{\mu\nu}F^{\mu\nu} + O(a^6) + \ldots$$

$U_\mu(x) = \mathrm{e}^{-\mathrm{i}agA_\mu(x)}$

Adding fermions

Pick a suitable fermion action: $$S_f = \sum_{x,y} \bar{\psi}(x) M_{xy}(m_f)\, \psi(y)$$

Full QCD partition function:

$$Z(N_s, N_\tau; \beta, m_f) = \int DU \, \prod_f \det M(m_f)\, \mathrm{e}^{-S_g[U]} \ ,$$

$$U_\mu(\tau, \mathbf{x}) = U_\mu(\tau + N_\tau, \mathbf{x}),$$

$$\psi(\tau, \mathbf{x}) = -\psi(\tau + N_\tau, \mathbf{x}) \ .$$

Wilson fermions:

$$S_f^W = \frac{1}{2a} \sum_{x,\mu,f} a^4\, \bar{\psi}_f(x)[(\gamma_\mu - r) U_\mu(x) \psi_f(x+\hat{\mu}) - (\gamma_\mu + r) U_\mu^\dagger(x-\hat{\mu}) \psi_f(x-\hat{\mu})]$$

$$+ (m + 4\frac{r}{a}) \sum_{x,f} a^4\, \bar{\psi}_f(x) \psi_f(x)$$

pick your poison

- Wilson fermions
  add irrelevant ops. (going away in CL) to make doublers very massive
  breaks chiral symmetry for non-zero a
- staggered (Kogut-Susskind) fermions
  distribute spinor components on different sites, reduces to 4 flavours
  take 4th root of determinant to get to one flavour, keeps reduced chiral symm.
  non-local operation, have to take CL before chiral limit, mixing of spin, flavour
- domain wall fermions
  introduce 5th dimension, fermions massive in that dim. and chiral in the other
  expensive
- overlap fermions
  non-local formulation with modified chiral symmetry even for finite a
  orders of magnitude more expensive than Wilson

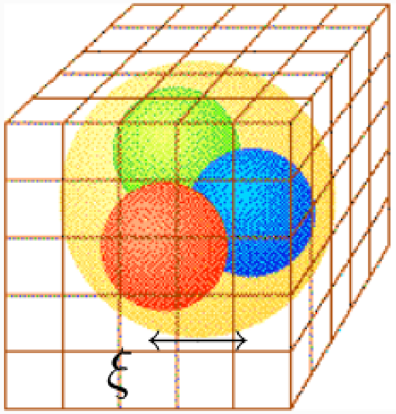
Monte Carlo evaluation

$$Z = \int D\bar{\psi} D\psi DU \, \mathrm{e}^{-S_g[U] - S_f[U,\bar{\psi},\psi]} = \int DU \prod_f (\det M) \, \mathrm{e}^{-S_g[U]}$$

Systematics: finite V,a effects

for hadron with m_H, $\xi \sim m_H^{-1}$

$a \ll \xi \ll aL$!

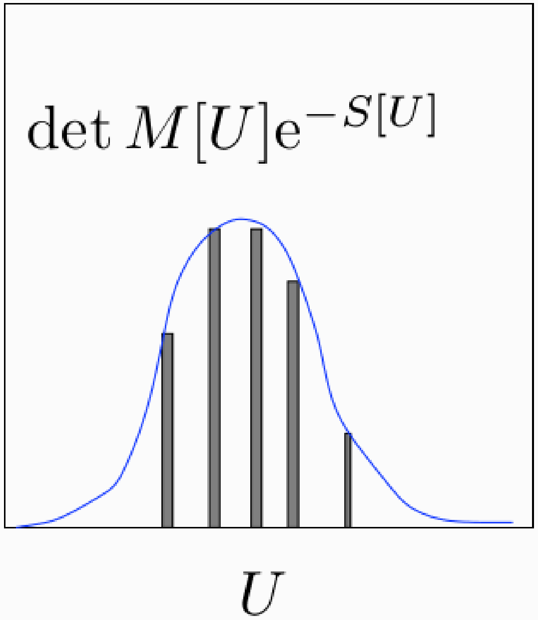


⇒e.g. $30^4 \sim 10^6$ lattice points

every point ⇒4 U's, every $U \in$ SU(3) ⇒8 independent components $\boxed{\Rightarrow 10^8\text{-dimensional integral!}}$

very peaked integrand!

$\Rightarrow$ Monte Carlo integration, importance sampling



Markov process: ensemble

$\{U_1\} \to \{U_2\} \to \{U_3\} \ldots \{U_N\}$

"$\to$ ": updating algorithm with associated probability, ergodic

$$\langle \mathcal{O} \rangle = Z^{-1} \int DU \, \det M \, \mathcal{O} \, e^{-S_g[U]} \approx \frac{1}{N} \sum_{n=1}^{N} (\det M \mathcal{O})[U]$$

$\Rightarrow N$ "measurements" of $\mathcal{O}$ $\Rightarrow$ statistical error $\sim 1/\sqrt{N}$

Light fermions expensive:

$$\det M[U] = \lambda_1[U] \cdot \lambda_2[U] \cdot \lambda_3[U] \ldots , \qquad \text{cost}(\det M) \sim \frac{1}{m_q^n}, \quad n > 5$$

Non-local: every eigenvalue depends on every link

Continuum limit

$$\frac{1}{T} \equiv aN_\tau$$

Fixed scale approach:

- For a given lattice spacing, N_τ controls temperature;
- Allows only discrete temperatures, too large for many applications;
- Continuum limit requires series of lattice spacings

Fixed N_τ approach:

- For a given N_τ, vary the lattice spacing via $\beta(a)$;
- Allows continuous temperatures, but each T value has different cut-off!
- Continuum limit requires series of N_τ

Topics

I. Karpenko: Relativistic hydrodynamics and its application to relativistic heavy ion collisions
– Standard Course

A. Beraudo: Heavy quarks and hard probes in relativistic heavy ion collisions

K. Fukushima: Magnetic effects in relativistic heavy ion collisions

Topics

M. Pappagallo: Hadron Spectroscopy Techniques (Special Seminar) Pentoquark discovery

http://www.ggi.fi.infn.it/talkfiles/slides/talk3912.pdf

Exotic Hadron Spectroscopy

Marco Pappagallo

INFN and University of Bari

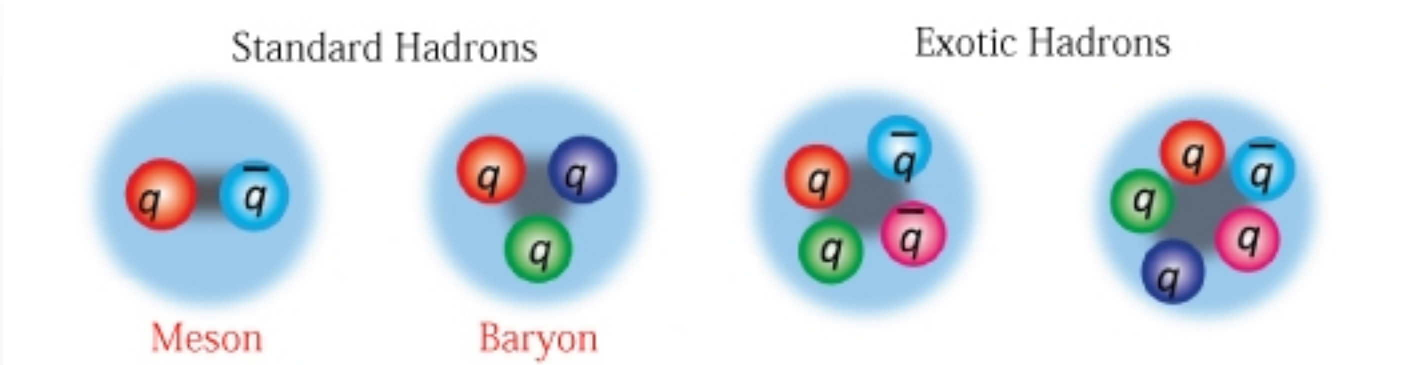
Galileo Galilei Institute

23 February 2017, Florence, Italy

OUTLINE

- Introduction
  - Spectroscopy Techniques
  - Amplitude/Dalitz Analyses
- Search for Pentaquarks $P_c^+ \rightarrow J/\psi\ p$
  - Amplitude Analysis of $\Lambda_b \rightarrow J/\psi\ p\ K^-$ Decay
  - Model Independent Analysis of $\Lambda_b \rightarrow J/\psi\ p\ K^-$ Decay
  - Amplitude Analysis of $\Lambda_b \rightarrow J/\psi\ p\ \pi^-$ Decay
- Search for a tetraquark $X(5568)^{\pm} \rightarrow B_s\ \pi^{\pm}$
- Amplitude Analysis for $B^+ \rightarrow J/\psi\ \phi\ K^+$

INTRODUCTION: "EXOTIC"



Tetra- and Penta-quarks conceived at the birth of the quark model

Volume 8, number 3 PHYSICS LETTERS 1 February 1964

A SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN
California Institute of Technology, Pasadena, California

Received 4 January 1964

A simpler and more elegant scheme can be constructed if we allow non-integral values for the charges. We can dispense entirely with the basic baryon b if we assign to the triplet t the following properties: spin $\frac{1}{2}$, $z = -\frac{1}{3}$, and baryon number $\frac{1}{3}$. We then refer to the members $u^{\frac{2}{3}}$, $d^{-\frac{1}{3}}$, and $s^{-\frac{1}{3}}$ of the triplet as "quarks" 6) q and the members of the anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations $(q\,q\,q)$, $(q\,q\,q\,q\,\bar{q})$, etc., while mesons are made out of $(q\,\bar{q})$, $(q\,q\,\bar{q}\,\bar{q})$, etc. It is assuming that the lowest baryon configuration $(q\,q\,q)$ gives just the representations **1**, **8**, and **10** that have been observed, while

8419/TH.412
21 February 1964

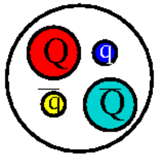
AN SU_3 MODEL FOR STRONG INTERACTION SYMMETRY AND ITS BREAKING
II *)

G. Zweig **)
CERN---Geneva

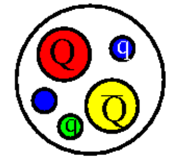
*) Version I is CERN preprint 8182/TH.401, Jan. 17, 1964.

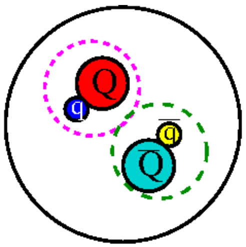
6) In general, we would expect that baryons are built not only from the product of three aces, AAA, but also from $\bar{A}$AAAA, $\bar{A}\bar{A}$AAAAA, etc., where $\bar{A}$ denotes an anti-ace. Similarly, mesons could be formed from $\bar{A}$A, $\bar{A}\bar{A}$AA etc. For the low mass mesons and baryons we will assume the simplest possibilities, $\bar{A}$A and AAA, that is, "deuces and treys".

Models for Tetra- and Penta-quarks

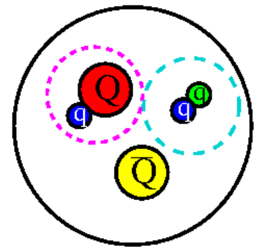


"plain"

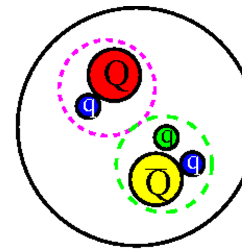


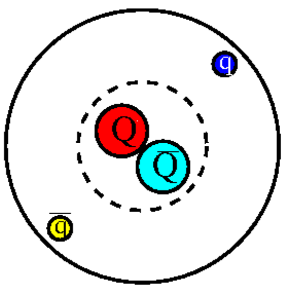


diquark model

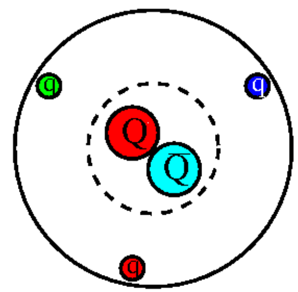


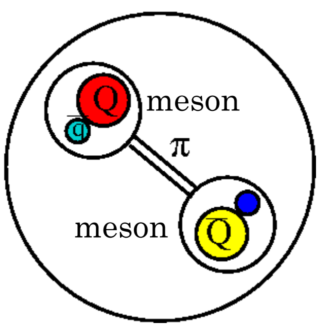
triquark model



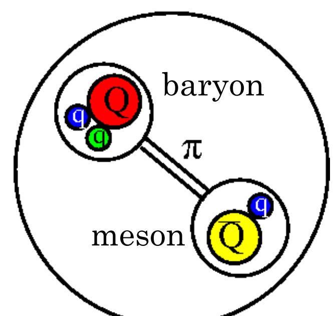


hydro-charmonium model



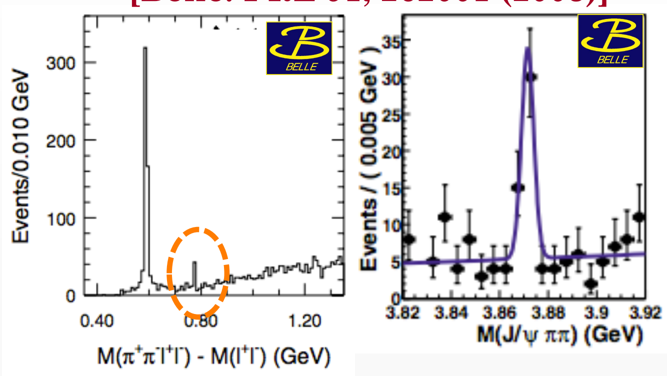


molecular model



The X(3872) State

[Belle: PRL 91, 262001 (2003)]



Discovered in 2003 by the Belle collaboration in the $B \to KX(3872)$ decay where $X(3872) \to J/\psi\pi^+\pi^-$

- ⊛ Mass is roughly equal to $m(D^0) + m(D^{*0})$
- ⊛ Width is surprisingly narrow (< 1.2 MeV)
- ⊛ Large production rate in $p\bar{p}$ collisions

LHC experiments are largely contributing to shed light on the nature of the X(3872) state

- ➢ Determination of the quantum numbers $J^{PC} = 1^{++}$ [PRL110 222001 (2013)][PRD92 011102 (2015)]
- ➢ Measurement of $\mathcal{B}$(X(3872)→ψ(2S) γ)/$\mathcal{B}$(X(3872)→J/ψ γ) [Nucl.Phys.B886 (2014) 665]

$$\frac{BR(X(3872) \to \psi(2S)\gamma)}{BR(X(3872) \to J/\psi\gamma)} = 2.46 \pm 0.64 \pm 0.29$$

➡ *Pure molecule scenario disfavored*

- ➢ Precise mass measurement [EPJC 72 (2012) 1972] [JHEP 06 (2013) 065]

$$E_B = m(D^0) + m(D^{*0}) - m(X(3872)) = 3 \pm 192\,\mathrm{keV}/c^2$$

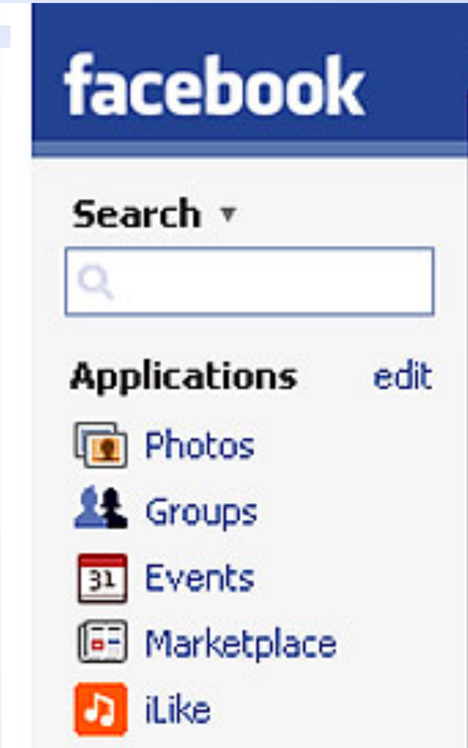
➡ *Loosely bound in the molecule scenario*

- ➢ Production cross-section in *pp* collisions at √s = 7 TeV [EPJC 72 (2012) 1972,]
- ➢ Search for new decay modes (e.g. X(3872) →$p\bar{p}$) [arXiv: 1607.06446]

$$\frac{\mathcal{B}(B^+ \to X(3872)K^+) \times \mathcal{B}(X(3872) \to p\bar{p})}{\mathcal{B}(B^+ \to J/\psi K^+) \times \mathcal{B}(J/\psi \to p\bar{p})} < 0.25 \times 10^{-2} \text{ @ } 95\%\ \mathrm{CL}$$

…AND FRIENDS

Eur.Phys.J. C74 (2014) 10, 2981

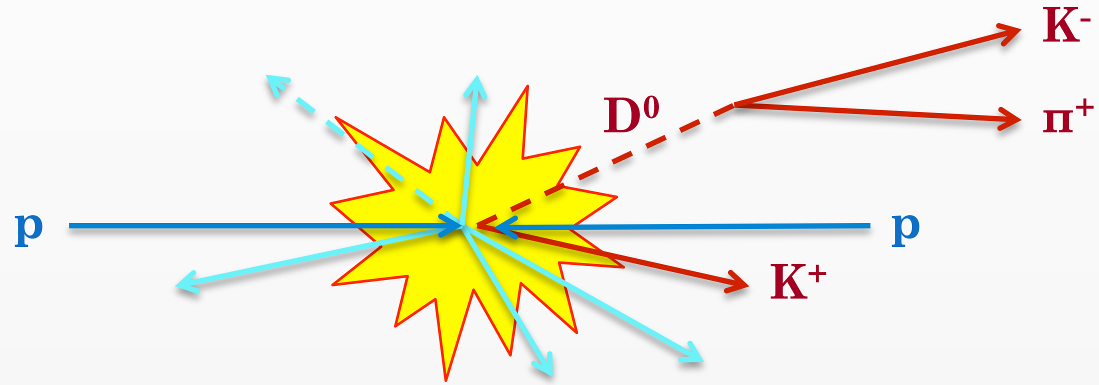


State	M, MeV	Γ, MeV	J^{PC}	Process (mode)	Experiment (#σ)	Year	Status
$X(3872)$	3871.68 ± 0.17	< 1.2	1^{++}	$B \to K(\pi^+\pi^- J/\psi)$	Belle [810, 1030] (>10), BaBar [1031] (8.6)	2003	Ok
				$p\bar{p} \to (\pi^+\pi^- J/\psi) \ldots$	CDF [1032, 1033] (11.6), D0 [1034] (5.2)	2003	Ok
				$pp \to (\pi^+\pi^- J/\psi) \ldots$	LHCb [1035, 1036] (np)	2012	Ok
				$B \to K(\pi^+\pi^-\pi^0 J/\psi)$	Belle [1037] (4.3), BaBar [1038] (4.0)	2005	Ok
				$B \to K(\gamma J/\psi)$	Belle [1039] (5.5), BaBar [1040] (3.5)	2005	Ok
					LHCb [1041] (> 10)		
				$B \to K(\gamma \psi(2S))$	BaBar [1040] (3.6), Belle [1039] (0.2)	2008	NC!
					LHCb [1041] (4.4)		
				$B \to K(D\bar{D}^*)$	Belle [1042] (6.4), BaBar [1043] (4.9)	2006	Ok
$Z_c(3885)^+$	3883.9 ± 4.5	25 ± 12	1^{+-}	$Y(4260) \to \pi^-(D\bar{D}^*)^+$	BES III [1044] (np)	2013	NC!
$Z_c(3900)^+$	3891.2 ± 3.3	40 ± 8	$?^{?-}$	$Y(4260) \to \pi^-(\pi^+ J/\psi)$	BES III [1045] (8), Belle [1046] (5.2)	2013	Ok
					T. Xiao *et al.* [CLEO data] [1047] (>5)		
$Z_c(4020)^+$	4022.9 ± 2.8	7.9 ± 3.7	$?^{?-}$	$Y(4260, 4360) \to \pi^-(\pi^+ h_c)$	BES III [1048] (8.9)	2013	NC!
$Z_c(4025)^+$	4026.3 ± 4.5	24.8 ± 9.5	$?^{?-}$	$Y(4260) \to \pi^-(D^*\bar{D}^*)^+$	BES III [1049] (10)	2013	NC!
$Z_b(10610)^+$	10607.2 ± 2.0	18.4 ± 2.4	1^{+-}	$\Upsilon(10860) \to \pi(\pi\Upsilon(1S, 2S, 3S))$	Belle [1050–1052] (>10)	2011	Ok
				$\Upsilon(10860) \to \pi^-(\pi^+ h_b(1P, 2P))$	Belle [1051] (16)	2011	Ok
				$\Upsilon(10860) \to \pi^-(B\bar{B}^*)^+$	Belle [1053] (8)	2012	NC!
$Z_b(10650)^+$	10652.2 ± 1.5	11.5 ± 2.2	1^{+-}	$\Upsilon(10860) \to \pi^-(\pi^+\Upsilon(1S, 2S, 3S))$	Belle [1050, 1051] (>10)	2011	Ok
				$\Upsilon(10860) \to \pi^-(\pi^+ h_b(1P, 2P))$	Belle [1051] (16)	2011	Ok
				$\Upsilon(10860) \to \pi^-(B^*\bar{B}^*)^+$	Belle [1053] (6.8)	2012	NC!
$Y(3915)$	3918.4 ± 1.9	20 ± 5	$0/2^{?+}$	$B \to K(\omega J/\psi)$	Belle [1088] (8), BaBar [1038, 1089] (19)	2004	Ok
				$e^+e^- \to e^+e^-(\omega J/\psi)$	Belle [1090] (7.7), BaBar [1091] (7.6)	2009	Ok
$\chi_{c2}(2P)$	3927.2 ± 2.6	24 ± 6	2^{++}	$e^+e^- \to e^+e^-(D\bar{D})$	Belle [1092] (5.3), BaBar [1093] (5.8)	2005	Ok
$X(3940)$	3942^{+9}_{-8}	37^{+27}_{-17}	$?^{?+}$	$e^+e^- \to J/\psi\,(D\bar{D}^*)$	Belle [1086, 1087] (6)	2005	NC!
$Y(4008)$	3891 ± 42	255 ± 42	1^{--}	$e^+e^- \to (\pi^+\pi^- J/\psi)$	Belle [1046, 1094] (7.4)	2007	NC!
$\psi(4040)$	4039 ± 1	80 ± 10	1^{--}	$e^+e^- \to (D^{(*)}\bar{D}^{(*)}(\pi))$	PDG [1]	1978	Ok
				$e^+e^- \to (\eta J/\psi)$	Belle [1095] (6.0)	2013	NC!
$Z(4050)^+$	4051^{+24}_{-43}	82^{+51}_{-55}	$?^{?+}$	$\bar{B}^0 \to K^-(\pi^+\chi_{c1})$	Belle [1096] (5.0), BaBar [1097] (1.1)	2008	NC!
$Y(4140)$	4145.8 ± 2.6	18 ± 8	$?^{?+}$	$B^+ \to K^+(\phi J/\psi)$	CDF [1098] (5.0), Belle [1099] (1.9),	2009	NC!
					LHCb [1100] (1.4), CMS [1101] (>5)		
					D0 [1102] (3.1)		
$\psi(4160)$	4153 ± 3	103 ± 8	1^{--}	$e^+e^- \to (D^{(*)}\bar{D}^{(*)})$	PDG [1]	1978	Ok
				$e^+e^- \to (\eta J/\psi)$	Belle [1095] (6.5)	2013	NC!
$X(4160)$	4156^{+29}_{-25}	139^{+113}_{-65}	$?^{?+}$	$e^+e^- \to J/\psi\,(D^*\bar{D}^*)$	Belle [1087] (5.5)	2007	NC!
$Z(4200)^+$	4196^{+35}_{-30}	370^{+99}_{-110}	1^{+-}	$\bar{B}^0 \to K^-(\pi^+ J/\psi)$	Belle [1103] (7.2)	2014	NC!
$Z(4250)^+$	4248^{+185}_{-45}	177^{+321}_{-72}	$?^{?+}$	$\bar{B}^0 \to K^-(\pi^+\chi_{c1})$	Belle [1096] (5.0), BaBar [1097] (2.0)	2008	NC!
$Y(4260)$	4250 ± 9	108 ± 12	1^{--}	$e^+e^- \to (\pi\pi J/\psi)$	BaBar [1104, 1105] (8), CLEO [1106, 1107] (11)	2005	Ok
					Belle [1046, 1094] (15), BES III [1045] (np)		
				$e^+e^- \to (f_0(980) J/\psi)$	BaBar [1105] (np), Belle [1046] (np)	2012	Ok
				$e^+e^- \to (\pi^- Z_c(3900)^+)$	BES III [1045] (8), Belle [1046] (5.2)	2013	Ok
				$e^+e^- \to (\gamma X(3872))$	BES III [1108] (5.3)	2013	NC!
$Y(4274)$	4293 ± 20	35 ± 16	$?^{?+}$	$B^+ \to K^+(\phi J/\psi)$	CDF [1098] (3.1), LHCb [1100] (1.0),	2011	NC!
					CMS [1101] (>3), D0 [1102] (np)		
$X(4350)$	$4350.6^{+4.6}_{-5.1}$	13^{+18}_{-10}	$0/2^{?+}$	$e^+e^- \to e^+e^-(\phi J/\psi)$	Belle [1109] (3.2)	2009	NC!
$Y(4360)$	4354 ± 11	78 ± 16	1^{--}	$e^+e^- \to (\pi^+\pi^-\psi(2S))$	Belle [1110] (8), BaBar [1111] (np)	2007	Ok
$Z(4430)^+$	4458 ± 15	166^{+37}_{-32}	1^{+-}	$\bar{B}^0 \to K^-(\pi^+\psi(2S))$	Belle [1112, 1113] (6.4), BaBar [1114] (2.4)	2007	Ok
					LHCb [1115] (13.9)		
				$\bar{B}^0 \to K^-(\pi^+ J/\psi)$	Belle [1103] (4.0)	2014	NC!
$X(4630)$	4634^{+9}_{-11}	92^{+41}_{-32}	1^{--}	$e^+e^- \to (\Lambda_c^+\bar{\Lambda}_c^-)$	Belle [1116] (8.2)	2007	NC!
$Y(4660)$	4665 ± 10	53 ± 14	1^{--}	$e^+e^- \to (\pi^+\pi^-\psi(2S))$	Belle [1110] (5.8), BaBar [1111] (5)	2007	Ok
$\Upsilon(10860)$	10876 ± 11	55 ± 28	1^{--}	$e^+e^- \to (B^{(*)}_{(s)}\bar{B}^{(*)}_{(s)}(\pi))$	PDG [1]	1985	Ok
				$e^+e^- \to (\pi\pi\Upsilon(1S, 2S, 3S))$	Belle [1051, 1052, 1117] (>10)	2007	Ok
				$e^+e^- \to (f_0(980)\Upsilon(1S))$	Belle [1051, 1052] (>5)	2011	Ok
				$e^+e^- \to (\pi Z_b(10610, 10650))$	Belle [1051, 1052] (>10)	2011	Ok
				$e^+e^- \to (\eta\Upsilon(1S, 2S))$	Belle [986] (10)	2012	Ok
				$e^+e^- \to (\pi^+\pi^-\Upsilon(1D))$	Belle [986] (9)	2012	Ok
$Y_b(10888)$	10888.4 ± 3.0	$30.7^{+8.9}_{-7.7}$	1^{--}	$e^+e^- \to (\pi^+\pi^-\Upsilon(nS))$	Belle [1118] (2.3)	2008	NC!

