Search for $X(3872)$ in B meson decays at CMS

Workshop : *The hunt for exotics multi-quarks*

Chiara Basile

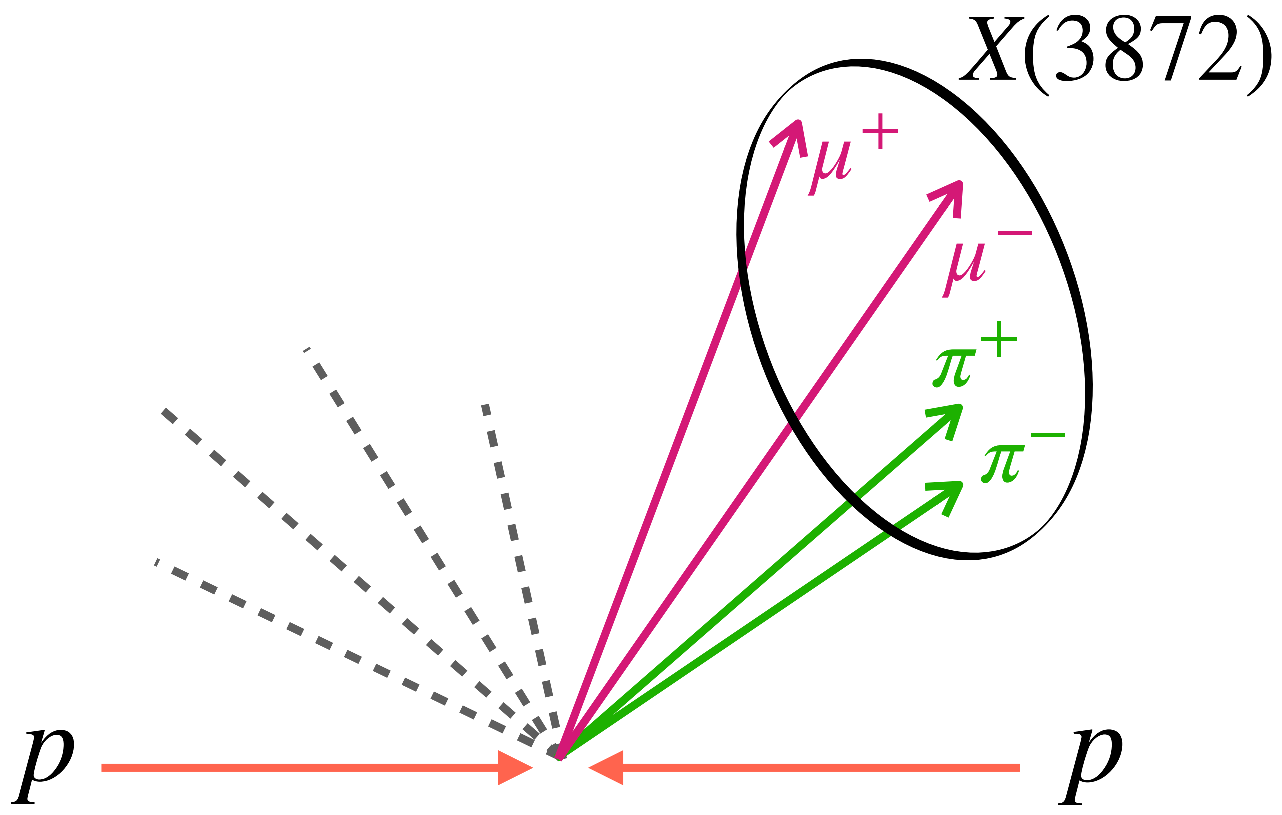
Rome, 7/11/2022

X(3872) production @ CMS

RUN 1 ($L = 4.8$ **fb**$^{-1}$)

➜ prompt production

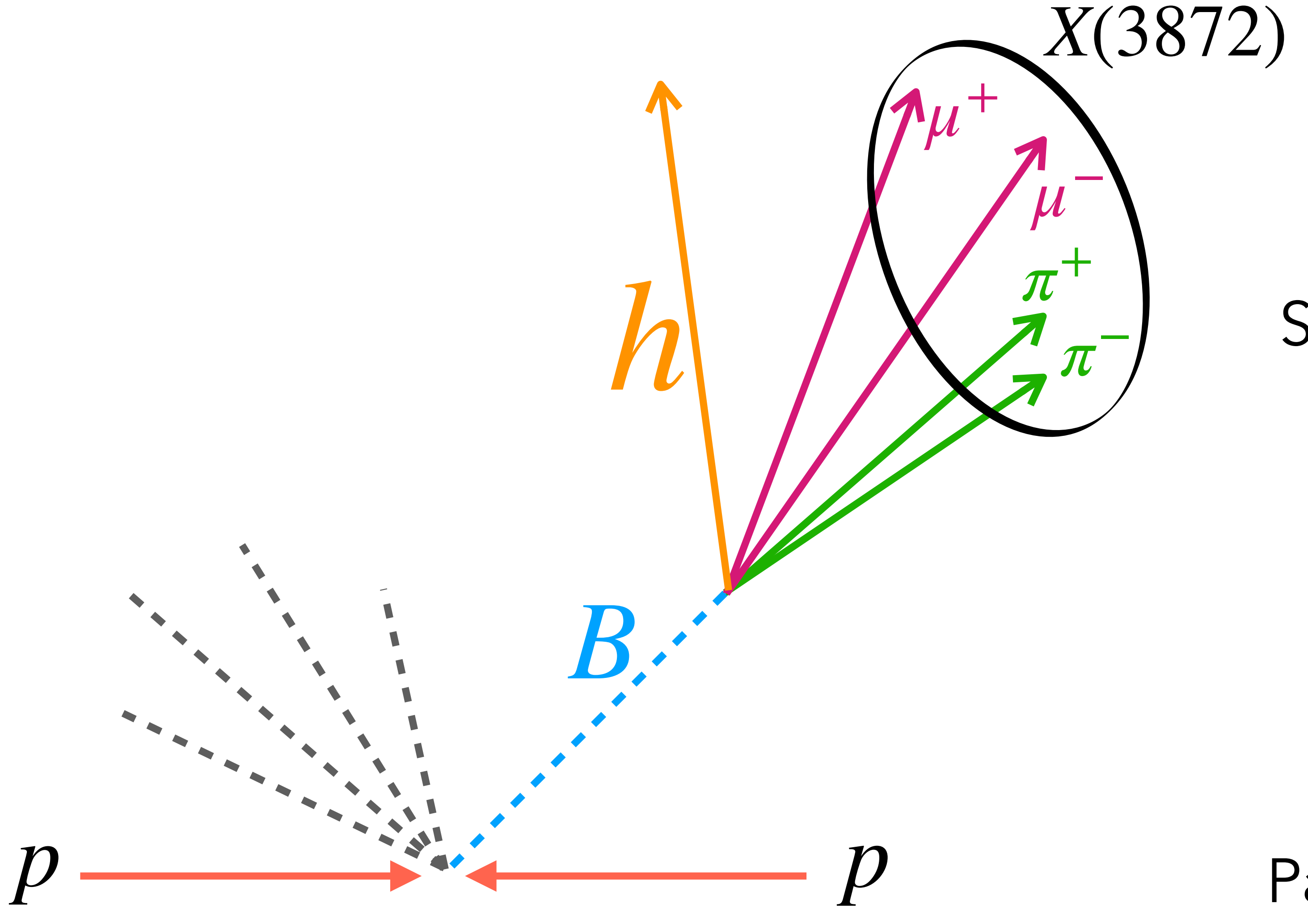
JHEP 04 (2013) 154



RUN 2 ($L = 140$ **fb**$^{-1}$)

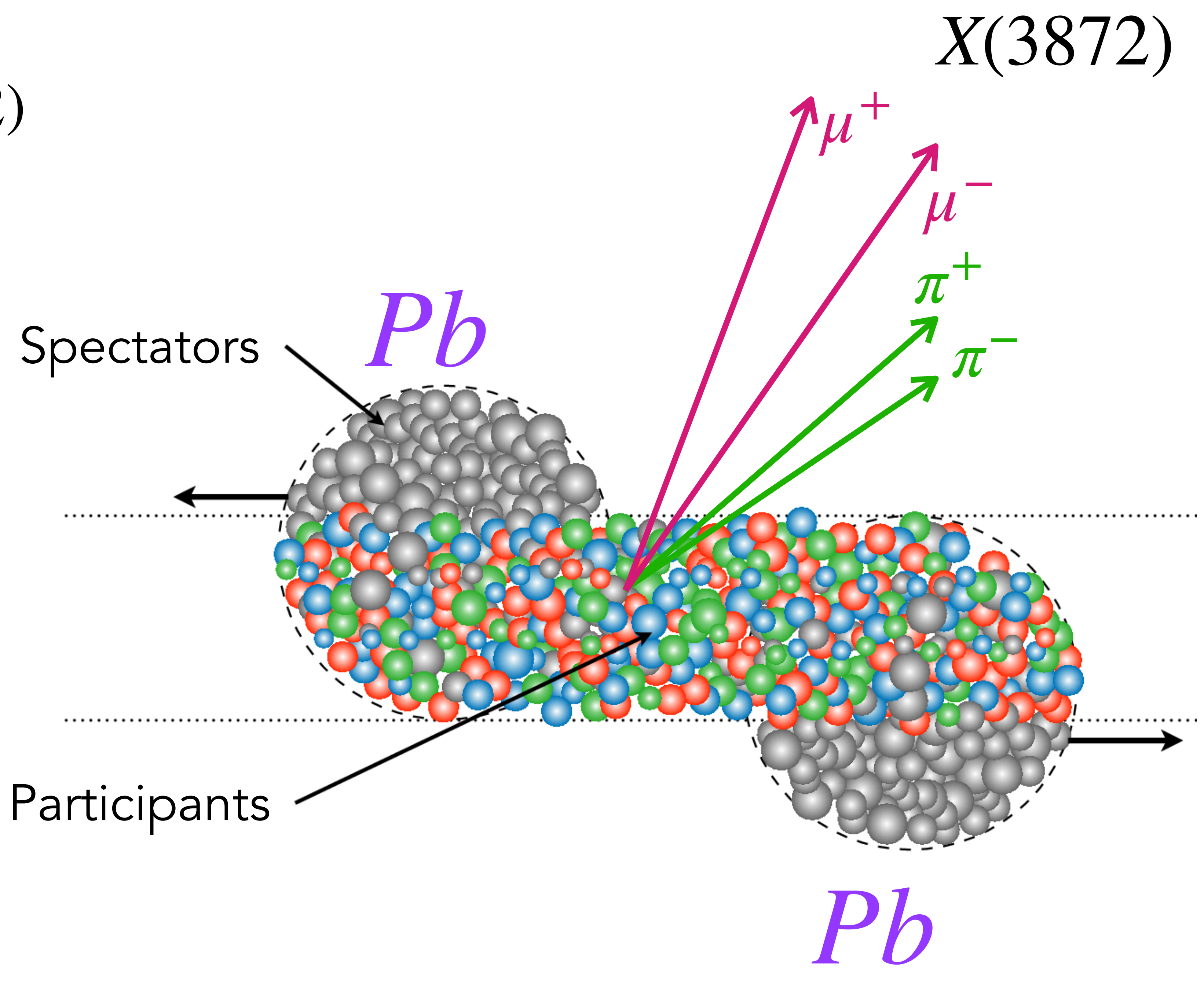
➜ non-prompt production in association with light meson

➜ $Pb - Pb$ collisions



$B_s^0 \to X(3872)\phi$

10.1103/PhysRevLett.125.152001



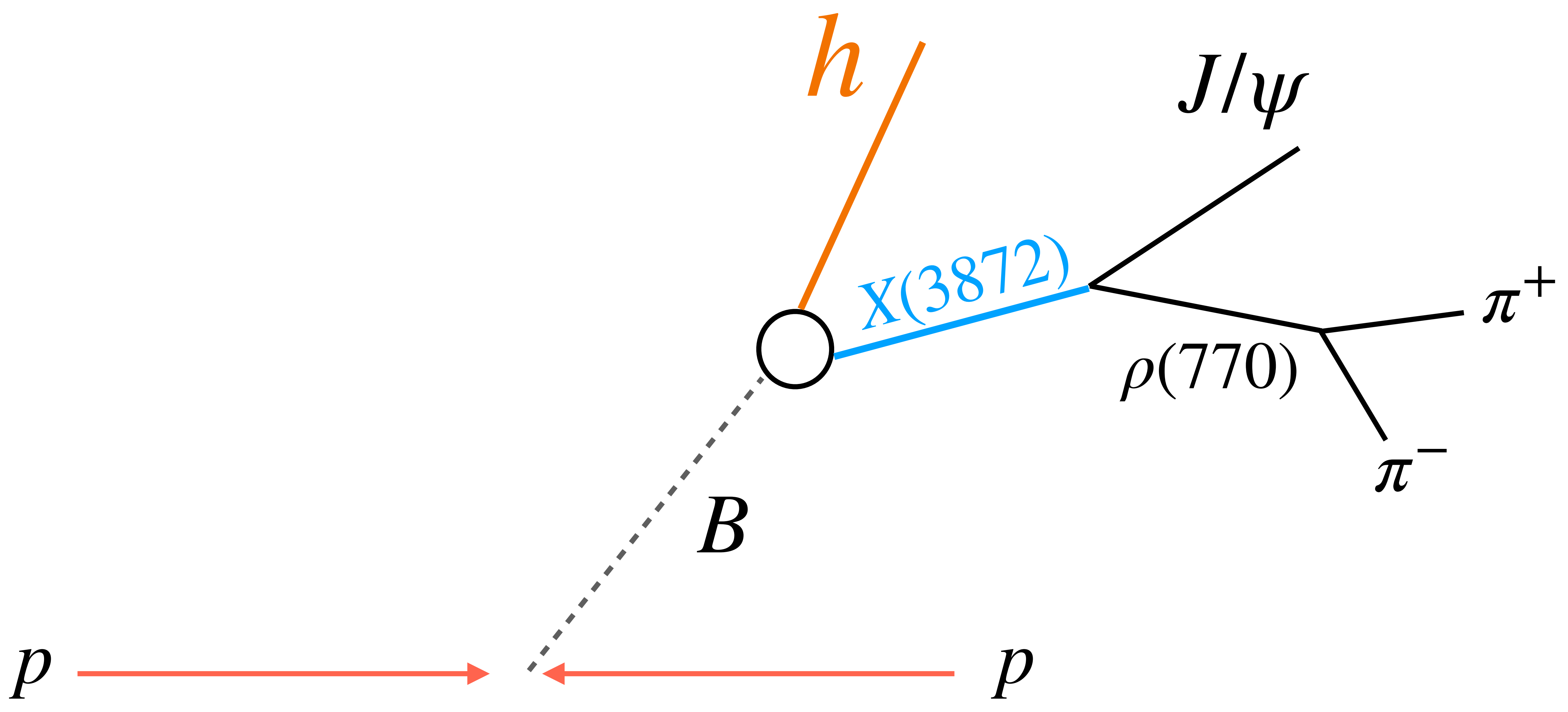
PhysRevLett.128.032001

Non-prompt production

- Study B **mesons decays** in $X(3872)$ + a light hadron (h) for different B mesons and h

- **Measure** precisely and **compare** the branching fractions

  ➜ extract information on $X(3872)$ production mechanism and internal structure



GOAL

$$Br[B \to X(3872)\ h] \cdot Br[X(3872) \to J/\Psi\pi^+\pi^-]$$

STRATEGY

$$R = \frac{Br[B \to X(3872)\ h] \cdot Br[X(3872) \to J/\Psi\pi^+\pi^-]}{Br[B \to \Psi(2S)\ h] \cdot Br[\Psi(2S) \to J/\Psi\pi^+\pi^-]}$$

$$R = \frac{N_{B\to X(3872)\ h}}{\varepsilon_{B\to X(3872)\ h} \cdot \sigma \cdot L} \cdot \frac{\varepsilon_{B\to\Psi(2S)\ h} \cdot \sigma \cdot L}{N_{B\to\Psi(2S)\ h}}$$

Majority of systematic uncertainties cancel out!

