$J/\psi J/\psi$ Spin-parity Analysis

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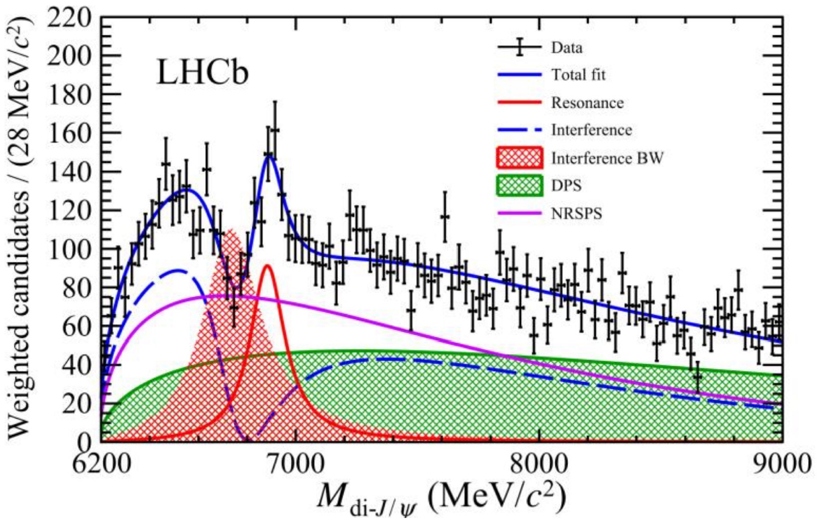
Outline

- Motivation
- Data samples and event selections
- Develop the spin-parity framework
  - Spin-parity and amplitudes
  - MC modeling
  - Discriminants
  - Fit model
- Fit validation
- Summary

Motivation

- Structures in $J/\psi J/\psi$ mass spectrum at LHCb, CMS, ATLAS
- Dips observed in data —— explained by interference in all three experiments
- Theoretical situation difficulty & confusing
  - Same J^{PC} between components? $J^{PC} = ?$



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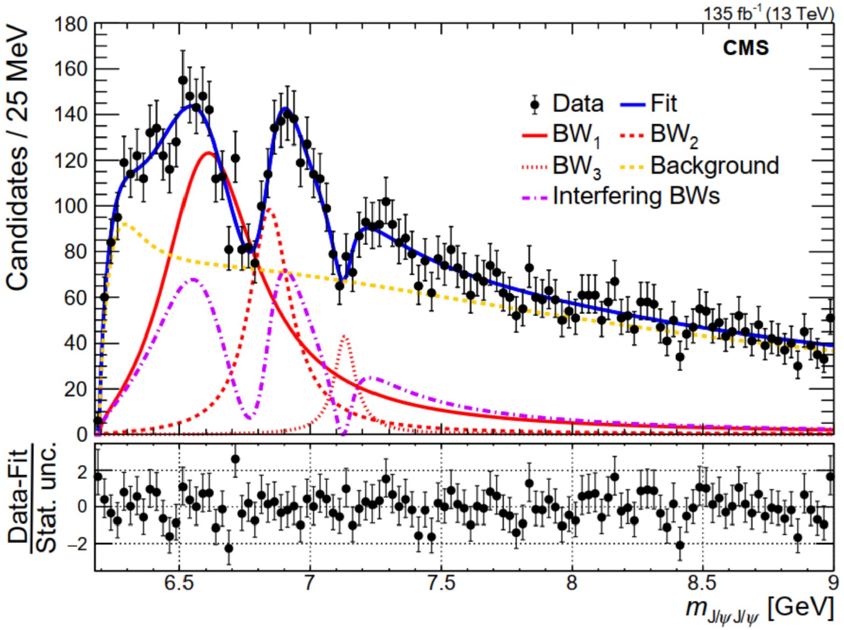

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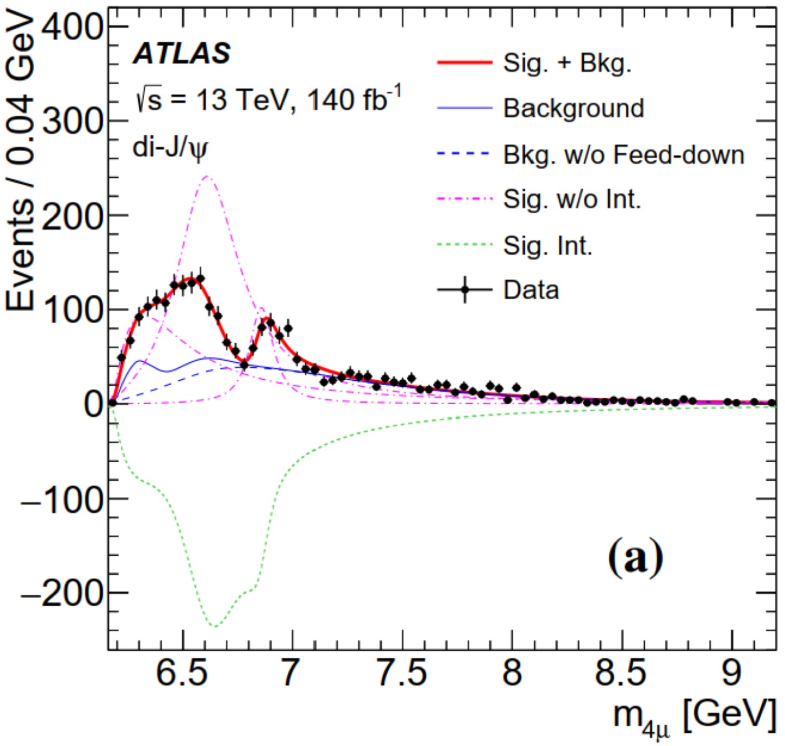

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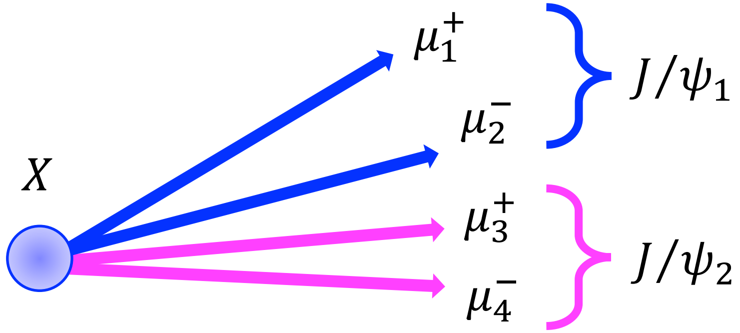
Data samples and event selections

- Use the same data sample and event selection criteria in BPH-21-003
- 135 fb^{-1} CMS data taken in 2016, 2017 and 2018 LHC runs



$p_T(\mu) > 2$ GeV (2016) & $p_T(\mu) > 3.5$ GeV (2017, 2018)
$|\eta(\mu)| < 2.4$
$2.95\ GeV \leq M(\mu^+\mu^-) \leq 3.25\ GeV$, then constrain to J/ψ mass
$p_T(J/\psi) > 3.5$ GeV
Soft Muon ID (very loose)
$Vertex\ Probability(\mu^+\mu^-\mu^+\mu^-) > 0.5\%$

- Main selections:
  - Fire corresponding trigger in each year & offline selection
  - Multiple candidates' treatment:

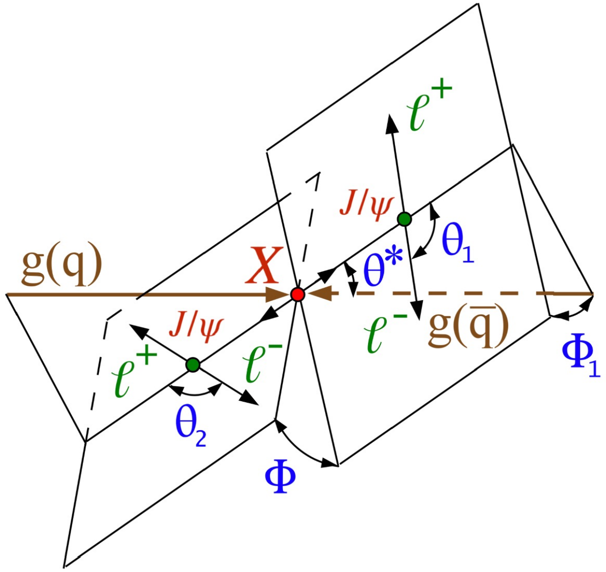
    Select best combination of same 4μ (~0.2%) with

$$\chi_m^2 = \left(\frac{m_1(\mu^+\mu^-) - M_{J/\psi}}{\sigma_{m_1}}\right)^2 + \left(\frac{m_2(\mu^+\mu^-) - M_{J/\psi}}{\sigma_{m_2}}\right)^2$$

    Keep all candidates arising from > 4μ (~0.2%)

- Signal and background MC samples produced by Pythia8, JHUGen, …

Spin-parity analysis



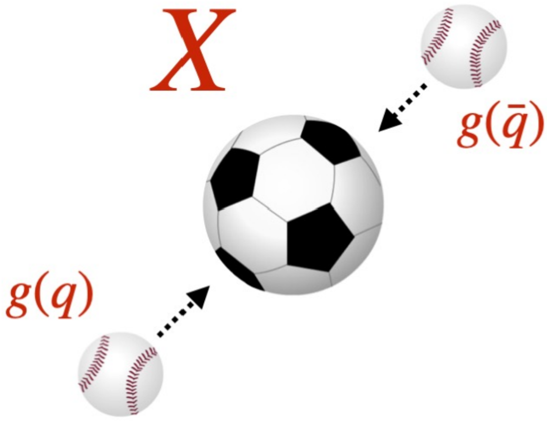
❑ General case

- Characterized by $\vec{\Omega} = (cos\theta^*, \Phi_1, \Phi, cos\theta_1, cos\theta_2)$
  - θ^*: the angle between incoming $g(q)$ momentum and J/ψ momentum in the X rest frame
  - Φ_1: the azimuthal angle between J/ψ decay plane and l^+l^- decay plane in the X rest frame
  - Φ: the azimuthal angle between two l^+l^- decay planes defined in the X rest frame
  - θ_1: the helicity angle between J/ψ_1 momentum and l momentum defined in the J/ψ_1 rest frame
  - θ_2: the helicity angle between J/ψ_2 momentum and l momentum defined in the J/ψ_2 rest frame

- Multiple dimension fit
  - Using all amplitudes (likelihood fit, full amplitude analysis)

❑ Follow the Higgs approach, two simplifications
  - Hypothesis testing
  - One observable optimal for separating two hypotheses (evaluated using MC & MELA)

Spin-parity and amplitudes



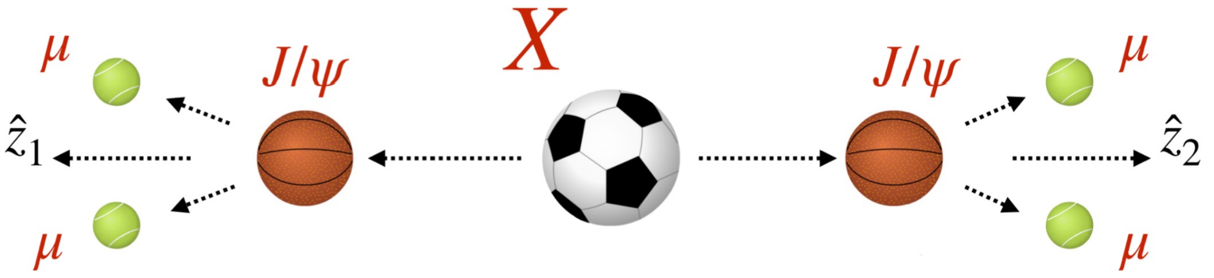
❑ Polarization in production

- spin-0: unpolarized in any case, $gg \to X$
- spin-1: $q\bar{q} \to X$ produce $J_z = \pm 1$
- spin-2: $gg \to X$ produce $J_z = 0, \pm 2$, minimal coupling: $J_z = \pm 2$
  $q\bar{q} \to X$ produce $J_z = \pm 1$

❑ Polarization in decay

Constraints: parity conservation, identical J/ψ bosons

$A_{\lambda_1\lambda_2}$ helicity amplitude, $\lambda(= +, -, 0)$ helicity of J/ψ



A_{++}
A_{--}
A_{00}
A_{+0}
A_{0+}
A_{-0}
A_{0-}
A_{+-}
A_{-+}

Spin-0: $A_{++} = A_{--}, A_{00}$ for 0^+ (2 amplitudes remain)