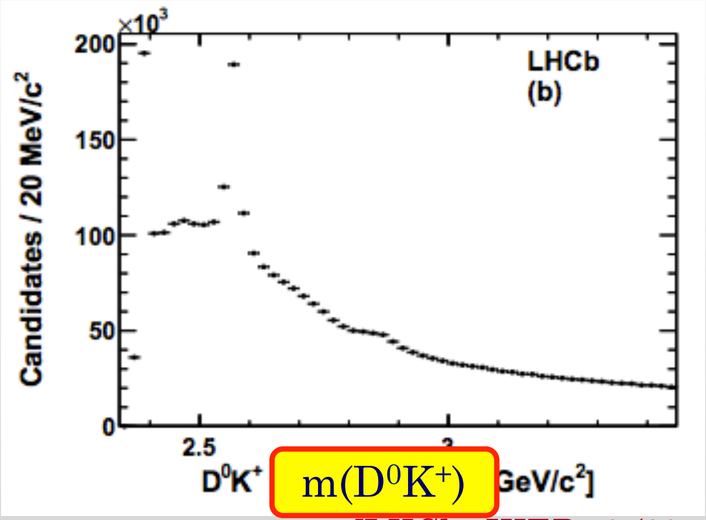
How to do spectroscopy?

"Inclusive Analysis"

(e.g. $e^+e^- \rightarrow D^{**}(\rightarrow D\pi) + X$ or $pp \rightarrow B_s^{**}(\rightarrow BK) + X$)



- Large cross sections 😄
- Large combinatorial background 😞
- Resonances appear as bumps
- Hard to disentangle broad structures
- Difficult to assess spin due to the unknown initial polarization 😰
- Presence of "reflections"/"feed-downs"



[LHCb: JHEP 10 (2012) 151]

How to do spectroscopy?

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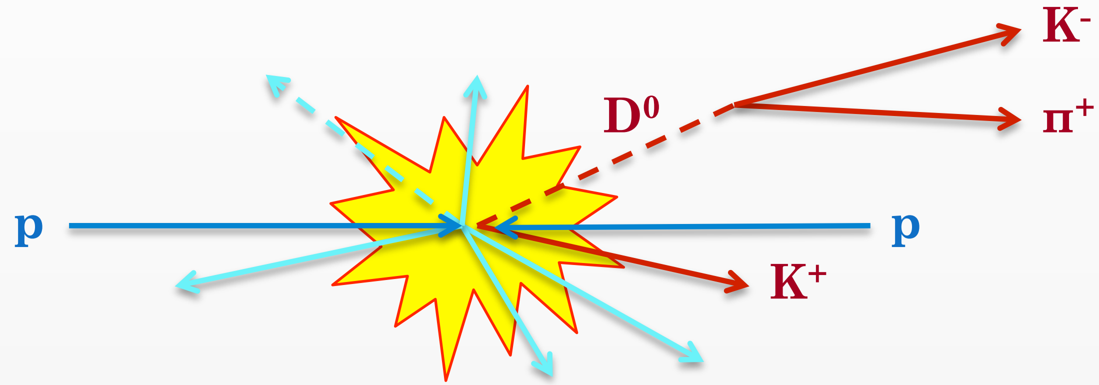

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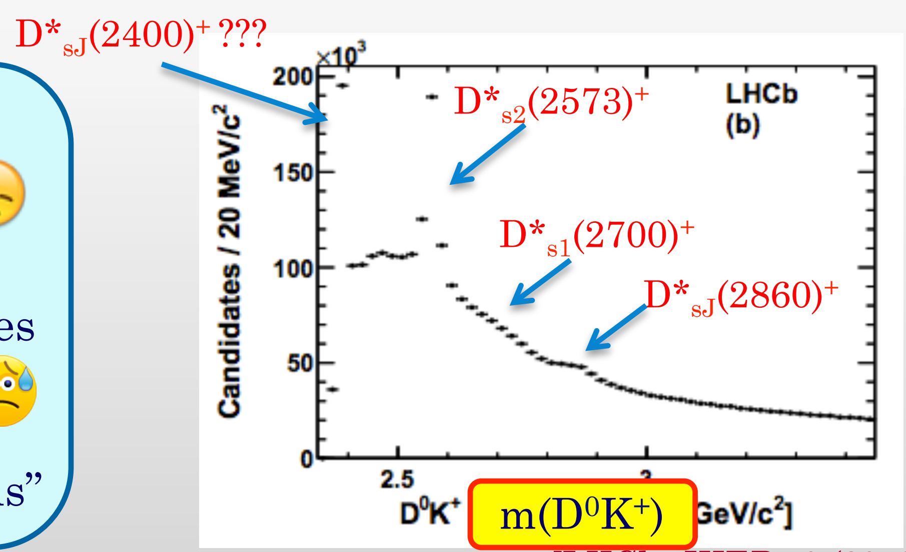
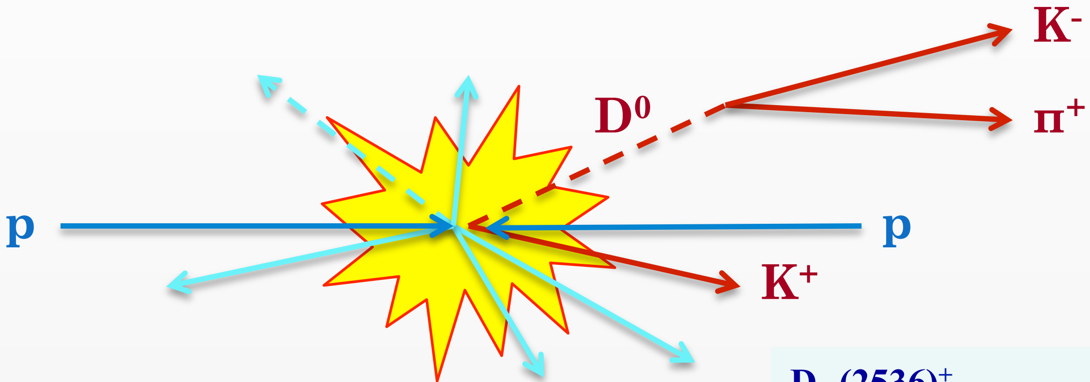


[LHCb: JHEP 10 (2012) 151]

HOW TO DO SPECTROSCOPY?

"Inclusive Analysis"

(e.g. $e^+e^- \rightarrow D^{**}(\rightarrow D\pi) + X$ or $pp \rightarrow B_s^{**}(\rightarrow BK) + X$)



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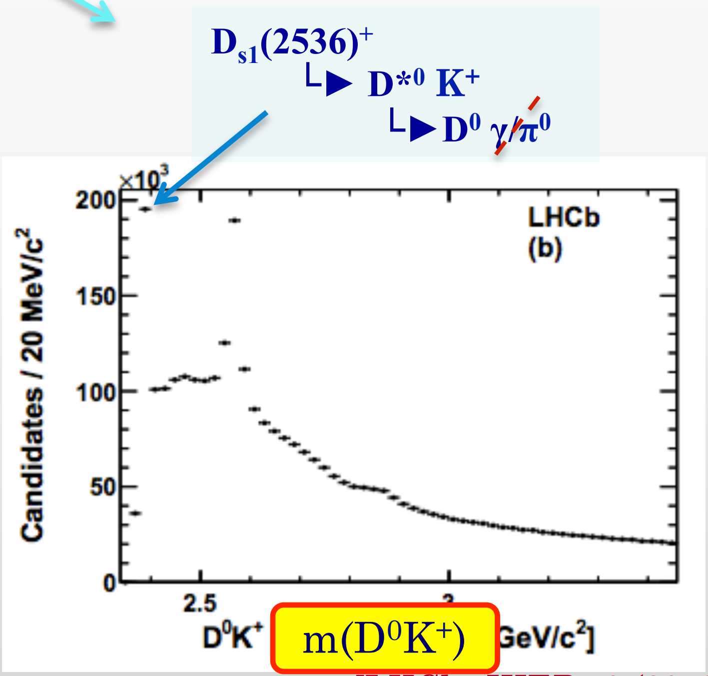


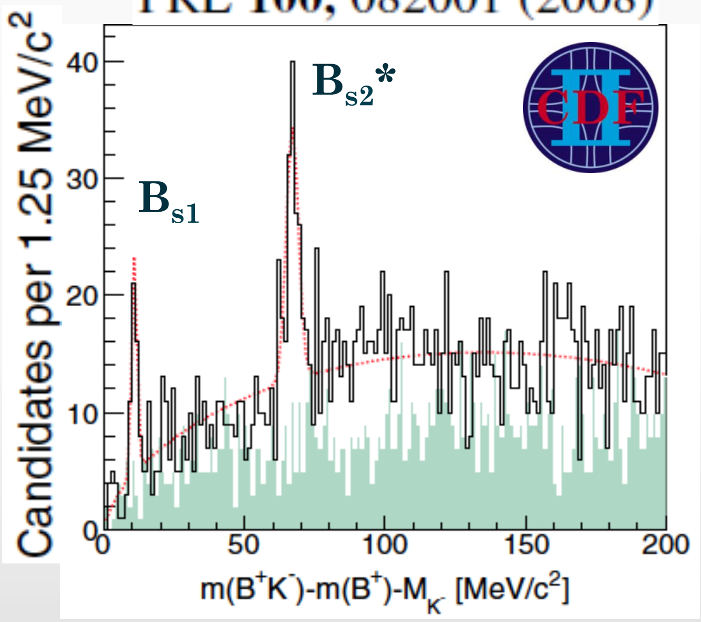
[LHCb: JHEP 10 (2012) 151]

$B_{s1}(5830)^0$ AND $B_{s2}^*(5840)^0$

- Two narrow peaks observed in the B^+K^- by CDF
- B_{s2}^* is the only narrow state expected. What is the nature of the second signal?

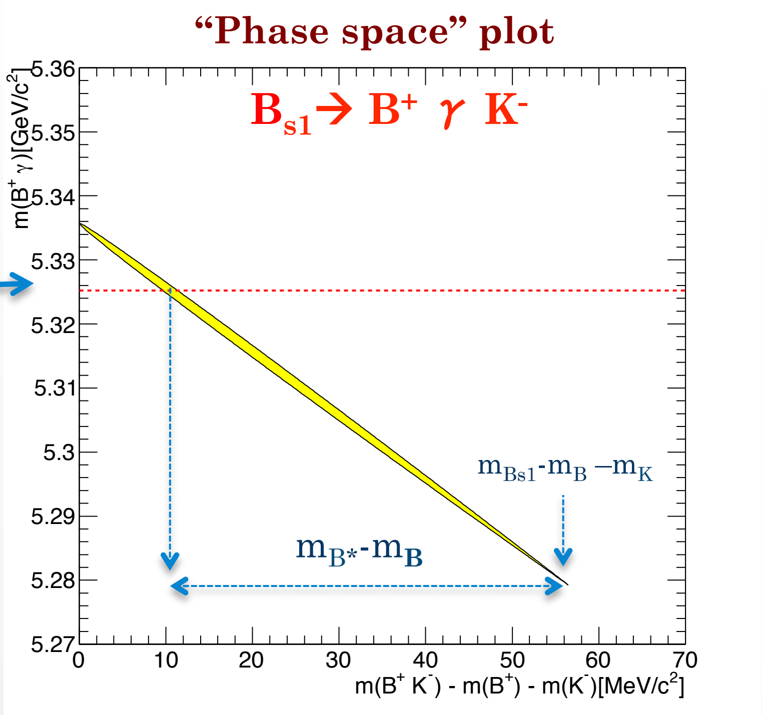
	j_q	J^P	Allowed decay mode B^+K^-	$B^{*+}K^-$
B_{s0}^*	1/2	0^+	yes	no
B_{s1}'	1/2	1^+	no	yes
B_{s1}	3/2	1^+	no	yes
B_{s2}^*	3/2	2^+	yes	yes

PRL 100, 082001 (2008)



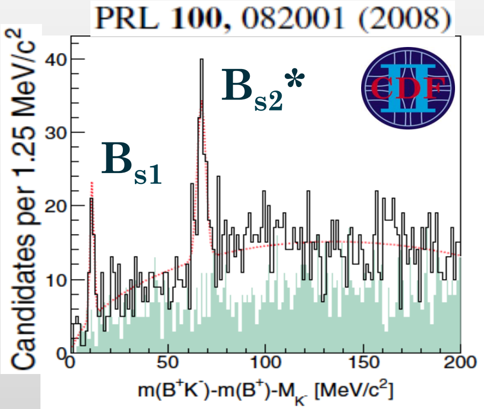
It is interpreted as a feed-down of the $B_{s1} \to B^{*+}K^-$ decay followed by $B^{*+} \to B^+ \gamma$, where the photon is not observed

$B_{s1}(5830)^0$ FEED-DOWN



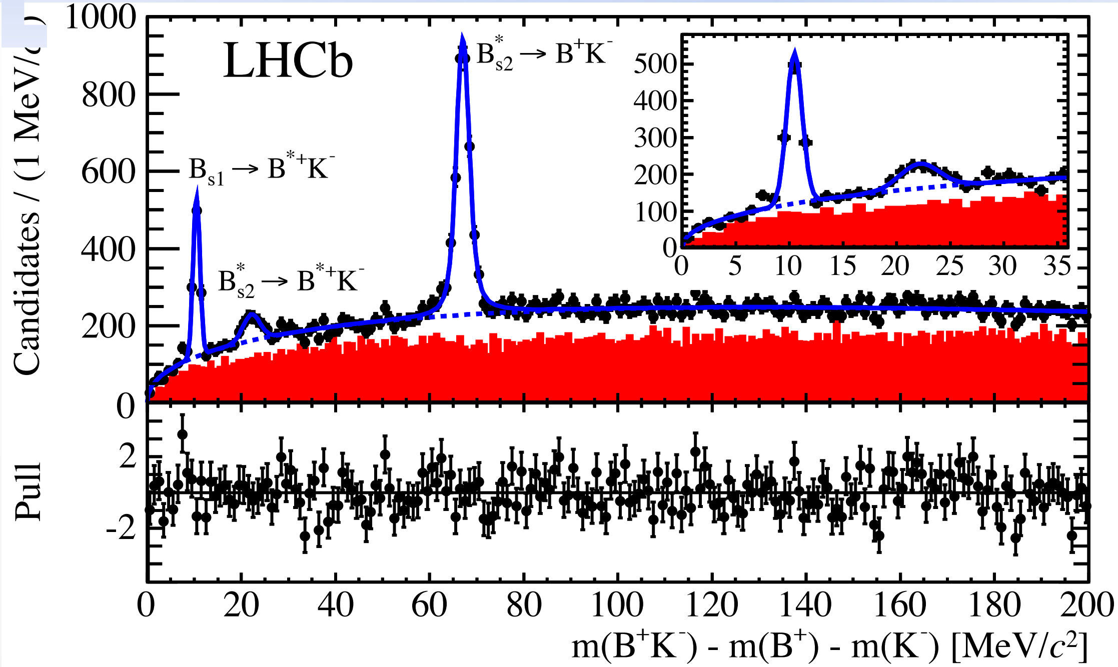
$$B_{s1} \rightarrow B^{*+} K^- \\ \rightarrow B^+ \gamma$$

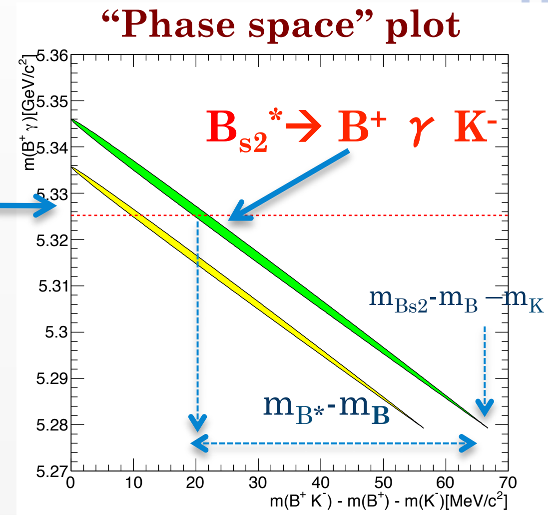
The peak is shifted by the B^{*+} - B^+ mass difference (~ 45 MeV) due to missing momentum of the photon



- Swapping the identification would lead to a large mass splitting of the j=3/2 doublet
- The B_{s1} state is not confirmed by D0

$B_{s1}(5830)^0$ AND $B_{s2}^*(5840)^0$



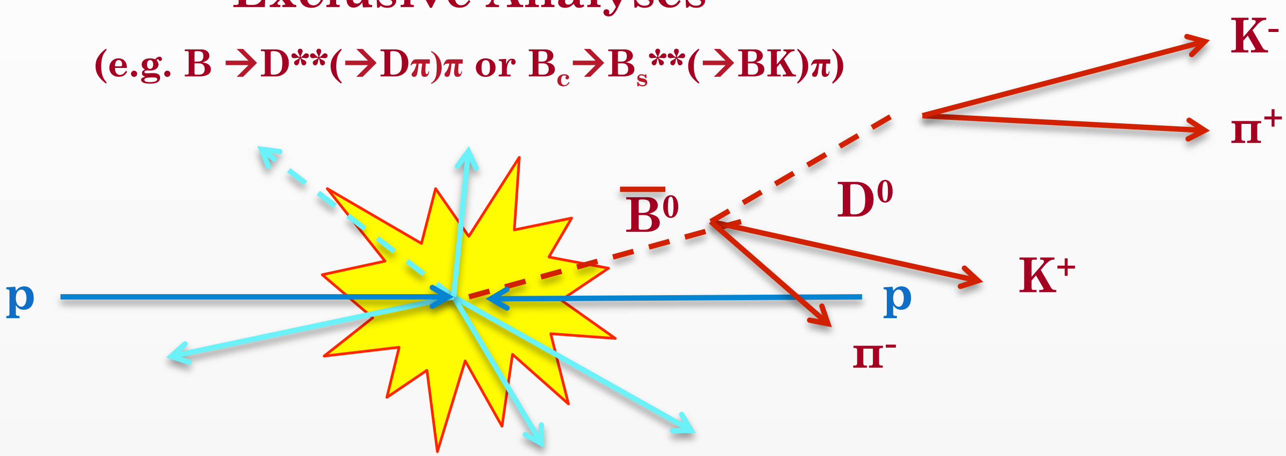


	j_q	J^P	Allowed decay mode B^+K^-	$B^{*+}K^-$
B_{s0}^*	1/2	0^+	yes	no
B_{s1}'	1/2	1^+	no	yes
B_{s1}	3/2	1^+	no	yes
B_{s2}^*	3/2	2^+	yes	yes

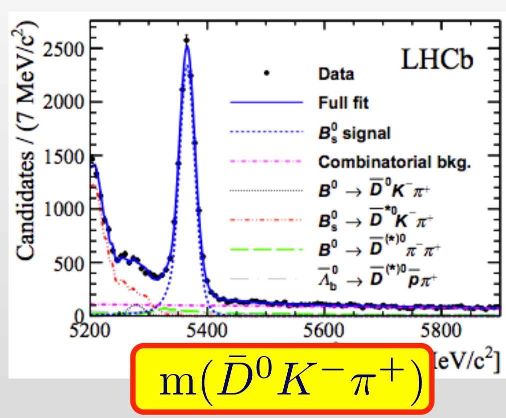
How to do spectroscopy?(II)

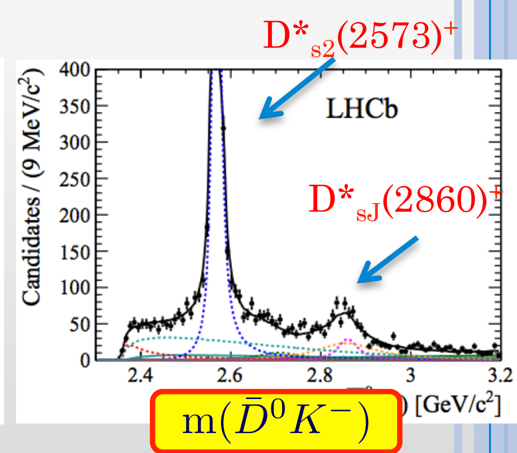
"Exclusive Analyses"

(e.g. B →D(→Dπ)π or B_c→B_s**(→BK)π)**



- Limited statistics
- Small background
- Resonance characterized by amplitude (i.e. bump) AND phase (i.e. interference)
- Suitable to study broad resonances
- Spin-parity assignment by amplitude analysis

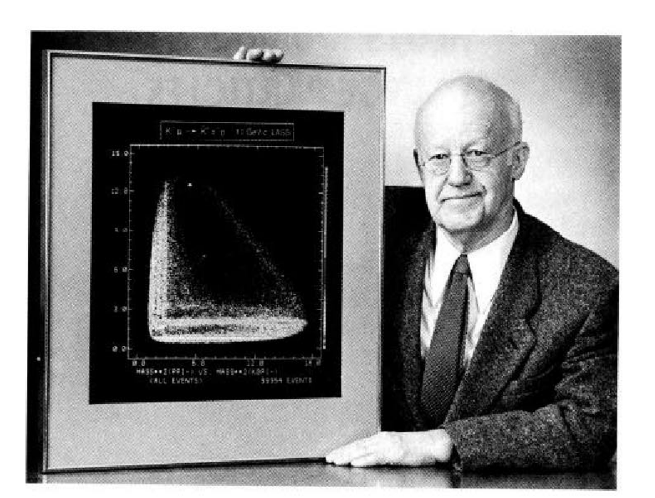




[LHCb: PRL 113 (2014) 162001, PRD 90 (2014) 072003]

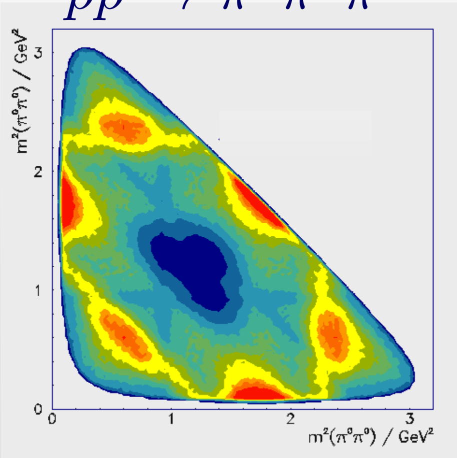
DALITZ PLOT

"I visualize geometry better than numbers."