$M_{X(3872)} - M_{\psi(2S)} \simeq 185$ MeV

Search $B_s^0 \to X(3872)\ \phi$

10.1103/PhysRevLett.125.152001

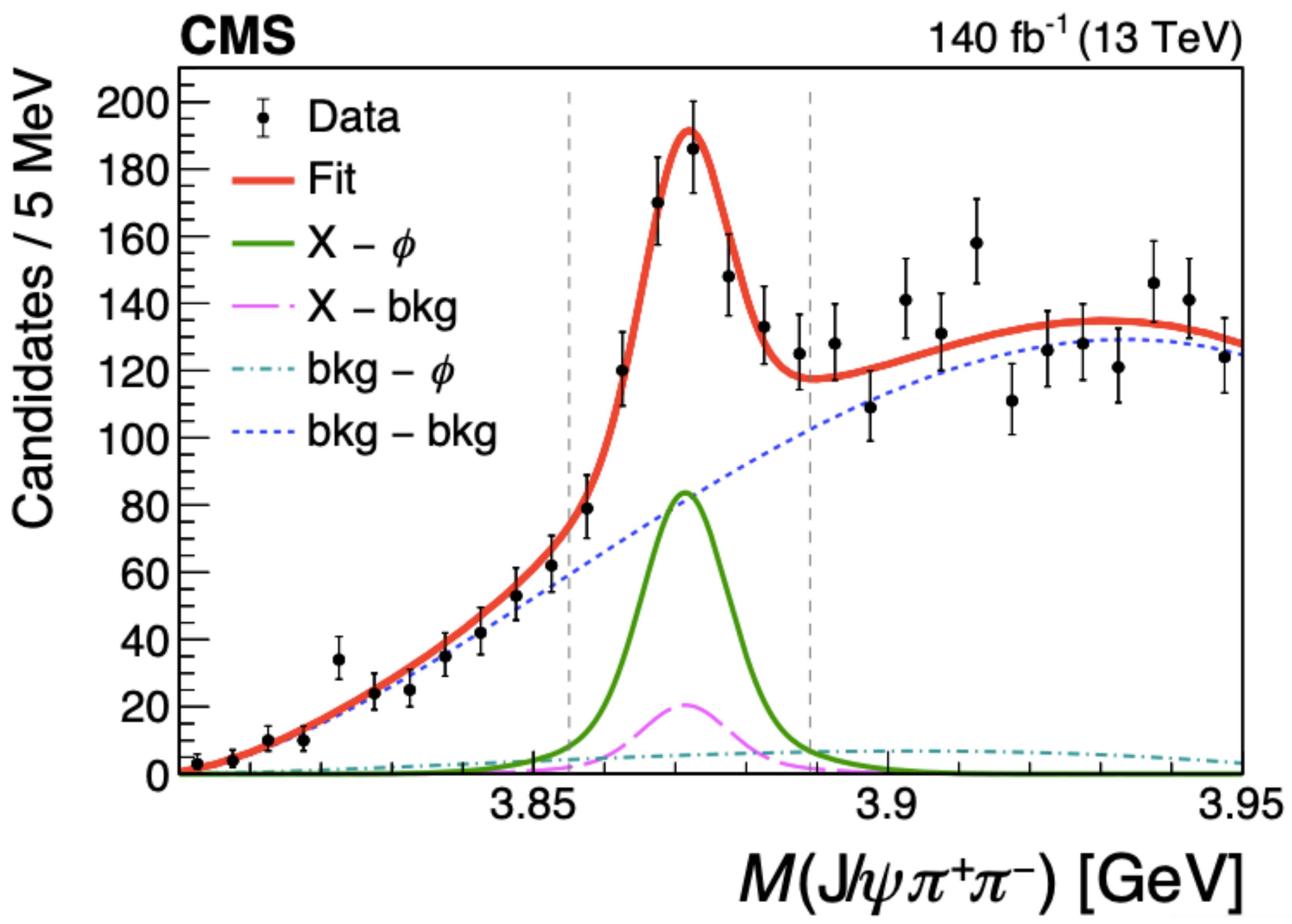
RUN-2: pp collision at $\sqrt{s} = 13$ TeV; $\mathcal{L} = 140$ fb^{-1}

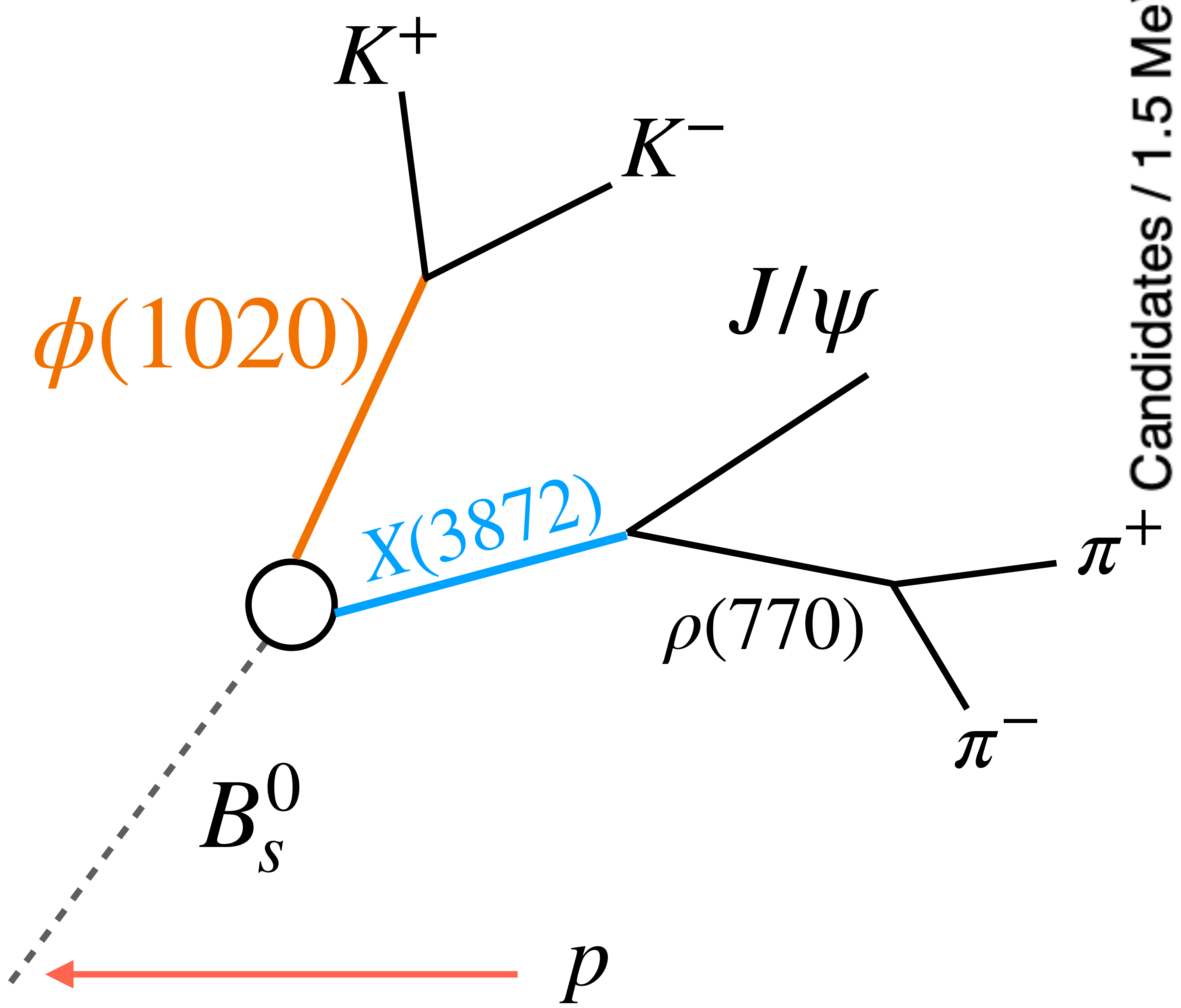
$$R = \frac{N_{B_s^0 \to X(3872)\ \phi}}{N_{B_s^0 \to \Psi(2S)\ \phi}} \cdot \frac{\varepsilon_{B_s^0 \to \Psi(2S)\ \phi}}{\varepsilon_{B_s^0 \to X(3872)\ \phi}} = \frac{299 \pm 39}{15359 \pm 171} \cdot 1.136 \pm 0.026$$

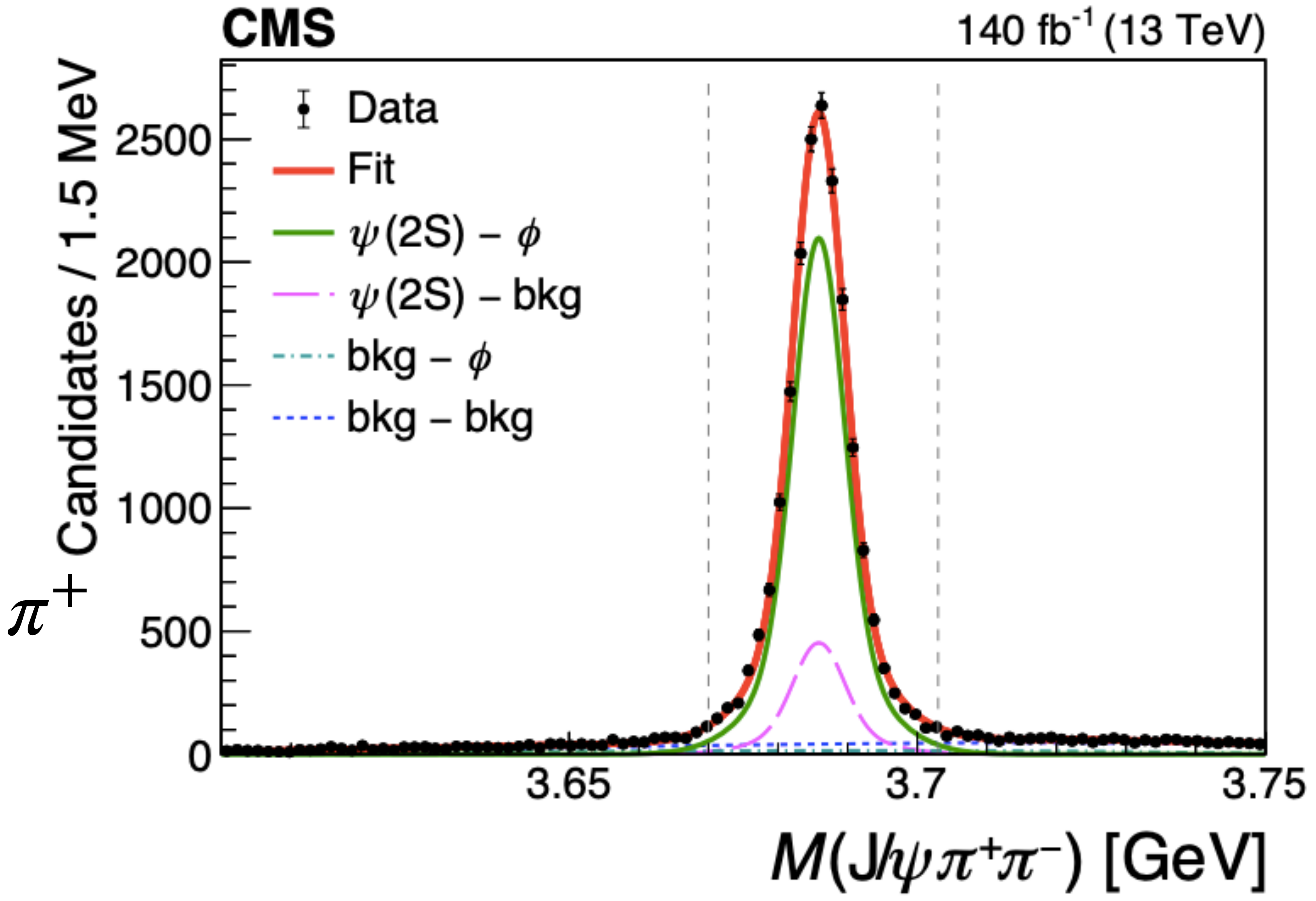
Signal channel $B_s^0 \to X(3872)\phi$

SAME SELECTION

Normalization channel $B_s^0 \to \psi(2S)\phi$







CMS results $B_s^0 \to X(3872)\ \phi$

10.1103/PhysRevLett.125.152001

$$Br[B_s^0 \to X(3872)\phi] \cdot Br[X(3872) \to J/\psi\pi^+\pi^-] = (4.14 \pm 0.54(stat) \pm 0.32(sys)) \times 10^{-6}$$

