How well can we resolve two bosons with near degenerate masses?

$H \rightarrow ZZ \rightarrow 4l$ channel

Andrey Korytov
(personal perspective)

small print: legal disclaimer

- No ATLAS/CMS public results on separation of two bosons with near degenerate masses near 126 GeV are available
- What follows are **back-of-envelope estimates** obtained using publicly available results
- I bare the full responsibility for all mistakes
- Neither ATLAS nor CMS underwrite quantitative estimates and qualitative opinions stated in these slides

Experimental questions to ask

(1) Small mass split: $\Delta m \ll$ instrumental resolution

- couplings not SM Higgs-like ? May be a smoking gun, but indirect (not in this talk)
- **presence of different J^{CP} contributions ?**
- should two states interfere, a more delicate search may be in order (not in this talk)

(2) Moderate mass split: $\Delta m \approx$ instrumental resolution

- distorted mass line shape?
  - is the apparent total width consistent with zero (experimentally, 4 MeV = 0) ? (not in this talk)
  - **fit for two narrow mass peaks ?**
  - two-peak fit assisted by different J^{CP} assumptions? (not in this talk)

(3) Large mass split: $\Delta m \gg$ instrumental resolution

- just keep searching for an independent small peak (not in this talk)

Alternative approach:

- **assume** that one of the bosons is **THE SM Higgs boson** and use it as a part of the SM background; certainly, it is very model dependent (not in this talk)

Note: *"instrumental resolution"* depends on integrated luminosity

J^{CP}-**fraction**: introduction

- two bosons X_1 and X_2 with very close masses: **Δm << det. resolution**
- **no interference**:
  - either different spins
  - or different initial states (e.g. gg->X_1 and qq->X_2)
  - or Δm >> Γ for the same production mechanisms and same spins
- **both decay to ZZ->4l**,
- but have **different spin-parity** quantum numbers.

Relative production rates for these two bosons can be assessed from **kinematics of four leptons** in the final state

J^{CP}-fraction: quantifying results

- Relative rates can be defined:
  - either for the total cross sections pp->X->ZZ->4l (σ)
  - or for cross sections within experimental acceptance (A)

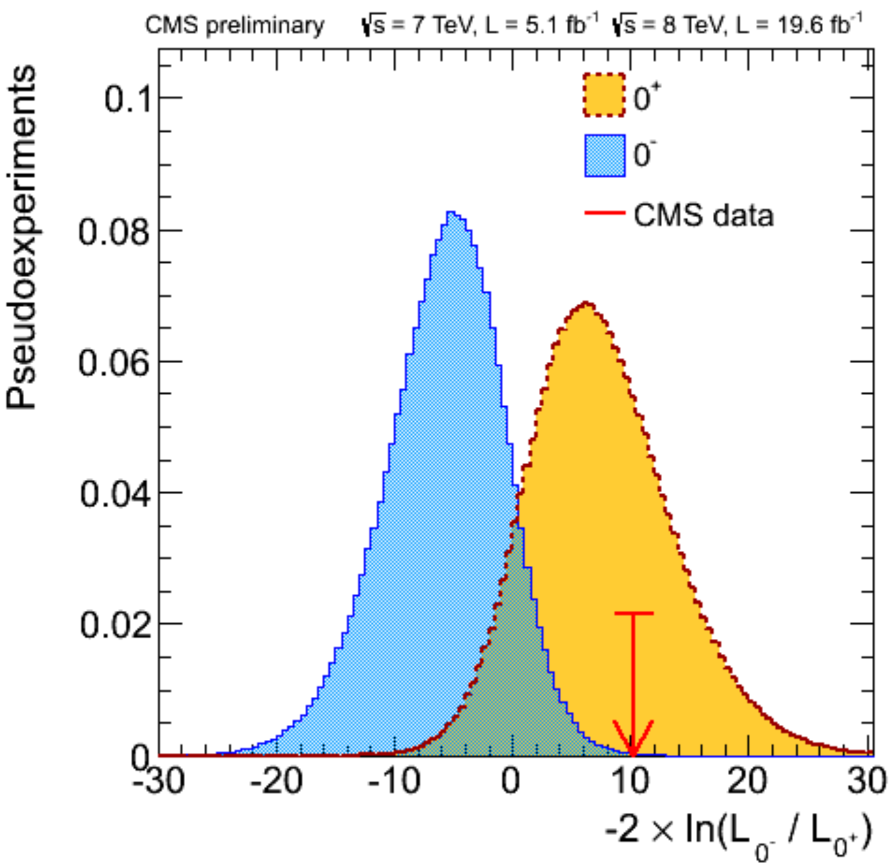
$$r = \frac{\sigma_2}{\sigma_1 + \sigma_2}$$