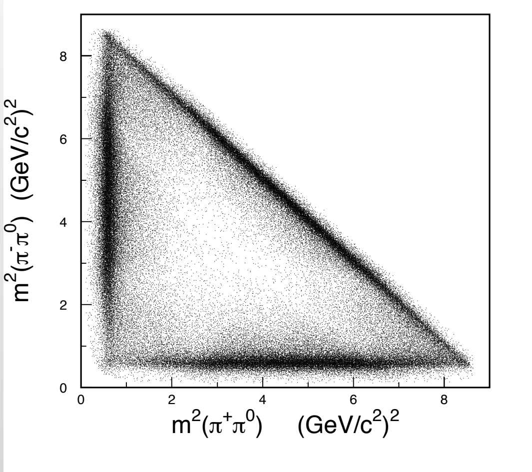


The scatter plot m_{12}^2 vs m_{23}^2 is usually called *Dalitz* plot

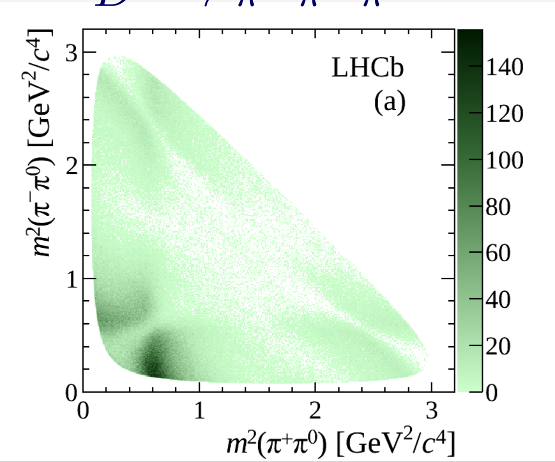
$p\bar{p} \to \pi^0\pi^0\pi^0$



$J/\psi \to \pi^+\pi^-\pi^0$



$D^0 \to \pi^+\pi^-\pi^0$



THE FIRST "DALITZ PLOT"

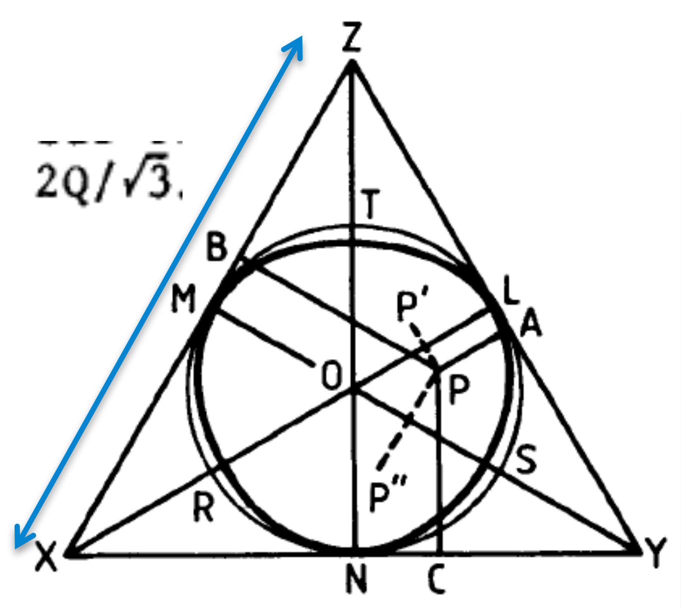


Fig. 1. Phase-space plot for $\tau^+ \to \pi^+\pi^+\pi^-$ events.

Viviani's theorem

$$\overline{PA} + \overline{PB} + \overline{PC} = K$$

$$T = \int \vec{v} \cdot d\vec{p}$$ Kinetic energy

Q = 3-body decay energy

If $T_1 = \overline{PA}, T_2 = \overline{PB}, T_3 = \overline{PC}$

Energy conservation
$$T_1 + T_2 + T_3 = Q$$

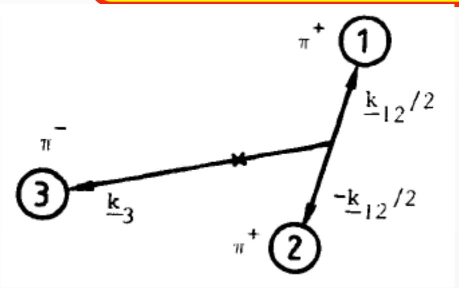
Points inside the inscribed circle preserve the momentum as well

Boundary distorted in relativistic regime

The first "Dalitz Plot"

$\theta^+ \to \pi^+\pi^0$

$\tau^+ \to \pi^+\pi^-\pi^+$



$$J = l_{12} + L$$

Assuming parity conservation:

$$P(\theta) = P(\pi^+)P(\pi^0)(-1)^L = (-1)^L$$

Assuming parity conservation:

$$P(\tau^+) = P(\pi^+)P(\pi^-)P(\pi^+)(-1)^{l_{12}}(-1)^L = -1(-1)^{l_{12}}(-1)^L$$

By Bose symmetry, wavefunction symmetric under exchange of π's, so l_{12}=even

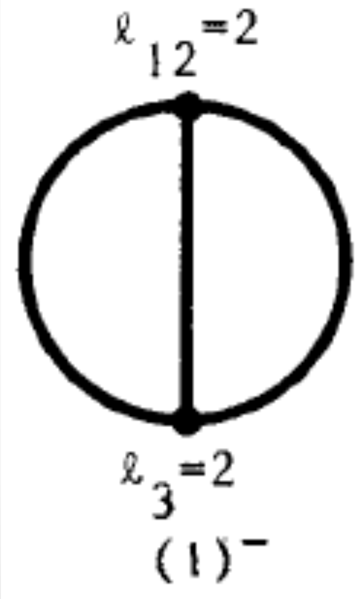
$$P(\theta^+) = -(-1)^L$$

$$J^P = 0^+, 1^-, 2^+, \ldots$$

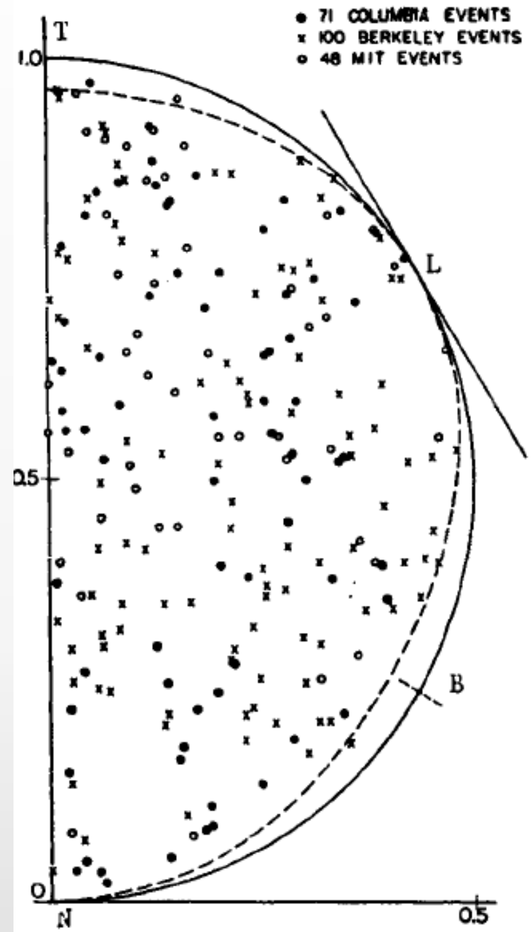
$$J^P = 0^-, 1^\pm, 2^\mp, \ldots$$

The first "Dalitz Plot"

$J^P = 0^+, 1^-, 2^+, \ldots$



No indication that event distribution vanishes at the boundary



Θ and τ are different states?
P violation in weak interactions?

Today we identify both states with K+ and *P* symmetry is broken

DALITZ PLOT TODAY

The scatter plot in m_{12}^2 e m_{23}^2 is called *Dalitz plot*

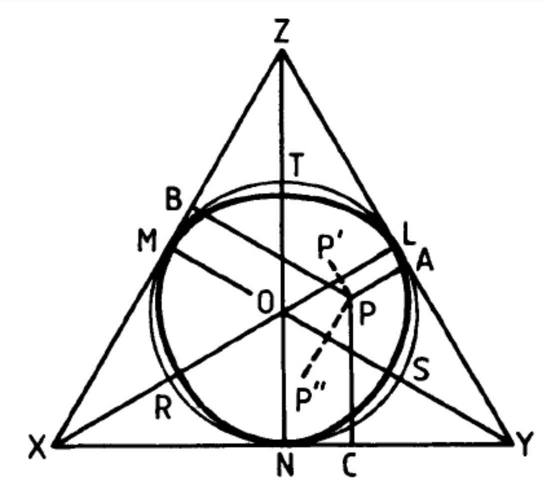
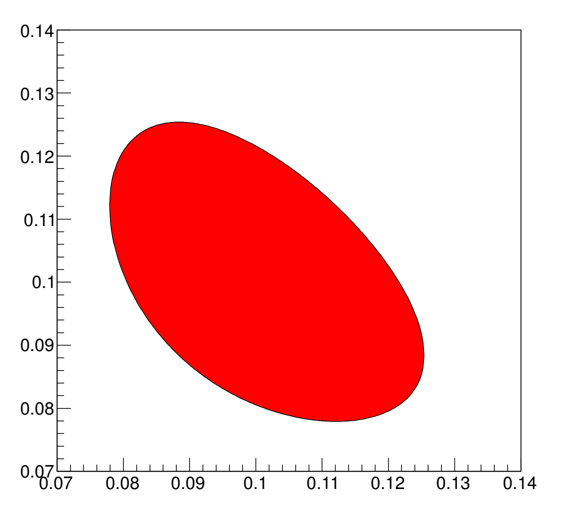


Fig. 1. Phase-space plot for $\tau^+ \to \pi^+\pi^+\pi^-$ events.

$$T_1 = \frac{(m_K - m_\pi)^2 - M_{23}^2}{2m_K}$$

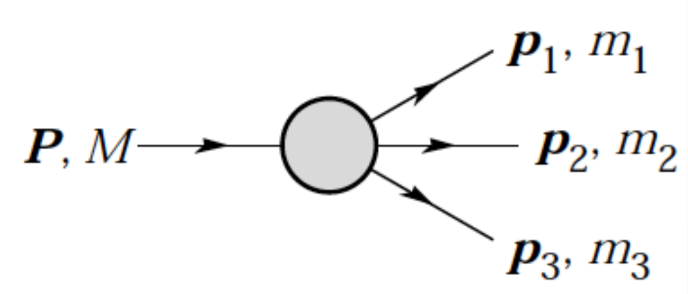


- M^2_{12} and M^2_{23} are covariant
- Complete description of the decay
  - 3-body decays proceed by intermediated resonances
  - Easy to identify resonances as bands on the DP

Dalitz Plot by eye

3-body decay. All particles are scalars

Constraints	Degree of freedom
3 four-vectors	12
4-momentum conservation	-4
3 masses	-3
3 Euler angles	-3
TOT	2



$$d\Gamma = \frac{1}{(2\pi)^3}\frac{1}{32M^3}\overline{|\mathcal{M}|^2}dm_{12}^2 dm_{23}^2$$

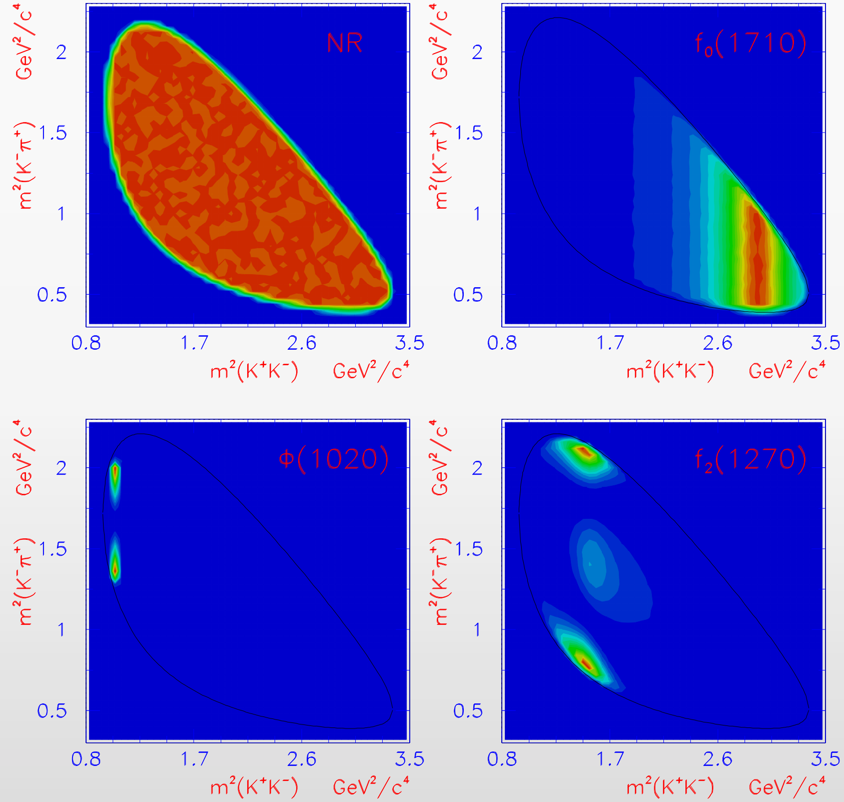
$\overline{|\mathcal{M}|^2} = Const \Rightarrow$ Dalitz uniformly populated

Nonuniformity $\Rightarrow$ Information on $\overline{|\mathcal{M}|^2}$

Dalitz Plot by eye

Simulation of $D_s^+ \rightarrow K^+K^-\pi^+$ decay through an intermediate resonance:

$$D_s^+ \rightarrow R\pi^+$$
$$\hookrightarrow K^+K^-$$



Number of zeros equals the spin of resonance

DALITZ PLOT BY EYE

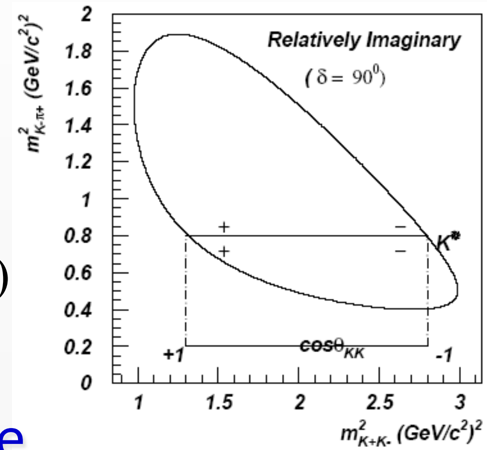
Interference patterns between vector and scalar:

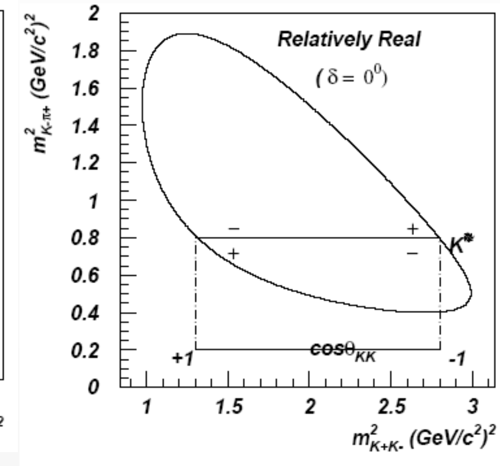
$$\mathcal{M} = \frac{\cos\theta_{KK}}{M_r^2 - M_{K\pi}^2 - i\Gamma M_r} + a(\cos\delta + i\sin\delta)$$

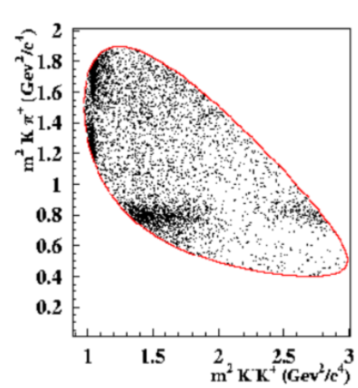
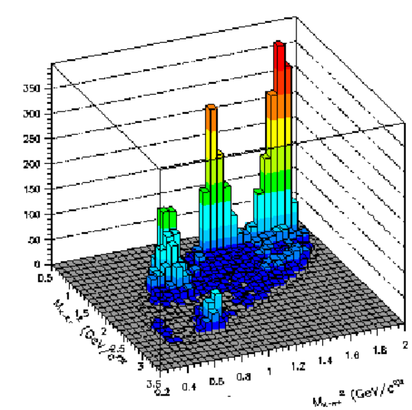
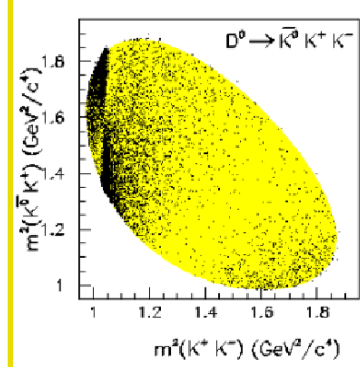
Vector

Constant

Relative phase

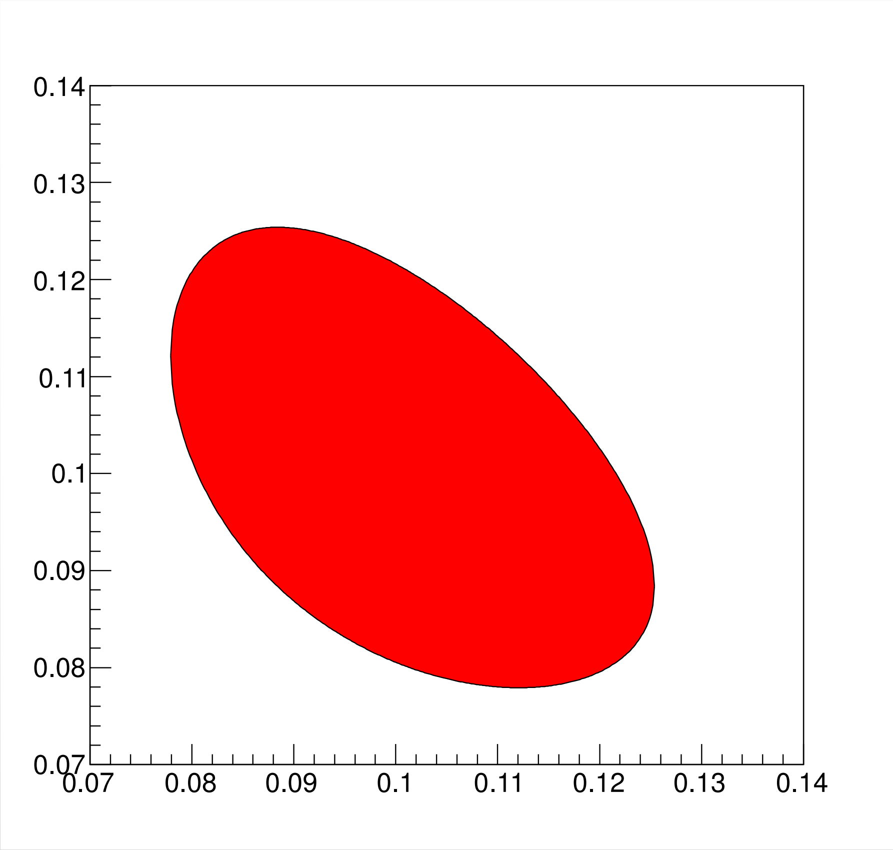




$D^+ \to K^+K^-\pi^+$	$D^0 \to \bar{K}^0K^+K^-$
 	

DP SHAPE

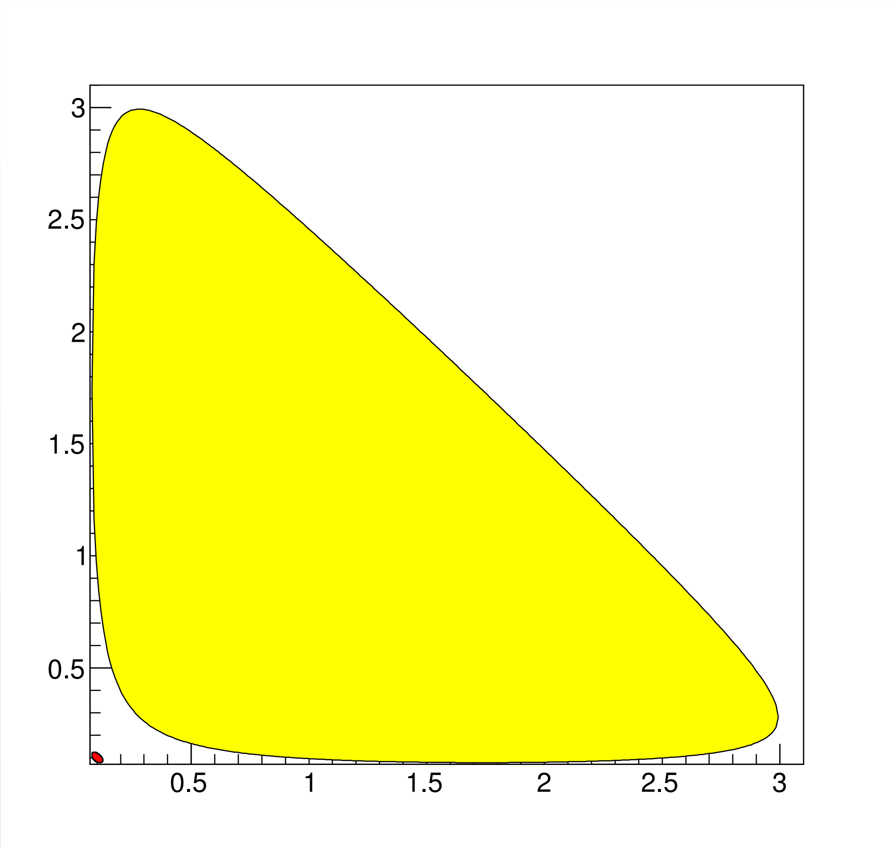
- Q→0 (Non-relativistic regime) ⟷ DP shape → "Egg"
- Q→∞ (Relativistic regime) ⟷ DP shape → Triangle