- strong **disagreement** with charmonium hypothesis
- possible **compatibility** with tetraquark structure

$$\frac{BR[B_s^0 \to X(3872)\phi]}{BR[B^+ \to X(3872)K^+]} \simeq \frac{1}{2} \neq \frac{BR[B_s^0 \to \psi(2S))\phi]}{BR[B^+ \to \psi(2S)K^+]} \simeq 1$$

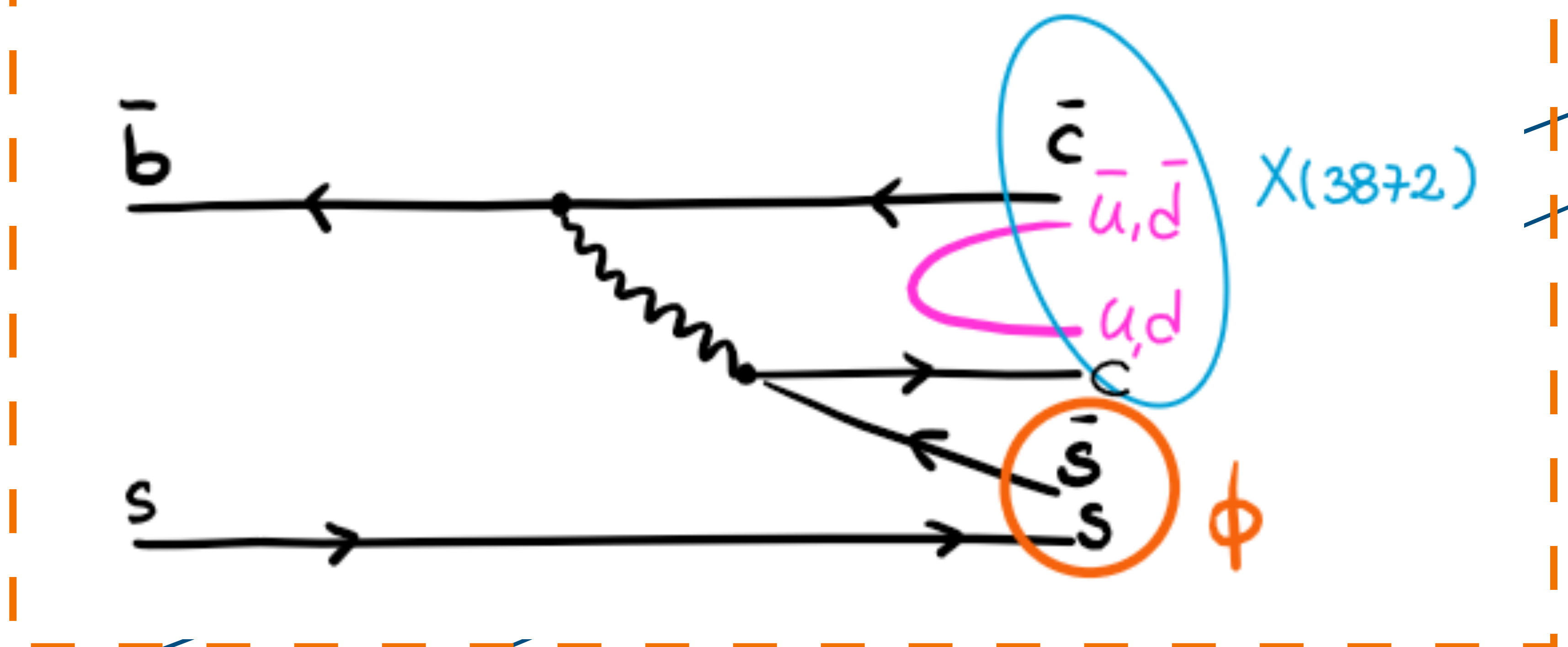
Phys. Rev. D 98, 030001 (2018)

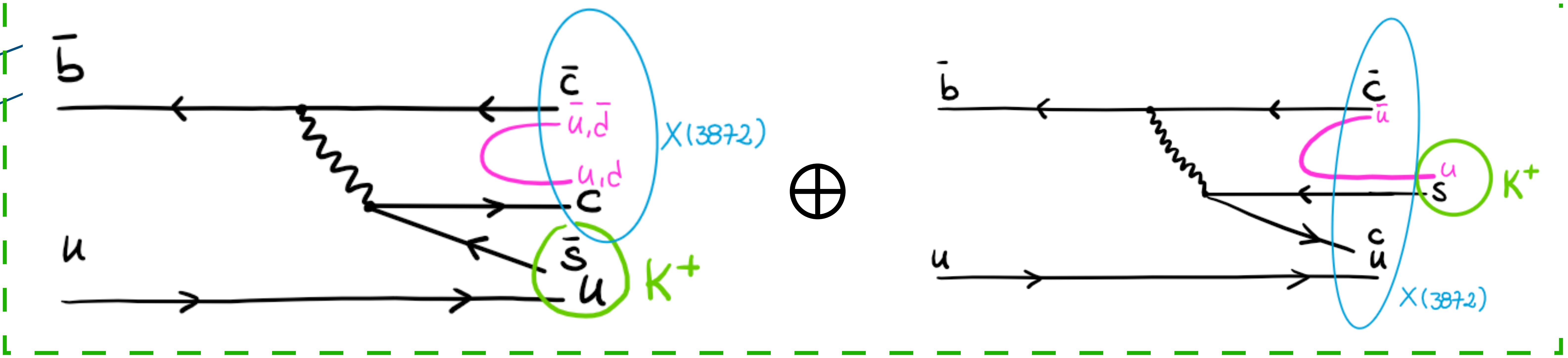
In the simplest **tetraquark formation-diagram**, the B^+ decay has additional contribution from spectators

PhysRevD.102.034017

$B_s^0 \to X(3872)\phi$

$B^+ \to X(3872)K^+$





WHAT'S NEXT? Precise measurement of other channels to tune the parameters of the model (i.e. $B^0 \to X(3872)K^0$)

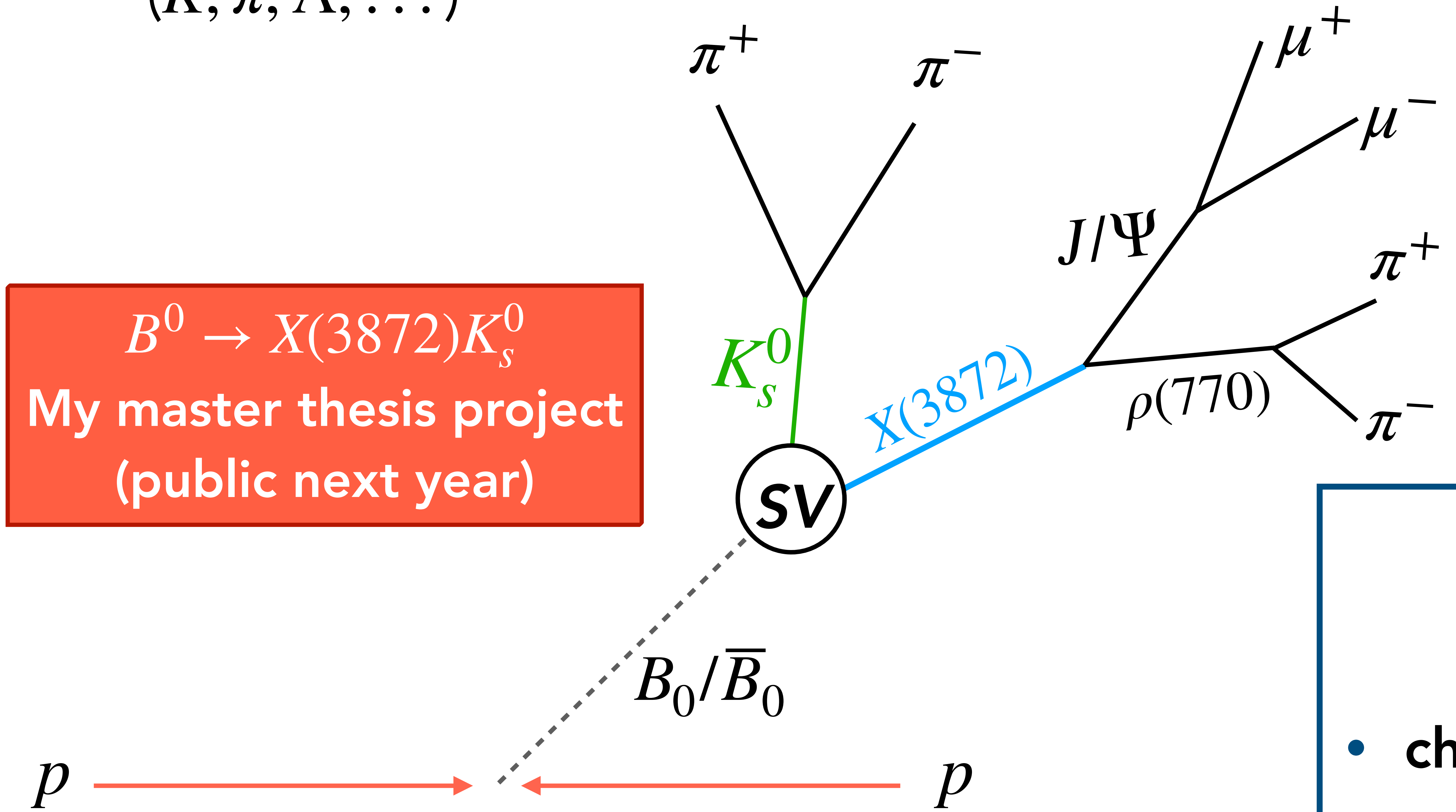
$B^0 \to X(3872)K_s^0$ @ CMS-Roma

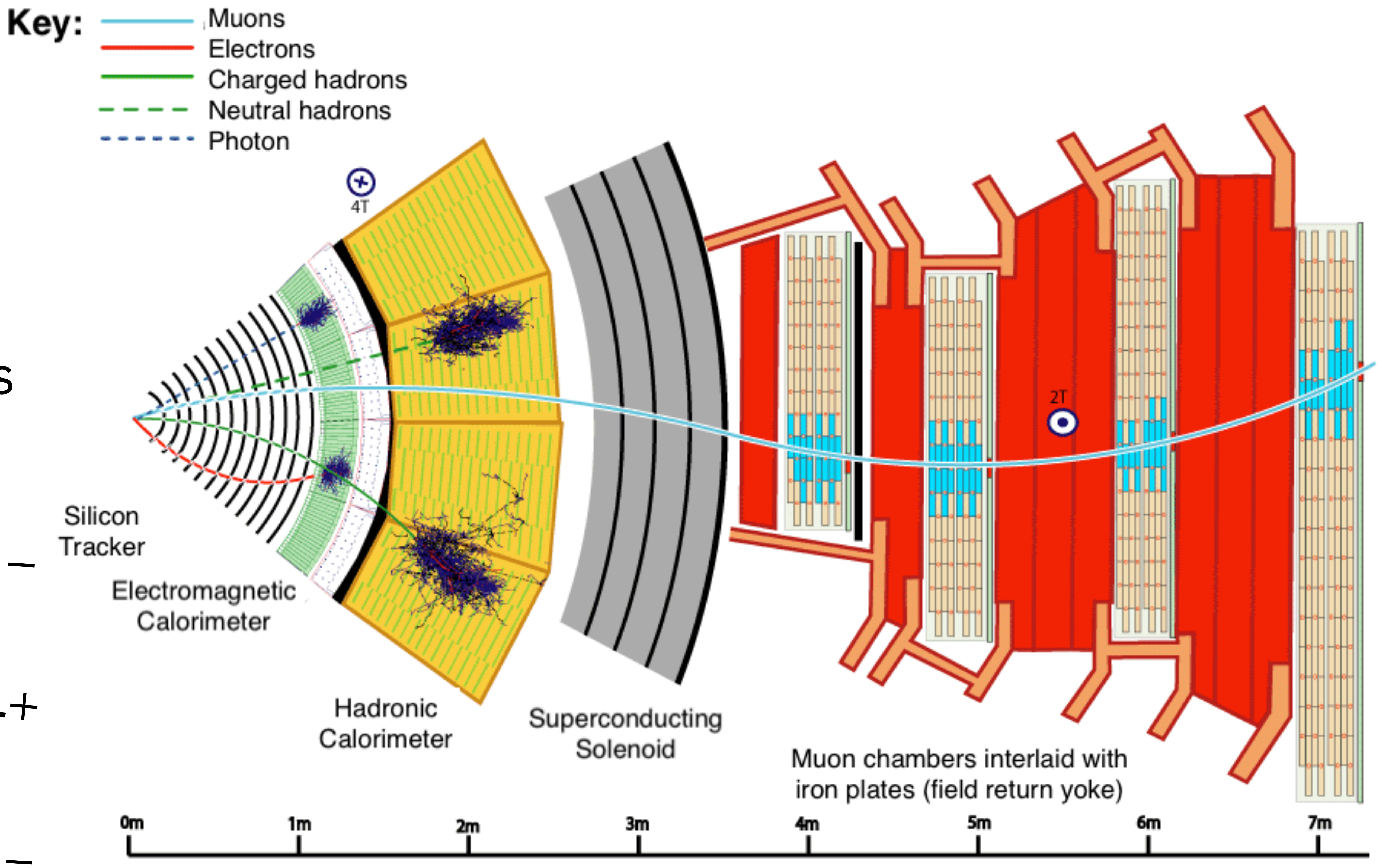
Work in progress

FINAL STATE :

- 2 muons $\mu^+\mu^-$ ➜ tracker + muon chambers
- 4 pions $\pi^+\pi^-\pi^+\pi^-$ ➜ tracker + ECAL + HCAL
  - ➜ **NO particle identification** for charged hadrons $(K, \pi, \Lambda, \ldots)$