$$f = \frac{A_2 \cdot \sigma_2}{A_1 \cdot \sigma_1 + A_2 \cdot \sigma_2}$$

$$r = \left(1 + \frac{A_2}{A_1}\left(\frac{1}{f} - 1\right)\right)^{-1}$$

- Both definitions are useful/relevant:
  - ratio ***r*** is appropriate for **projecting sensitivities** and for **reporting null search results**
  - ratio ***f*** is more appropriate for **reporting the first evidence** for presence of two J^{CP}-contributions at the time when their origins have not been established yet

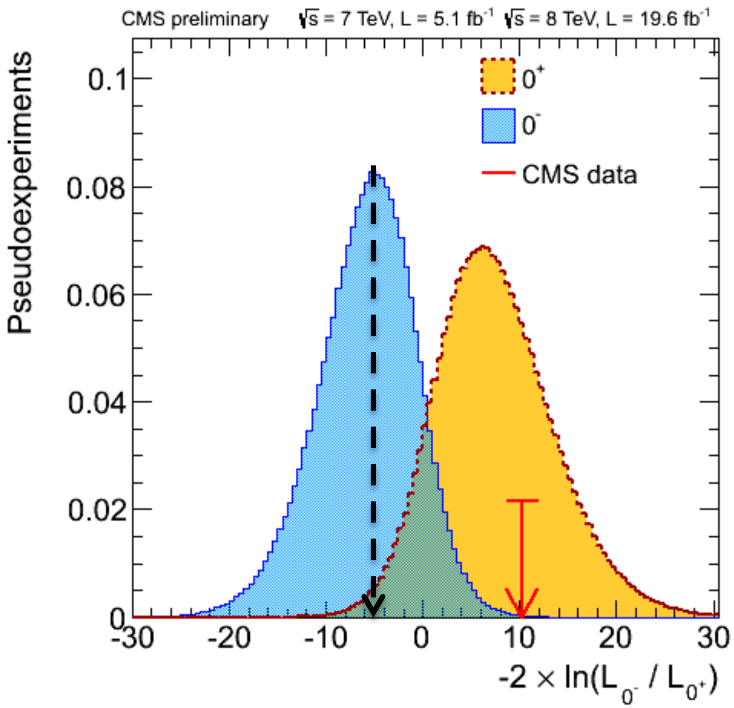
J^{CP}-**fraction**: back-of-envelope stat. model

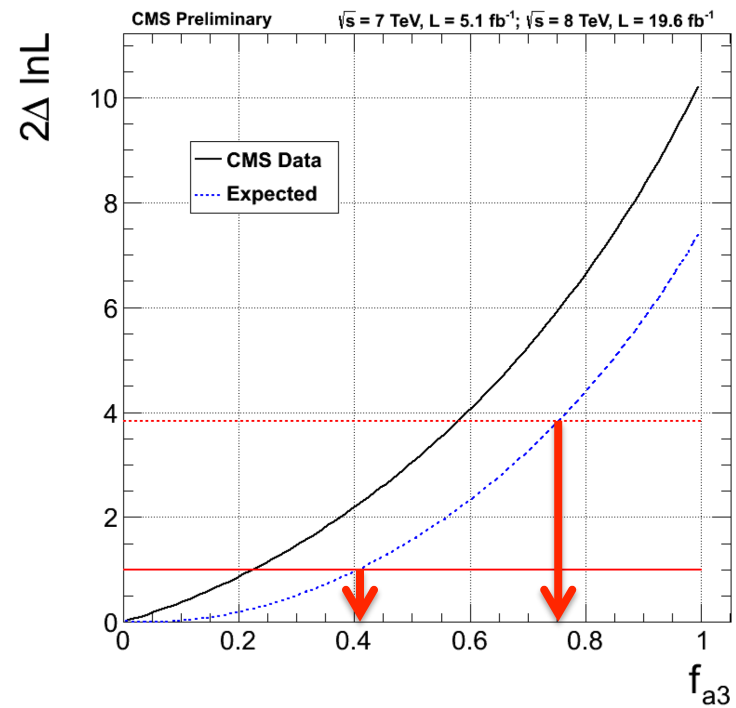


Test statistic distributions for J^{CP} tests are fairly Gaussian

- Hence, statistically, we are close to the asymptotic regime
- Then, if the separation of pure 0^+ and J^{CP} states is $N\sigma$, a mixture $(1–f) \times 0^+ + f \times J^{CP}$ is expected to manifest itself with significance $f \times N\sigma$ with respect to pure 0^+