- $K^+ \rightarrow \pi^+\pi^-\pi^+$

DP SHAPE

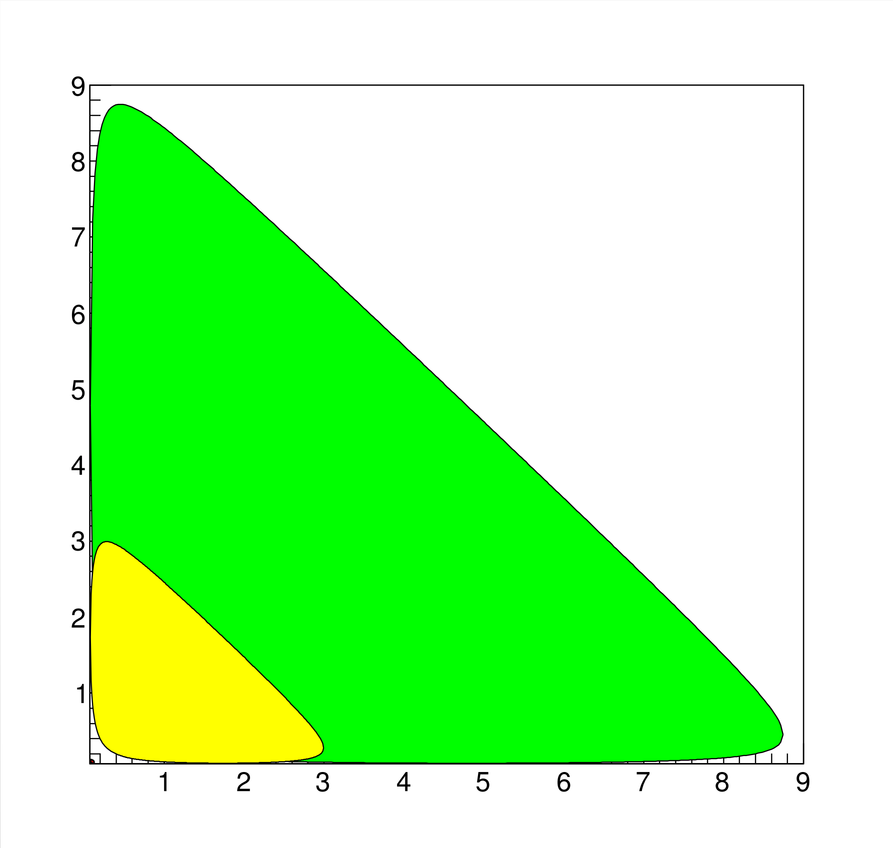
- $Q \to 0$ (Non-relativistic regime) ⟷ DP shape → "Egg"
- $Q \to \infty$ (Relativistic regime) ⟷ DP shape → Triangle



- $D^+ \to \pi^+\pi^-\pi^+$
- $K^+ \to \pi^+\pi^-\pi^+$

DP SHAPE

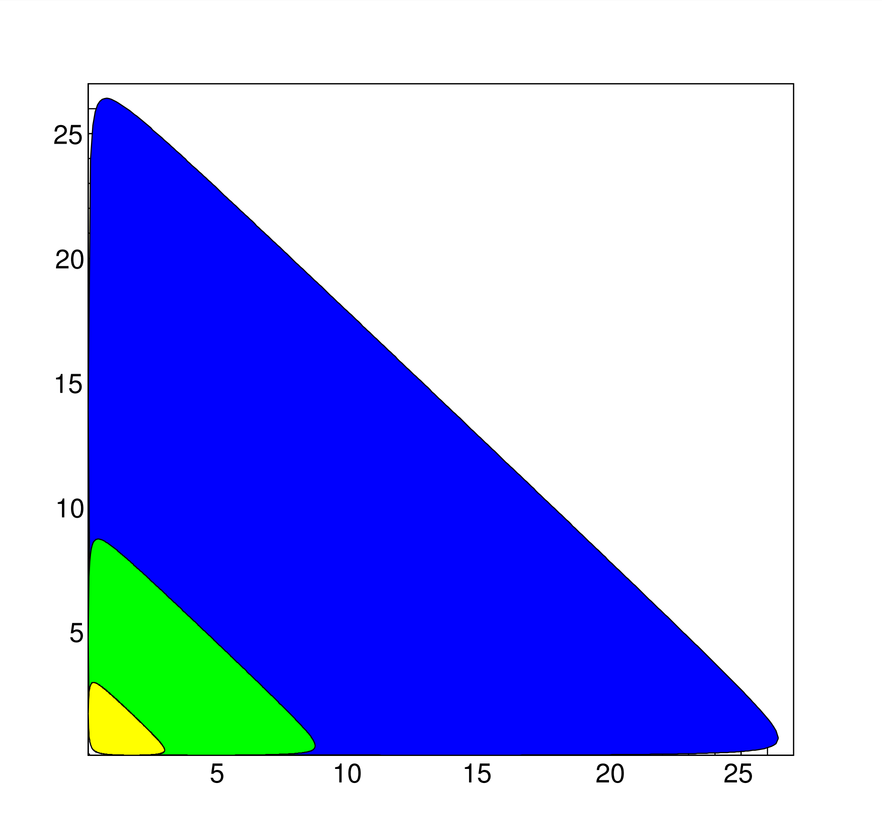
- $Q \rightarrow 0$ (Non-relativistic regime) ⟷ DP shape → "Egg"
- $Q \rightarrow \infty$ (Relativistic regime) ⟷ DP shape → Triangle



- $J/\psi \rightarrow \pi^+\pi^-\pi^+$
- $D^+ \rightarrow \pi^+\pi^-\pi^+$
- $K^+ \rightarrow \pi^+\pi^-\pi^+$

DP SHAPE

- $Q \to 0$ (Non-relativistic regime) ⟷ DP shape → "Egg"
- $Q \to \infty$ (Relativistic regime) ⟷ DP shape → Triangle



- $B^+ \to \pi^+\pi^-\pi^+$
- $J/\psi \to \pi^+\pi^-\pi^+$
- $D^+ \to \pi^+\pi^-\pi^+$
- $K^+ \to \pi^+\pi^-\pi^+$

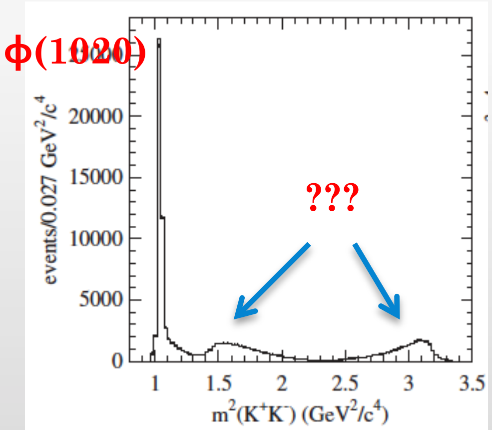
KINEMATICAL REFLECTIONS/SHADOWS

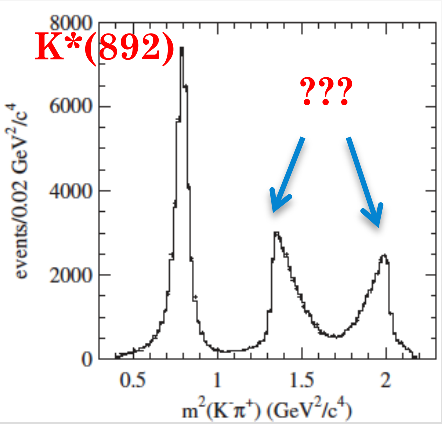
(e.g.) $D_s^+ \to K^+K^-\pi^+$

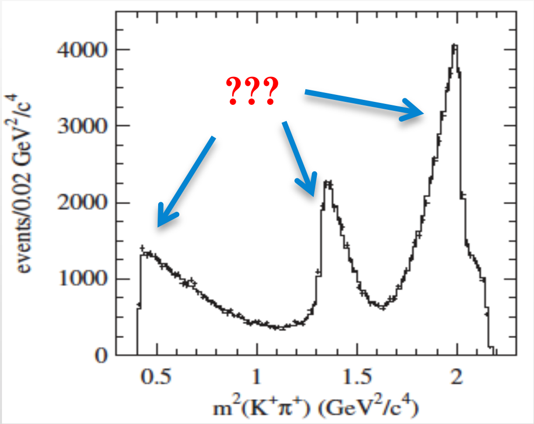
$$D_s^+ \to R\pi^+, \quad R \to K^+K^-$$

or

$$D_s^+ \to RK^+, \quad R \to K^-\pi^+$$



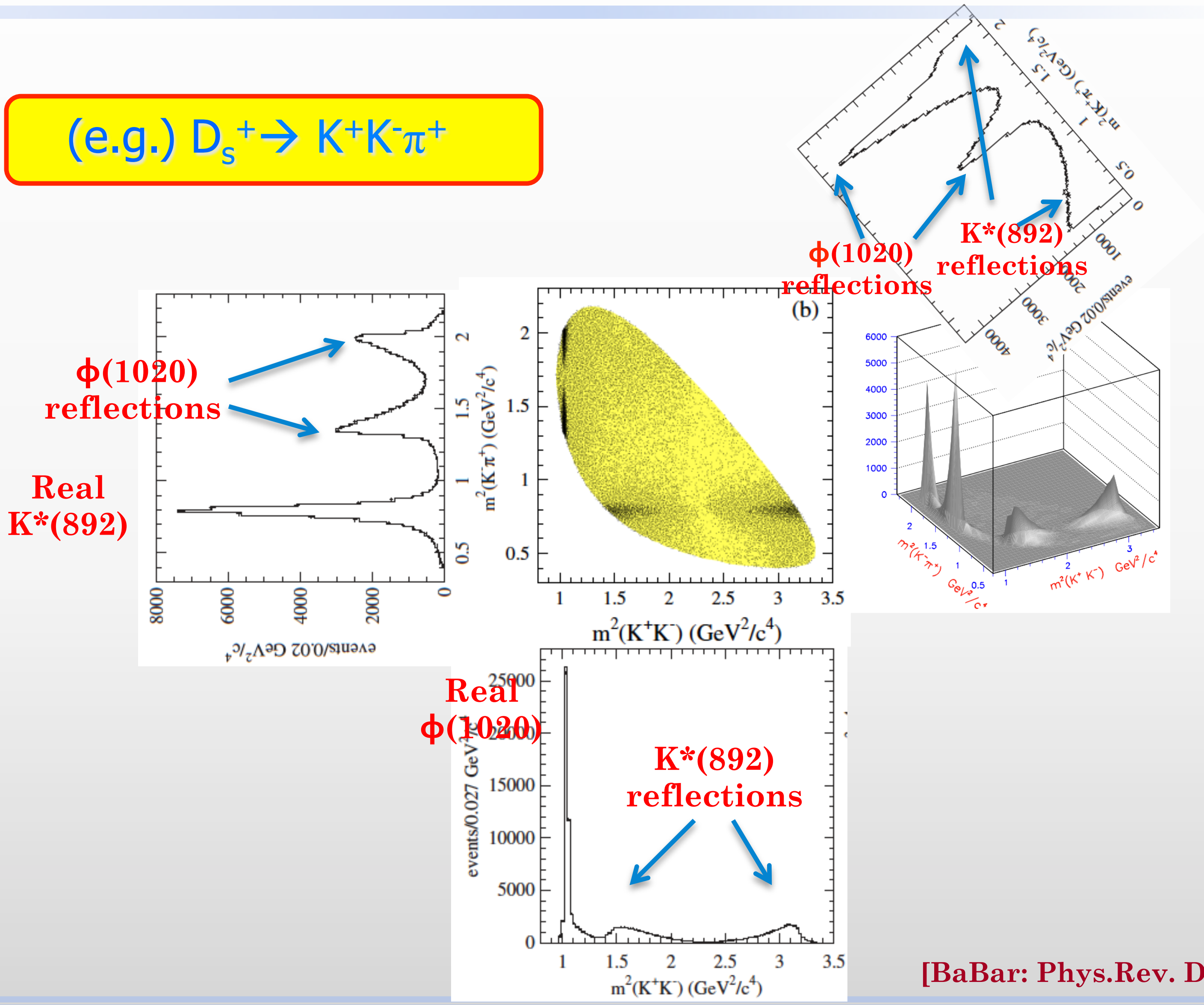




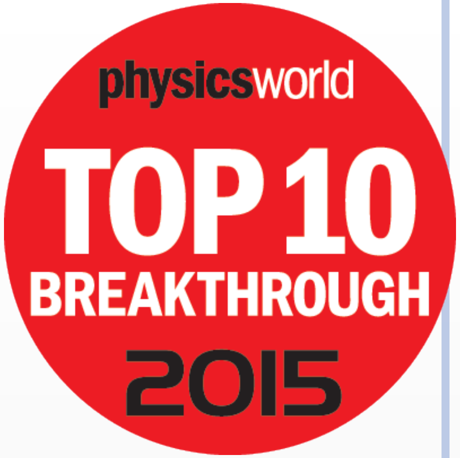
[BaBar, Phys.Rev. D83 (2011) 052001]

KINEMATICAL REFLECTIONS/SHADOWS

(e.g.) $D_s^+ \rightarrow K^+K^-\pi^+$



[BaBar: Phys.Rev. D83 (2011) 052001]



Observation of J/ψ p resonances consistent with pentaquark states in $\Lambda_b \rightarrow J/\psi\, p\, K^-$ decays

(Amplitude analysis of $\Lambda_b \rightarrow J/\psi\, p\, K^-$)

[LHCb: PRL 115 (2015) 072001]

Pentaquark: The Return of the Living Dead

After 50 years no undisputed experimental evidence have been found for pentaquarks

- Most famous candidates:
  - ✓ $\Theta^{+} \to K^{0}p$, $K^{+}n$, m=1.54 GeV, Γ~10 MeV
  - ✓ Resonance in $D^{*-}p$ at 3.1 GeV, Γ=12 MeV
  - ✓ $\Xi^{--} \to \Xi^{-}\pi^{-}$, m=1.862 GeV, Γ<18 MeV
- In general they were observed in "bump" searches

K.H. Hicks, "On the conundrum of the pentaquark", Eur.Phys.J. H37 (2012) 1

First Observation of $\Lambda_b \rightarrow J/\psi\ K^- p$

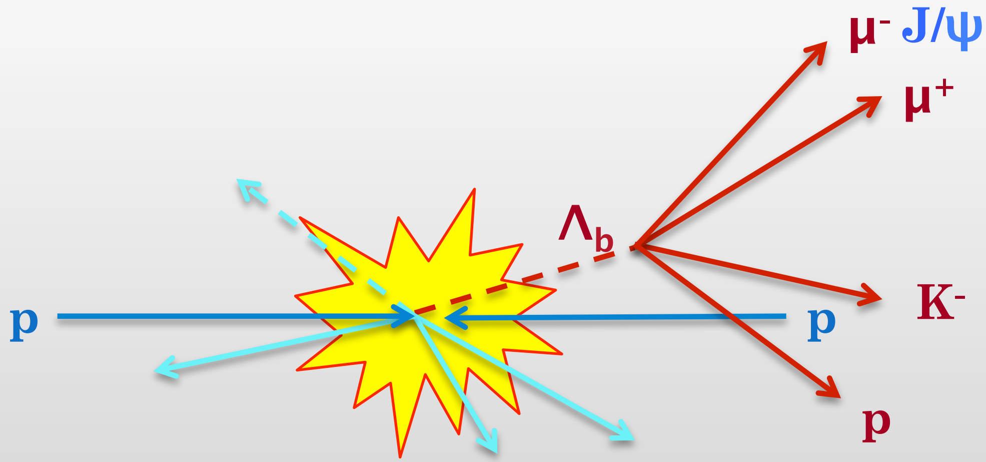
[LHCb: PRL 111 (2013) 102003]

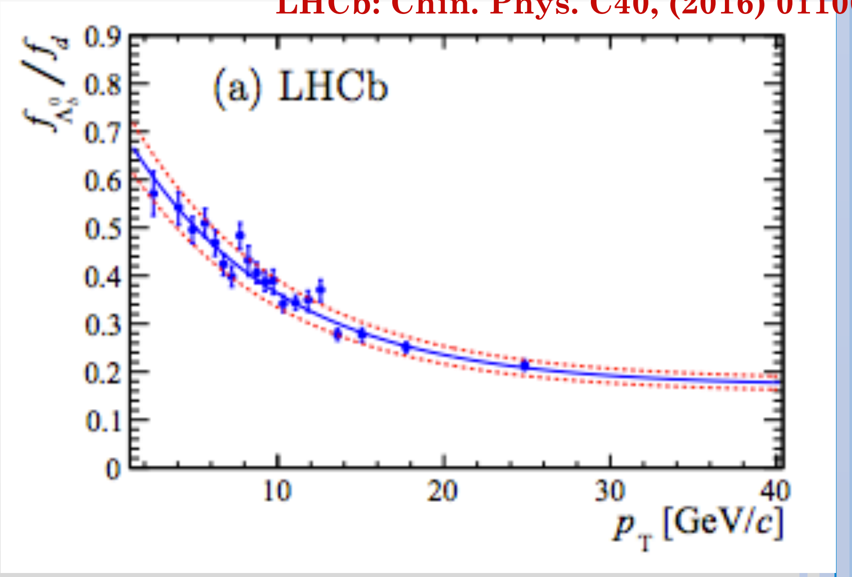
Why did LHCb arrive first? The decay was not observed before!

- ✓ J/ψ → Large trigger efficiency
- ✓ 4 Tracks → Large detection efficiency
- ✓ Large Λ_b production

LHCb: JHEP 08(2014)143

LHCb: Chin. Phys. C40, (2016) 011001

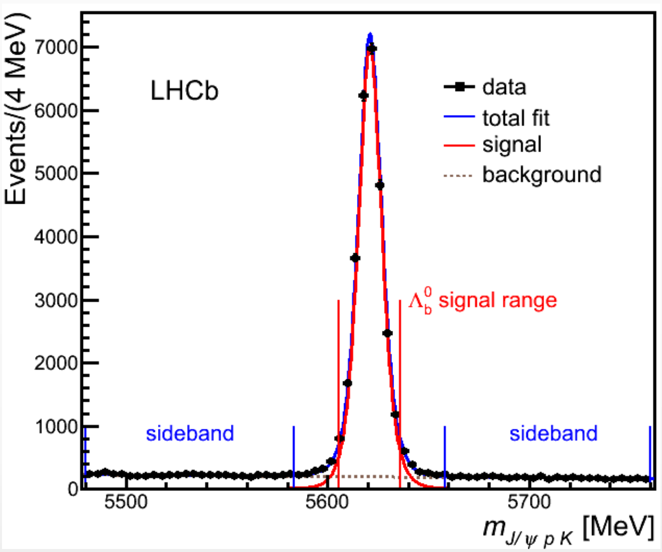


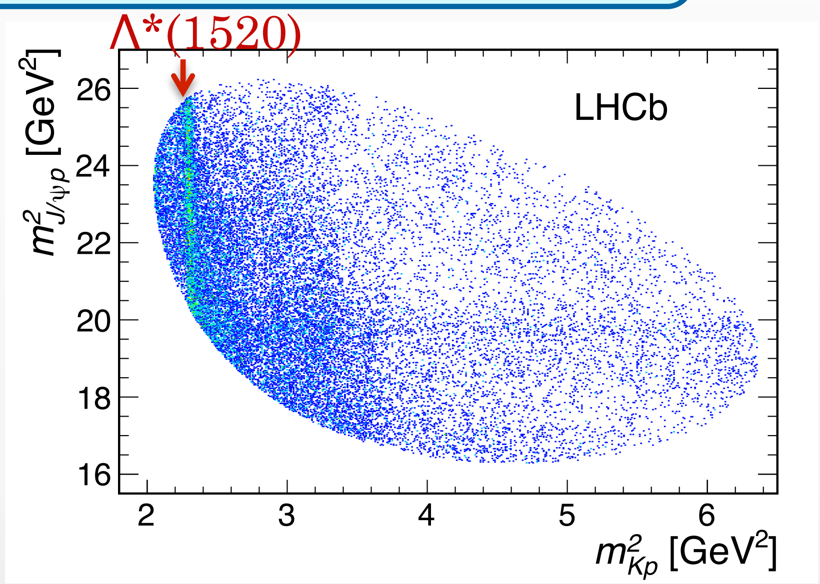


Observation of a Narrow Band in the Λ_b Dalitz plane

[LHCb: PRL 115, 072001 (2015)]

Selection updated with the full Run I dataset ($3fb^{-1}$)
26k Λ_b^0 candidates. Background ~ 5.4%





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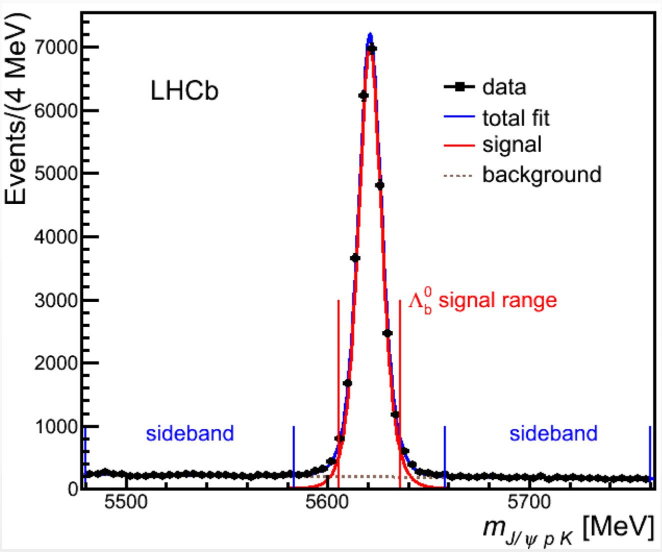
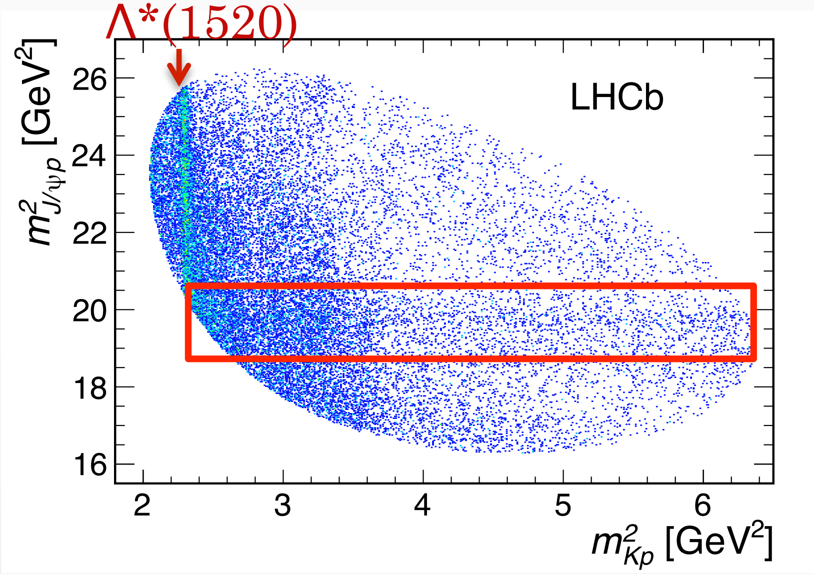
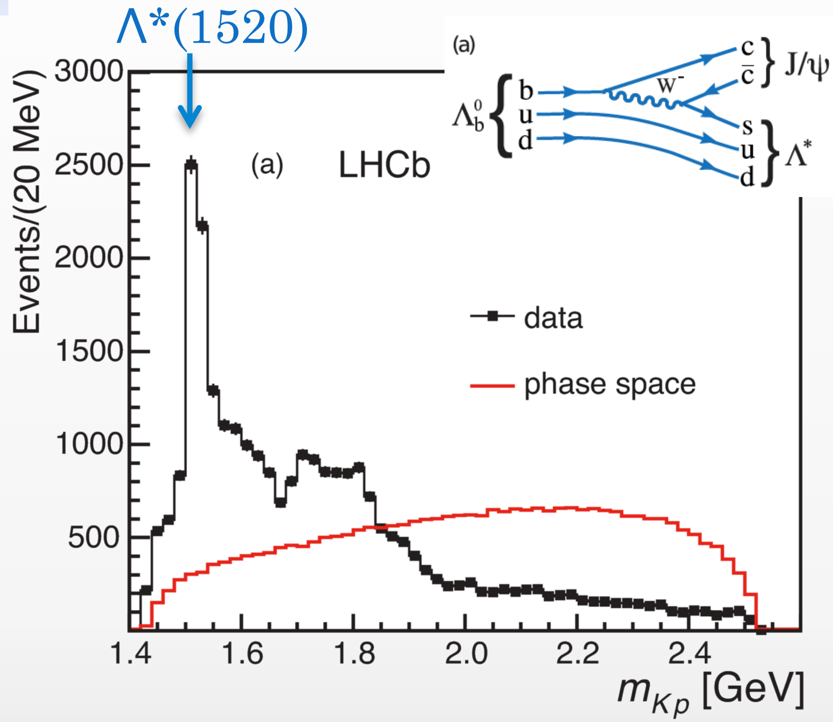