$A_{++} = -A_{--}, A_{00} = 0$ for 0^-

Spin-1: $A_{++} = A_{--} = A_{00} = 0, A_{+0} = -A_{0+} = A_{-0} = -A_{0-}$ for 1^-

$A_{++} = A_{--} = A_{00} = 0, A_{+0} = -A_{0+} = -A_{-0} = A_{0-}$ for 1^+

Spin-2: $A_{++} = A_{--}, A_{+0} = A_{0+} = A_{-0} = A_{0-}, A_{+-} = A_{-+}$ for 2^+

$A_{++} = -A_{--}, A_{+0} = A_{0+} = -A_{-0} = -A_{0-},$
$A_{00} = A_{-+} = -A_{+-} = 0$ for 2^-

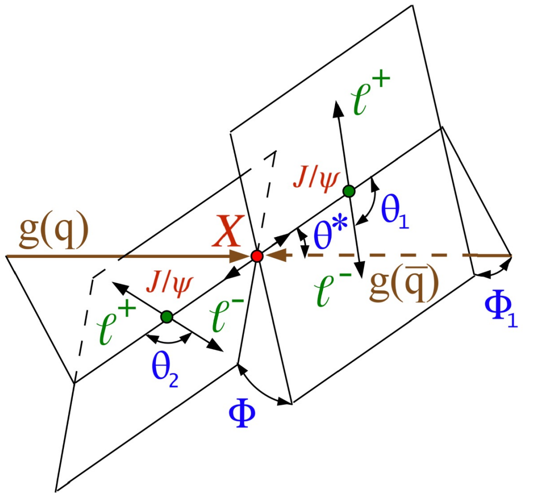
Monte Carlo modeling

Pythia8: **NRSPS**—Non-Resonant Single Parton Scattering

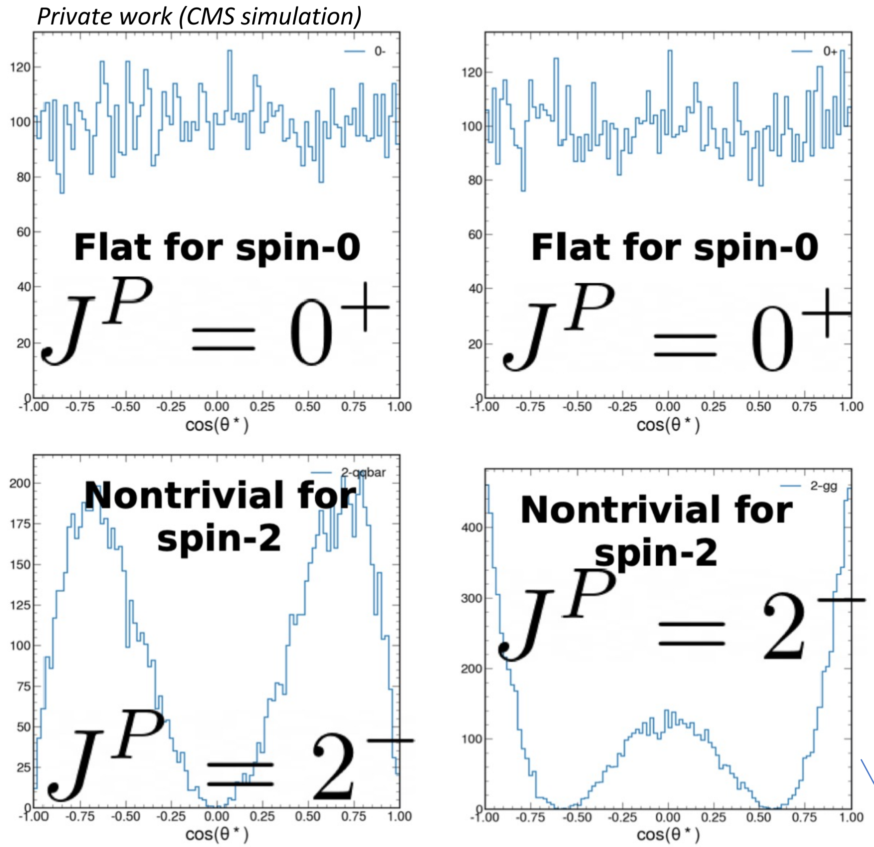
$gg(99\%) \rightarrow J/\psi J/\psi \rightarrow \mu^+\mu^-\mu^+\mu^-$

DPS—Non-Resonant Double Parton Scattering

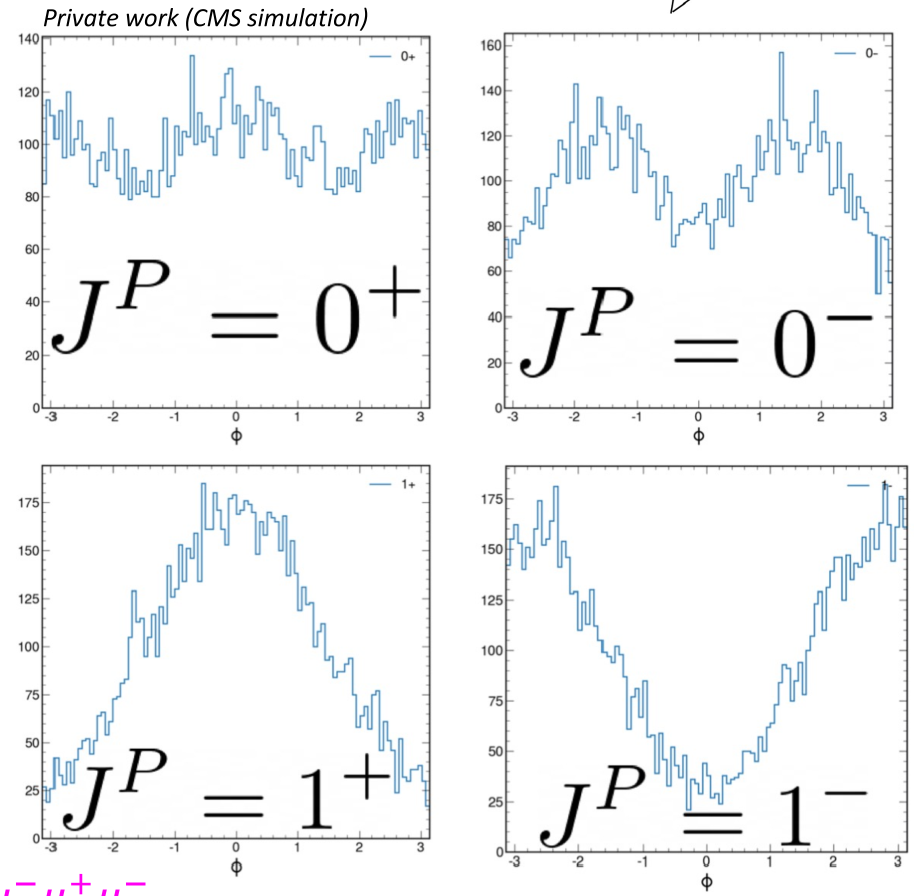
JHUGen: generate $gg(q\bar{q}) \rightarrow X \rightarrow J/\psi\, J/\psi \rightarrow 4\mu$ with different J^P : $0^+, 0^-, 1^+, 1^-, 2^+, 2^-$



$\cos\theta^*$



Φ



$q\bar{q} \rightarrow \mathrm{BW} \rightarrow J/\psi J/\psi \rightarrow \mu^+\mu^-\mu^+\mu^-$ $\quad$ $gg \rightarrow \mathrm{BW} \rightarrow J/\psi J/\psi \rightarrow \mu^+\mu^-\mu^+\mu^-$

Spin-parity discriminants

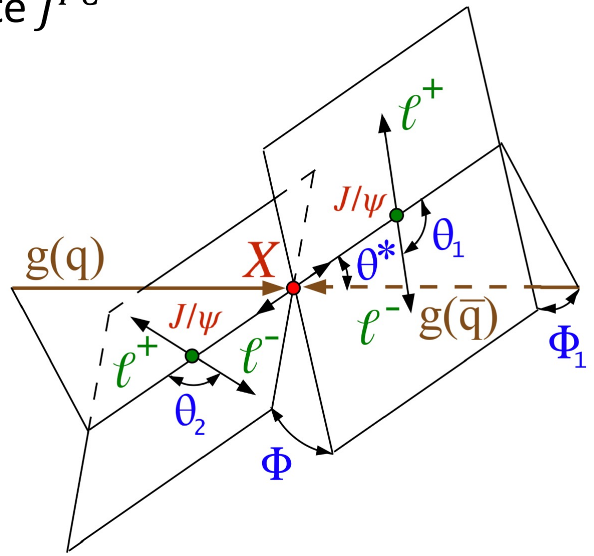
MELA (Matrix Element Likelihood Approach): create an optimal observable to separate J^{PC}

$$D_{ij}(m_X, \vec{\Omega}) = \frac{P_i(m_X, \vec{\Omega})}{P_i(m_X, \vec{\Omega}) + c_{ij} \times P_j(m_X, \vec{\Omega})}$$

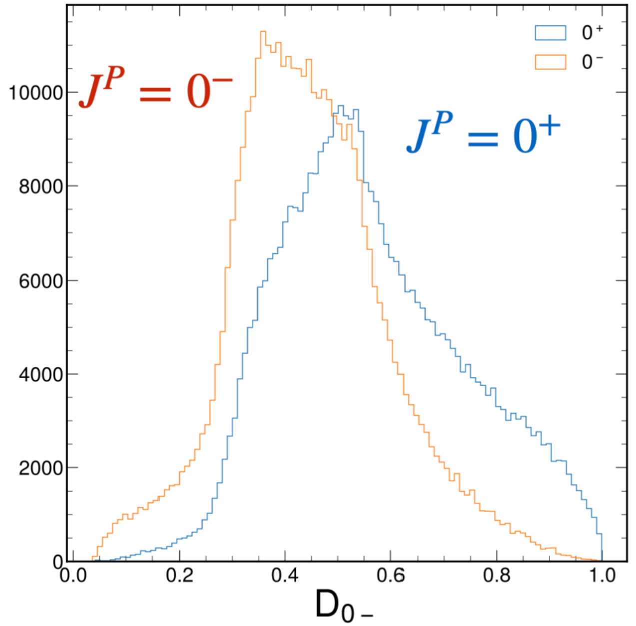
$$\vec{\Omega} = (cos\theta^*, \Phi_1, \Phi, cos\theta_1, cos\theta_2)$$

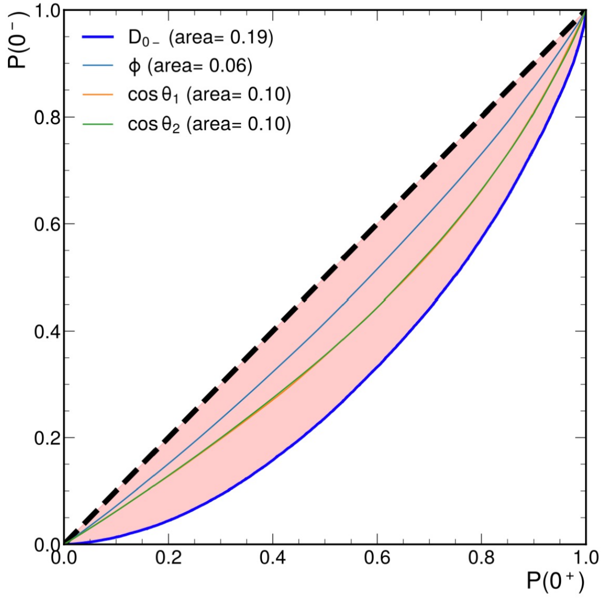
P_i the matrix element squared

c_{ij} calibration constant for a given value of m_X



Private work (CMS simulation)





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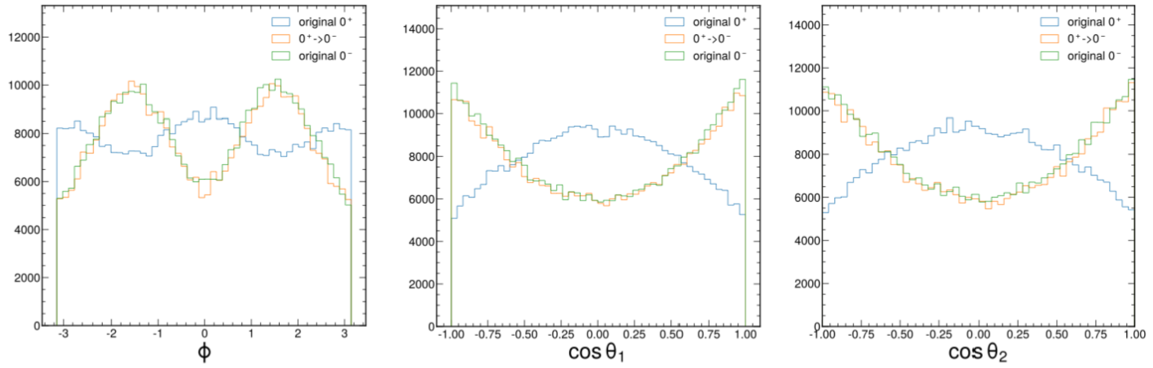