J^{CP}-fraction: stat. model validation





CMS:

the expected separation for
pure 0^+ and **pure 0^-** states is **2.6σ**

Back-of-envelope projections:

- **1σ**-sensitivity for f=1/2.6=**0.38**
- **2σ**-sensitivity for f=2/2.6=**0.77**

compare

CMS:

- expected 1σ-sensitivity for ***f*=0.41**
- expected 2σ-sensitivity for ***f*=0.75**

J^{CP}-fractions: back-of-envelope sensitivities

$$f = \frac{A_X \cdot \sigma_X}{A_X \cdot \sigma_X + A_H \cdot \sigma_H}$$

$$r = \frac{\sigma_X}{\sigma_X + \sigma_H}$$

$X = J^{CP}$; $H = 0^+$; $\sigma -$ cross section; $A -$ four-lepton acceptance (varies from 0.3 to 0.6)

JCP state	Current sensitivities for separating pure J^{CP} and 0^+	Projected 2σ-sensitivity for *f*	Projected 2σ-sensitivity for *r*	Projected 2σ-sensitivity for *r* (300 fb^{-1}, 14 TeV)
gg → 0^-	2.6σ (CMS) / 3.1σ (ATLAS)	**0.77** *	**0.78**	**0.15**
gg → 0^+_h	1.7σ (CMS)	-	-	**0.20**
qq → 1^-	2.8σ (CMS) / 3.1σ (ATLAS)	**0.71**	**0.81**	**0.20**
qq → 1^+	2.3σ (CMS) / 2.9σ (ATLAS)	**0.87**	**0.91**	**0.22**
gg → 2^+_m	1.8σ (CMS) / 1.5σ (ATLAS)	-	-	**0.21**
qq → 2^+_m	1.7σ (CMS)	-	-	**0.25**
gg → 2^-	2.7σ (ATLAS)	**0.73**	**0.74**	**0.14**

*** CMS public results for *f(0⁻)*:** **expected limit: < 0.75 at 95%CL**
observed < 0.58 (better than the expected 0.75 due to some statistical luck)

Mass line shape: introduction

- Narrow four-lepton mass peak
- Fairly flat background
- Good signal-to-background ratio
- But very few events…

Mass line shape: simplified model

- Four-lepton mass distribution

- No additional discriminators,
like ME-based KD, jet tags, $p_T(4l)$, VD(m_{jj}, $\Delta\eta_{jj}$):
  - only very little help in the mass line shape analysis
  - one may not want to use them without knowing the nature of one of the two or even both bosons