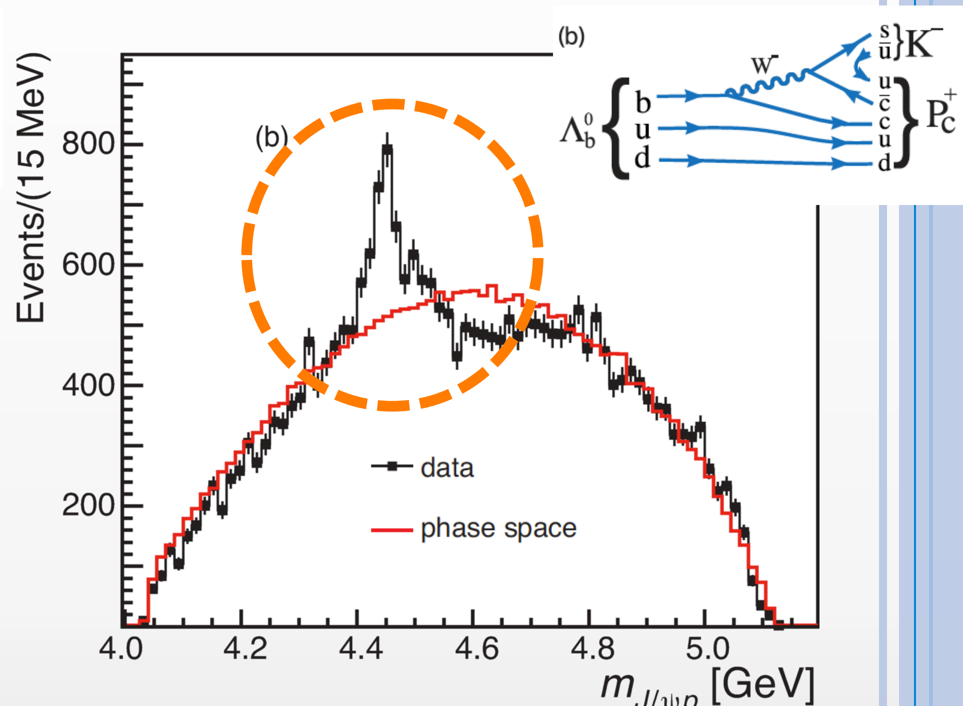


- Efficiency flat over the "Dalitz" plot
- Cross checks:
  - ✓ Veto $B_s \rightarrow J/\psi KK$ & $B^0 \rightarrow J/\psi K\pi$ after swapping the mass hypothesis of the Λ_b daughters: p ←→K or p ←→ π
  - ✓ Clone and ghost tracks carefully removed
  - ✓ Not a partially reconstructed Ξ_b decay

UNEXPECTED NARROW PEAK IN m(J/ψ p)

[LHCb: PRL 115, 072001 (2015)]



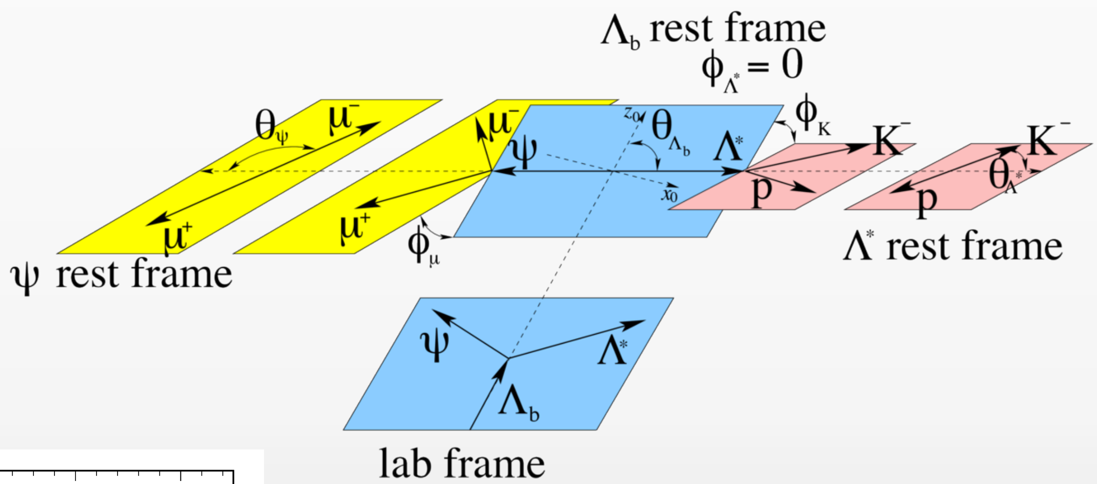


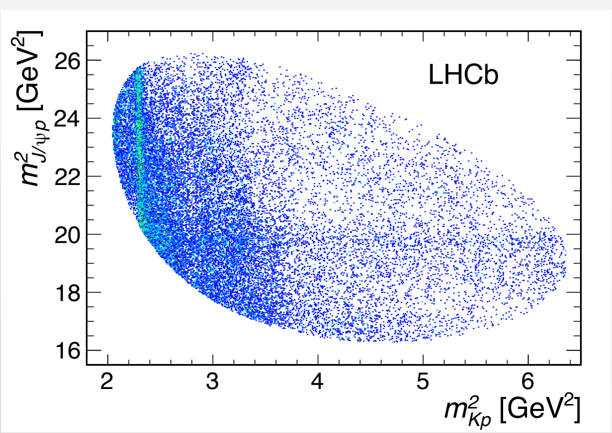
- ➢ A lot of structures in $m(pK^-)$!
- ➢ Could it be a reflection of the interfering Λ^*'s → pK^-?

Amplitude analysis

The $\Lambda_b \to J/\psi\ K\ p$ Decay

6D unbinned maximum likelihood fit (m_{Kp}, $\theta_{\Lambda b}$, θ_{Λ^*}, ϕ_K, θ_ψ, ϕ_μ)

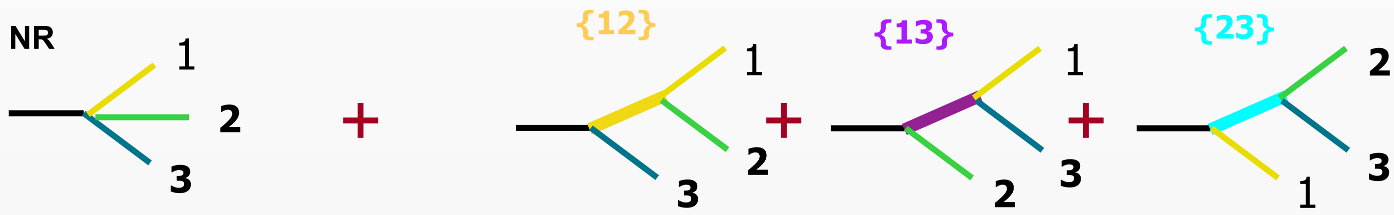




N.B. The "Dalitz" plot is itself a projection of a 6-D space

The Isobar Model

Isobar model: total decay amplitude as a coherent sum of processes where one daughter is spectator



Three-body amplitude for $\Lambda_b \rightarrow J/\psi\, p\, K$

Sum over all Λ^* resonances

P_c^+ components

$$|\mathcal{M}(\Phi)|^2 = \sum_{\lambda_{\Lambda_b}} \sum_{\lambda_p} \sum_{\Delta\lambda_u} \left| A^{\Lambda^*}_{\lambda_{\Lambda_b},\lambda_p,\Delta\lambda_u}(m_{pK},\Omega) + e^{i\Delta\lambda_\mu \alpha_\mu} \sum_{\lambda_p^{P_c}} A^{P_c}_{\lambda_{\Lambda_b},\lambda_p^{P_c},\Delta\lambda_u}(m_{J/\psi p},\Omega) \right|^2$$

Defined unless a phase and a constant

Rotation by α due to different helicity frame

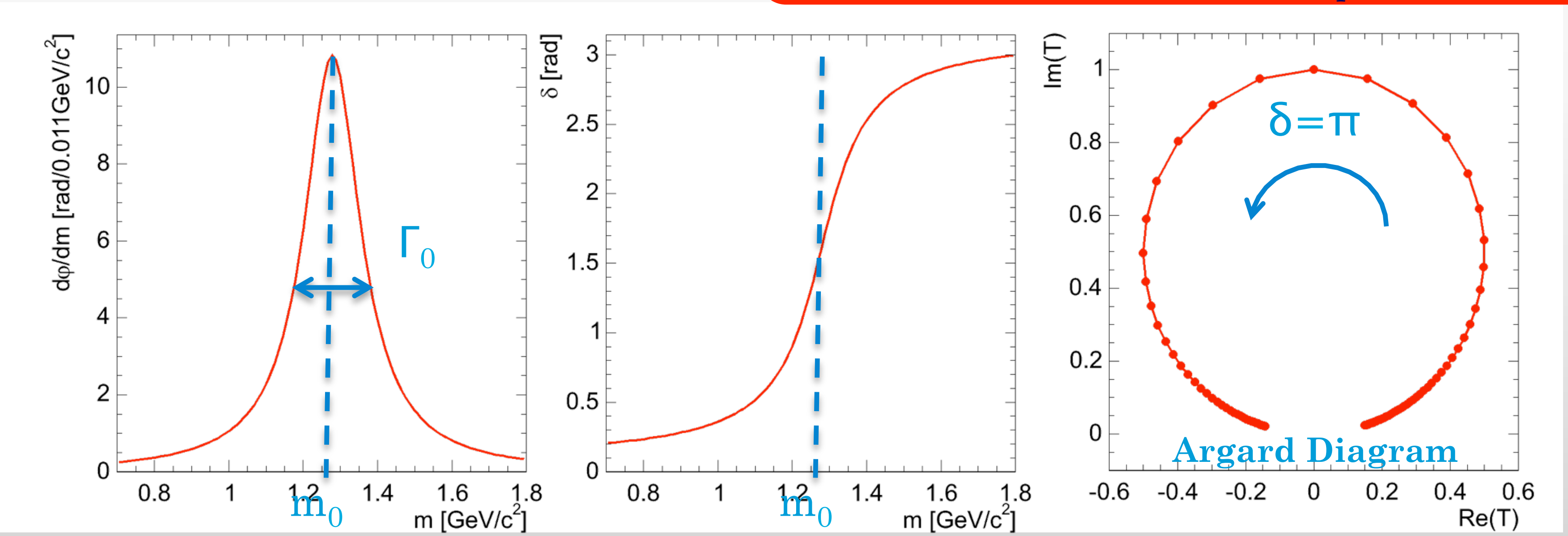
How to model a single term

$$A^{\Lambda^*}_{\lambda_\psi,\Delta\lambda_\mu}(m_{pK},\Omega) = H^{\Lambda^*}_{\lambda_\psi} A^{\Lambda^*}(m_{pK}) d^{J(\Lambda^*)}_{\lambda_\psi,0}(\theta_{\Lambda^*}) \times e^{i\lambda_\psi\phi} d^{1}_{\lambda_\psi,\Delta\lambda_\mu}(\theta_\psi)$$

Free parameters
+
m_0, Γ_0 (in case of a new state)

Relativistic Breit-Wigner

$$A^{\Lambda^*}(m_{pK}) = \frac{1}{m_0^2 - m_{pK}^2 - i m_o \Gamma_0}$$



Λ* Decay Models

[LHCb: PRL 115, 072001 (2015)]

Two models: Reduced and Extended
L = angular momentum between J/ψ and Λ*

No high-J^P high-mass states, limited *L*

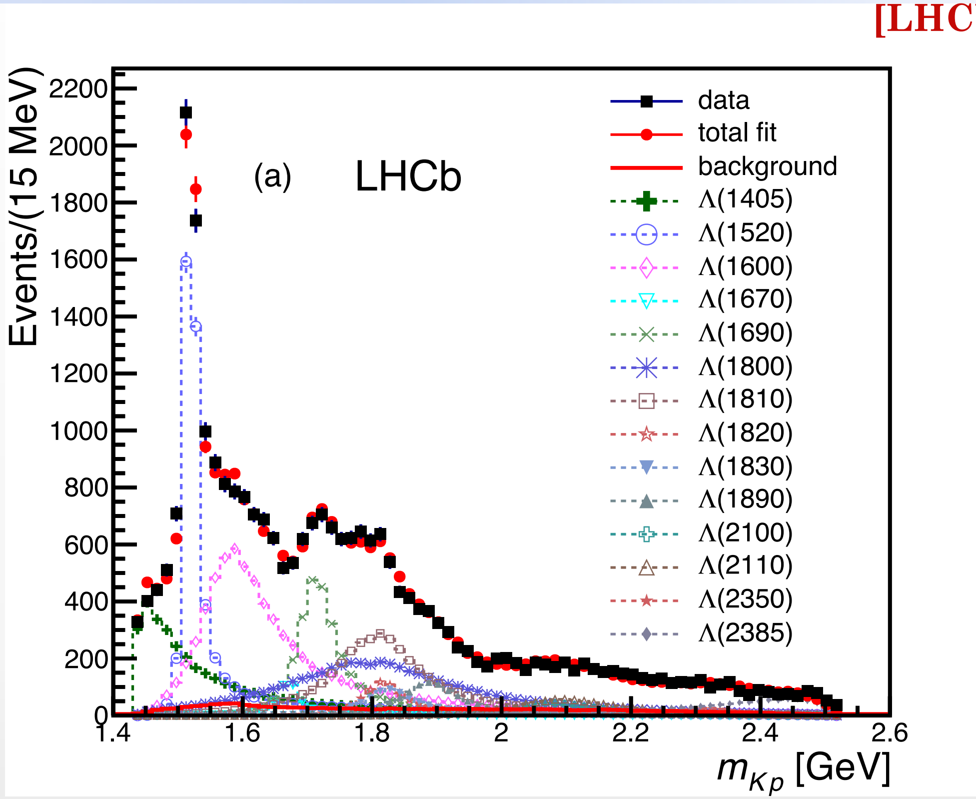
All states, all *L*

All known Λ* states

State	J^P	M_0 (MeV)	Γ_0 (MeV)	# Reduced	# Extended
$\Lambda(1405)$	$1/2^-$	$1405.1^{+1.3}_{-1.0}$	50.5 ± 2.0	3	4
$\Lambda(1520)$	$3/2^-$	1519.5 ± 1.0	15.6 ± 1.0	5	6
$\Lambda(1600)$	$1/2^+$	1600	150	3	4
$\Lambda(1670)$	$1/2^-$	1670	35	3	4
$\Lambda(1690)$	$3/2^-$	1690	60	5	6
$\Lambda(1800)$	$1/2^-$	1800	300	4	4
$\Lambda(1810)$	$1/2^+$	1810	150	3	4
$\Lambda(1820)$	$5/2^+$	1820	80	1	6
$\Lambda(1830)$	$5/2^-$	1830	95	1	6
$\Lambda(1890)$	$3/2^+$	1890	100	3	6
$\Lambda(2100)$	$7/2^-$	2100	200	1	6
$\Lambda(2110)$	$5/2^+$	2110	200	1	6
$\Lambda(2350)$	$9/2^+$	2350	150	0	6
$\Lambda(2585)$	?	$\approx$2585	200	0	6
# of fit parameters:				64	146

Fit with Λ*→pK States only

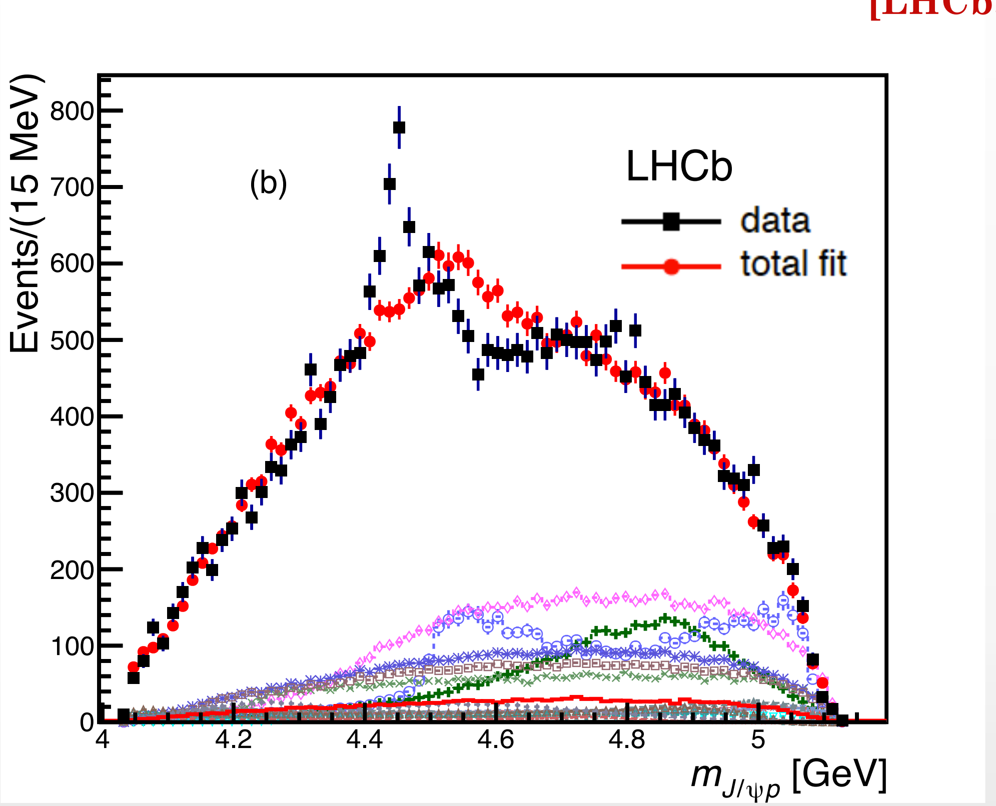
[LHCb: PRL 115, 072001 (2015)]



Use of extended model, so all possible known Λ* amplitudes: m_{Kp} projection looks fine, but…

Fit with Λ*→pK States only

[LHCb: PRL 115, 072001 (2015)]

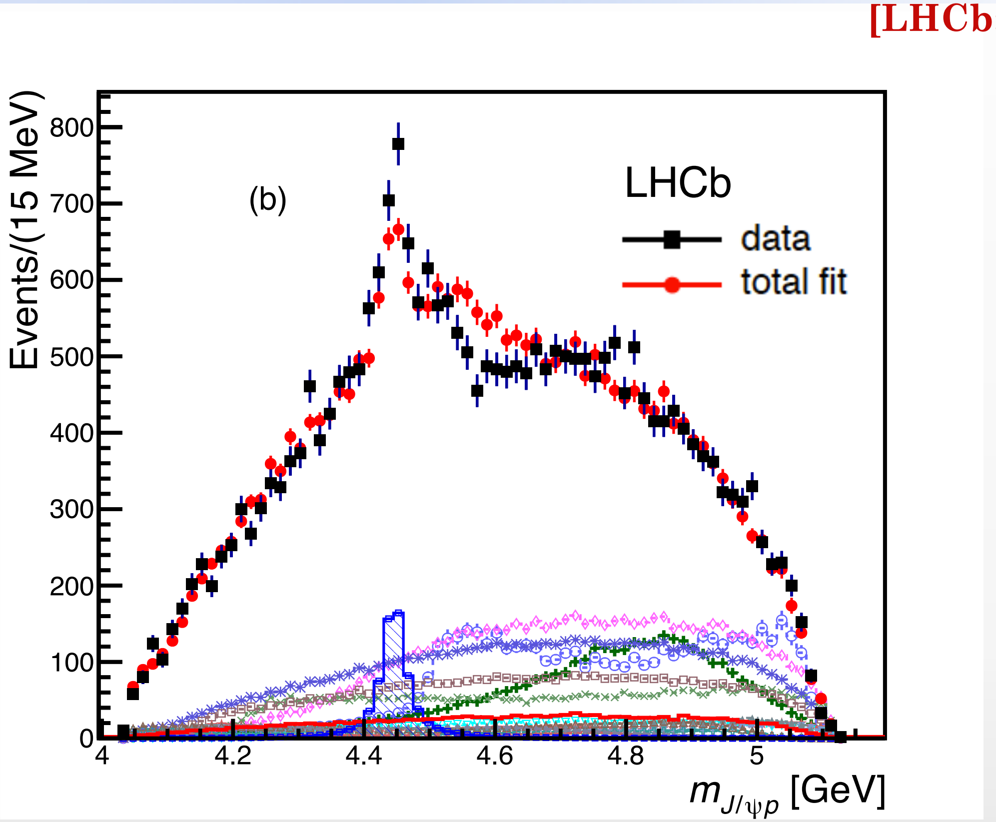


Extended Λ* model:

- …the fit projection can't reproduce the peaking structure in J/ψ p
- Adding non-resonant term, Σ*'s or extra unknown Λ*'s doesn't help

Adding $P_c \rightarrow J/\psi\, p$ amplitudes

[LHCb: PRL 115, 072001 (2015)]

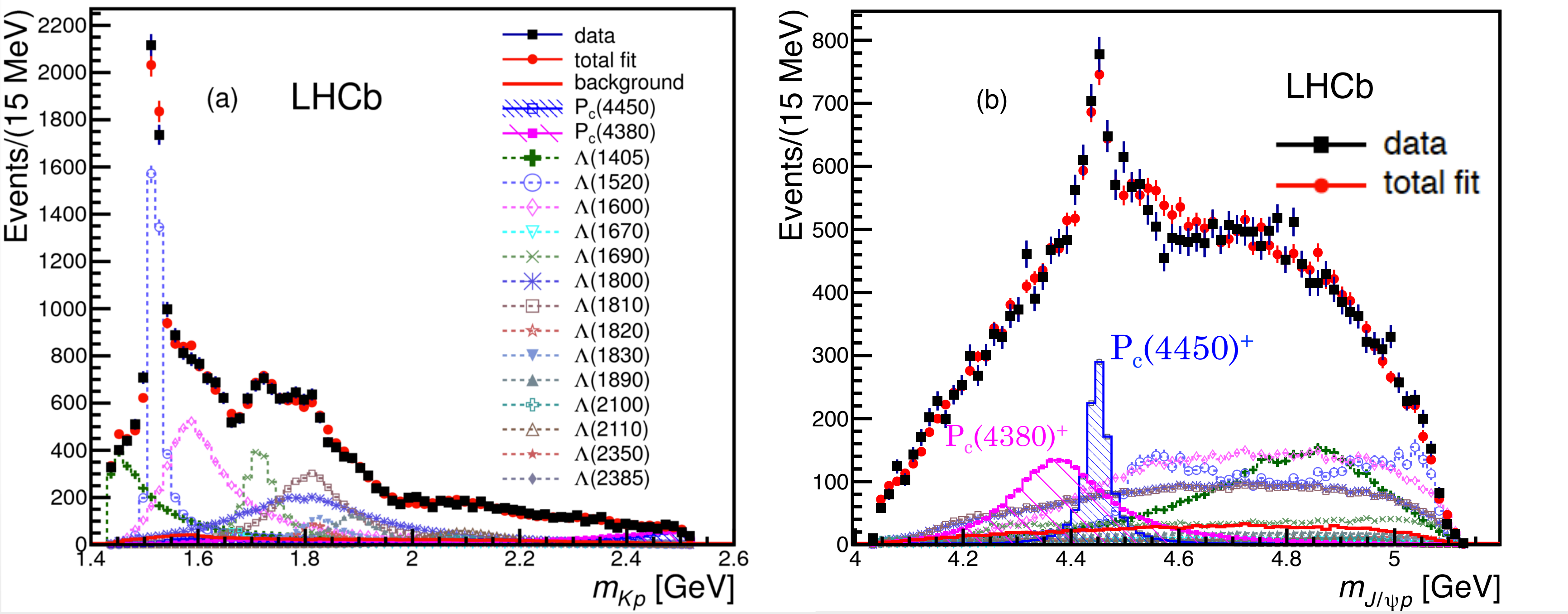


Extended Λ* model + 1 Pentaquark decaying to J/ψ p

- Try all J^P of P_c^+ up to $7/2^{\pm}$
- Best fit has $J^P = 5/2^{\pm}$. Still not a good fit