Fit model

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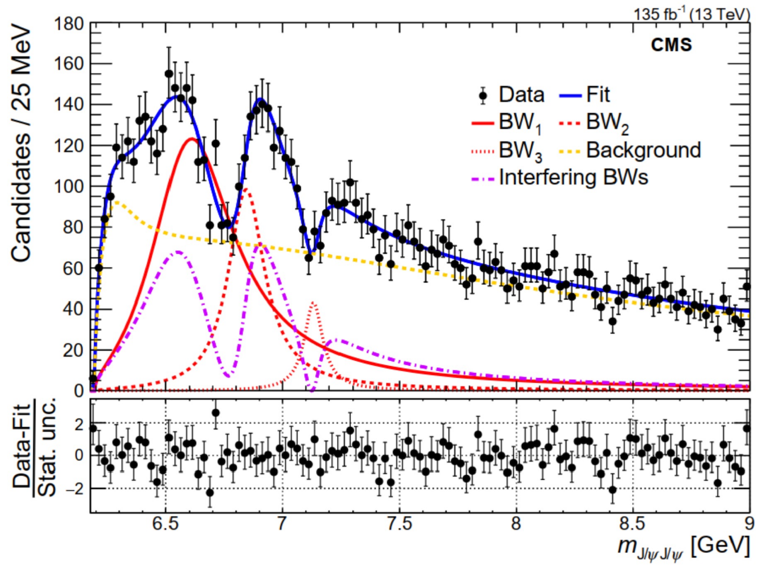


1D template fit is NOT good at separating spin-parity hypothesis → 2D template

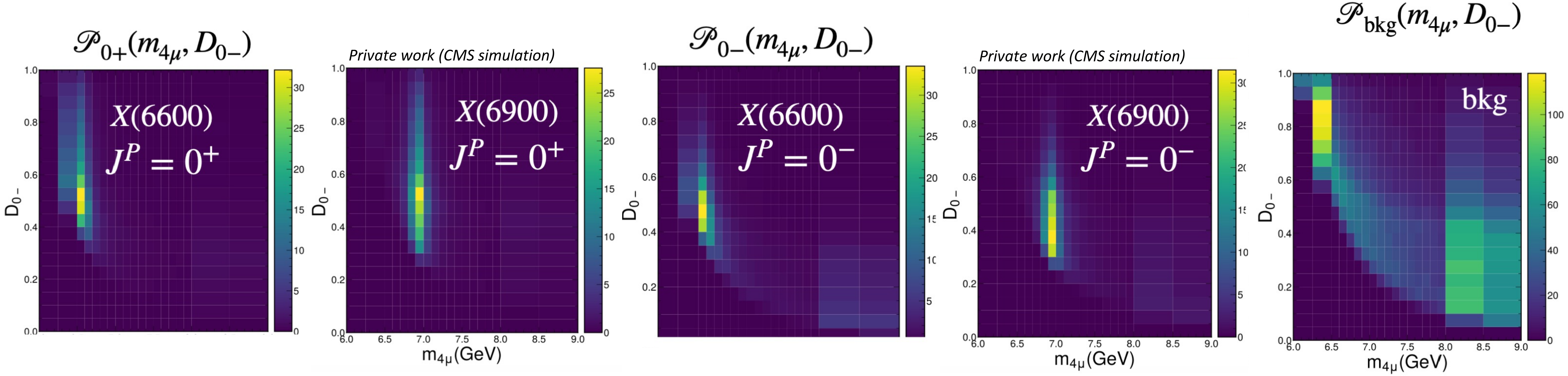
- **Mass**: separate signal and background

$$pdf_m(m) = N_{BW_0} \cdot |BW_0|^2 \otimes R(M_0) + N_{NRSPS} \cdot pdf_{NRSPS} + N_{DPS} \cdot pdf_{DPS}$$
$$+|r_1 \cdot \exp(i\phi_1) \cdot BW_1 + BW_2 + r_3 \cdot \exp(i\phi_3) \cdot BW_3|^2$$

- $\boldsymbol{D_{0^-}}$: distinguish between different spin parities

- $\boldsymbol{T(m_X, D_{0^-})}$: 2D template from JHUGen for $m_X - D_{0^-}$ correlation

— template fit:



Fit model

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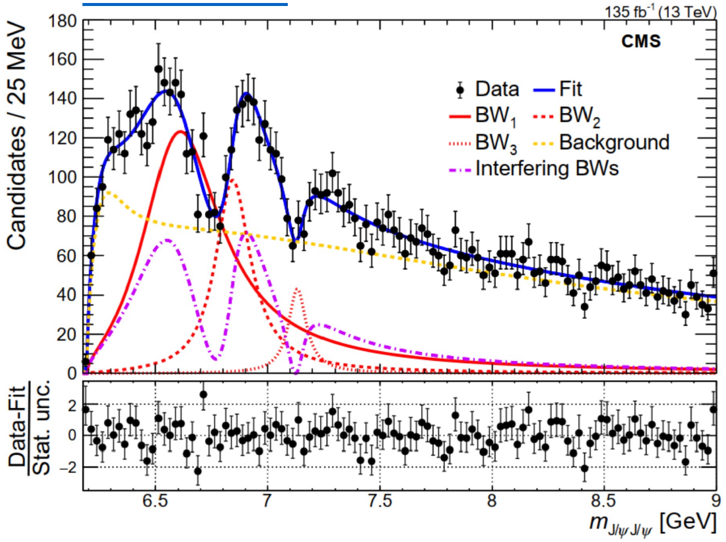


- **Mass shape from MC is not perfect → use analytic mass shape!**

  $$\boldsymbol{pdf_i(m_X, D_{0^-}) = pdf_i(m_X) * T_i(D_{0^-}|m_X)}$$

  $pdf(m_X)$: analytic function

  $T(D_{0^-}|m_X)$: conditional template, normalized on D_{0^-}

  $$T(D_{0^-}|m_X) = \frac{T(m_X, D_{0^-})}{\int_{D_{0^-}} T(m_X, D_{0^-})}$$

  $T(m_X, D_{0^-})$: 2D template from MC simulation by JHUGen for $m_X - D_{0^-}$ correlation

- **Final 2D fit model:** $\boldsymbol{pdf(m_X, D_{0^-})} =$

  $$N_{NRSPS} * pdf_{NRSPS}(m_X, D_{0^-})$$
  $$+N_{DPS} * pdf_{DPS}(m_X, D_{0^-})$$
  $$+N_{BW0} * pdf_{BW0}(m_X, D_{0^-})$$
  $$+N_{(interf-BW1BW2BW3)} * [f_{0^+} * pdf_{0^+(interf-BW1BW2BW3)}(m_X, D_{0^-})$$
  $$+(1 - f_{0^+}) * pdf_{0^-(interf-BW1BW2BW3)}(m_X, D_{0^-})]$$

f_{0^+}: fraction of 0^+ signal component

- **Perform pseudo-experiments**
  - ✓ Validate the fit package
  - ✓ Test the expected sensitivity of the fit model over the toy dataset

Summary

❑ **Develop the spin-parity framework**

✓ Create discriminants to separate different spin parities

✓ Construct 2D interference fit model

❑ **Checks on the framework are done**

✓ Validate the fit package

- fit is unbiased, and the uncertainties are appropriately estimated

✓ Evaluate the sensitivity

- achieves a separation between $J^P = 0^+$ and $J^P = 0^-$ with a significance of >> 5σ

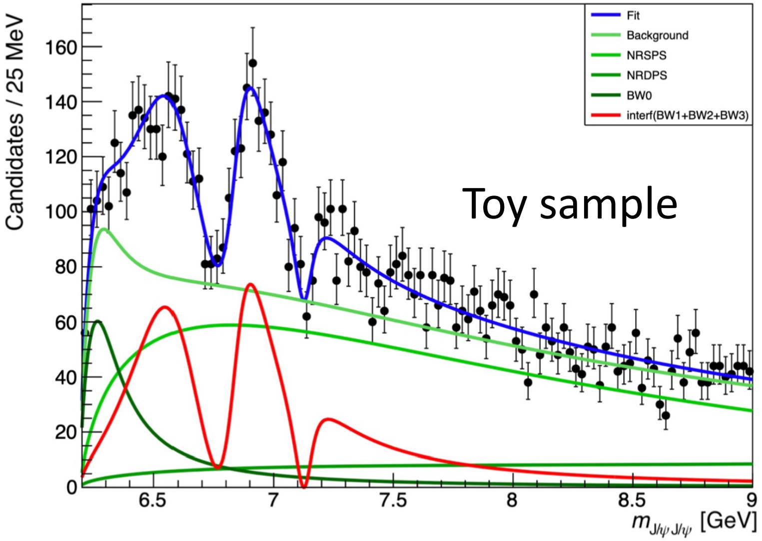
THANKS!

Fit validation

Perform pseudo-experiments to validate the fit package

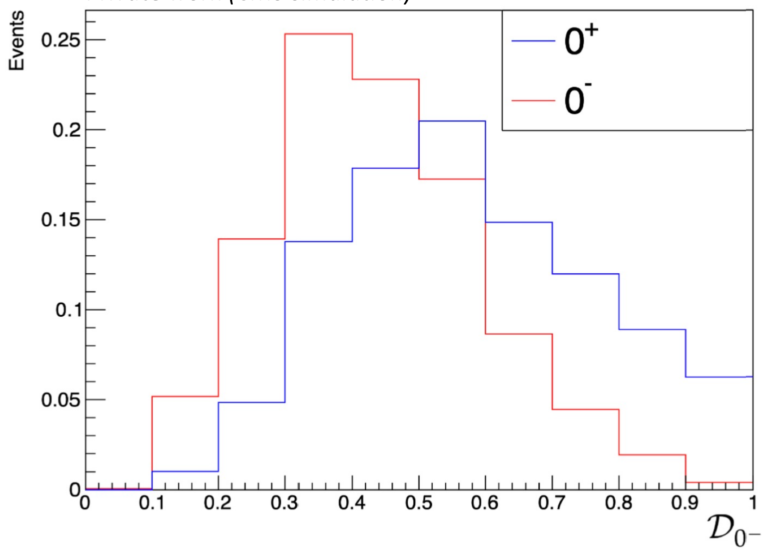
- Generate toy samples from the final 2D model
- The yield of each component is determined by the fit to the J/ψ J/ψ mass spectrum in data
- True value of f_{0^+} is 0.5: 50% 0^+ signal + 50% 0^- signal
- Perform unbinned likelihood fit to each toy sample (only float f_{0^+})

A fit projection of mass

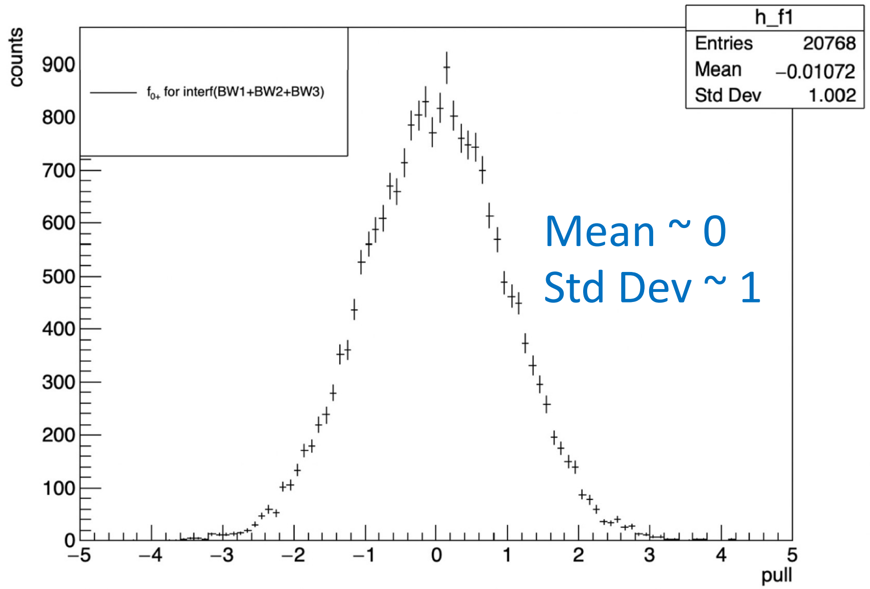


Projection of $T(D_{0^-}|m_X)$ on D_{0^-}

Private work (CMS simulation)