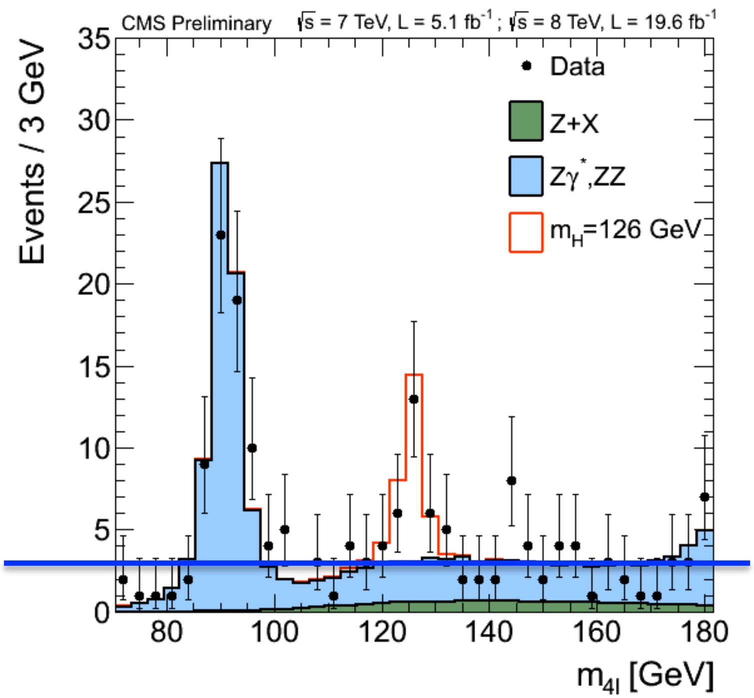
- No split by flavor

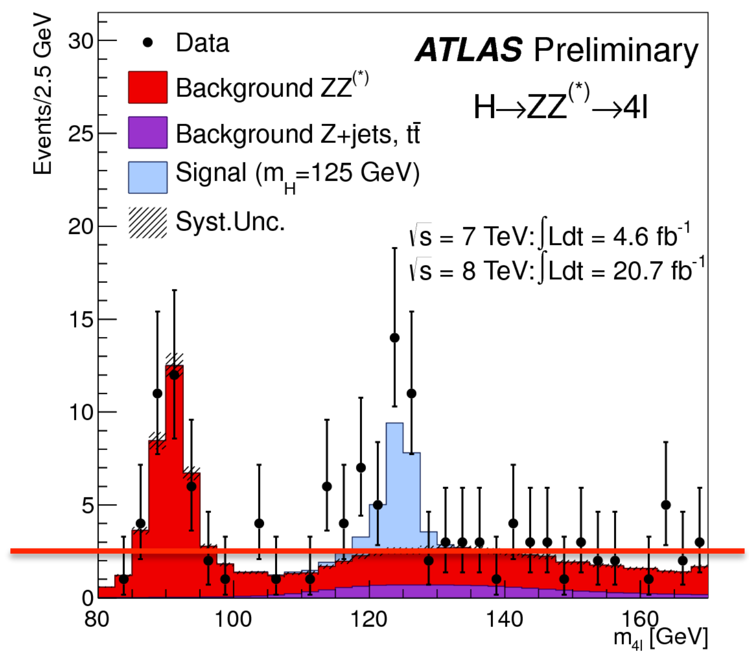
Mass line shape: background model

Background under the peak:

– **flat, 1 event/GeV**

– very similar for ATLAS and CMS



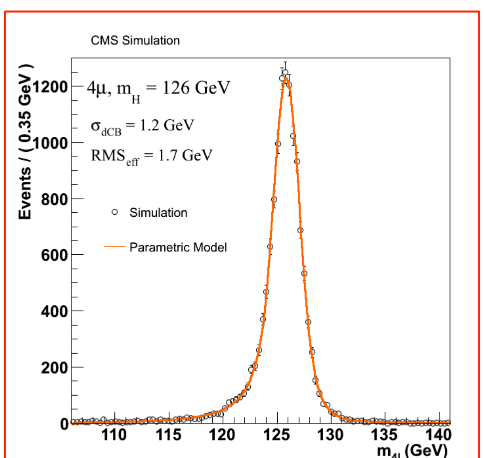


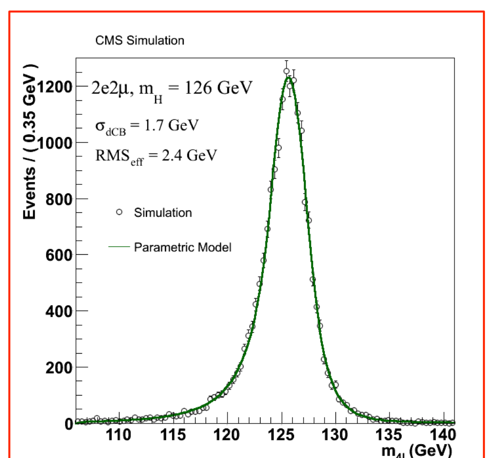
Mass line shape: signal model

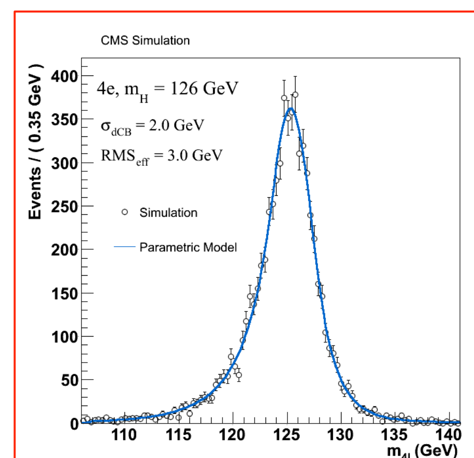
- Take total event yield **expected** for the SM Higgs boson: **21 events**
  - CMS: **21.1** (m_H=126)
  - ATLAS: **20.6** (average between m_H=125 and 127)
  - NOTE: observed signal strengths are somewhat different: 0.9±0.3 (CMS) and 1.7±0.5 (ATLAS)