ADDING $P_c \rightarrow J/\psi\, p$ AMPLITUDES

[LHCb: PRL 115, 072001 (2015)]

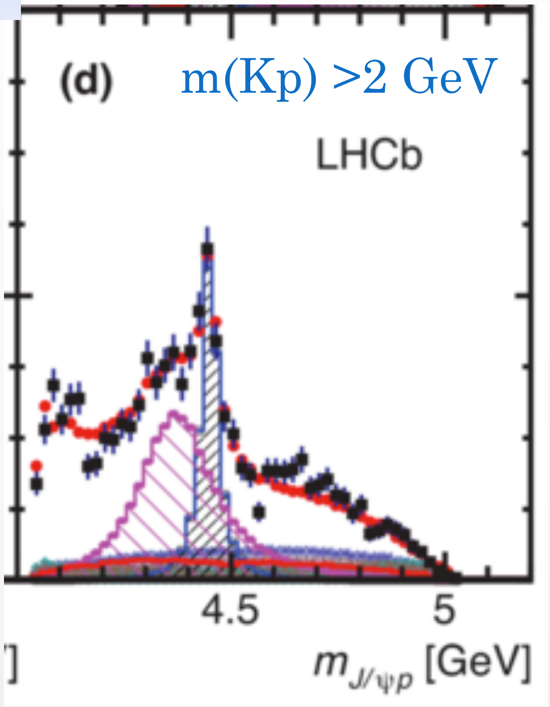


Reduced Λ* model + 2 Pentaquarks decaying to J/ψ p

- Obtain good fits even with the reduced Λ* model
- Best fit has $J^P=(3/2^-, 5/2^+)$, also $(3/2^+, 5/2^-)$ & $(5/2^+, 3/2^-)$ are preferred
- Adding more amplitudes doesn't improve the fit quality

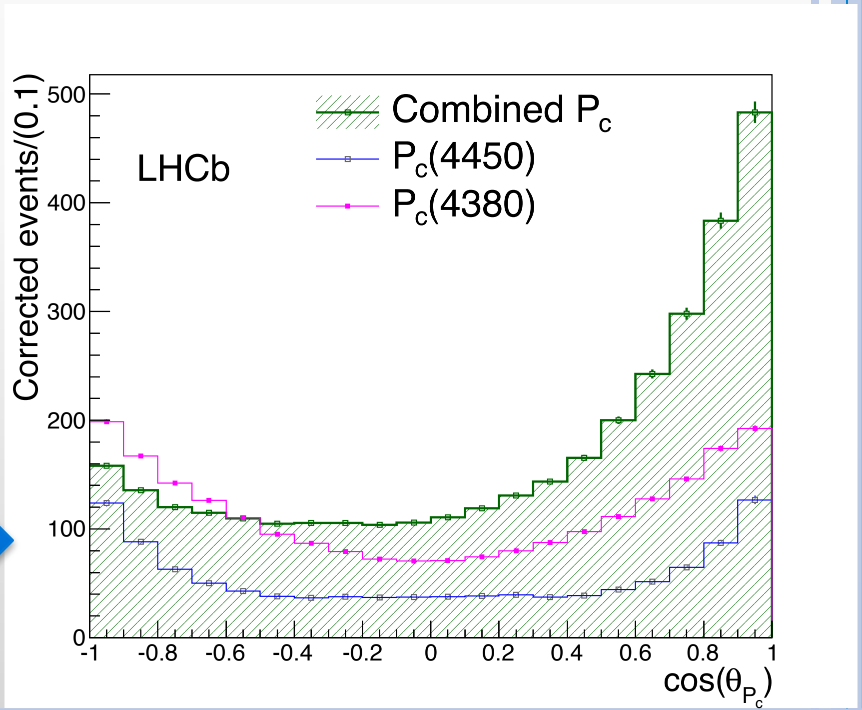
DO WE REALLY NEED 2 P_c^+'S? YES

[LHCb: PRL 115, 072001 (2015)]



Clear need for the 2nd broad P_c^+ where the $\Lambda^* \rightarrow pK^-$ contribution is the smallest

Evidence of an interference pattern in the angular distribution



SIGNIFICANCES AND RESULTS

[LHCb: PRL 115, 072001 (2015)]

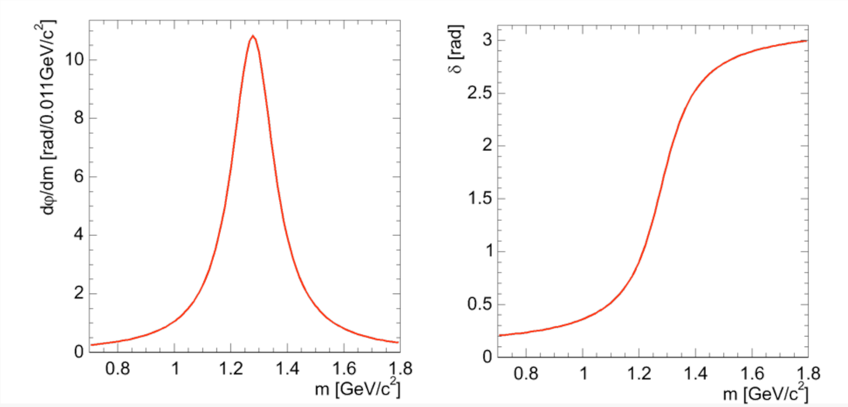
- Simulations of pseudo-experiments are used to quote the significances:
  - ✓ Significance of $P_c(4450)^+$ state is 12σ
  - ✓ Significance of $P_c(4380)^+$ state is 9σ
- Main systematic uncertainty: difference between extended and reduced fit models. Taken in account while computing the significances

State	Mass (MeV)	Width (MeV)	Fit fraction (%)
$P_c(4380)^+$	4380 ±8±29	205±18±86	8.4±0.7±4.2
$P_c(4450)^+$	4449.8±1.7±2.5	39 ± 5±19	4.1±0.5±1.1
Λ(1405)			15±1±6
Λ(1520)			19±1±4

Probing the Resonant Character of P_c^+

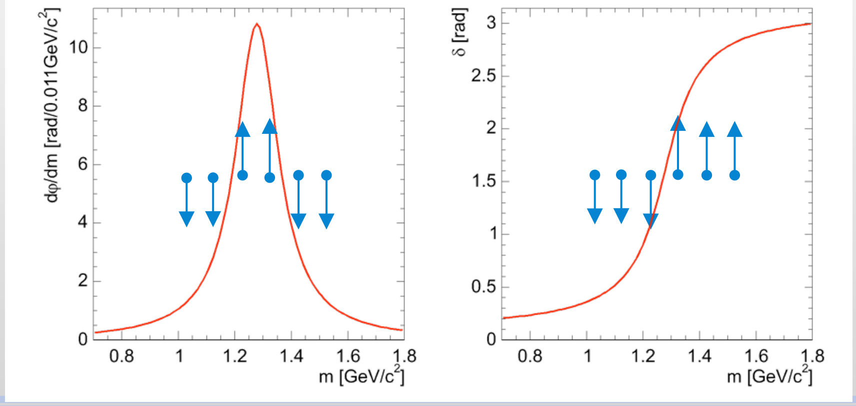
[LHCb: PRL 115, 072001 (2015)]

Nominal fit



4 free parameters:
m_0, Γ_0 + complex constant

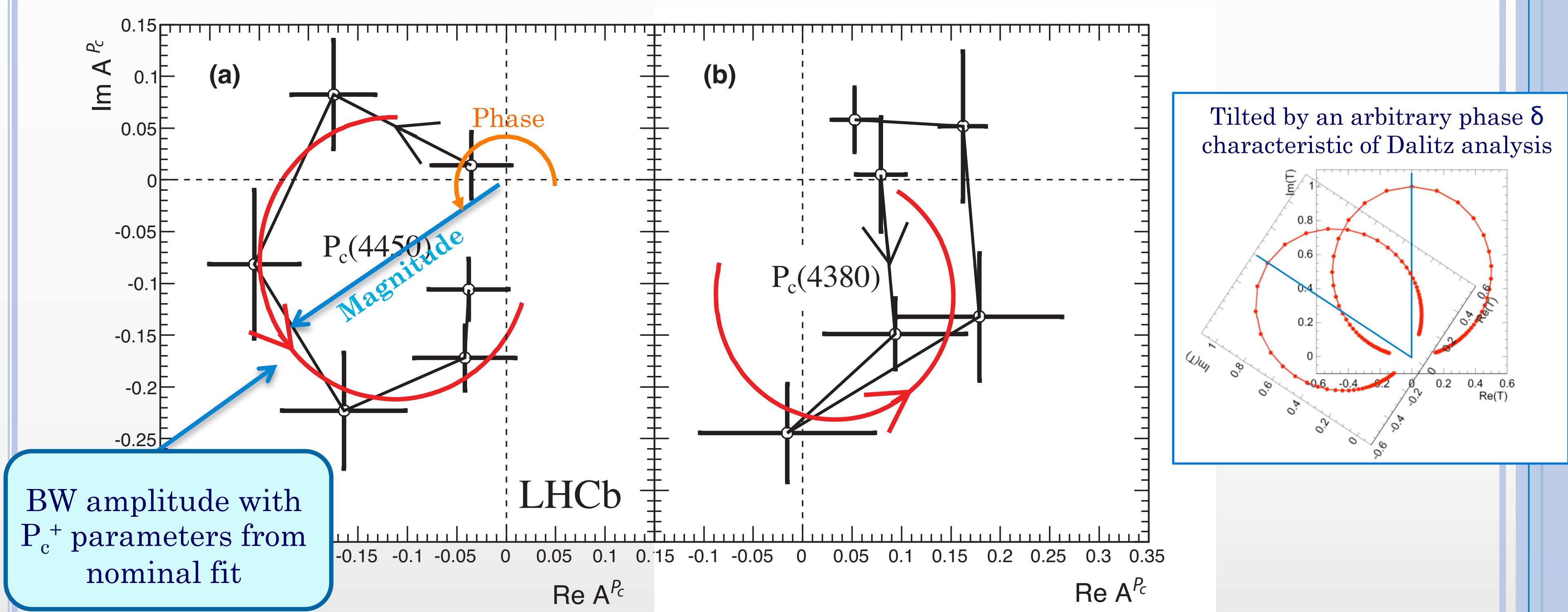
Alternative fit
Replace BW amplitude with 6 independent complex numbers in 6 bins of $m(J/\psi\, p)$ in region $m_0 \pm \Gamma_0$, where m_0 is the mass of P_c^+



12 free parameters

Argard Diagrams

[LHCb: PRL 115, 072001 (2015)]



- ➢ Good evidence for the resonant character of $P_c(4450)^+$
- ➢ The errors for $P_c(4380)^+$ are too large to be conclusive

Model-independent evidence for J/ψ p contributions to $\Lambda_b \to J/\psi\, p\, K^-$ decays

[LHCb: PRL 117 (2016) 082003]

Model Independent Analysis

[LHCb: PRL 117 (2016) 082003]

- Amplitude analyses are powerful tools but they are intrinsically model dependent:
  - How many Λ^* should be taken in account? How to deal with unknown/not observed states predicted by the quark model?
  - Not trivial to model NR components. Any mass dependence?
  - Possible 3-body contribution?
  - Isobar model has well known limitation: unitarity violation when adding broad overlapping states. K-matrix formalism? How to deal with the couplings to the exotic sector?

While studying the Z(4430) state, the BaBar collaboration developed a model-independent approach

Can the reflections of the structures in $m(pK)$ and $\cos\vartheta_{\Lambda^*}$ reproduce the $m(J/\psi p)$ distribution?

Intermezzo: Precision into determining the value of π

Arcsine [edit]

Observing an equilateral triangle and noting that

$$\sin\left(\frac{\pi}{6}\right) = \frac{1}{2}$$

yields

$$\pi = 6\sin^{-1}\left(\frac{1}{2}\right) = 6\left(\frac{1}{2} + \frac{1}{2\cdot 3\cdot 2^3} + \frac{1\cdot 3}{2\cdot 4\cdot 5\cdot 2^5} + \frac{1\cdot 3\cdot 5}{2\cdot 4\cdot 6\cdot 7\cdot 2^7} + \cdots\right)$$

$$= \frac{3}{16^0\cdot 1} + \frac{6}{16^1\cdot 3} + \frac{18}{16^2\cdot 5} + \frac{60}{16^3\cdot 7} + \cdots = \sum_{n=0}^{\infty} \frac{3\cdot\binom{2n}{n}}{16^n(2n+1)}$$

$$= \underbrace{3 + \frac{1}{8} + \frac{9}{640} + \frac{15}{7168} + \frac{35}{98304} + \frac{189}{2883584}}_{3.141} + \frac{693}{54525952} + \frac{429}{167772160} + \cdots$$

with a convergence such that each additional five terms yields at least three more digits.

Model Independent Approach

[LHCb: PRL 117 (2016) 082003]

H1: If no exotics in J/ψ K and J/ψ p

$(m_{pK}, \theta_{\Lambda b}, \theta_{\Lambda^*}, \phi_K, \theta_\psi, \phi_\mu) \rightarrow (m_{pK}, \theta_{\Lambda^*})$

Decompose angular distribution into Legendre moments

Legendre Polynomials

$$|\mathcal{M}(\theta_{K^*})|^2 = \langle P_0\rangle P_0 + \langle P_1\rangle P_1 + \langle P_2\rangle P_2 + \langle P_3\rangle P_3 + \langle P_4\rangle P_4 + \langle P_5\rangle P_5 + \langle P_6\rangle P_6 + \ldots$$

where the moments $\langle P_l \rangle$ determined from data: $\langle P_l\rangle = \sum_{i=1}^{N_{data}} \frac{1}{\epsilon_i} P_l(\cos\theta^i_{K^*})$

Recombine the "meaningful" moments up to a certain order

(driven by physics arguments)

Model Independent Approach

[LHCb: PRL 117 (2016) 082003]

H2: (e.g.) If only Λ* resonances up to J = 3/2

$$|\mathcal{M}(\theta_{K^*})|^2 = \underbrace{\langle P_0\rangle P_0 + \langle P_1\rangle P_1 + \langle P_2\rangle P_2 + \langle P_3\rangle P_3}_{} + \cancel{\langle P_4\rangle} P_4 + \cancel{\langle P_5\rangle} P_5 + \cancel{\langle P_6\rangle} P_6 + \cancel{\ldots}$$

Sum of the terms up to P_{Nmax}, where N_{max} = 2*J(Λ*), has to describe the data projections

Should it not happen →

There are Λ* resonances with J > 3/2
or
There are exotic(s) which make the high order terms non-zero!

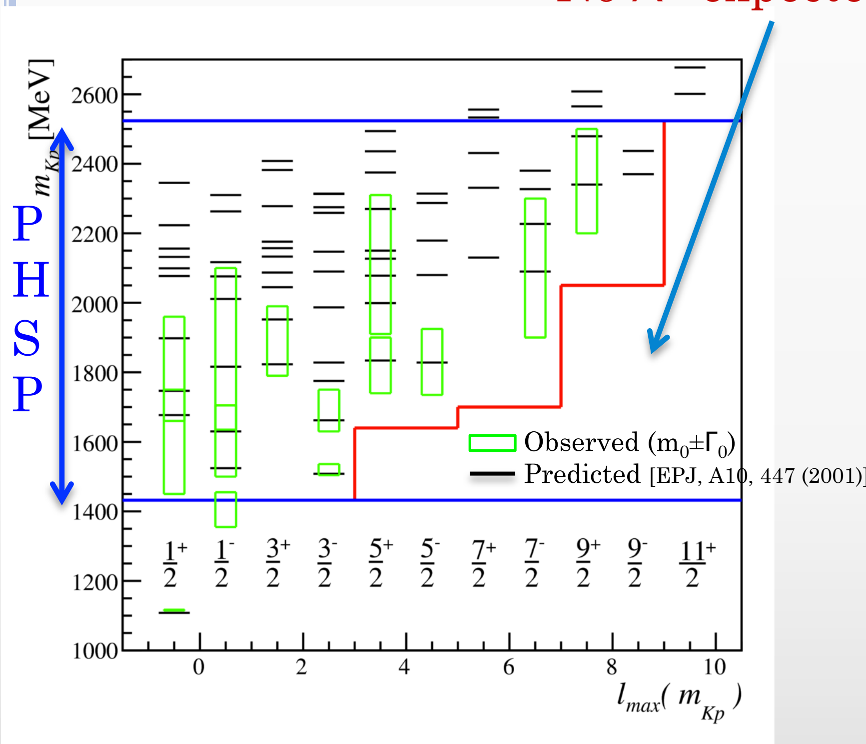
Qualitative Results from Model Independent Approach

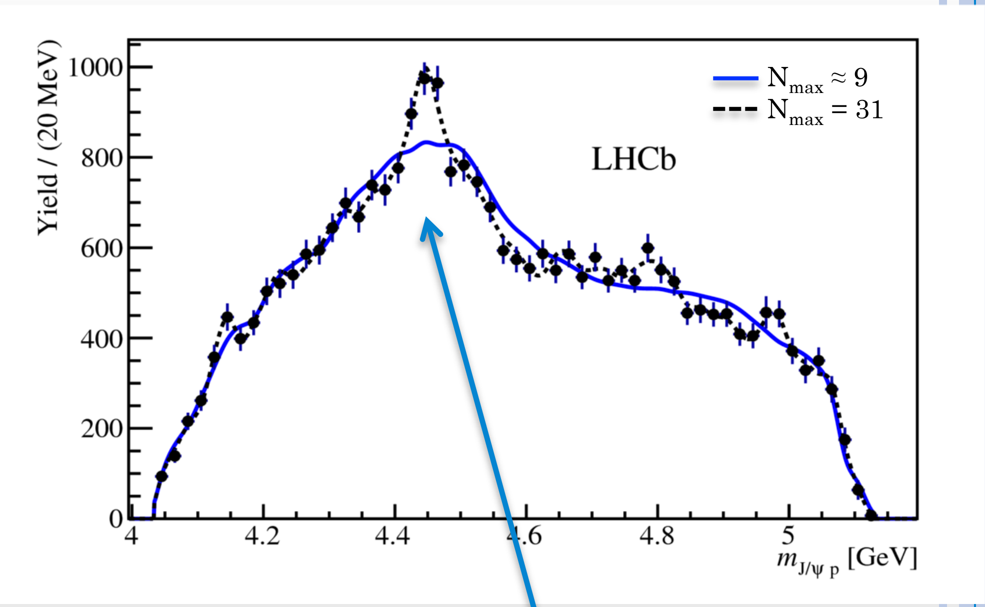
[LHCb: PRL 117 (2016) 082003]

$\Lambda^* \equiv$ excited Λ, excited Σ, NR

No Λ^* expected here

P
H
S
P





How much significant is the discrepancy after taking in account the statistical uncertainties?

Evidence for the Exotic Hadron Contributions to $\Lambda_b \rightarrow J/\psi\, p\, \pi^-$ decays

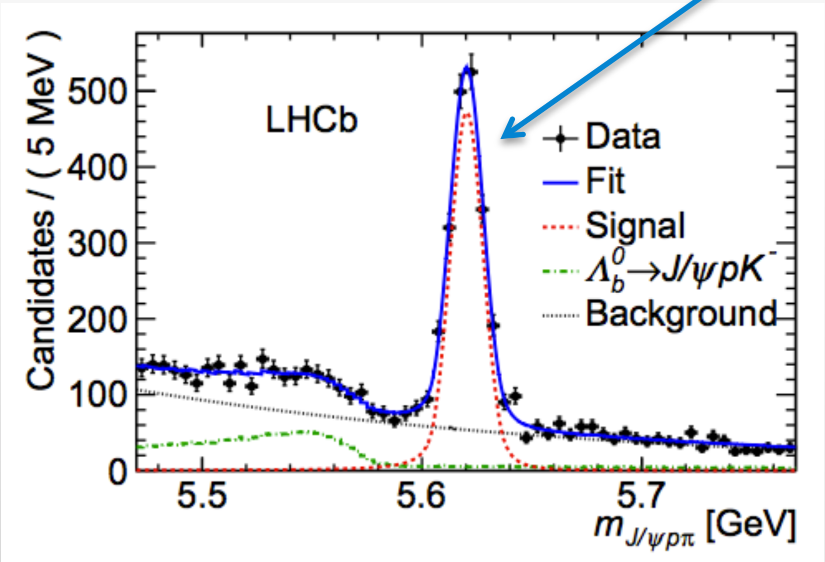
[LHCb: PRL 117 (2016) 082002]

How to Investigate the P_c^+ States Further?