$B^0 \to X(3872)K_s^0$
My master thesis project (public next year)





LOW ENERGY DECAYS

$B^0 \to X(3872)K_s^0$ and $B_s^0 \to X(3872)\phi$

- **challenging kinematical region** for CMS
- **combinatorial background**, the main challenge

Analysis strategy

- Need to reconstruct the **decay chain topology**
  - ➜ use **kinematic vertex fit** to find decay vertices

B-meson candidates

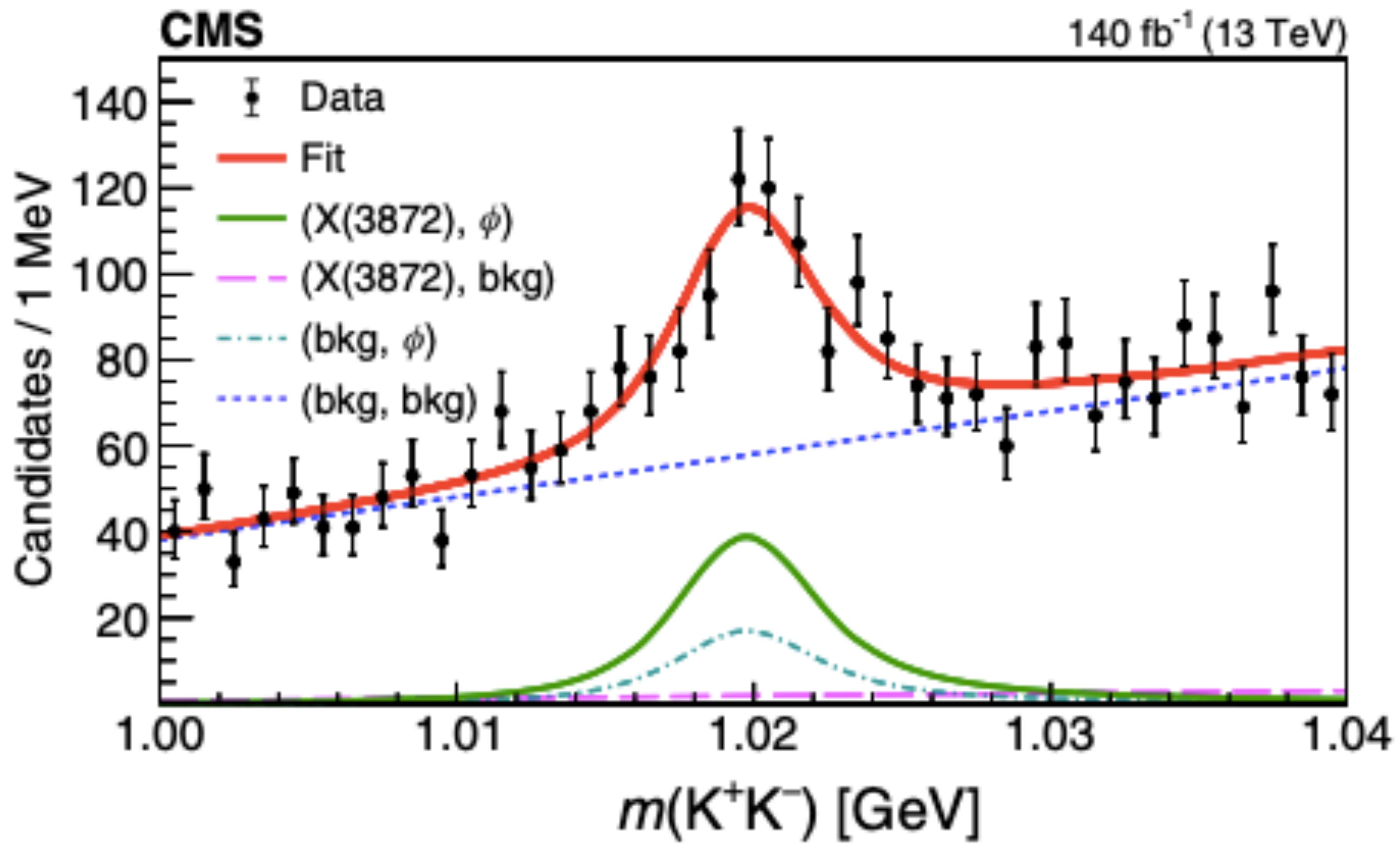
$B^0 \to J/\psi\pi^+\pi^- + K_s^0$

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

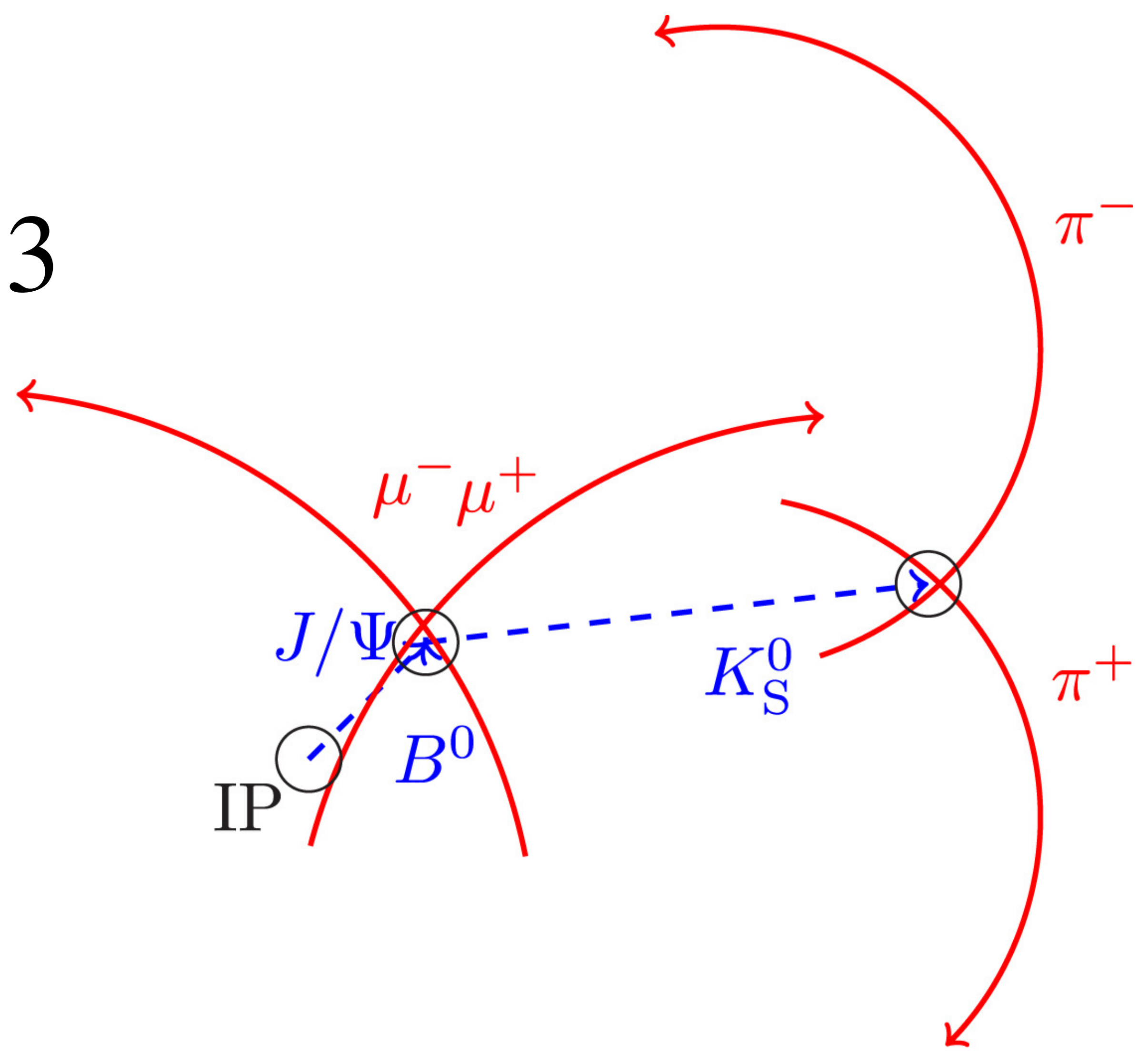
→ $\mu_1\mu_2 + 4$ tracks

FROM THE SAME SECONDARY VERTEX

➔ displacement significance $L_{xy}(B)/\sigma_{xy} > 3$



10.1103/PhysRevLett.125.152001



IDENTIFY $\phi \to K^+K^-$:

Mass assignment to 4 tracks such that

- $M(J/\psi\pi_1\pi_2) \simeq M^{PDG}_{X(3872)} \pm 2\,\%$
- $M(K^+K^-) \simeq M^{PDG}_{\phi} \pm 2\,\%$

IDENTIFY $K_s^0 \to \pi^+\pi^-$:

- Vertex fit of 2 tracks
- Constraint on $M(\pi_1\pi_2) \simeq M^{PDG}_{K^0} \pm 10\,\%$

EFFICIENCY $\sim 99\,\%$

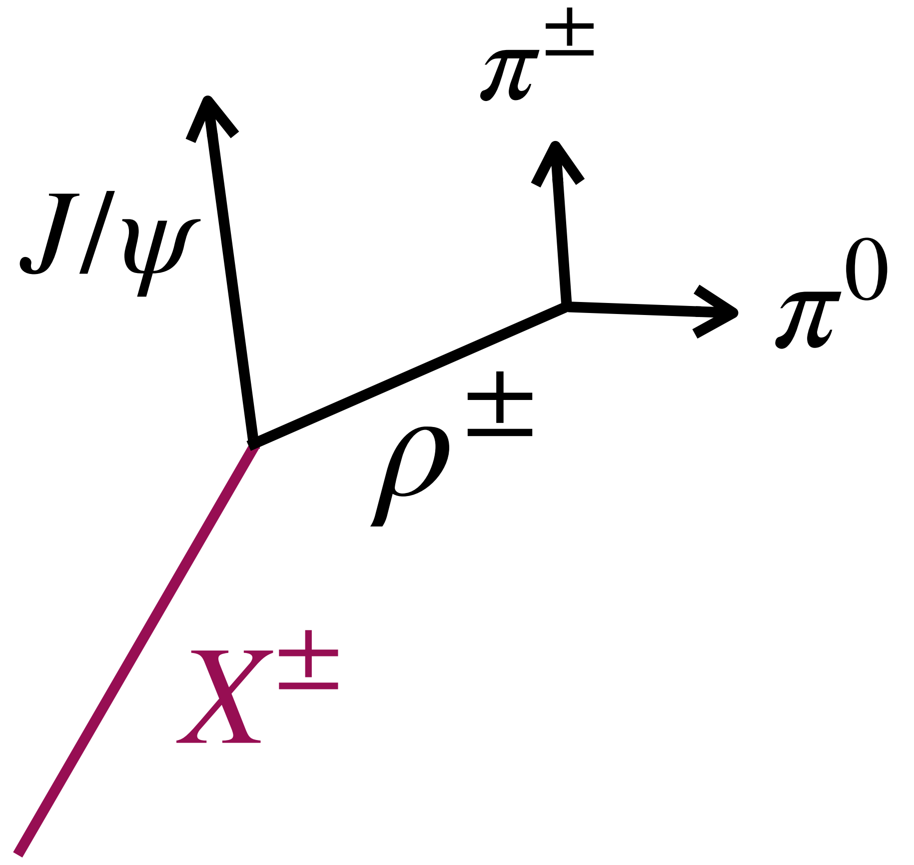
CMS has no detector dedicated to PID <u>BUT</u> is able to identify hadrons thanks to the inner tracker high resolution

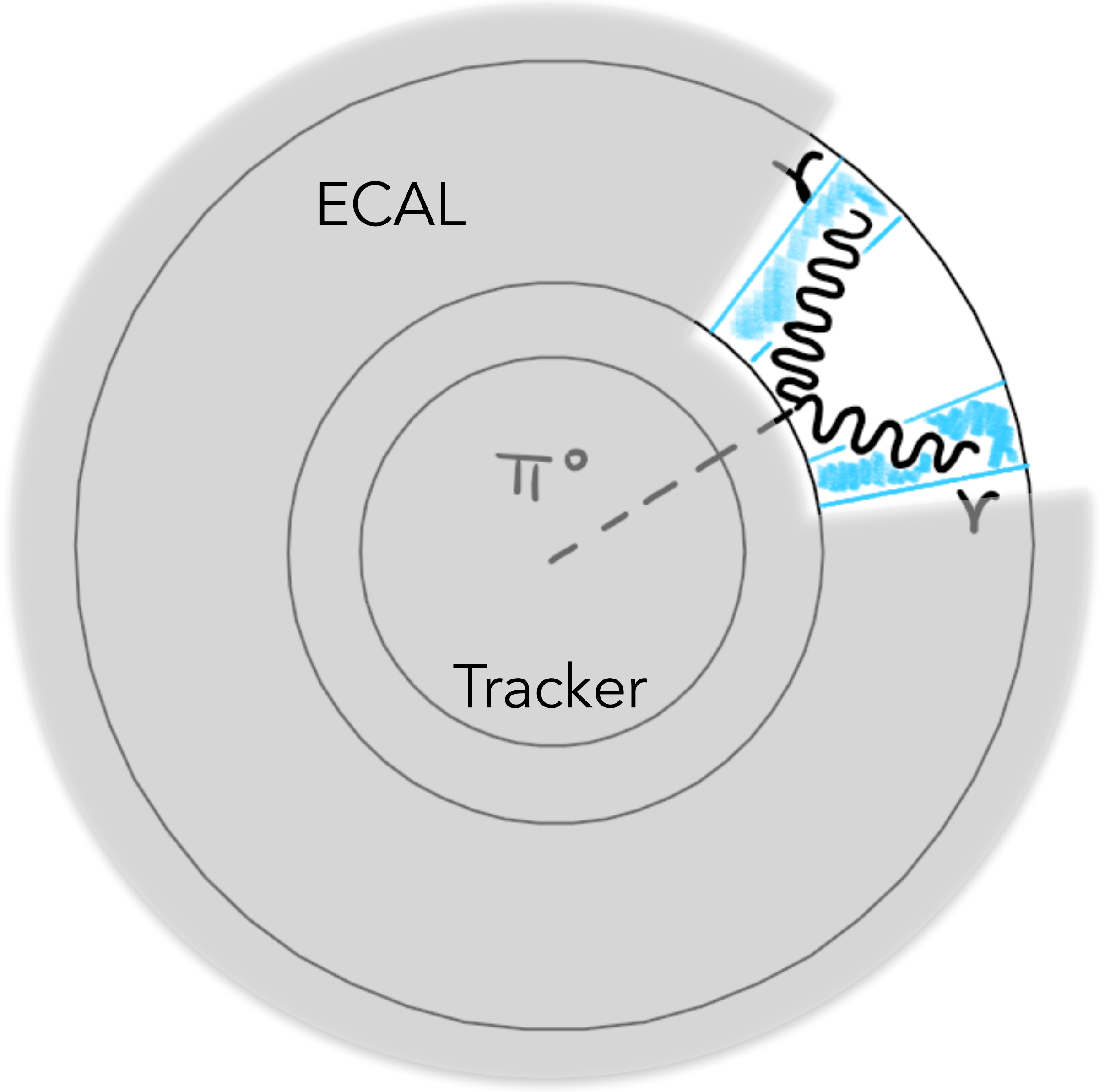
$Br[B_s^0 \to X(3872)\phi; X(3872) \to J/\psi\pi^+\pi^-] = (4.14 \pm 0.63) \times 10^{-6}$

$Br[B^0 \to X(3872)\ K_s^0; X(3872) \to J/\psi\pi^+\pi^-]$ work in progress!