- Approximate signal shape with **Gaussian** (ignore tails): **σ_m=1.7 GeV**
  - average over flavors and between Gaussian core σ and RMS for CMS (ATLAS number are about +20%)

CMS	**4μ**		**2e2μ**		**4e**	
	peak width	fraction	peak width	fraction	σ_m (GeV)	fraction
Core σ_m (GeV)	**1.2**	35%	**1.7**	46%	**2.0**	18%
RMS (GeV)	**1.7**		**2.4**		**3.0**	







Mass line shape: back-of-envelope stat. model

- Significance in general: $Z = \sqrt{2 \ln Q}$

- Likelihood ratio for one-peak and background-only hypotheses (the product runs over "infinitely small" bins i)

$$Q = \prod_i \frac{P(n_i \mid b_i + s_i)}{P(n_i \mid b_i)} = e^{-S_{TOT}} \cdot \prod_i \left(1 + \frac{s_i}{b_i}\right)^{n_i}, \quad \text{where } n_i = b_i + s_i$$

- Likelihood ratio for two-peak and one-peak hypotheses

$$Q = \prod_i \frac{P(n_i \mid b_i + (1-f) \cdot s_i(m_1) + f \cdot s_i(m_2))}{P(n_i \mid b_i + s_i(\tilde{m}))} = \prod_i \left(\frac{b_i + (1-f) \cdot s_i(m_1) + f \cdot s_i(m_2)}{b_i + s_i(\tilde{m})} \right)^{n_i},$$

where

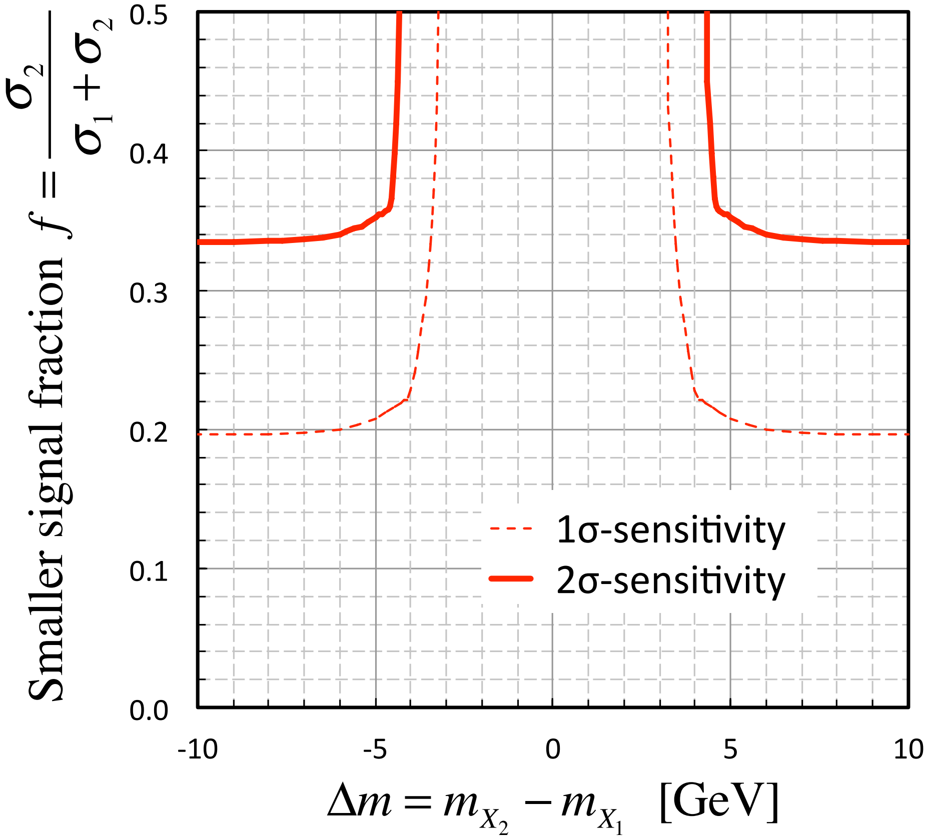
m_1 and m_2 – masses of bosons X_1 and X_2

f – fraction of the smaller peak wrt the total ($f < 0.5$)