[LHCb: PRL 117 (2016) 082002]

The confirmation of a new state passes through:

- Observation of a different decay:
  - $P_c^+ \rightarrow \chi_{c1}$ p (neutrals are involved)
  - $P_c^+ \rightarrow \Lambda_c$ D (long-lived hadrons $\rightarrow$low efficiency, small BR's)
- Observation in a different environment:
  - Prompt production pp $\rightarrow P_c^+$ + X (large track multiplicity at LHC)
  - $\Lambda_b \rightarrow J/\psi\, p\, \pi^-$: Cabibbo suppressed but feasible



Dataset: 3 fb^{-1}

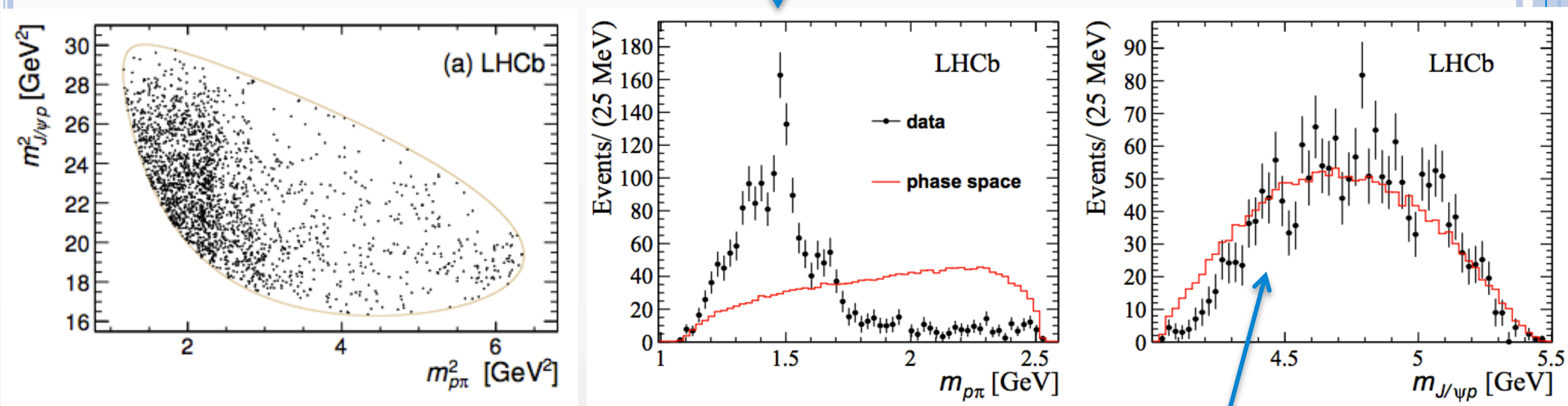
N_{events} = 1885 ± 50 (10x smaller than $\Lambda_b \rightarrow J/\psi$ p K)

Background ~ 20% (3x larger than $\Lambda_b \rightarrow J/\psi$ p K)

THE $\Lambda_B \rightarrow J/\psi\ p\ \pi^-$ DECAY

[LHCb: PRL 117 (2016) 082002]

N(1535)



No peaking structure in J/ψ p but P_c^+ 's could be still there

Amplitude Analysis

AMPLITUDE ANALYSIS OF $\Lambda_B \to J/\psi\, p\, \pi^-$ DECAY

FIT MODEL

[LHCb: PRL 117 (2016) 082002]

State	J^P	Mass (MeV)	Width (MeV)	RM	EM
NR $p\pi$	$1/2^-$	-	-	4	4
$N(1440)$	$1/2^+$	1430	350	3	4
$N(1520)$	$3/2^-$	1515	115	3	3
$N(1535)$	$1/2^-$	1535	150	4	4
$N(1650)$	$1/2^-$	1655	140	1	4
$N(1675)$	$5/2^-$	1675	150	3	5
$N(1680)$	$5/2^+$	1685	130	-	3
$N(1700)$	$3/2^-$	1700	150	-	3
$N(1710)$	$1/2^+$	1710	100	-	4
$N(1720)$	$3/2^+$	1720	250	3	5
$N(1875)$	$3/2^-$	1875	250	-	3
$N(1900)$	$3/2^+$	1900	200	-	3
$N(2190)$	$7/2^-$	2190	500	-	3
$N(2300)$	$1/2^+$	2300	340	-	3
$N(2570)$	$5/2^-$	2570	250	-	3
Free parameters				40	106

$N^* \to p\,\pi$

- Reduced model (RM) for central values, extended (EM) for systematics and significances
- Neglecting higher orbital angular momenta for most of the N* states

$P_c^+ \to J/\psi\, p$

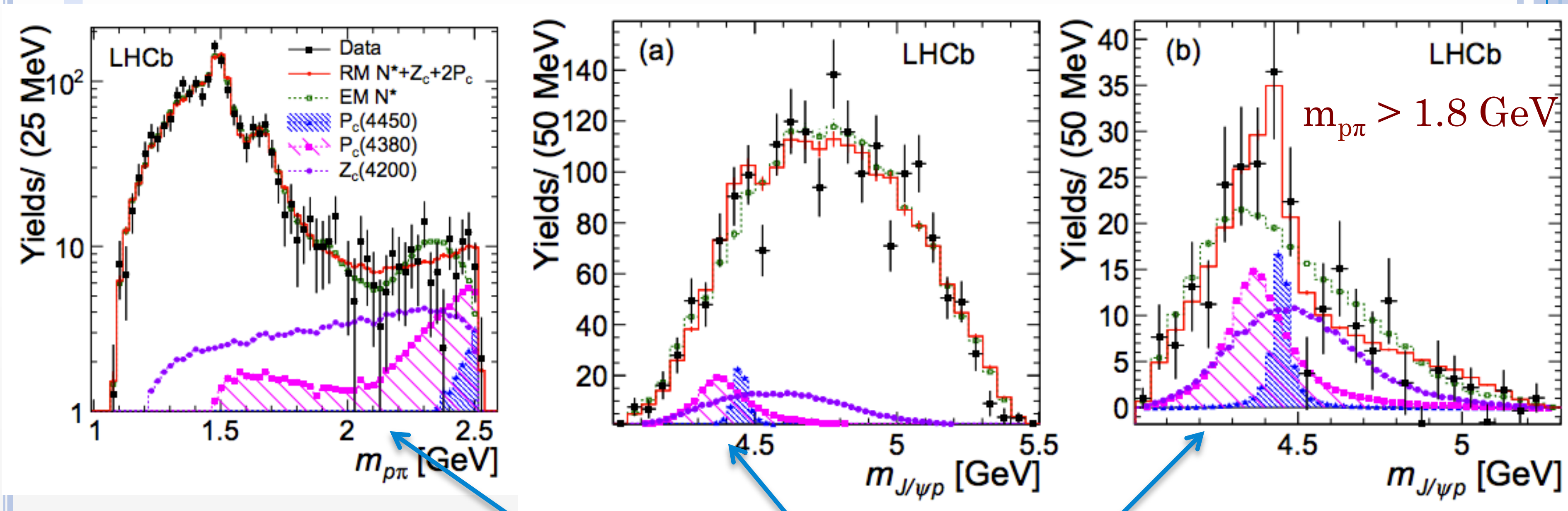
- Masses, widths and $J^P = (3/2^-, 5/2^+)$ fixed. Not possible to float them with the current statistic

$Z_c(4420)^+ \to J/\psi\ \pi$

- Observed by Belle [PRD, 90, 112009]
- Mass, width and $J^P = 1^+$ fixed

Amplitude Analysis of $\Lambda_B \rightarrow J/\psi\ p\ \pi^-$ Decay
Fit Results

[LHCb: PRL 117 (2016) 082002]



$P_c(4380)^+$, $P_c(4450)^+$, $Z_c(4200)^-$ overlap each other

- Significance of $P_c(4380)^+$, $P_c(4450)^+$, $Z_c(4200)^-$ taken together is 3.1σ (including systematic uncertainty) → Evidence for exotic hadrons.
- Individual exotic hadron contributions are not significant.
- Fit fractions consistent with what expected for the Cabibbo suppressed decay

Search for structure in the $B_s^0\pi^\pm$ invariant mass spectrum

(Inclusive Analysis)

[Phys. Rev. Lett. 117 (2016) 152003]

A New $B^0_s\pi^\pm$ State Claimed by DØ

[DØ: PRL 117 (2016) 022003]

Claimed observation/evidence of an exotic state $(\bar{b}s\bar{u}d)$

✓ $X(5568)^\pm \to B_s^0\pi^\pm$, $B_s^0 \to J/\psi\,\phi$, $J/\psi \to \mu^+\mu^-$, $\phi \to K^+K^-$

$$M = 5567.8 \pm 2.9^{+0.9}_{-1.9}\ \mathrm{MeV}/c^2$$

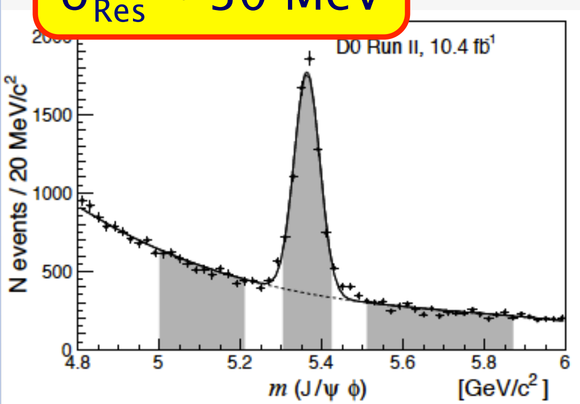
N.B. $m(\Xi_b) \sim 5790$ MeV

$$\Gamma = 21.9 \pm 6.4^{+5.0}_{-2.5}\ \mathrm{MeV}/c^2$$

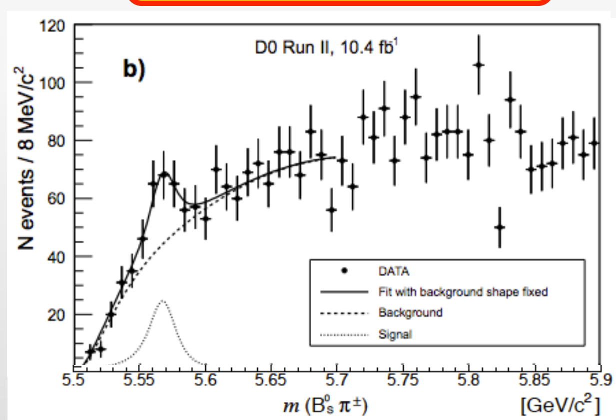
✓ Fraction of B_s^0 from $X^\pm$ decay: $\rho_X^{D\text{Ø}} = (8.6 \pm 1.9 \pm 1.4)\ \%$

"Cone" cut: $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 0.3$

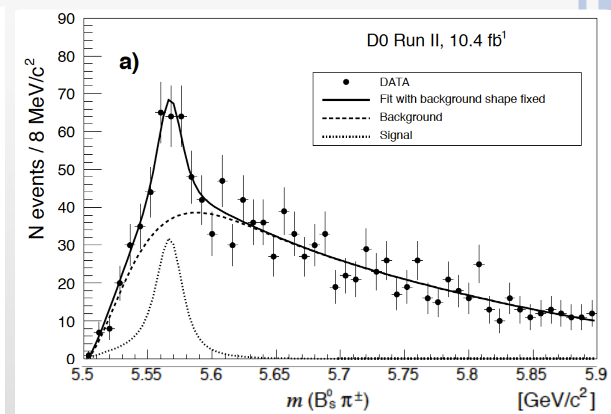
$N(B_s) \sim 5500$
$\sigma_{Res} \sim 30$ MeV



N(X) = 106 ± 23



N(X) = 133 ± 31



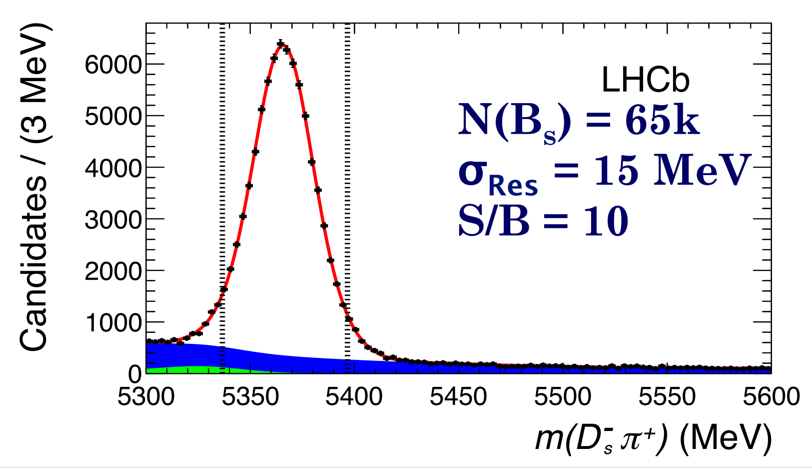
$3.9\,\sigma$ $5.1\,\sigma$

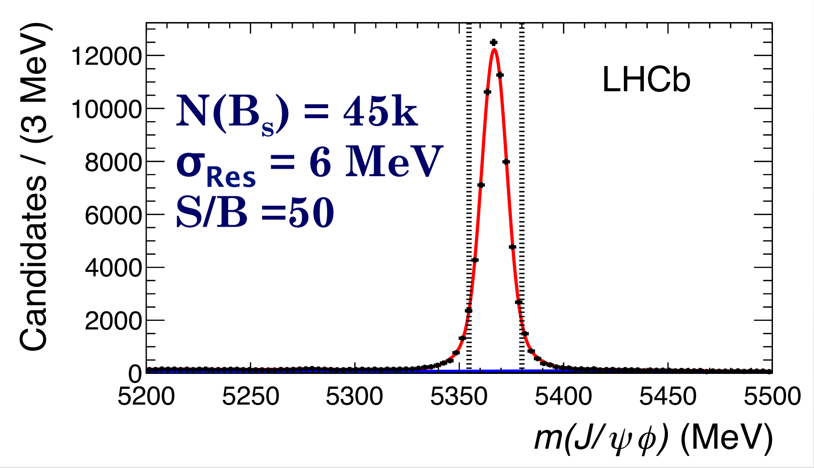
Signal significance

B_s SELECTION

[Phys. Rev. Lett. 117 (2016) 152003]

- RUN I data (3 fb^{-1})
- Cut-based selections aiming to very clean B_s^0 samples
  - ✓ Both $B_s^0 \rightarrow D_s^- \pi^+$ and $J/\psi\,\phi$ (Mass constraints on the D_s and J/ψ)
  - ✓ Stick closely to tried and trusted analysis methods:
    B** →Bπ and B_s** →BK
  - ✓ $p_T(\pi) > 500$ MeV/c
  - ✓ Baseline: $p_T(B_s^0) > 5$ GeV/c; Tight: $p_T(B_s^0) > 10$ GeV/c to match the DØ selection



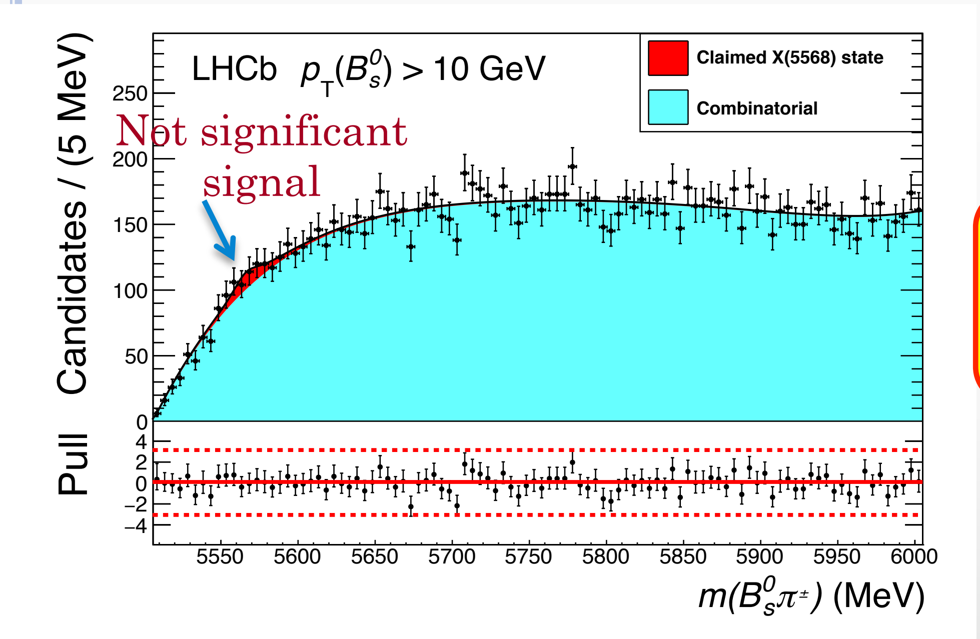


B_s sample 20x larger and much cleaner than DØ

Fit Result

[Phys. Rev. Lett. 117 (2016) 152003]

Both modes combined (no "Cone" cut applied): $p_T(B_s) > 10$ GeV/c



$$\rho_X^{\rm LHCb}(B_s^0\ p_T > 5\ {\rm GeV}/c) < 0.011\,(0.012)\ @\ 90\,(95)\,\%\ {\rm CL}$$
$$\rho_X^{\rm LHCb}(B_s^0\ p_T > 10\ {\rm GeV}/c) < 0.021\,(0.024)\ @\ 90\,(95)\,\%\ {\rm CL}$$
$$\rho_X^{\rm LHCb}(B_s^0\ p_T > 15\ {\rm GeV}/c) < 0.018\,(0.020)\ @\ 90\,(95)\,\%\ {\rm CL}$$

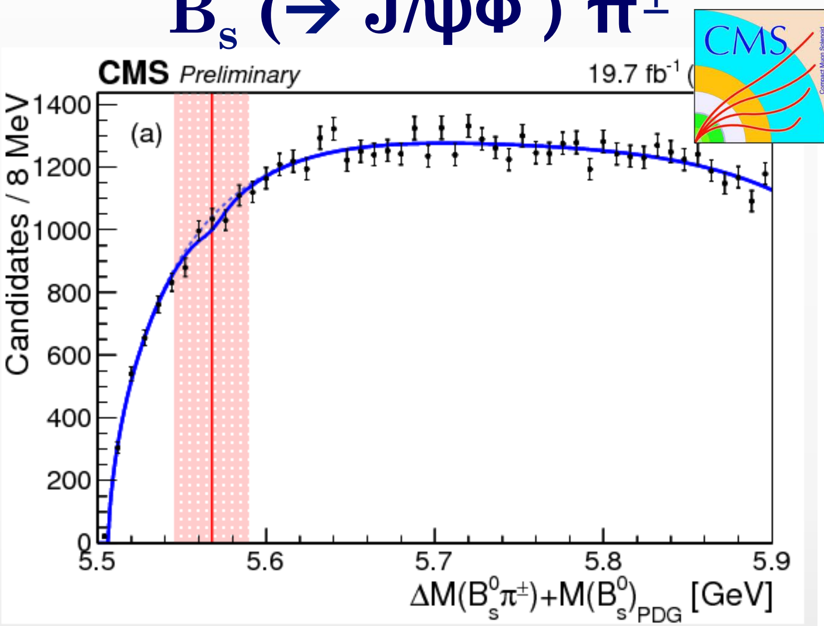
Limits are also set as function of mass (up to 6 GeV) and width (up to 50 MeV)

New Results @ ICHEP

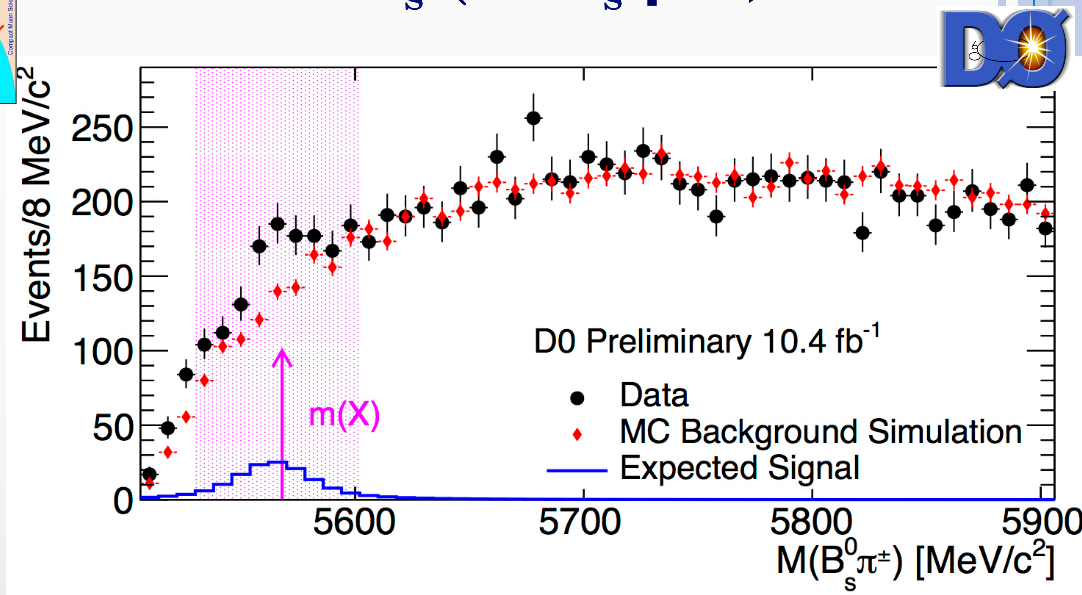
CMS-PAS-BPH-16-002

DØ Note 6488-CONF

B_s (→ $J/\psi\Phi$) $\pi^{\pm}$



B_s (→ D_s μ υ) $\pi^{\pm}$



$\rho_X < 3.9\%$ @95% C.L.

Amplitude analysis of $B^+ \rightarrow J/\psi\ \phi\ K^+$ decays

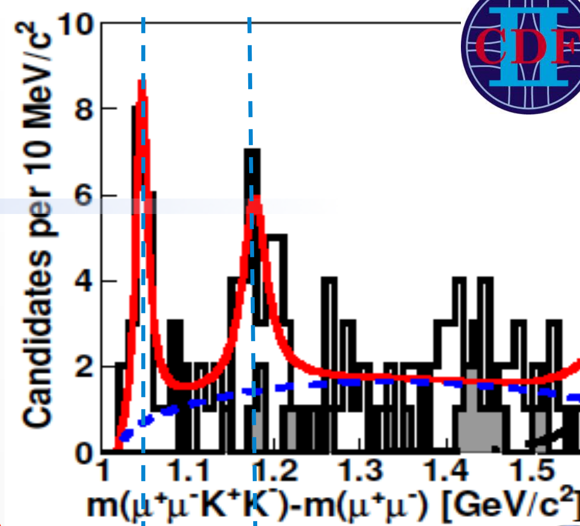
[LHCb: PRL 118 (2017) 022003]
[LHCb: PRD 95 (2017) 012002]

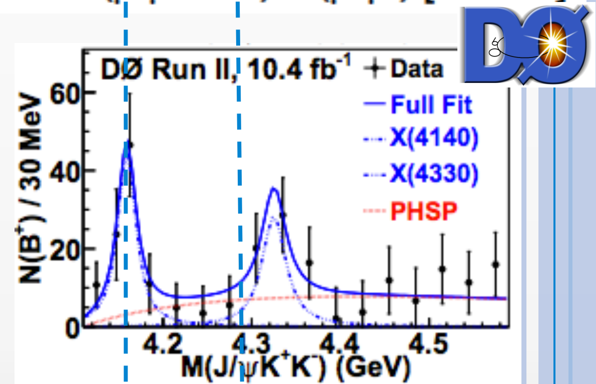
X(4140): A BIT OF HISTORY

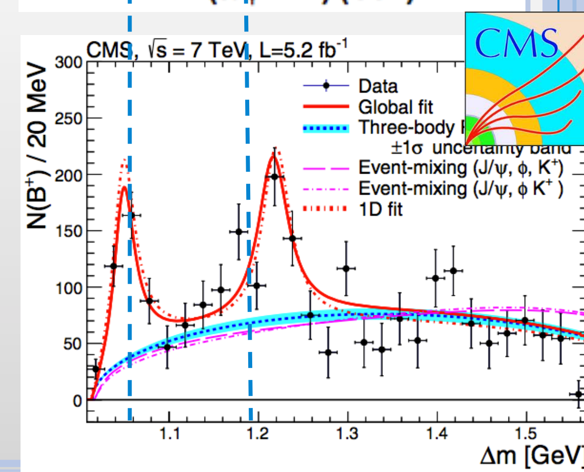
CDF: Evidence/"Observation" in $B^+ \to J/\psi\ \phi\ K^+$
[PRL 102, 242002 (2009), arXiv: 1101.6058]

X(4140)	**X(4274)**
$m = 4143.0^{+2.9}_{-3.0} \pm 0.6$ MeV $\Gamma = 15.3^{+10.4}_{-6.1} \pm 2.5$ MeV	$m = 4274.4^{+8.4}_{-6.7} \pm 1.9$ MeV $\Gamma = 32.3^{+21.9}_{-15.3} \pm 7.6$ MeV

- Belle: No evidence of X(4140) in $\gamma\gamma \to J/\psi\ \phi$. Observation of a new state X(4350) **[PRL 104, 112004 (2010)]**
- LHCb: No evidence of X(4140)/X(4274) in B decays but UL's don't disprove them **[PRD 85, 091103(R) (2012)]**
- DØ: "Threshold enhancement consistent with the X(4140) (3.1σ) …Second structure consistent with X(4350)" **[PRD89 012004 (2014)]**
- CMS: Peak in $J\psi\ \phi$ consistent with X(4140). Evidence of a 2[nd] peak affected by reflections **[PLB 734 (2014) 261]**
- BaBar: No evidence of X(4140)/X(4274) **[PRD 91, 012003 (2015)]**
- DØ: Evidence of X(4140) in prompt production **[PRL 115, 232001 (2015)]**