The pull distribution of f_{0^+}

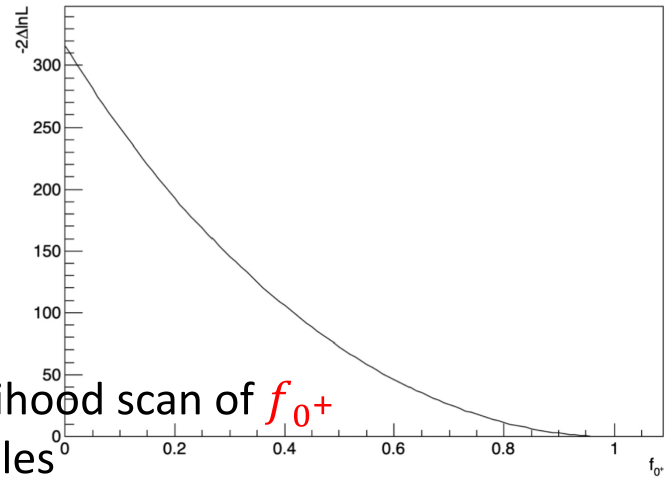


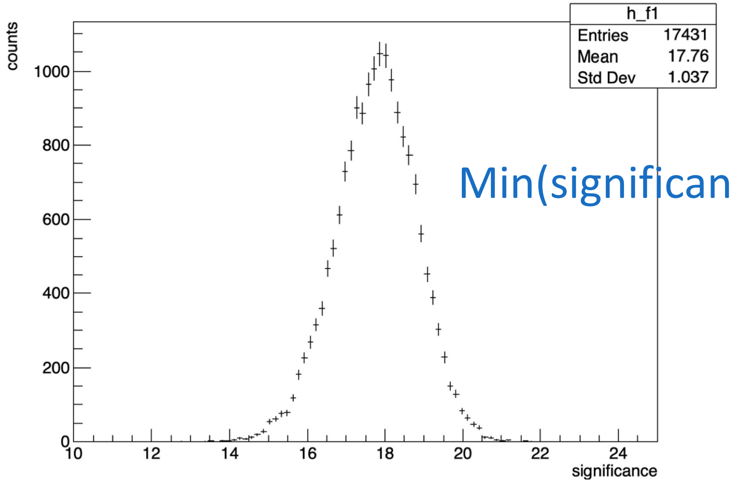
Expected separation 0^+ vs 0^-

Perform pseudo-experiments to test the expected sensitivity of the fit model over the toy dataset

- The yield of each component is determined by the fit to the J/ψ J/ψ mass spectrum in data
- True value of f_{0^+} is set to 0 and 1, separately
- calculate the significance of the separation between $J^P = 0^+$ and $J^P = 0^-$

True value of f_{0^+} is set to 1

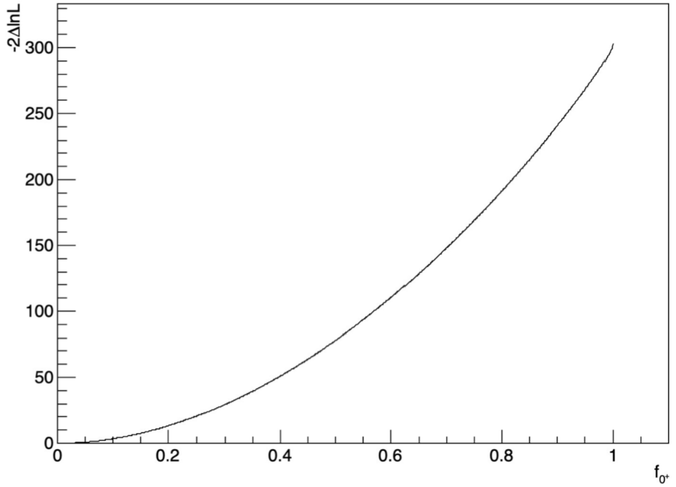


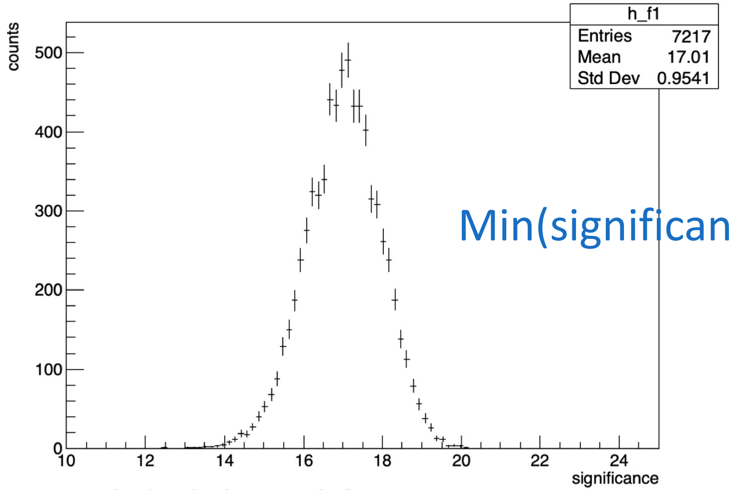


Min(significance) > 12σ >> 5σ

The average likelihood scan of f_{0^+} over all toy samples

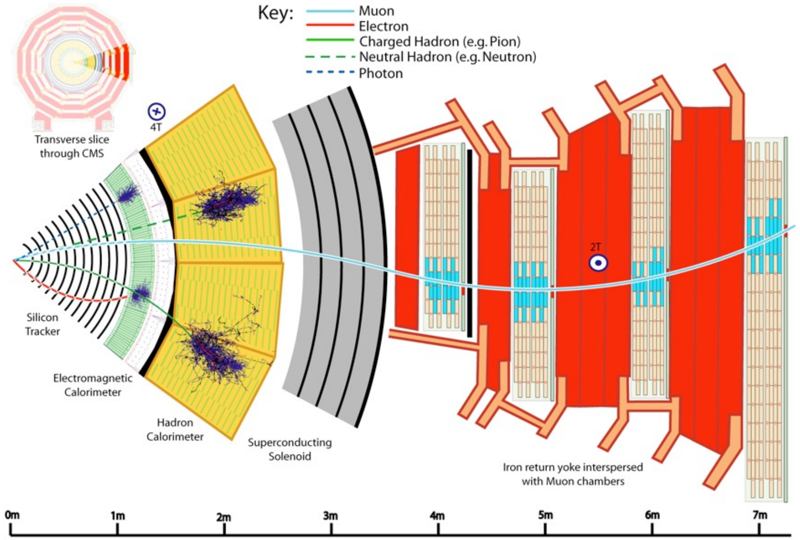
True value of f_{0^+} is set to 0



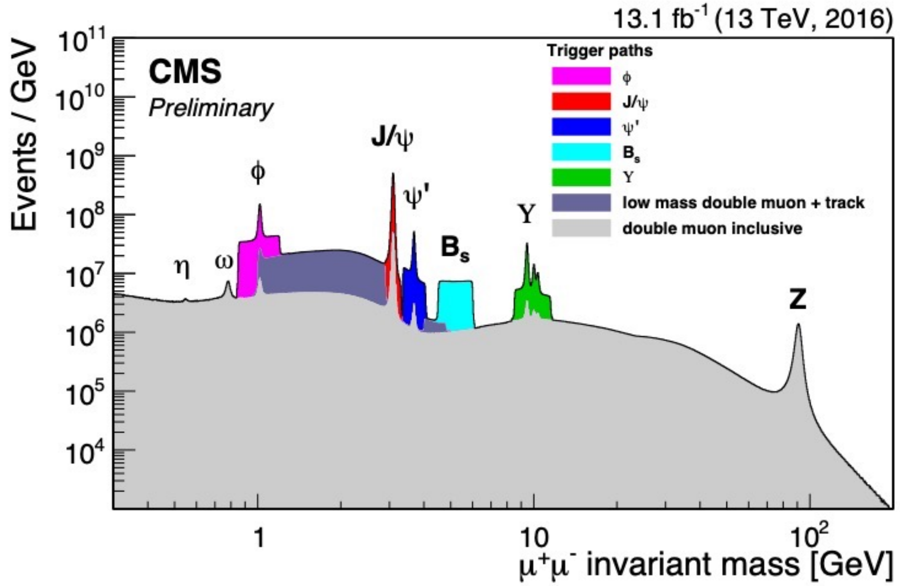


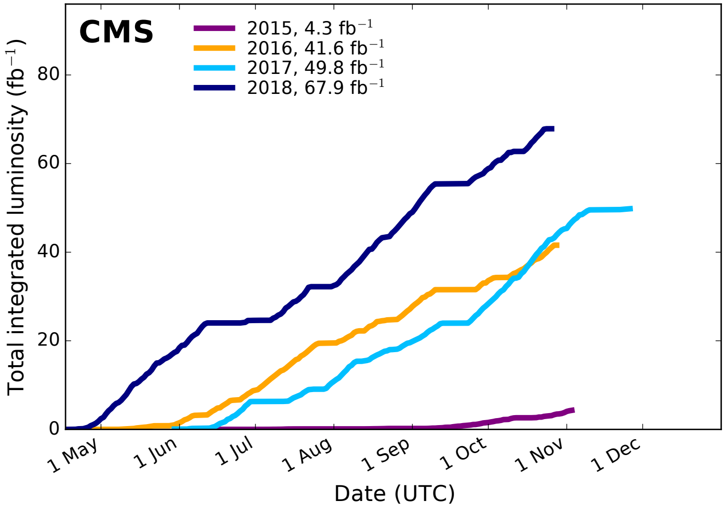
Min(significance) > 12σ >> 5σ

Backup



η coverage (track & muon): [-2.5,2.5]



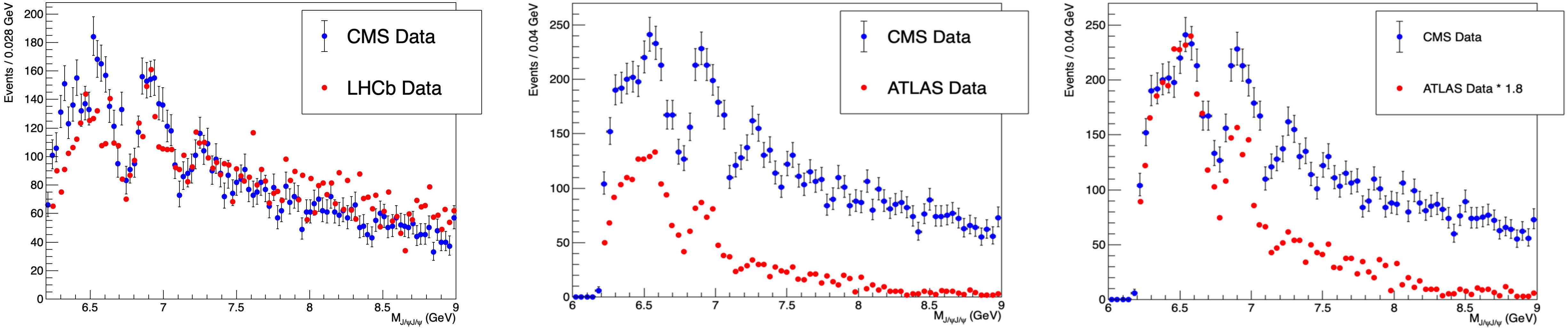


2016+2017+2018: ~145 fb^{-1}

Excellent detector for (exotic) quarkonium:

- Muon system
  High-purity muon ID, $\Delta m/m \sim 0.6\%$ for J/ψ
- Silicon Tracking detector, B=3.8T
  $\Delta p_T/p_T \sim 1\%$ & excellent vertex resolution
- Special triggers for different analysis at increasing Inst. Lumi.
  μ p_T, $(\mu\mu)$ p_T, $(\mu\mu)$ mass, $(\mu\mu)$ vertex, and additional μ