$n_i = b_i + (1-f) \cdot s_i(m_1) + f \cdot s_i(m_2)$

$\tilde{m}$ – best-fit mass for one peak in presence of two bosons

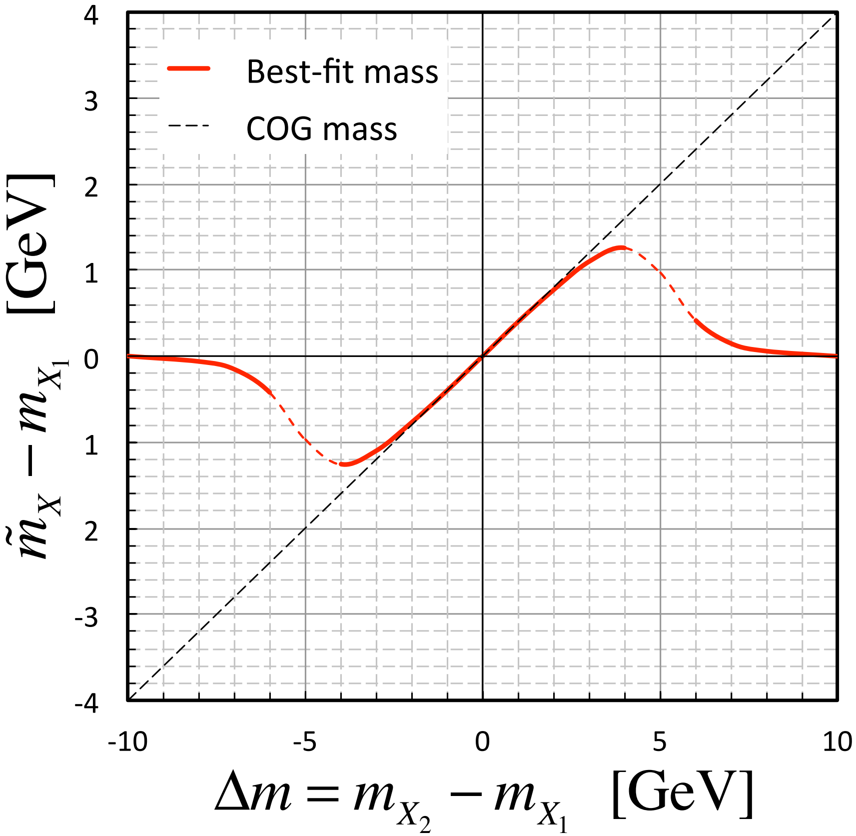
Two peaks: back-of-envelope sensitivity



- **Features:**
  - mass split "chimney"
  - min signal strength "base"
- **Current data:**
  - 3σ-sensitivity? – not yet
  - 2σ-sensitivity? – yes:
    - min mass split: **>4 GeV**
    - smaller peak signal strength: **>0.33**
- **L=300 fb^{-1}, 14 TeV:**
  - 3σ-sensitivity? – not yet
  - 2σ-sensitivity? – yes, if
    - min mass split: **>1.7 GeV**
    - smaller peak signal strength: **>0.05**

Two peaks: m_X from a single-peak fit

assume: (1-*f*)=0.6 and *f*=0.4



WORD OF CAUTION

- while inside the "chimney" (Δm < 4 GeV), the mass obtained in a single-peak fit tracks the center-of-gravity of two peaks
- outside the "chimney" (Δm > 6 GeV), the fit locks to the mass of the largest peak
- in the transition region, the single-peak mass fit results may be unstable (i.e. the fit may intermittently lock to the center-of-gravity of two peaks or to the largest peak, depending on small variations in data)

Back-of-envelope conclusions

- admixture of "wrong" J^{CP}-contribution (not mixed):
  - currently, very limited ability: ***r* > 0.8**
  - 300 fb^{-1}: ***r* > 0.2**
- mass lineshape:
  - currently: **Δm > 4 GeV, *f* > 0.3**
  - 300 fb^{-1}: **Δm > 2 GeV, *f* > 0.05**