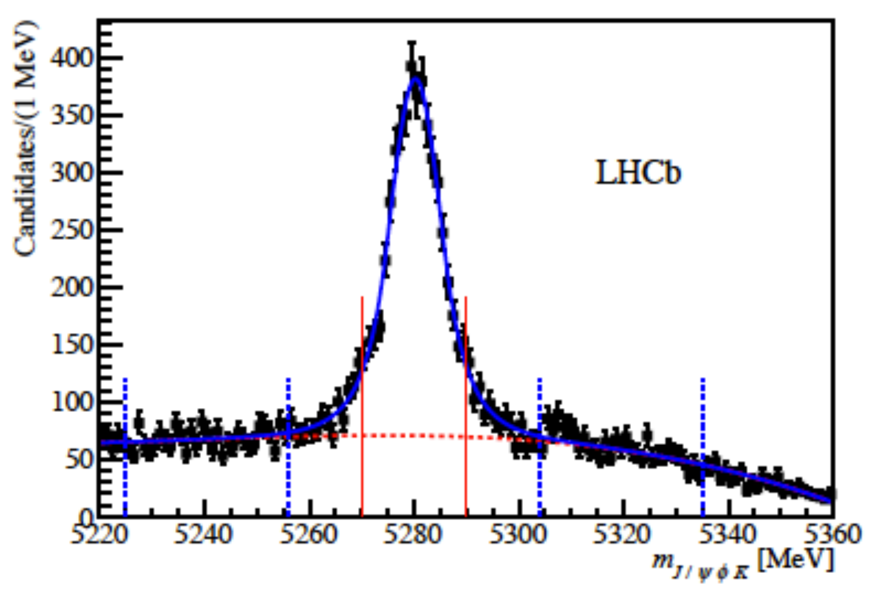


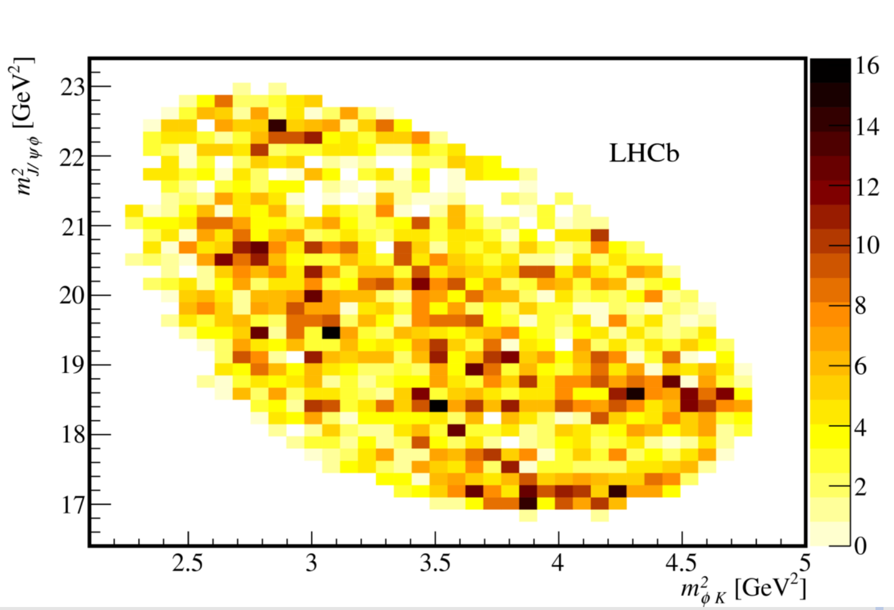




The $B^+ \to J/\psi\ \phi\ K^+$ Sample

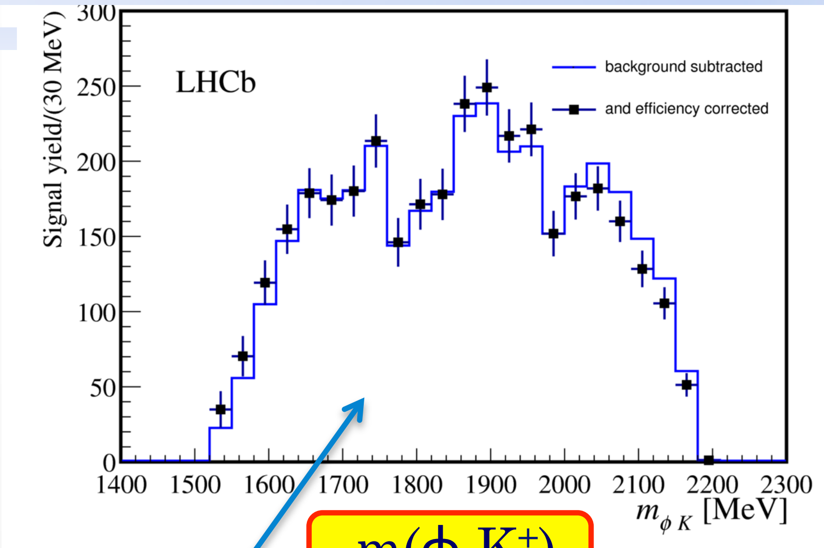
Run I data (3 fb^{-1})
$N_{Events} = 4289 \pm 151$
Background ~ 20%

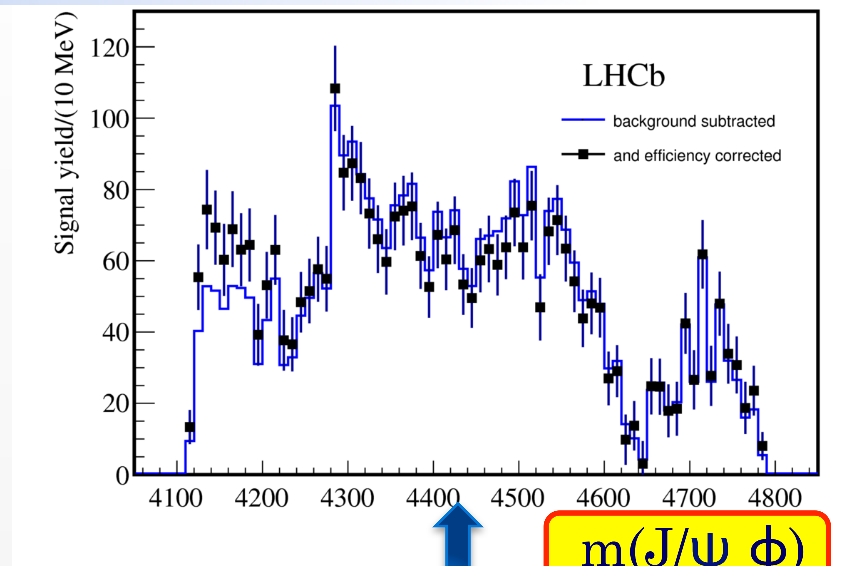




Statistically, the most powerful $B^+ \to J/\psi\ \phi$ K sample analyzed so far
First 6D amplitude analysis

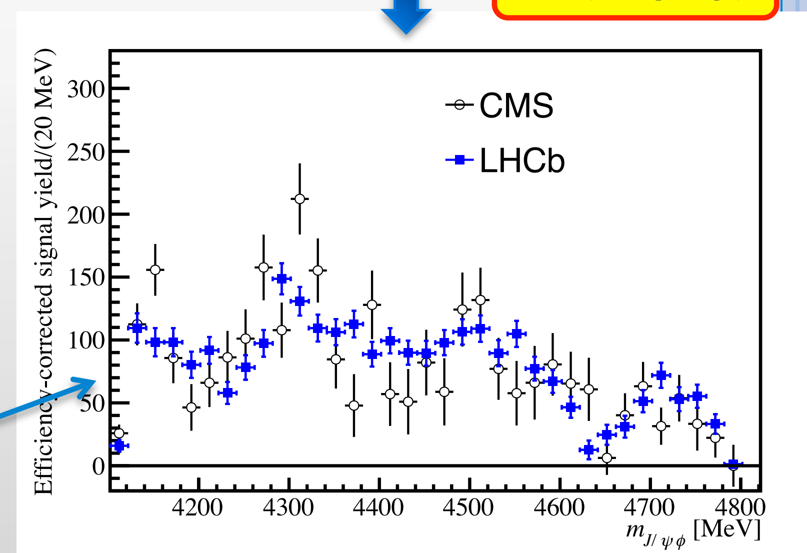
Mass Projections





m(ϕ K⁺)

m(J/ψ ϕ)

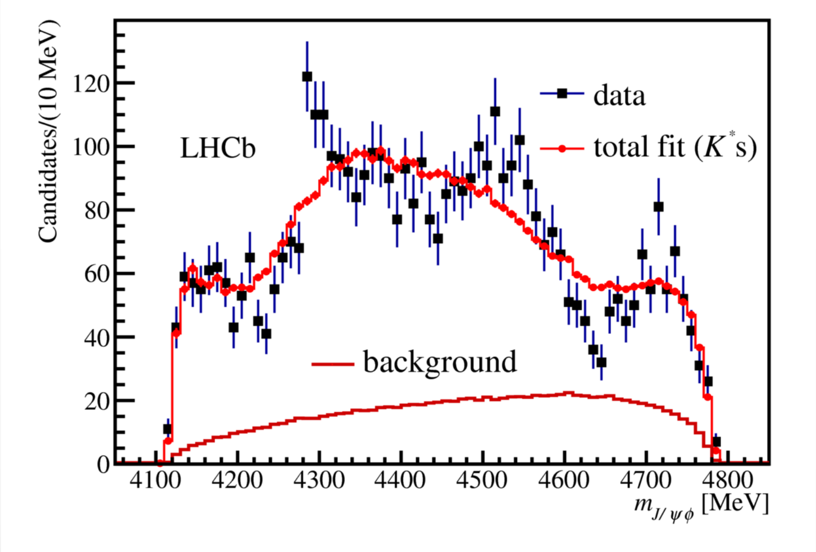


Smooth plot without any sharp structure but K* 's in such mass region have widths 150 < Γ < 400 MeV

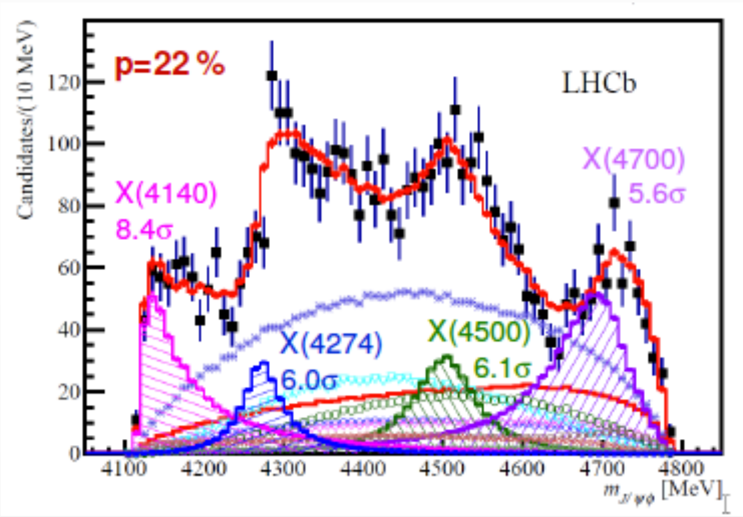
Qualitative agreement over the full mass range

Fit Results

Fit with K* only



Fit with K* + 4 X's!



	M_0 [MeV]	Γ_0 [MeV]
$X(4140)$	$4146.5 \pm 4.5 ^{+4.6}_{-2.8}$	$83 \pm 21 ^{+21}_{-14}$
$X(4274)$	$4273.3 \pm 8.3 ^{+17.2}_{-3.6}$	$56 \pm 11 ^{+8}_{-11}$
$X(4500)$	$4506 \pm 11 ^{+12}_{-15}$	$92 \pm 21 ^{+21}_{-20}$
$X(4700)$	$4704 \pm 10 ^{+14}_{-24}$	$120 \pm 31 ^{+42}_{-33}$

X(4140) ($J^{PC} = 1^{++}$)
- Mass consistent with the previous measurements but the width substantially larger

X(4274) ($J^{PC} = 1^{++}$)
- Consistent with the unpublished CDF results.

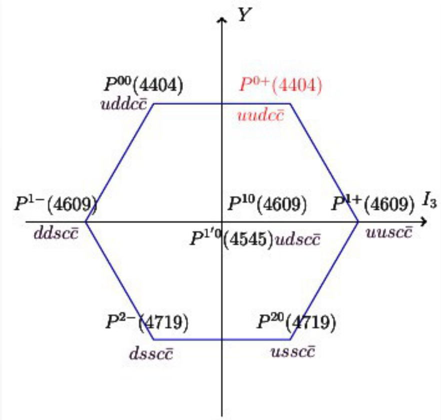
Two new states : **X(4500)** and **X(4700)** with ($J^{PC} = 0^{++}$)

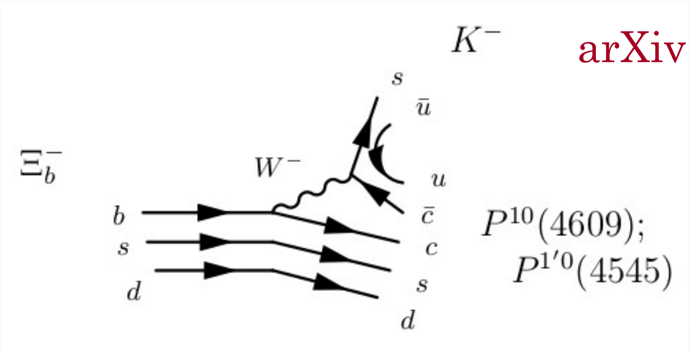
Summary & Prospect

- *The hunt to the next pentaquark is open!*
  - χ_{c1} p (Observation of P_c would rule out the cusp scenario)
  - $\Upsilon(1S) \rightarrow J/\psi\ p\,\bar{p}$
  - $D\,\Sigma_c$
  - Triple charged pentaquarks

Interplay between light and heavy quark spectroscopy: the poor knowledge of N*, Λ*, etc baryons has a large impact. PANDA, J-PARC, JLab and other hadron facilities could help into improving the current status

Summary & Prospect (II)

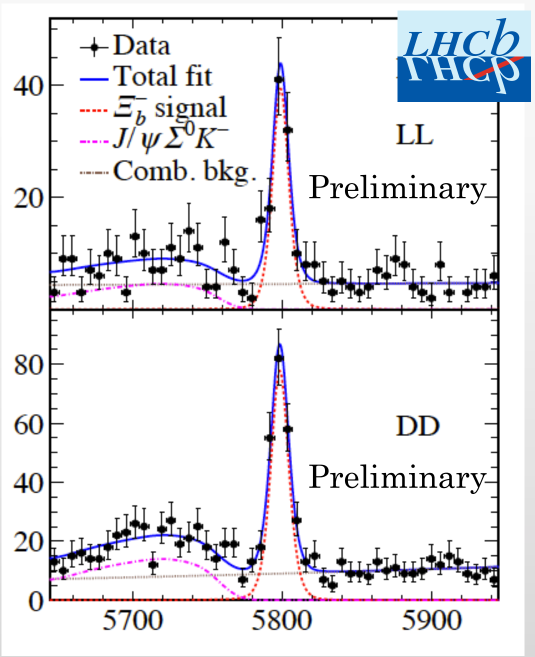




arXiv:1604.03769

LHCb-PAPER-2016-053 in preparation

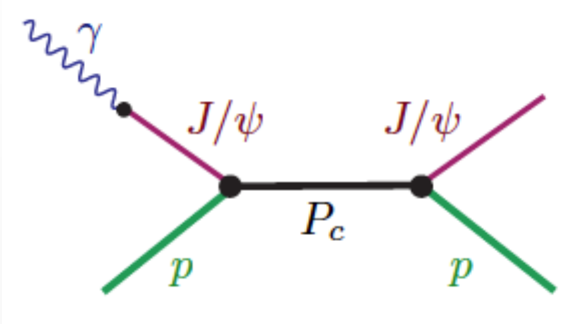
300 candidates of
$\Xi_b^- \to J/\psi\, \Lambda K^-$ (3 fb^{-1})

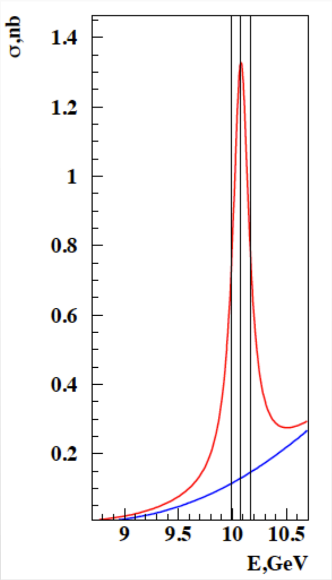


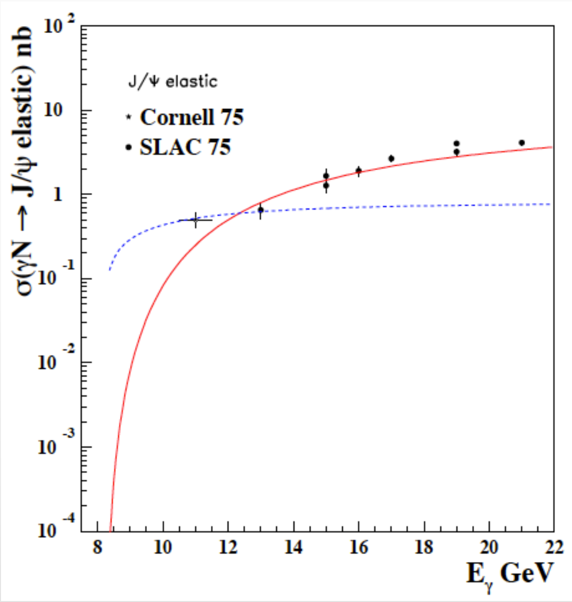
Photoproduction of Hidden-Charm Pentaquark in clas

arXiv:1609.00050
arXiv:1609.00676

The photoproduction of pentaquarks proceeds as an s-channel resonance





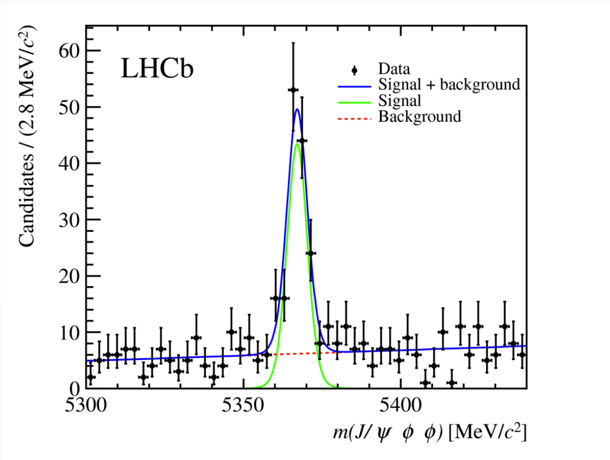


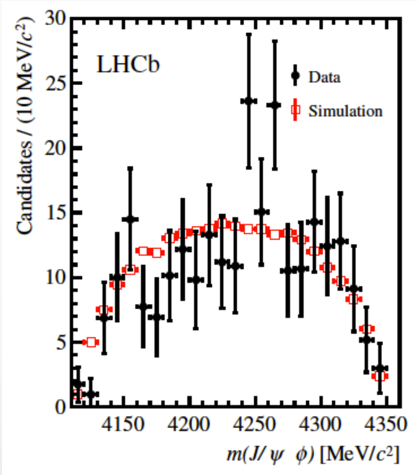
The lowest published energy is at E_γ = 11 GeV

With CLAS12 and 11 GeV electron beam, the threshold region can be studied in great details E12-12-001

SUMMARY & PROSPECT (III)

- Measurement of mass (~0.1 MeV) and width (~0.3 MeV) of X(3872)
- Search for new decays mode for X(3872): (e.g.) $\chi_{c1}\,\pi\,\pi$, $\bar{p}p$
- Search for X(4140) & X(4274) → $J/\psi\,\phi$ in B_s → $J/\psi\,\phi\phi$ decays





[LHCb: JHEP 03 (2016) 040]

- Exploration of $D_{(s)}\bar{D}^{(*)}_{(s)}$ mass spectra from B decays & Central Exclusive Production

X_b

- Search for Y(1S) ω (→π π π^0, μμ)

Amplitude Analyses are the way

Why amplitude analysis are strongly recommended?

Natural width of Z(4430) [MeV]

State	1D	2D	4D
Belle	$45\ ^{+18}_{-13}\ ^{+30}_{-13}$	$107^{+86}_{-43}\ ^{+74}_{-56}$	$200\ ^{+41}_{-46}\ ^{+26}_{-35}$
LHCb			$172 \pm 13\ ^{+37}_{-34}$

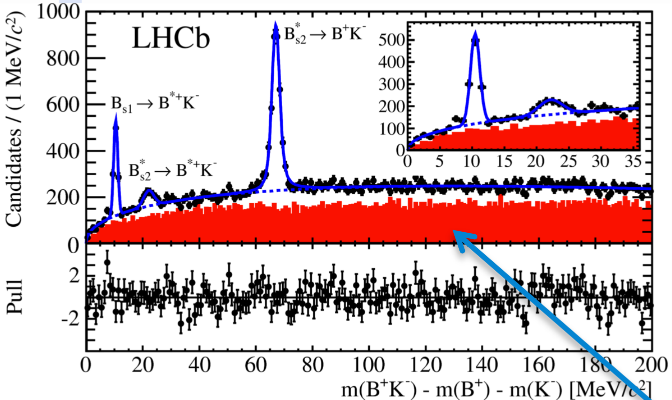
Natural width of X(4140) [MeV]

State	1D	6D
CDF	$15.3\ ^{+10.4}_{-6.1} \pm 2.5$	
LHCb		$83 \pm 21\ ^{+21}_{-14}$

- Broad structures may look narrow(er) in 1D mass projections.
- Amplitude analysis is a powerful tool to probe the quantum numbers and resonant character of the intermediate states.
- Limitation: poor knowledge of the light spectroscopy!

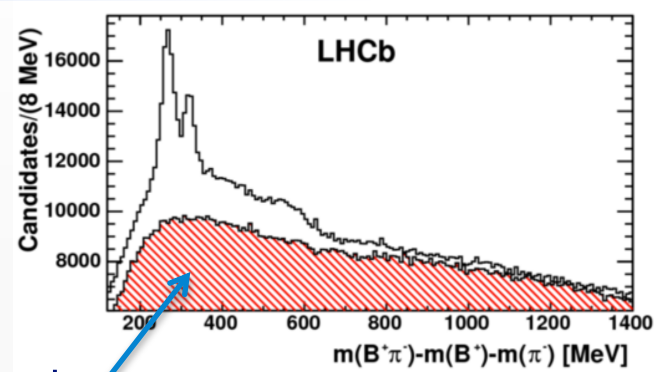
Back-up slides

OTHER "IMPLICIT" SEARCHES



PRL 110 (2013) 151803

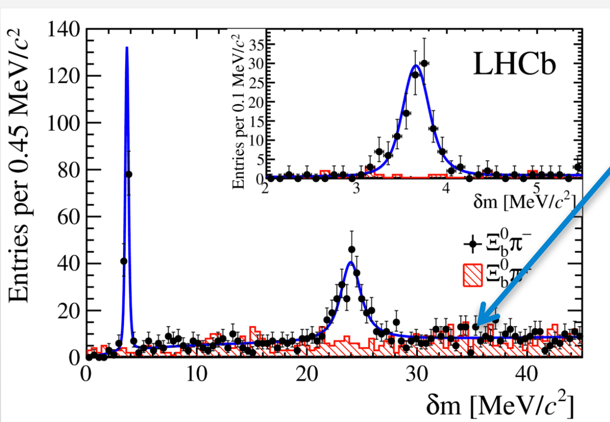
B^+K^+



$B^+\pi^+$

JHEP 1504 (2015) 024

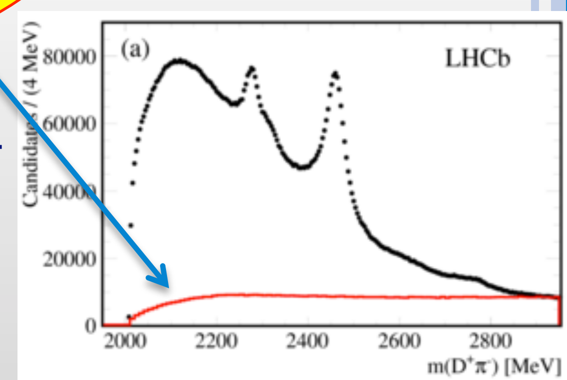
The red histograms, referred as Wrong Sign plots, are implicitly searches for tetra/ pentaquark



$\Xi_b^0\pi^+$

PRL 114 (2015) 062004

$D^+\pi^+$



JHEP 09 (2013) 145