$X(3872)$ charged partners

$X^{\pm}$ are expected to produce a π^0 in the final state

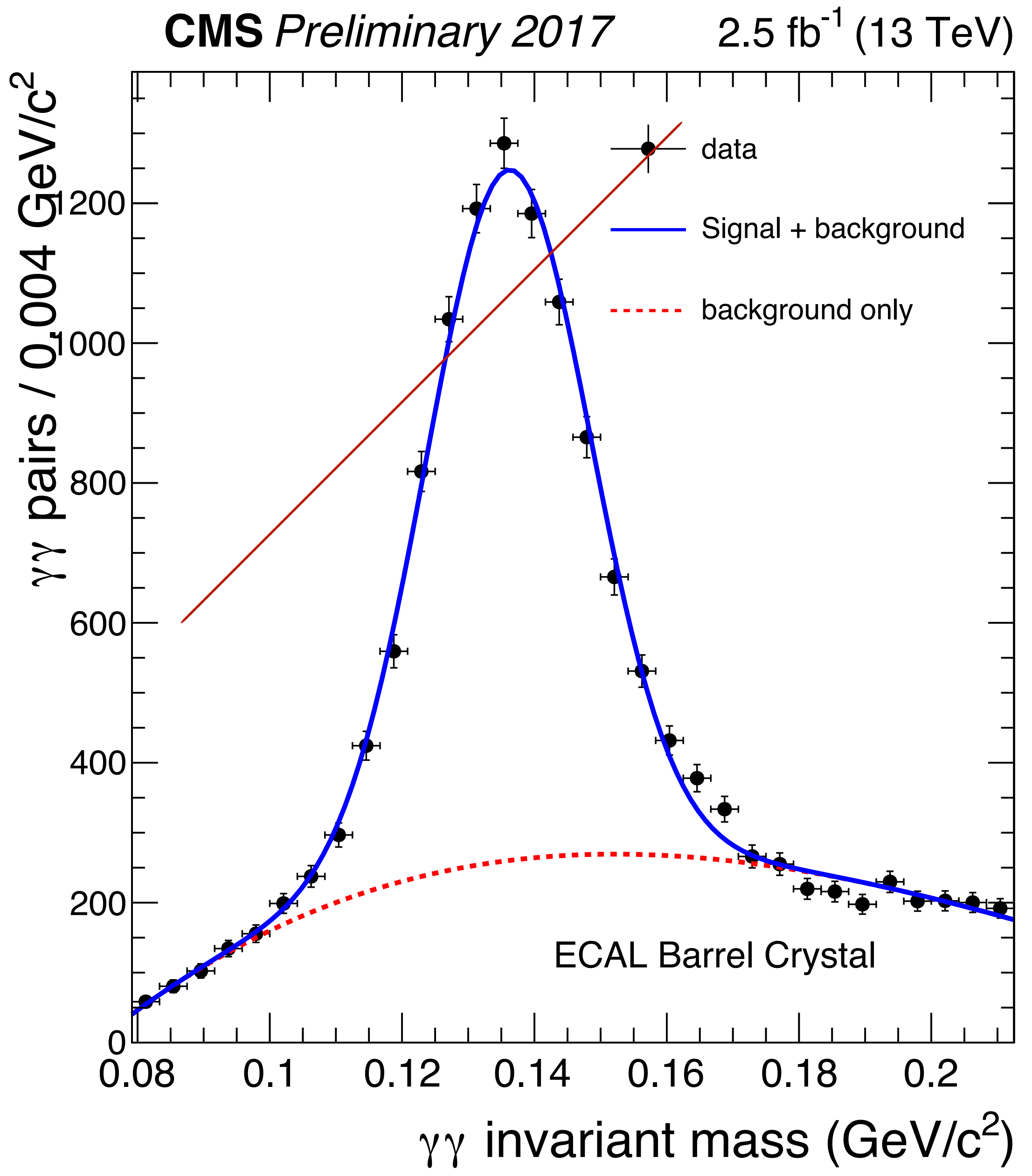


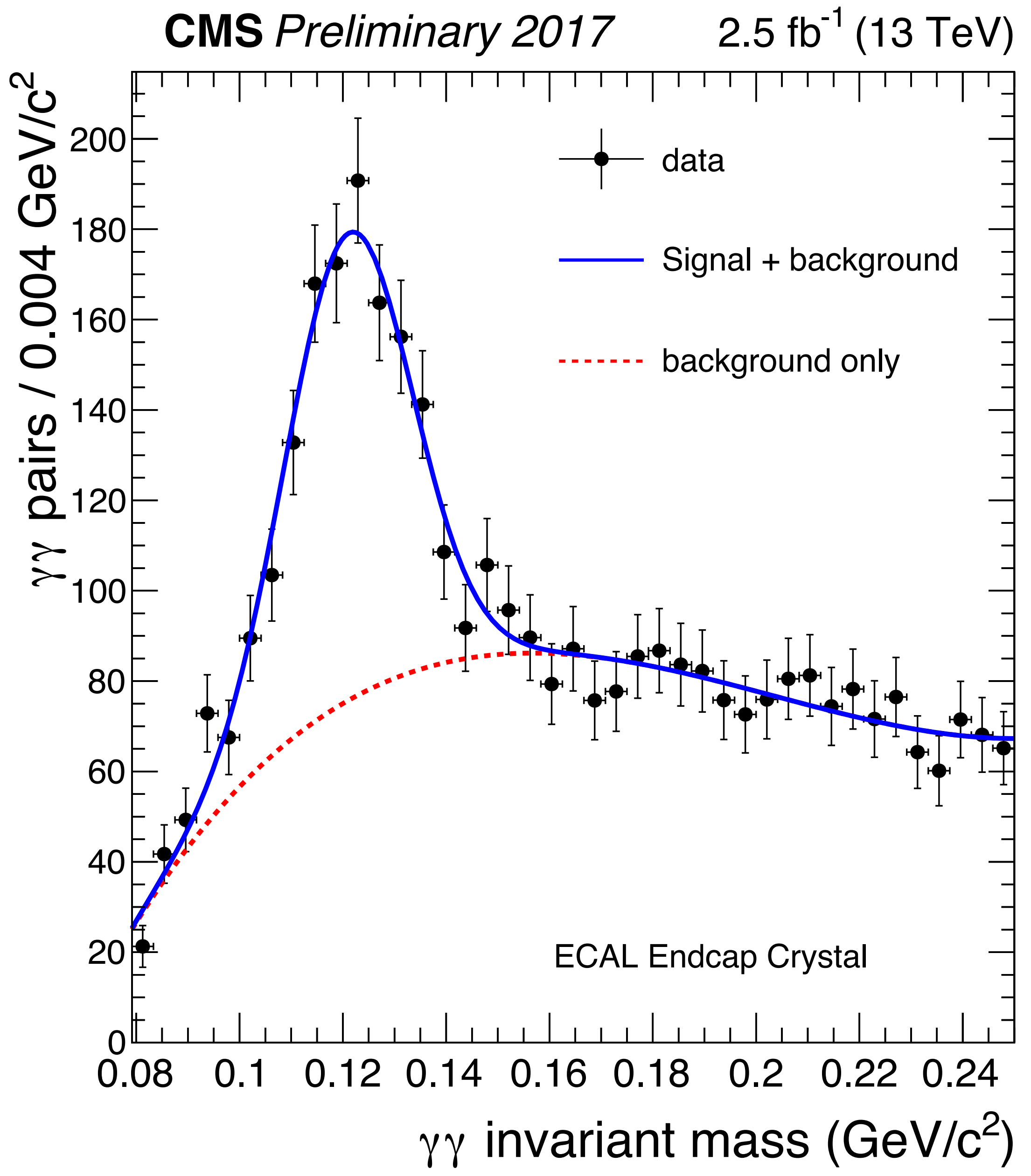


π^0 RECONTRUCTION @ CMS

- For **ECAL** crystals inter-calibration
- Not used in standard physics analysis
  - ➜ π^0 totally killed by ECAL energy thresholds
- **Only ECAL data around the e.m. deposit**
  - ➜ bandwidth and statistics
- Dedicated trigger stream
  - ➜ $\pi^0 \to \gamma\gamma$ event ~ 2 kB @ 7 kHz
- Standard physics trigger stream
  - ➜ physics event ~1 MB @ 1 kHz

CMS-DP-2017/023





Include π^0 reconstruction in physics analyses

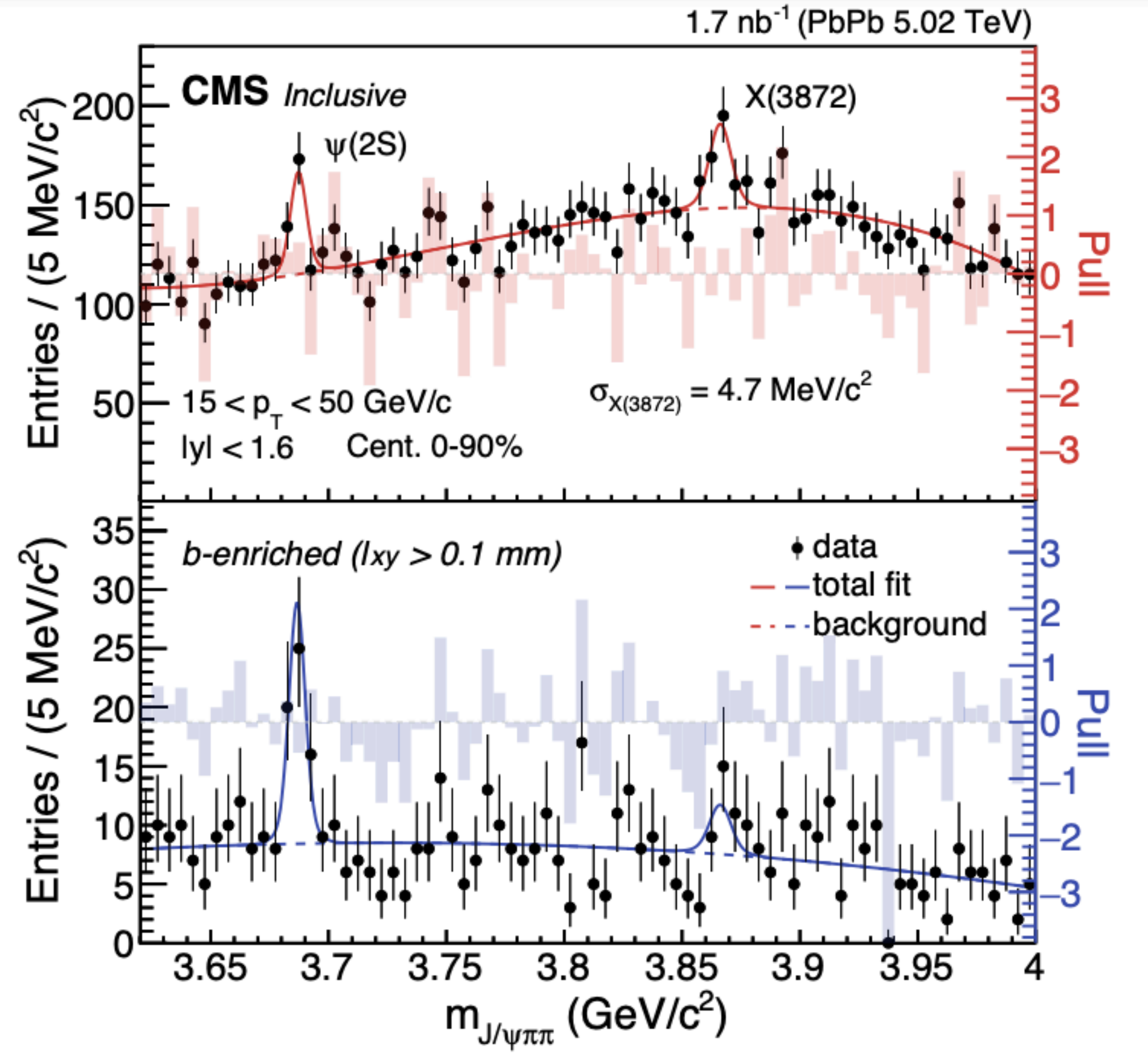
➜ Change the **online** trigger and the **offline** reconstruction algorithms