Backup



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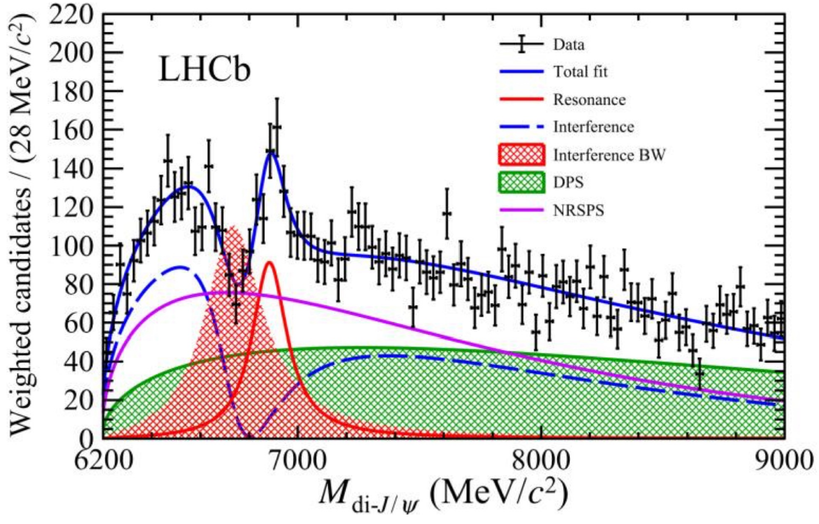
- **CMS vs LHCb comparisons:**
  - 135/9 ≈ 15X (int. lum.)
  - $(5/3)^4$ ≈ 8X (muon acceptance)
  - Higher muon p_T (>3.5 or 2.0 GeV vs >0.6 GeV)
  - Similar number of final events, but much less DPS
  - 2X yield @CMS for X(6900)
- **CMS vs ATLAS comparisons:**
  - ATLAS is 1/3 –1/2 of CMS data (trigger?)
  - ATLAS used dR cut—remove high mass events
  - CMS has slightly better resolution

- **CMS has good sensitivity to all-muon final state in this mass region**

Backup



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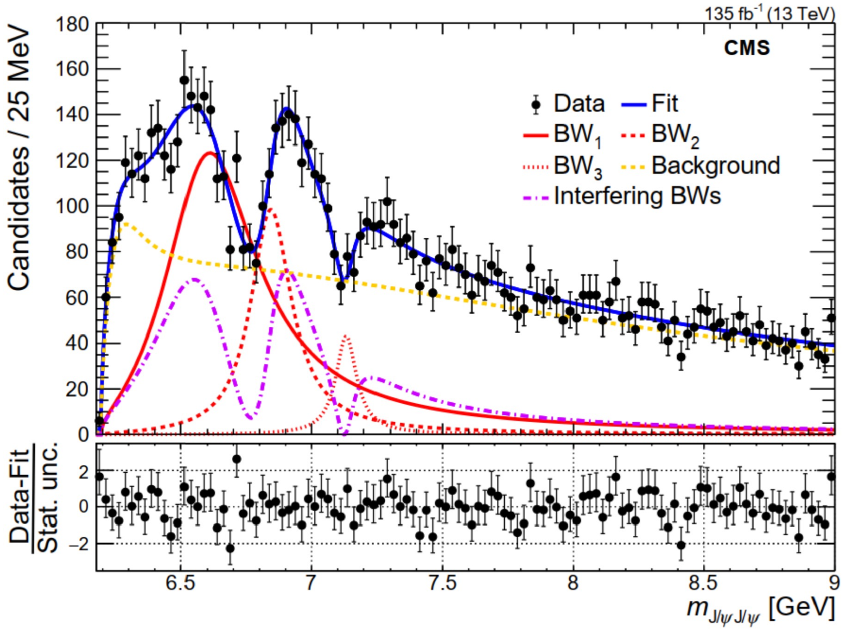

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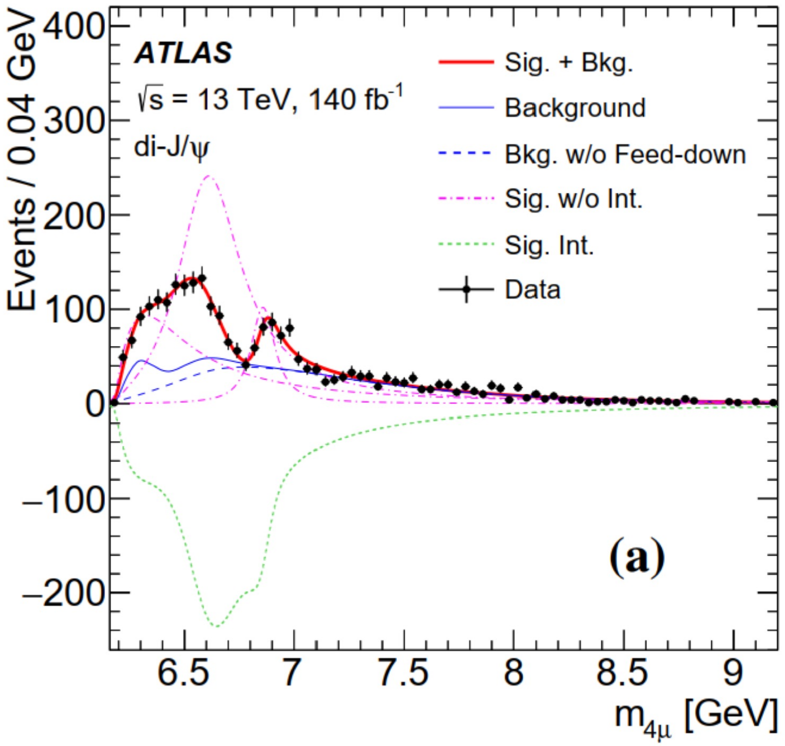


[Phys. Rev. Lett. 131 (2023) 151902]

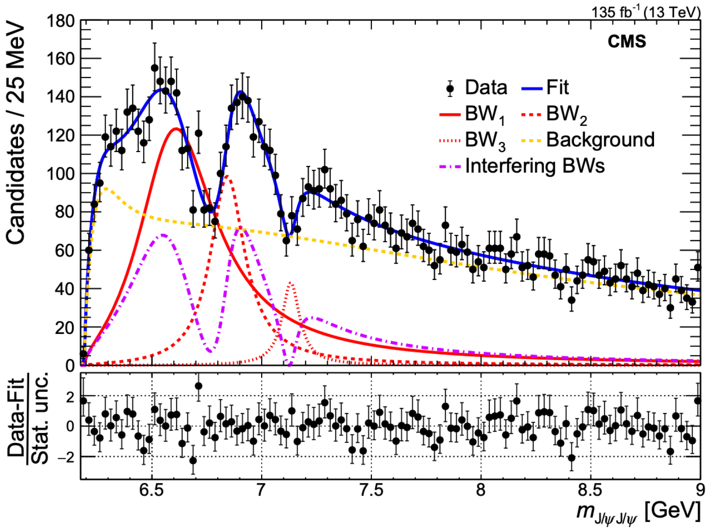
			X(6900)	X(6600)	X(7100)
LHCb		m [MeV]	$6886 \pm 11 \pm 11$		
		Γ [MeV]	$168 \pm 33 \pm 69$		
CMS		m [MeV]	6847^{+44+48}_{-28-20}	6638^{+43+16}_{-38-31}	7134^{+48+41}_{-25-15}
		Γ [MeV]	191^{+66+25}_{-49-17}	$440^{+230+110}_{-200-240}$	97^{+40+29}_{-29-26}
ATLAS	Model A	m [MeV]	$6860 \pm 30^{+10}_{-20}$		
		Γ [MeV]	$110 \pm 50^{+20}_{-10}$		
	Model B	m [MeV]	$6910 \pm 10 \pm 10$		
		Γ [MeV]	$150 \pm 30 \pm 10$		

Spin-parity analysis

- Develop the framework
  - MC modeling $gg(q\bar{q}) \to X \to J/\psi\, J/\psi \to 4\mu$ with different J^P
  - MELA developed to create optimal observable (discriminant) to separate pairs of hypotheses
  - Construct two dimensional template with mass(X) and discriminant
  - 2D template fit to data

➢ As the first stage:

- Work on interference
- Assume BW_1, BW_2, BW_3 have the same J^P
- Focus on $0^+, 0^-$



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$$pdf_m(m) = N_{BW_0} \cdot |BW_0|^2 \otimes R(M_0) + N_{NRSPS} \cdot pdf_{NRSPS} + N_{DPS} \cdot pdf_{DPS}$$
$$+|r_1 \cdot \exp(i\phi_1) \cdot BW_1 + BW_2 + r_3 \cdot \exp(i\phi_3) \cdot BW_3|^2$$

Monte Carlo modeling

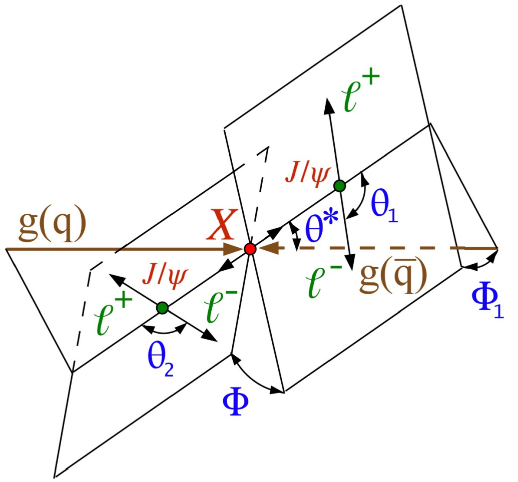
Pythia8: **NRSPS**—Non-Resonant Single Parton Scattering

$$gg(99\%) \rightarrow J/\psi J/\psi \rightarrow \mu^+\mu^-\mu^+\mu^-$$

DPS—Non-Resonant Double Parton Scattering

JHUGen: generate $gg(q\bar{q}) \rightarrow X \rightarrow J/\psi\, J/\psi \rightarrow 4\mu$

with different J^P : $0^+, 0^-, 1^+, 1^-, 2^+, 2^-$

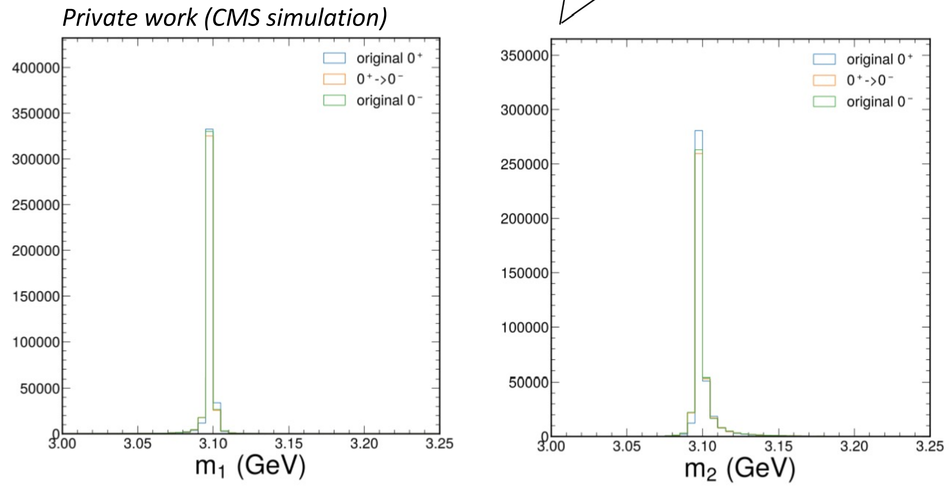


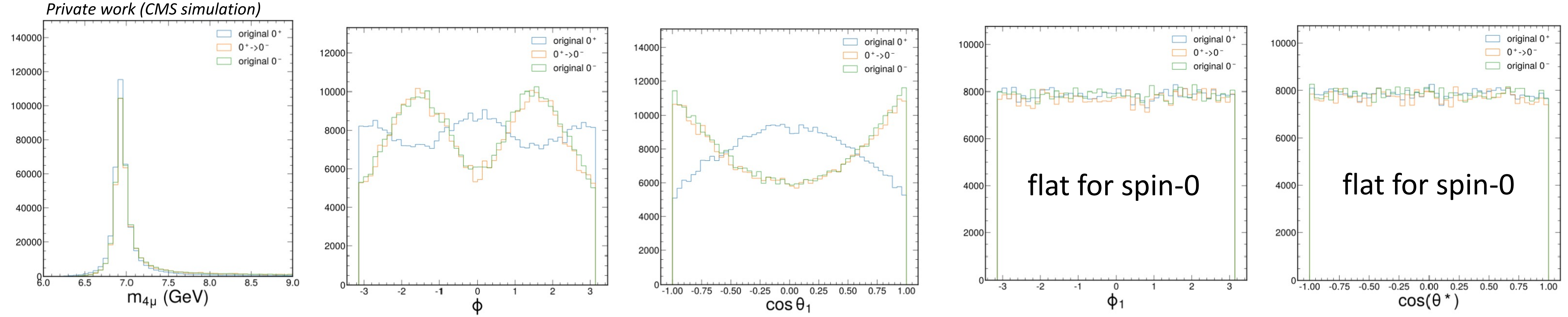
First focus on $J^P = 0^+$ vs. $J^P = 0^-$

$$A(X \rightarrow VV) = v^{-1}\left(g_1^{(0)} m_V^2 \epsilon_1^* \epsilon_2^* + g_2^{(0)} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + g_4^{(0)} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}\right)$$