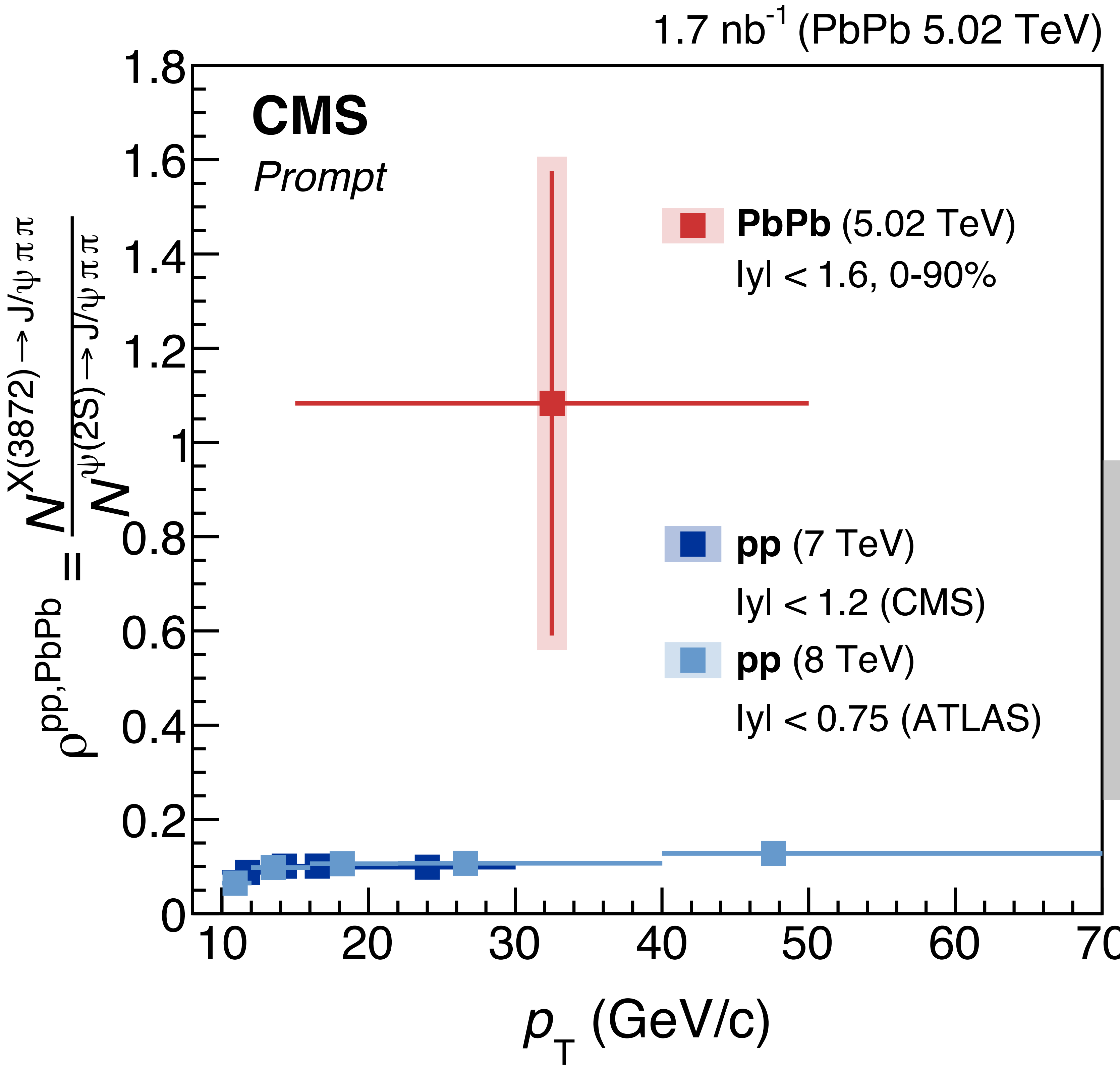
NOT in schedule

CMS : $X(3872)$ in Pb-Pb collisions

- **2020:** CMS reports the **first** evidence of inclusive $X(3872)$ production in Pb-Pb collisions @ LHC
  ➜ $X(3872)$ (either $\psi(2S)$) candidates reconstructed in 15 GeV $< p_T < 50$ GeV
- **Prompt $X(3872)$ to $\psi(2S)$ yield** ratio is found to be 10 times larger in Pb-Pb collision w.r.t. pp collisions

PhysRevLett.128.032001



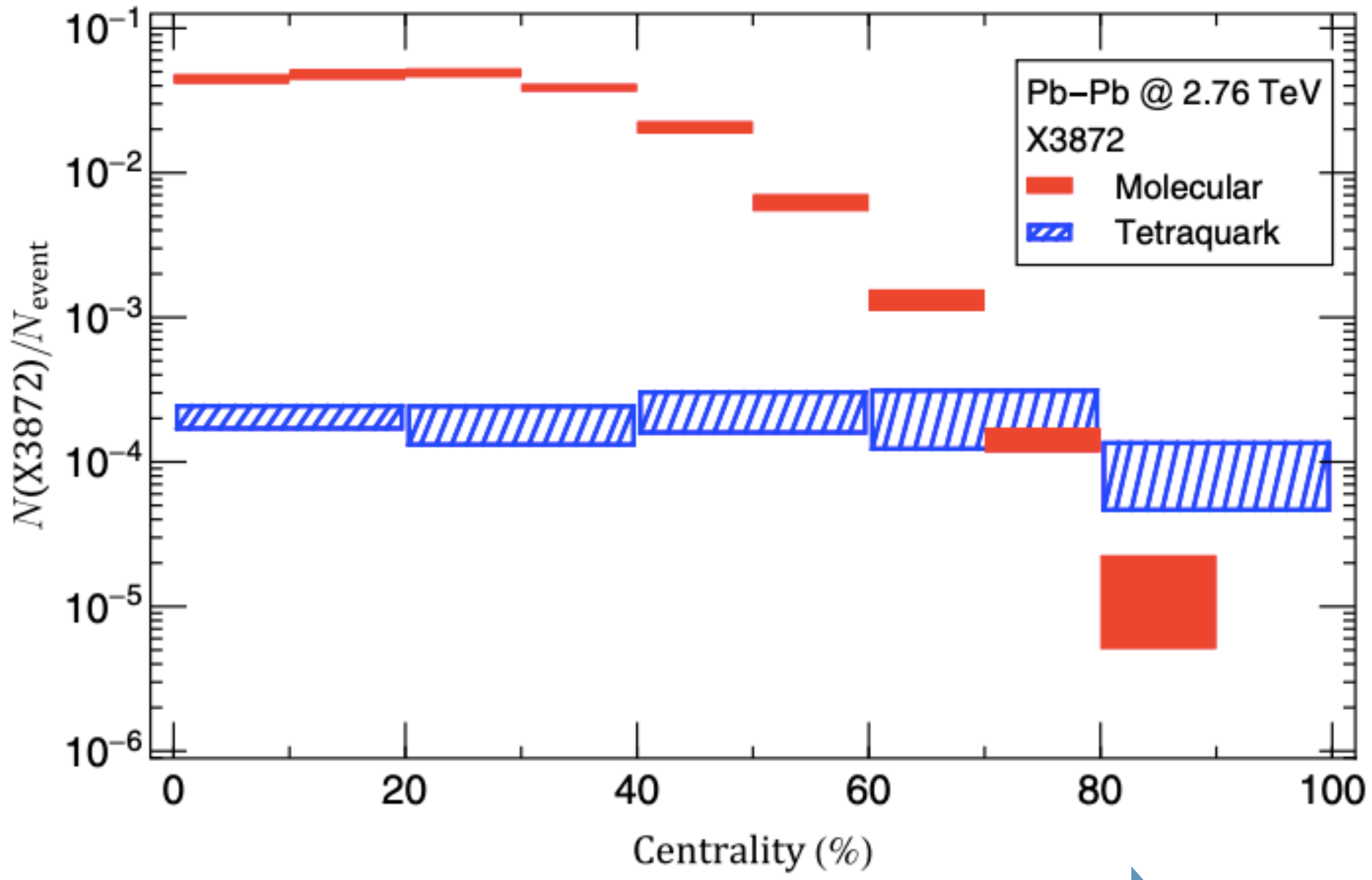


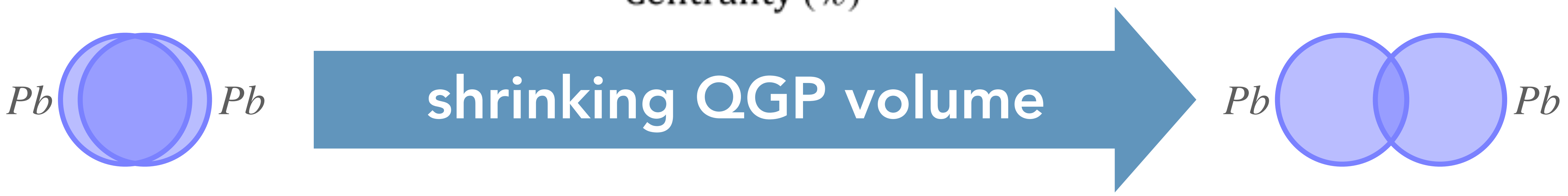
Never measured before at LHC !

$X(3872)$ production in Quark Gluon Plasma (QGP) strongly depends on its INTERNAL STRUCTURE !

A possible theoretical interpretation

10.1103/PhysRevLett.126.012301

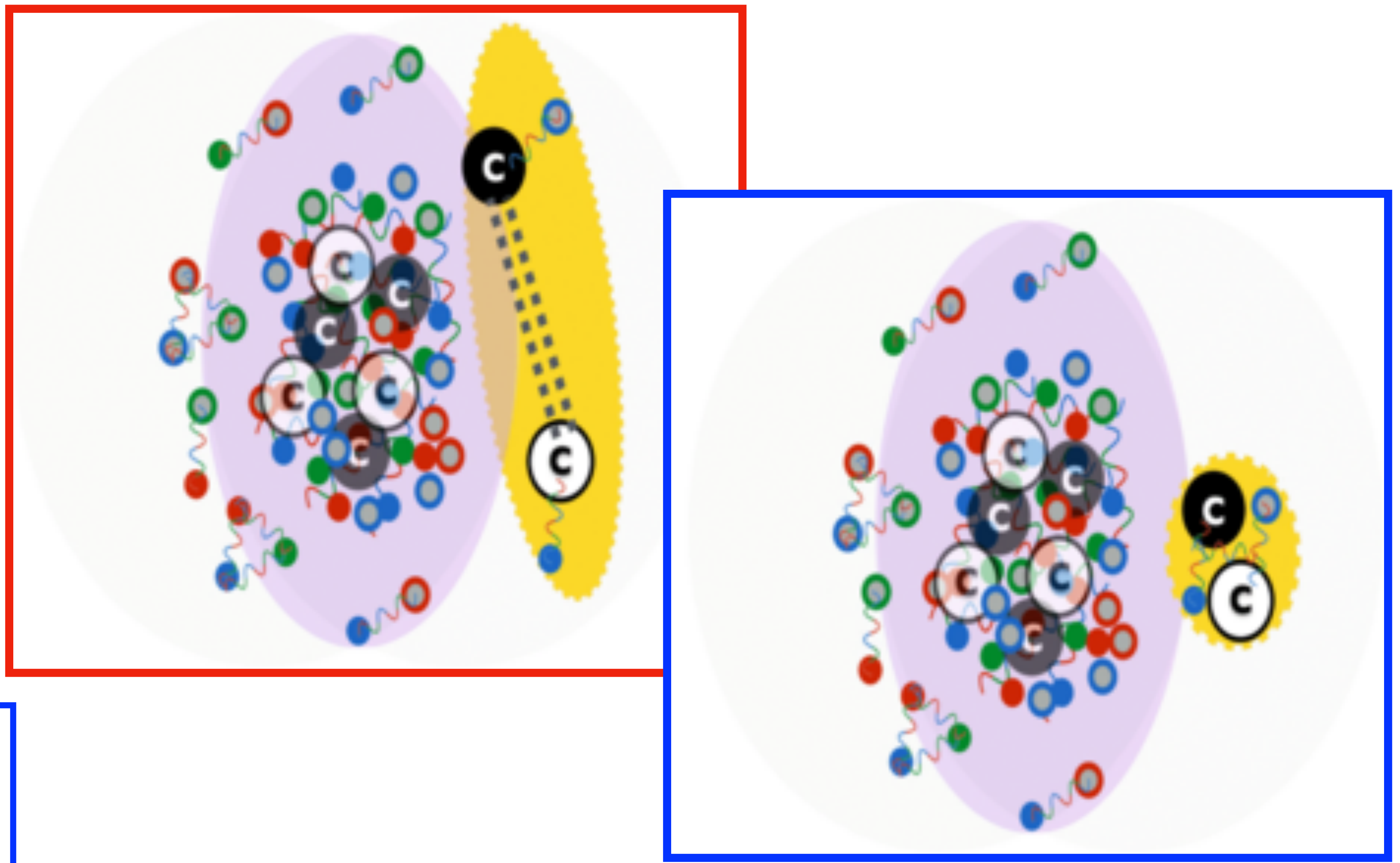




- Separated simulation of $X(3872)$ **yield** in QGP as a **meson-molecule** and a **tetraquark**
- **Meson-molecule** production strongly decreases in peripheral collisions
- **Tetraquark** production flat in centrality
- CMS could measure point in the plane $N_{X(3872)}$ **vs Centrality**

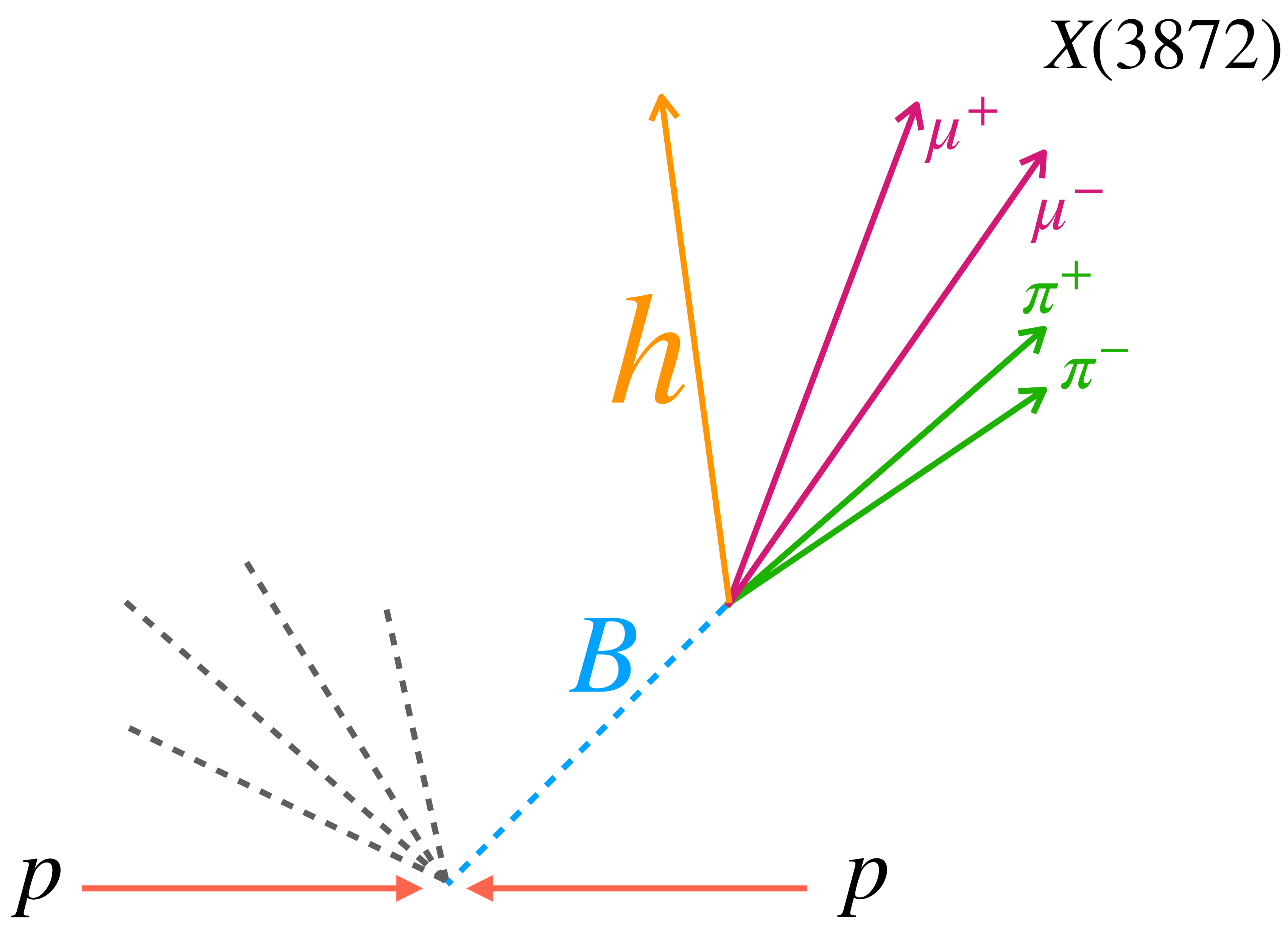
Too small w.r.t. $D^0 - \bar{D}^{0*}$ equilibrium distance (~5 fm)

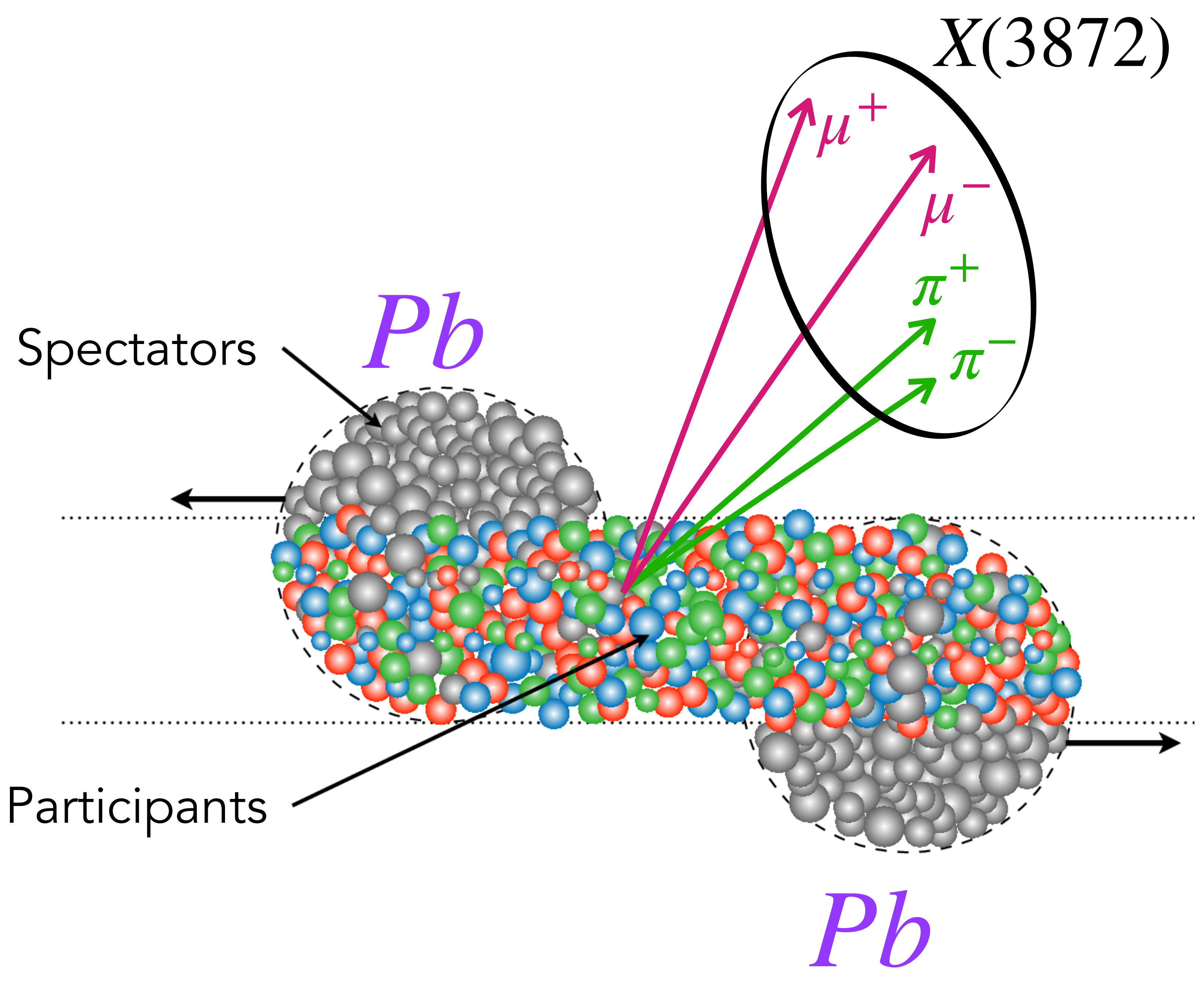
Compensation between decreasing number $c\bar{c}$ but small separation



Conclusions

- $X(3872)$ **NON-prompt production** in pp collisions
  - ➜ **Branching ratios of different decays** provide crucial information on its internal structure
  - ➜ **2020**: CMS-measurement for $B_s^0 \to X(3872)\phi$
  - ➜ **end of 2023:** target to publish master-thesis $B^0 \to X(3872)K_s^0$ analysis



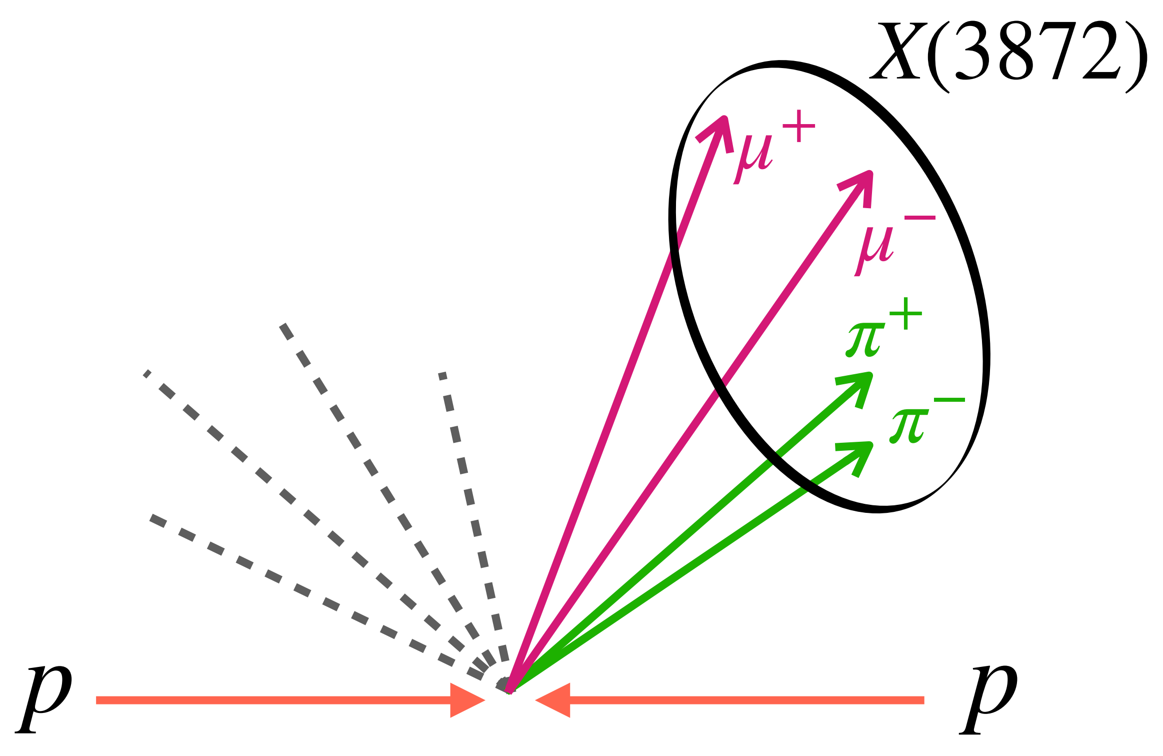


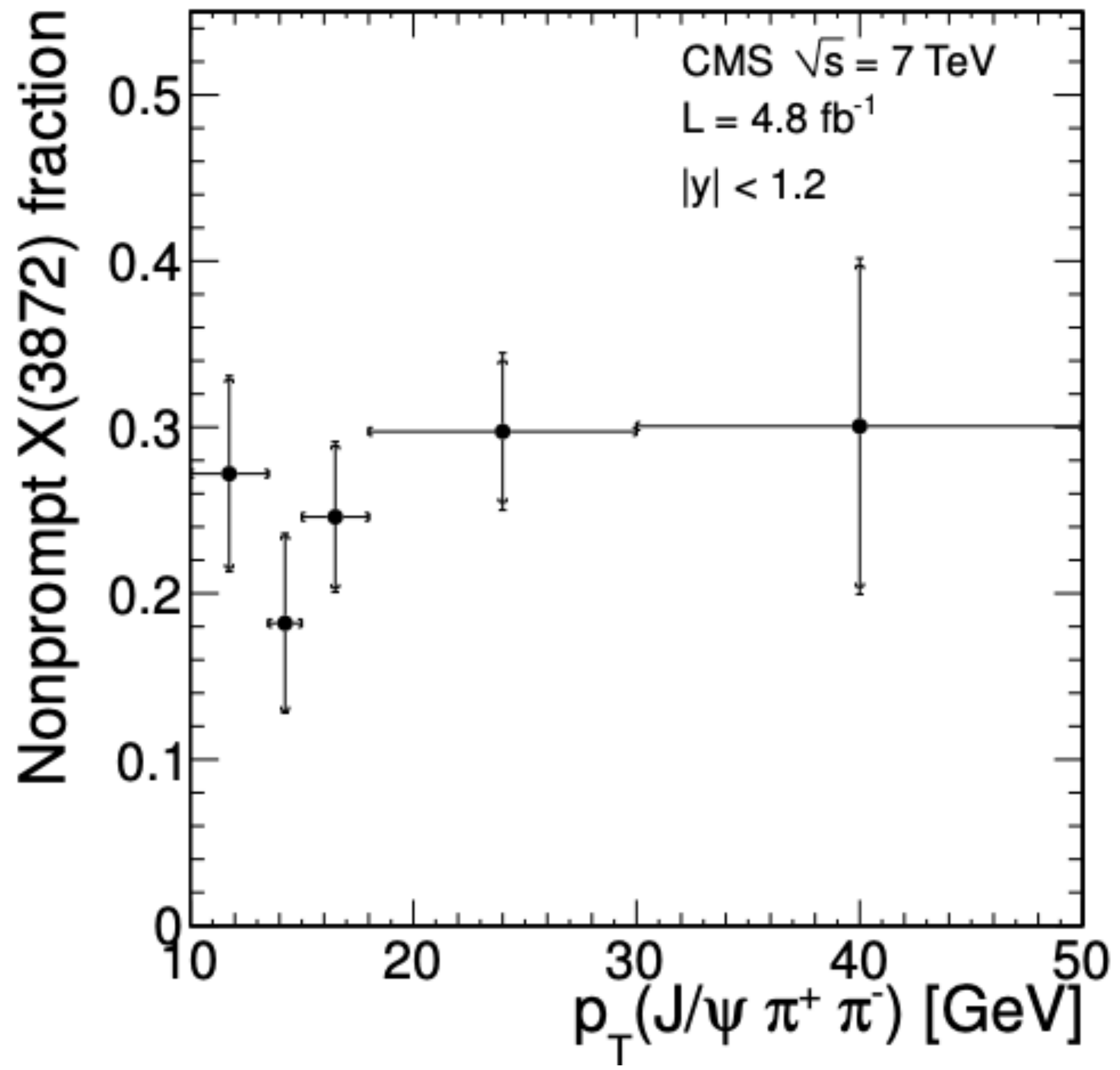
- **Prompt production** in PbPb collisions
  - ➜ $X(3872)$ **yield** strongly depends on its nature
  - ➜ Both **experimental** and **theoretical** studies will improve the understanding of the $X(3872)$ puzzle
  - ➜ Almost 7 times larger dataset from **RUN 3**