$J^P = 0^+$ $\quad 0_h^+ \quad$ $J^P = 0^-$

MELA can re-weight $J^P = 0^+$ to $J^P = 0^-$ to increase statistic



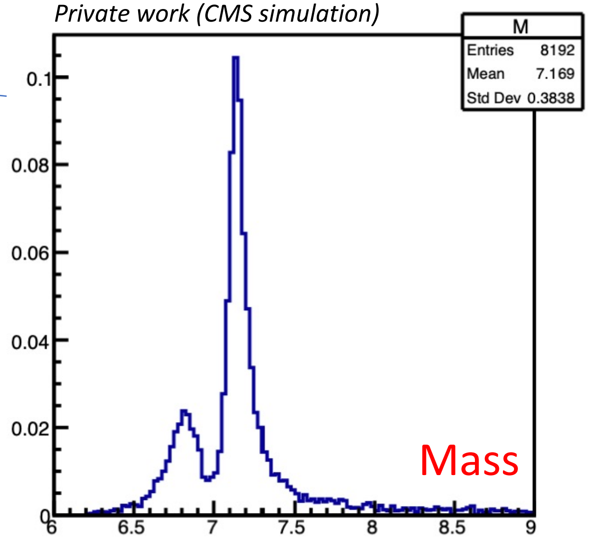


Modeling of Interference

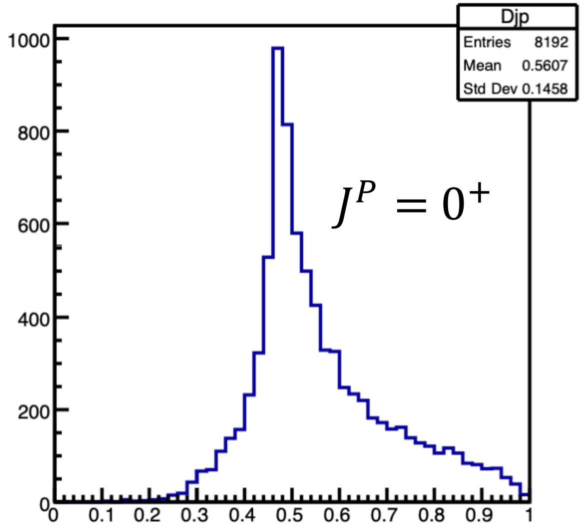
- Generation is based on JHUGen+MCFM
  - Interference of any pairs of resonances
  - Based on modeling of off-shell Higgs + new resonance
  - Mohit and Jeff did custom work to adjust to $X + Y \rightarrow \psi\psi \rightarrow 4f$

$$\left|r_1 A_1 e^{i\varphi_1} + r_2 A_2 + r_3 A_3 e^{i\varphi_3}\right|^2 =$$
$$r_1{}^2 \times |A_1|^2 + r_2{}^2 \times |A_2|^2 + r_3{}^2 \times |A_3|^2$$
$$+ r_1 r_2 \cos\varphi_1 \times Re(2A_1A_2^*) + r_1 r_2 sin\varphi_1 \times Im(-2A_1A_2^*)$$
$$+ r_2 r_3 \cos\varphi_3 \times Re(2A_2A_3^*) + r_2 r_3 sin\varphi_3 \times Im(2A_2A_3^*)$$
$$+ r_3 r_1 \cos(\varphi_3 - \varphi_1) \times Re(2A_3A_1^*) + r_3 r_1 sin(\varphi_3 - \varphi_1) \times Im(-2A_3A_1^*)$$

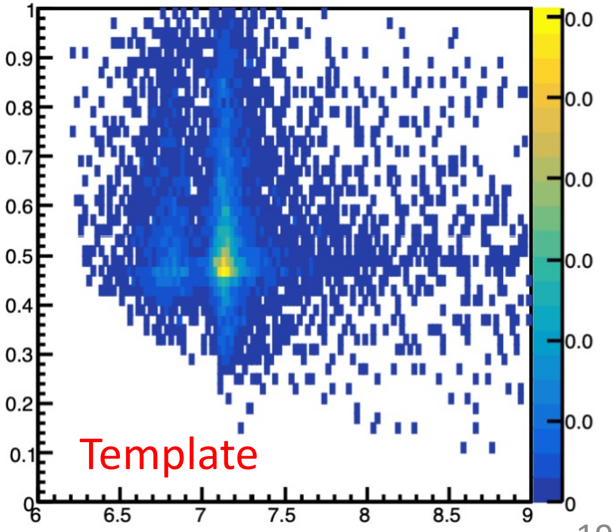
Interference of two BWs



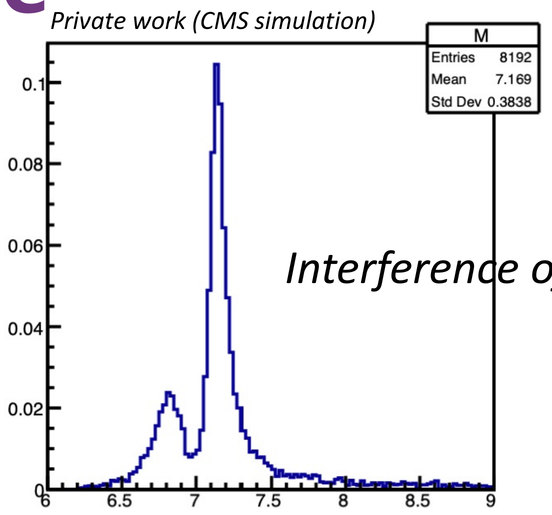
- Create templates
  - Pure terms: MC modeling directly
  - Interference terms?



Discriminant



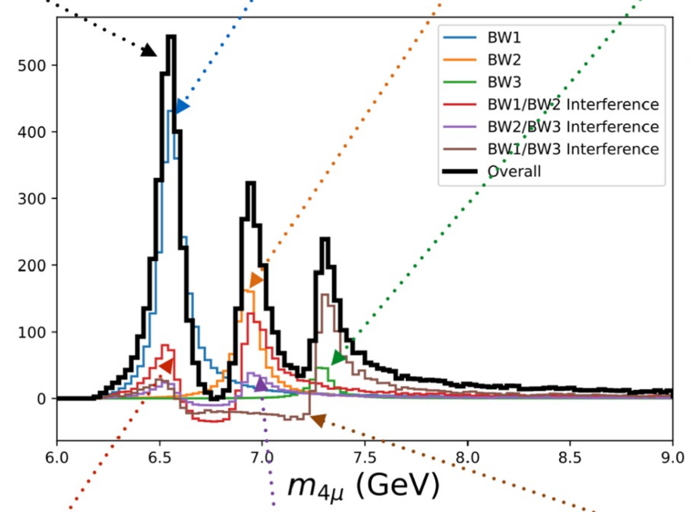
Modeling of Interference



Interference of two BWs

- ❑ Create templates
  - Interference of 2 BWs: $|\boldsymbol{A_1}+\boldsymbol{A_2}|^2 = |A_1|^2 + |A_2|^2 + Re(2A_1A_2^*)$
  - Subtract pure terms out to get interference term
  - Repeat for each pair with real/imaginary couplings
    - $Re(2A_1A_2^*) = |\boldsymbol{A_1}+\boldsymbol{A_2}|^2 - |A_1|^2 - |A_2|^2$
    - $Im(-2A_1A_2^*) = |\boldsymbol{A_1}e^{i\frac{\pi}{2}}+\boldsymbol{A_2}|^2 - |A_1|^2 - |A_2|^2$
    - ……
  - 9 templates (3 pure + 3 real + 3 imaginary)

$$|A+B+C|^2 = |A|^2 + |B|^2 + |C|^2$$



$X + Y \to \psi\psi \to 4f$

$J^P = 0^+$

here $\varphi_i = 0$

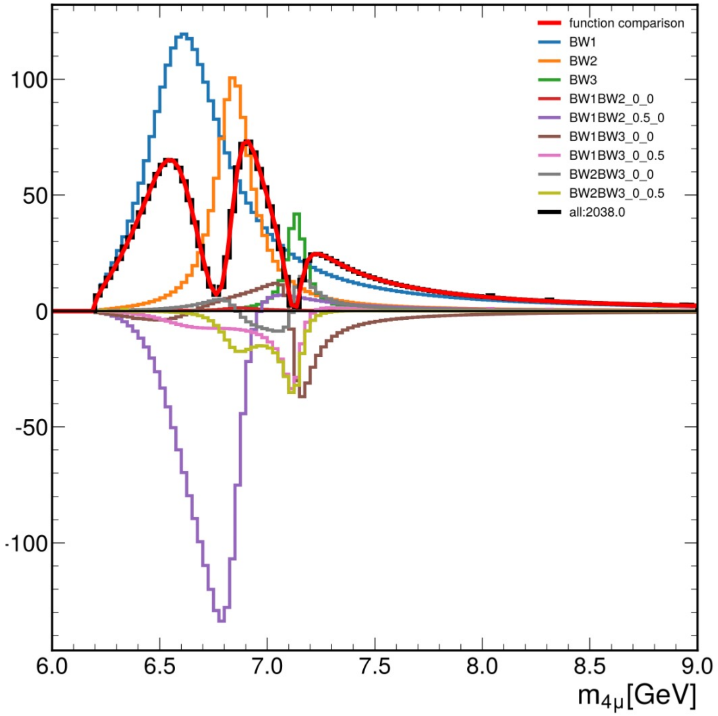
$$+2Re(AB^*) + 2Re(BC^*) + 2Re(CA^*)$$

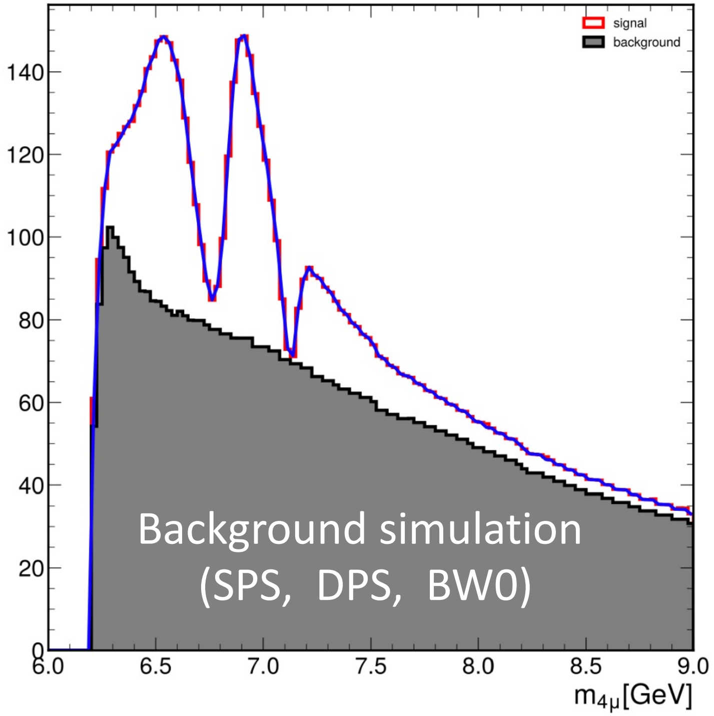
$$\left|r_1A_1e^{i\varphi_1} + r_2A_2 + r_3A_3e^{i\varphi_3}\right|^2 =$$
$$r_1^2\times|A_1|^2 + r_2^2\times|A_2|^2 + r_3^2\times|A_3|^2$$
$$+r_1r_2\cos\varphi_1\times Re(2A_1A_2^*) + r_1r_2 sin\varphi_1\times Im(-2A_1A_2^*)$$
$$+r_2r_3\cos\varphi_3\times Re(2A_2A_3^*) + r_2r_3 sin\varphi_3\times Im(2A_2A_3^*)$$
$$+r_3r_1\cos(\varphi_3-\varphi_1)\times Re(2A_3A_1^*) + r_3r_1 sin(\varphi_3-\varphi_1)\times Im(-2A_3A_1^*)$$

Fit parameters: $r_1, r_3, \varphi_1, \varphi_3$

Modeling of Interference

- JHUGen & MCFM package + weights: modeling of 9 contributions separately
- **Fit validation**: perform template fit to data (only one bin for discriminant)
- Consistent fit result with analytical fit to data



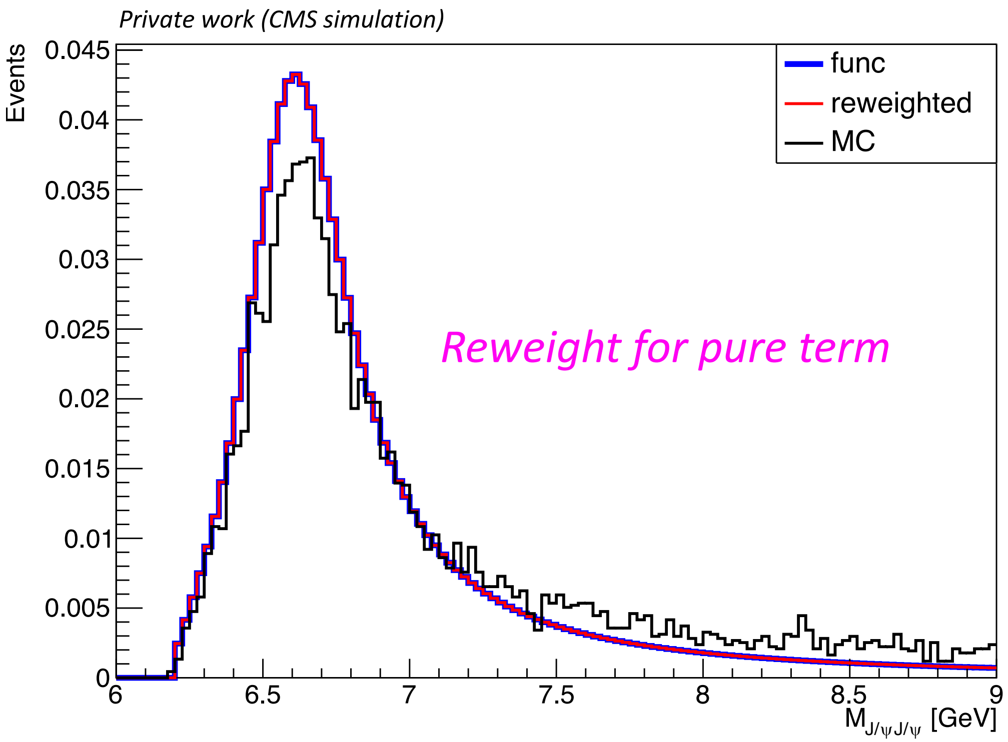


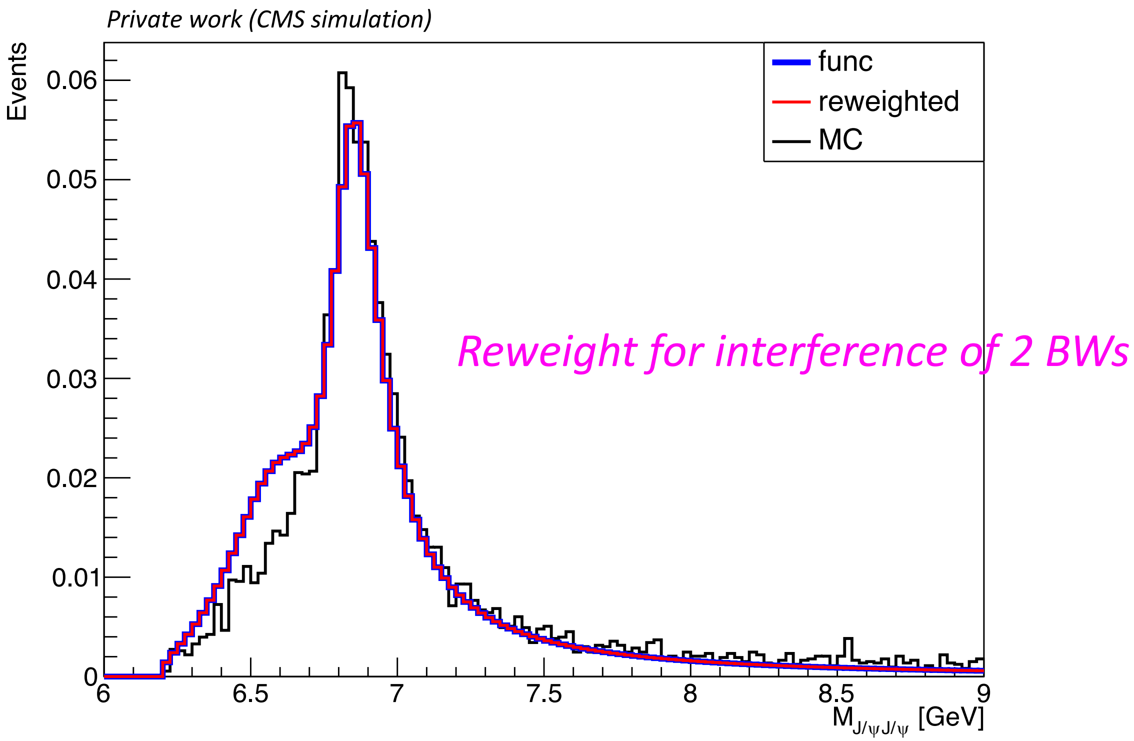
Consistent fit result

	1D template fit	Direct mass fit with roofit
r_1	$1.66^{+0.11}_{-0.11}$	$1.70^{+0.12}_{-0.10}$
ϕ_1	$1.57^{+0.11}_{-0.11}$	$1.56^{+0.11}_{-0.10}$
r_3	$0.46^{+0.19}_{-0.15}$	$0.53^{+0.14}_{-0.21}$
ϕ_3	$-0.94^{+0.18}_{-0.14}$	$-0.94^{+0.21}_{-0.11}$
N_{sig}	2021^{+82}_{-81}	2144^{+82}_{-81}

Monte Carlo: Re-weighting

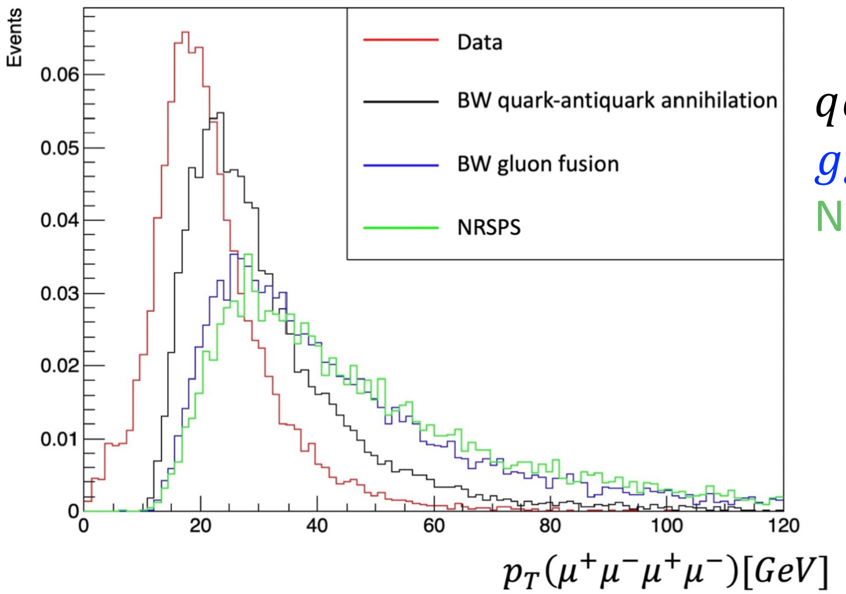
- Disagreement on mass distributions between MC and analytic functions from published paper
- Reweight mass distributions to match analytic functions
- Reweighting is not a necessary requirement. Templates can be made without reweighting





MC tuning

- Inconsistent kinematic distributions between data and MC samples



$q\bar{q} \to \mathrm{BW} \to J/\psi J/\psi \to \mu^+\mu^-\mu^+\mu^-$

$gg \to \mathrm{BW} \to J/\psi J/\psi \to \mu^+\mu^-\mu^+\mu^-$

NRSPS: $gg(99\%) \to J/\psi J/\psi \to \mu^+\mu^-\mu^+\mu^-$

} similar

- Discriminants are sensitive to p_T, angle, … distributions → sensitive to MC simulation
- MC tuning in Pythia8 to improve the agreement between MC and data
  - **NRSPS MC**:
    - ✓ *pTdampMatch=1, renormMultFac=10, pTmaxFudge=2*
  - **Signal MC**:
    - ✓ *pTmaxMatch=1, f.scale ∈ Uniform [5, 50]*

[Green light in Generator Meeting on Oct 16]

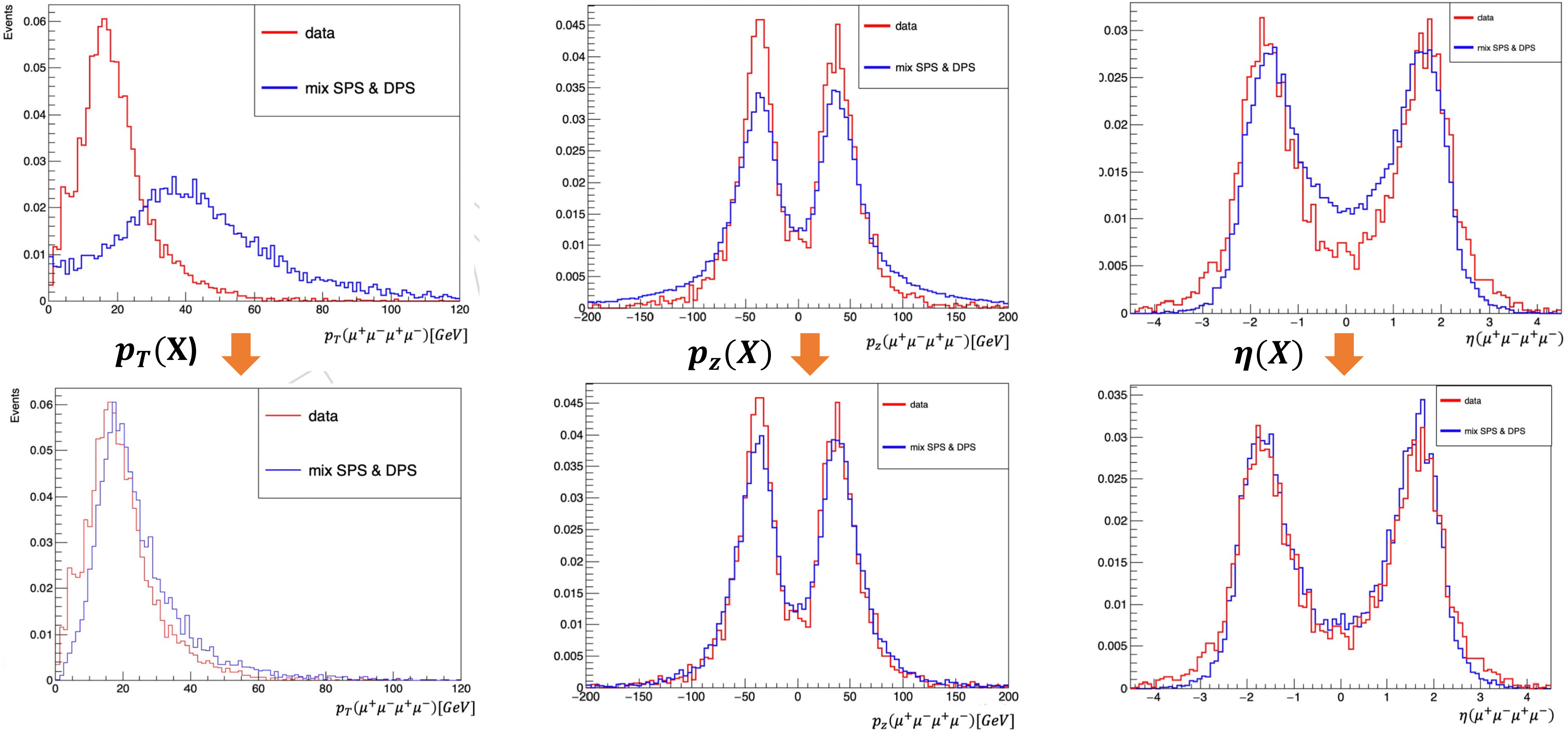
[report in P&P meeting on Nov 15]

➢ Perform **sideband** consistency study

…… Let's compare in the sideband region ……

Sideband consistency study

- Sideband region: M(X) ∈ [9, 15] GeV
- Mixing NRSPS and DPS: yield of is determined by the fit to the J/ψ J/ψ mass spectrum in data
- Improved agreement of kinematic distributions

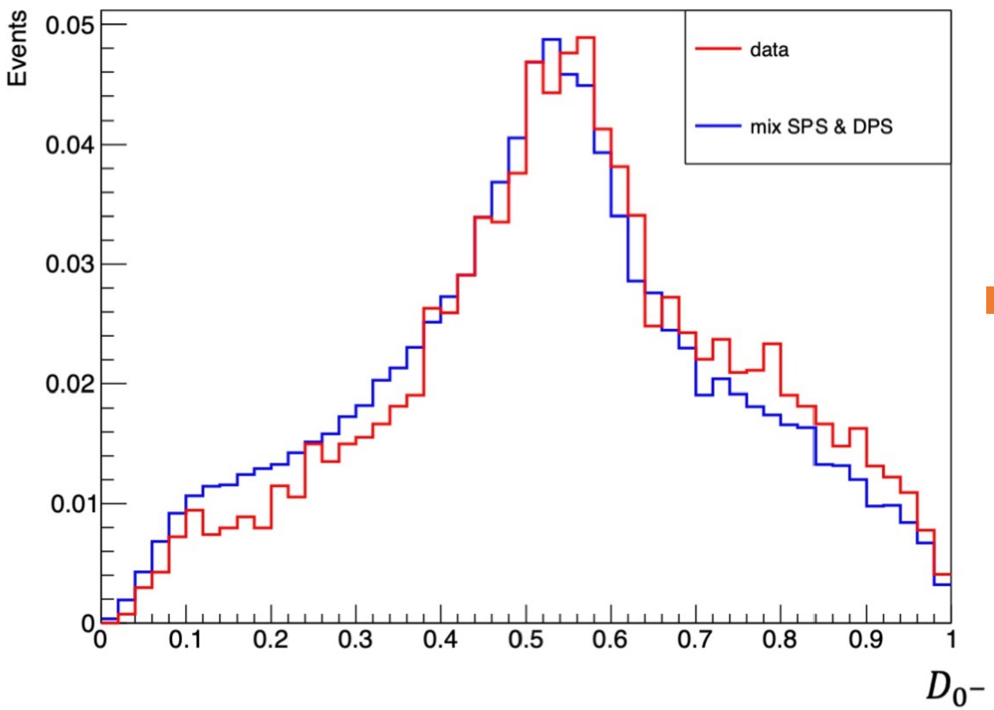


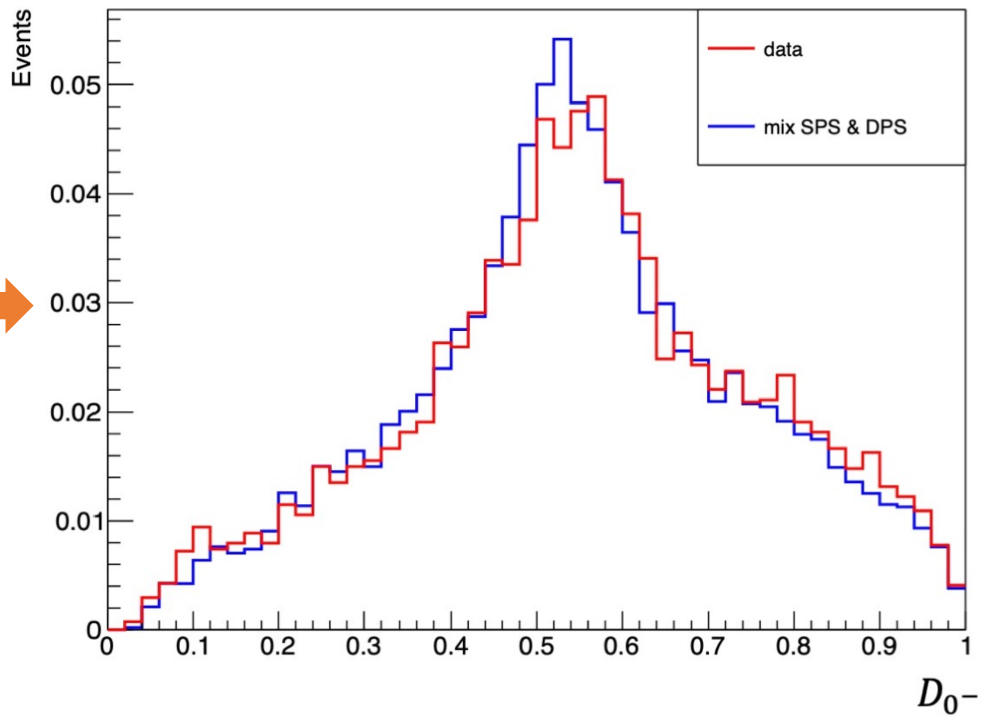
Sideband consistency study

Improved agreement of the discriminant D_{0^-} between tuned MC and data

Discriminant to distinguish between 0+ and 0-:

$$D_{0^-}(m_X, \vec{\Omega}) = \frac{P_{0^-}(m_X, \vec{\Omega})}{P_{0^+}(m_X, \vec{\Omega}) + c_{0^-} \times P_{0^-}(m_X, \vec{\Omega})}$$





Fit model

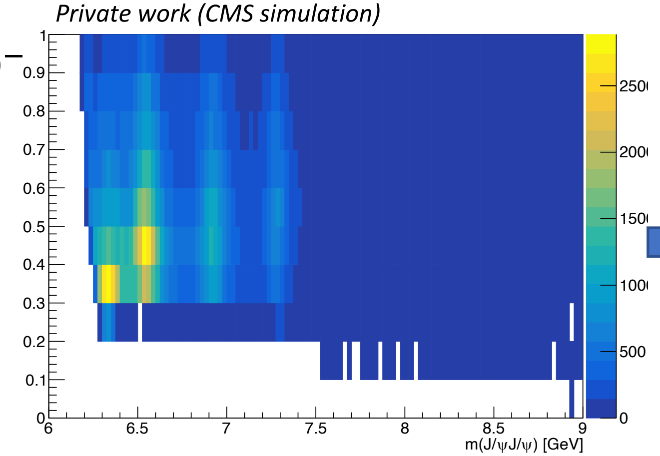
$$|r_1 \exp(i\phi_1)\, BW_1 + BW_2 + r_3 \exp(i\phi_3)\, BW_3|^2$$

$$pdf_i(m_X) * T_i(D_{0^-}|m_X)$$

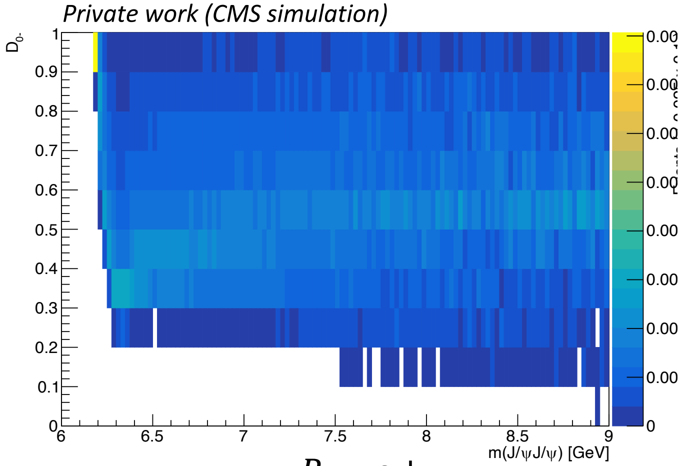
$T(m_X, D_{0^-})$ from MC simulation

$$T(D_{0^-}|m_X) = \frac{T(m_X, D_{0^-})}{\int_{D_{0^-}} T(m_X, D_{0^-})}$$

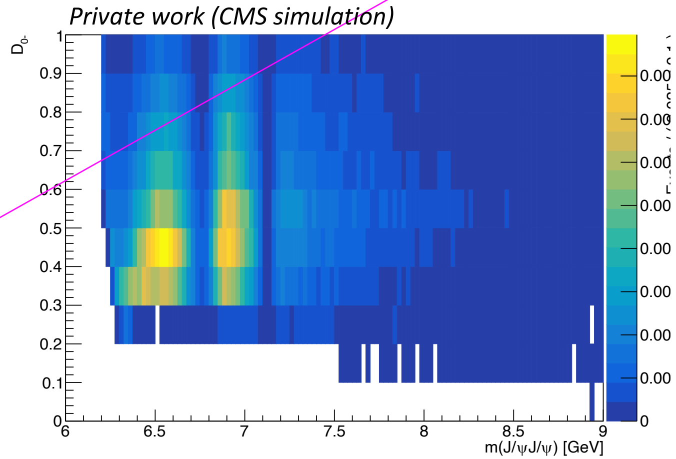
D_{0^-}



$J^P = 0^+$ m_X

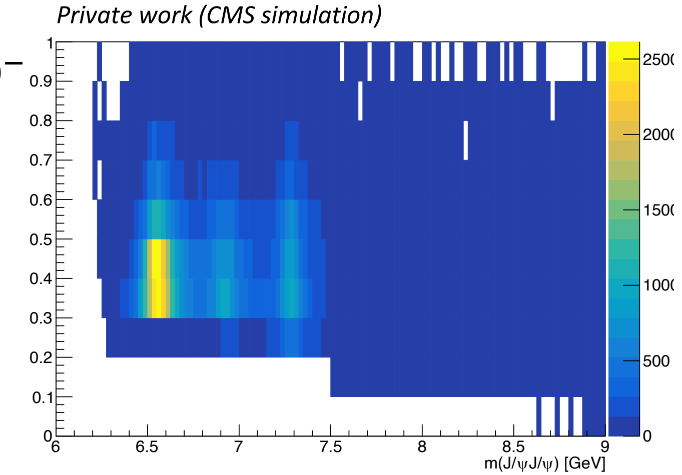


$J^P = 0^+$

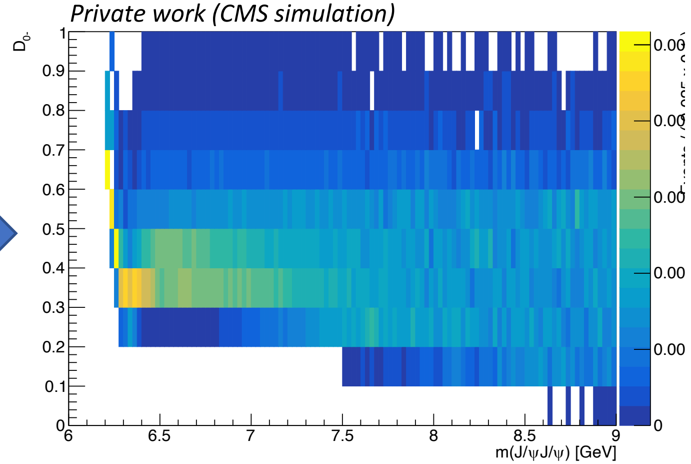


$J^P = 0^+$

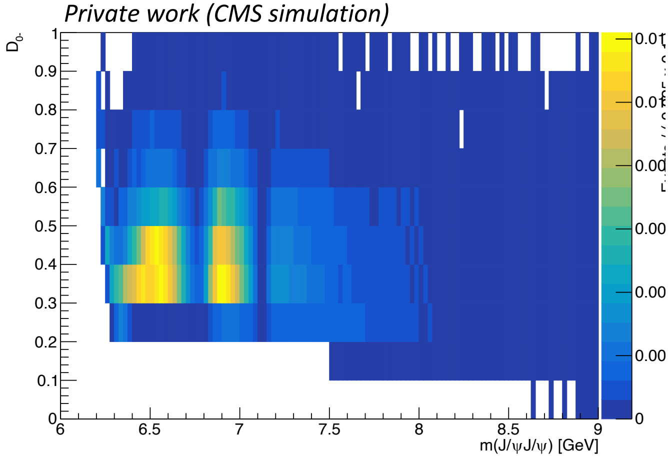
D_{0^-}



$J^P = 0^-$ m_X



$J^P = 0^-$



$J^P = 0^-$