BACKUP

Prompt production

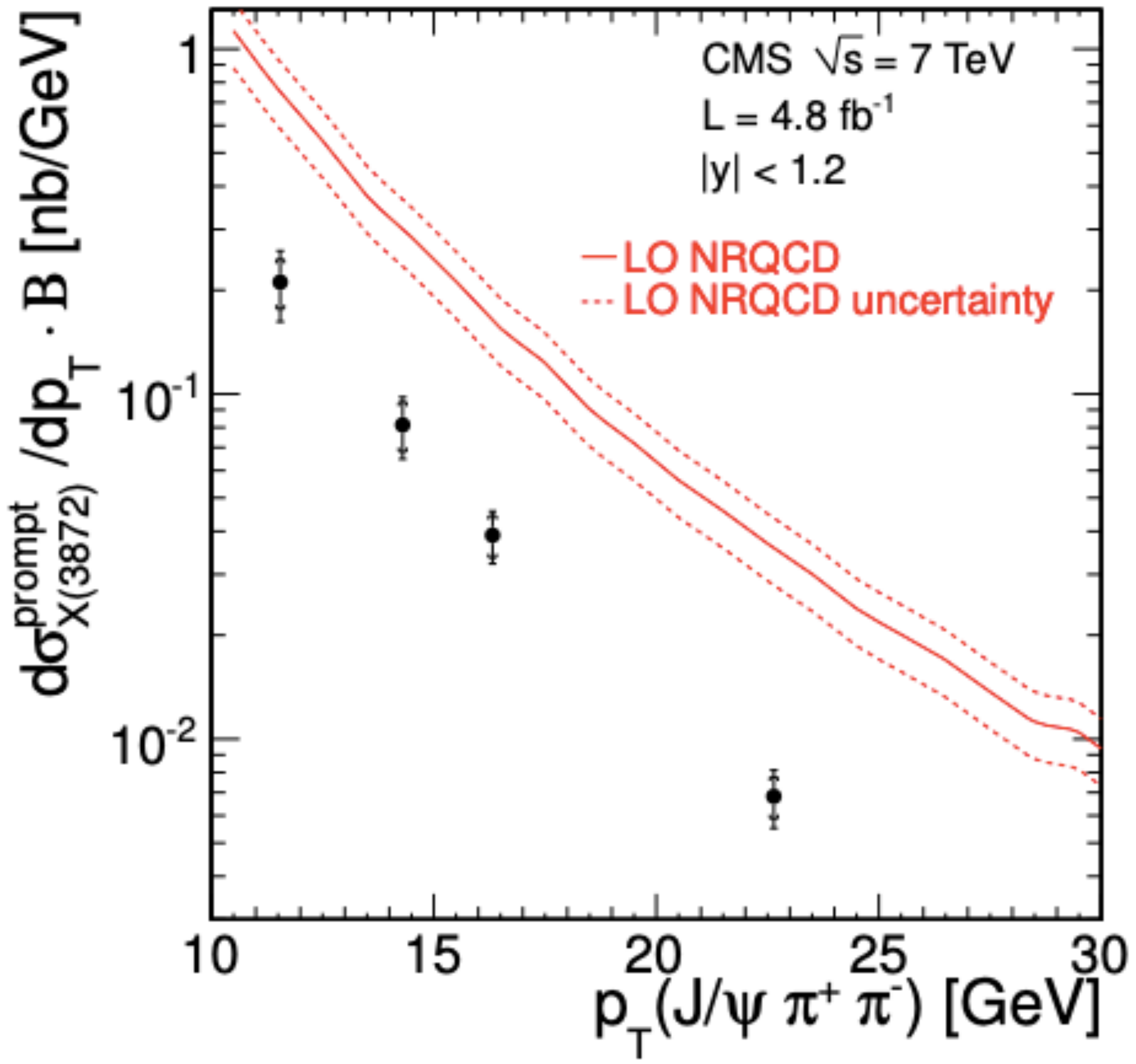
RUN-1: pp **collision at** $\sqrt{s} = 7$ **TeV;** $\mathcal{L} = 4.8$ **fb**$^{-1}$
~ 12000 $X(3872)$ **reconstructed**





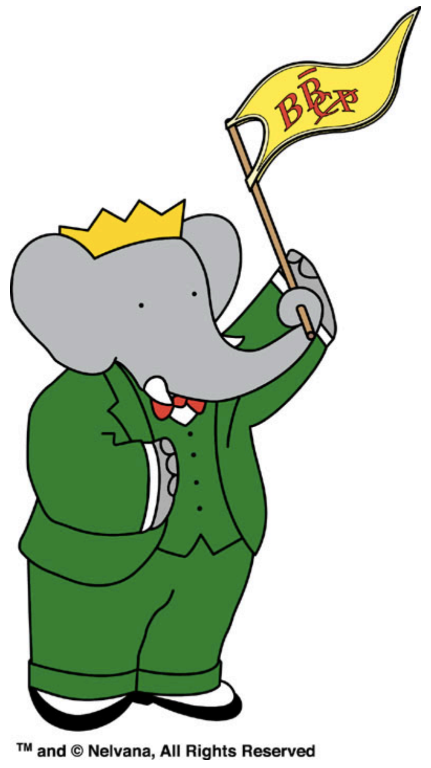
PHYSICS RESULTS

- Non-prompt fraction of $X(3872)$ yield vs p_T
  - ➜ Is only $\sim 30\,\%$ of the total yield
- Inclusive differential prompt cross-section $d\sigma^{\text{prompt}}/dp_T \cdot Br[X(3872) \to J/\psi\pi^+\pi^-]$
  - ➜ NRQCD simulation for a $c\bar{c}$ state overestimates the measured value by over 3σ
  - ➜ $X(3872)$ **not** compatible with S-wave charmonium model



JHEP 04 (2013) 154

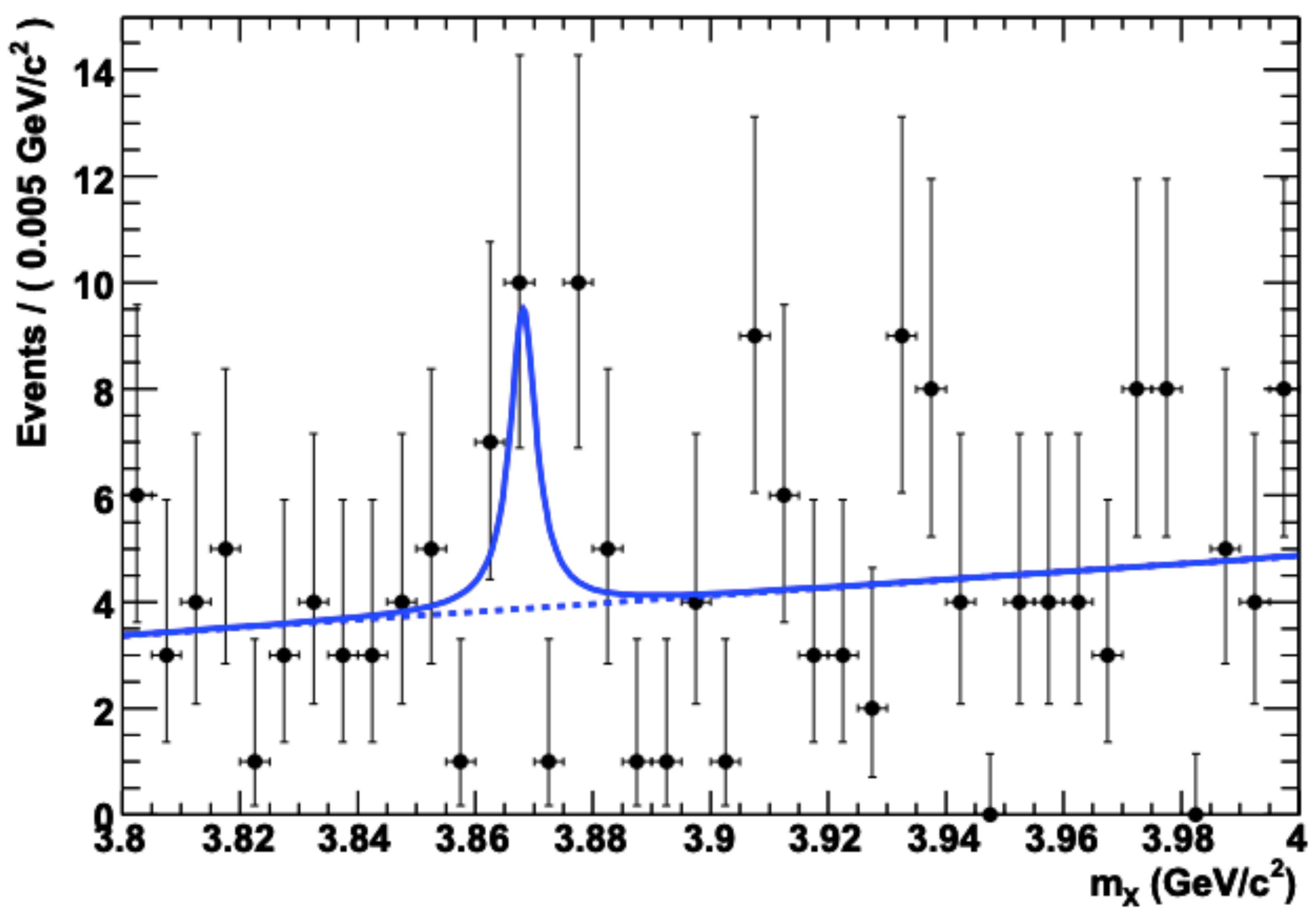
$B^0 \to X(3872)K_s^0$ @ BaBar

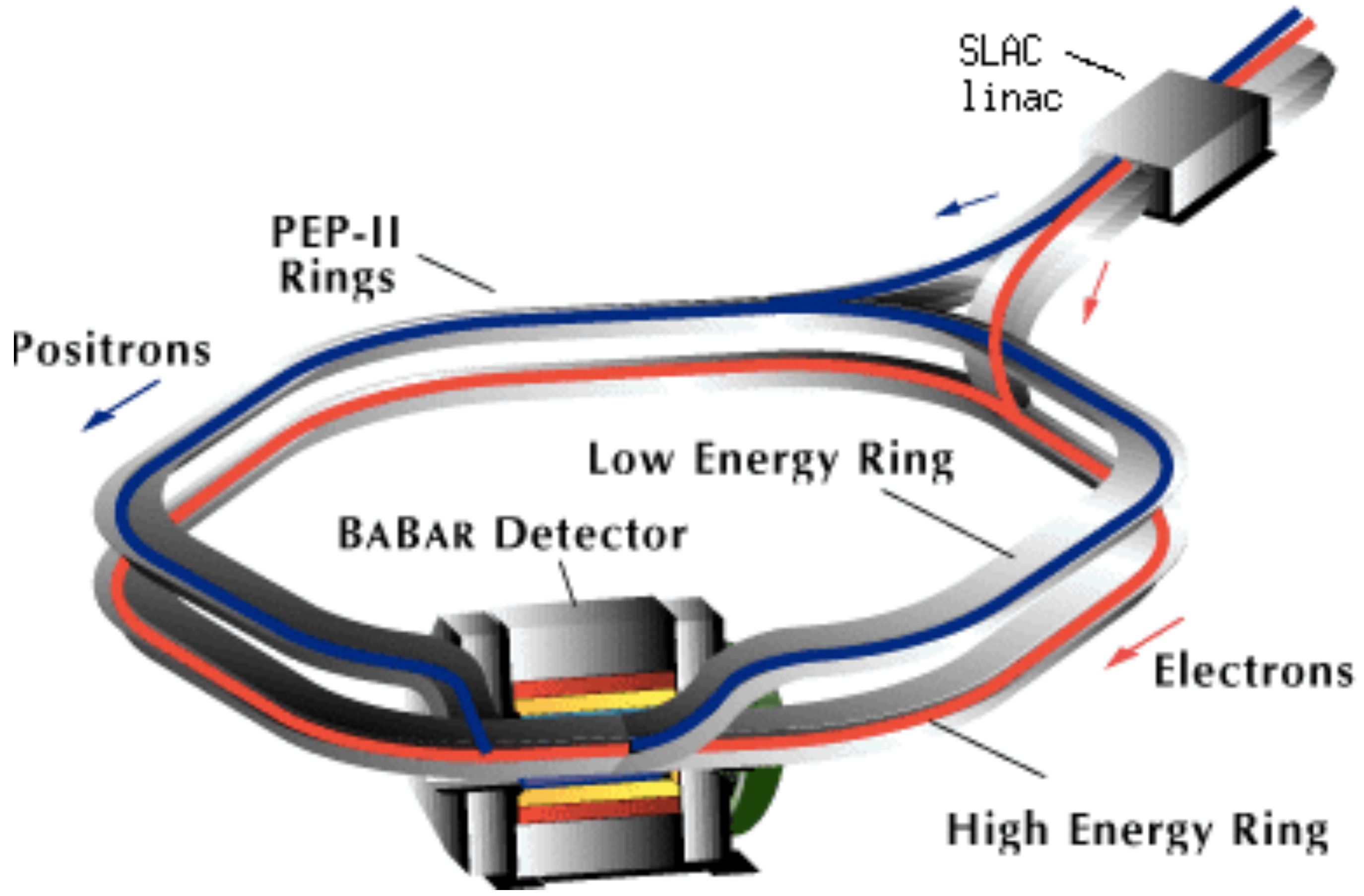


- e^+e^- asymmetric collisions $\sqrt{s} = M_{\Upsilon(4S)}$
- 9.4 reconstructed events
- Good reconstruction efficiency ($\sim 15\,\%$)
  - ➜ $J/\psi \to \mu^+\mu^-$ and $\to e^+e^-$
  - ➜ PID for tracks with DIRC (Ring Imaging Cherenkov Detector) + dE/dx measurements
- Poor statistics
  - ➜ large error on the branching ratio
- Large systematic uncertainties
  - ➜ number of $B^0\bar{B}^0$ pairs
  - ➜ reconstruction and tracking

CMS eliminates them using

$$R = \frac{N_{B\to X(3872)\ h}}{\varepsilon_{B\to X(3872)\ h}\cdot \sigma \cdot L}\cdot\frac{\varepsilon_{B\to\Psi(2S)\ h}\cdot\sigma\cdot L}{N_{B\to\Psi(2S)\ h}}$$



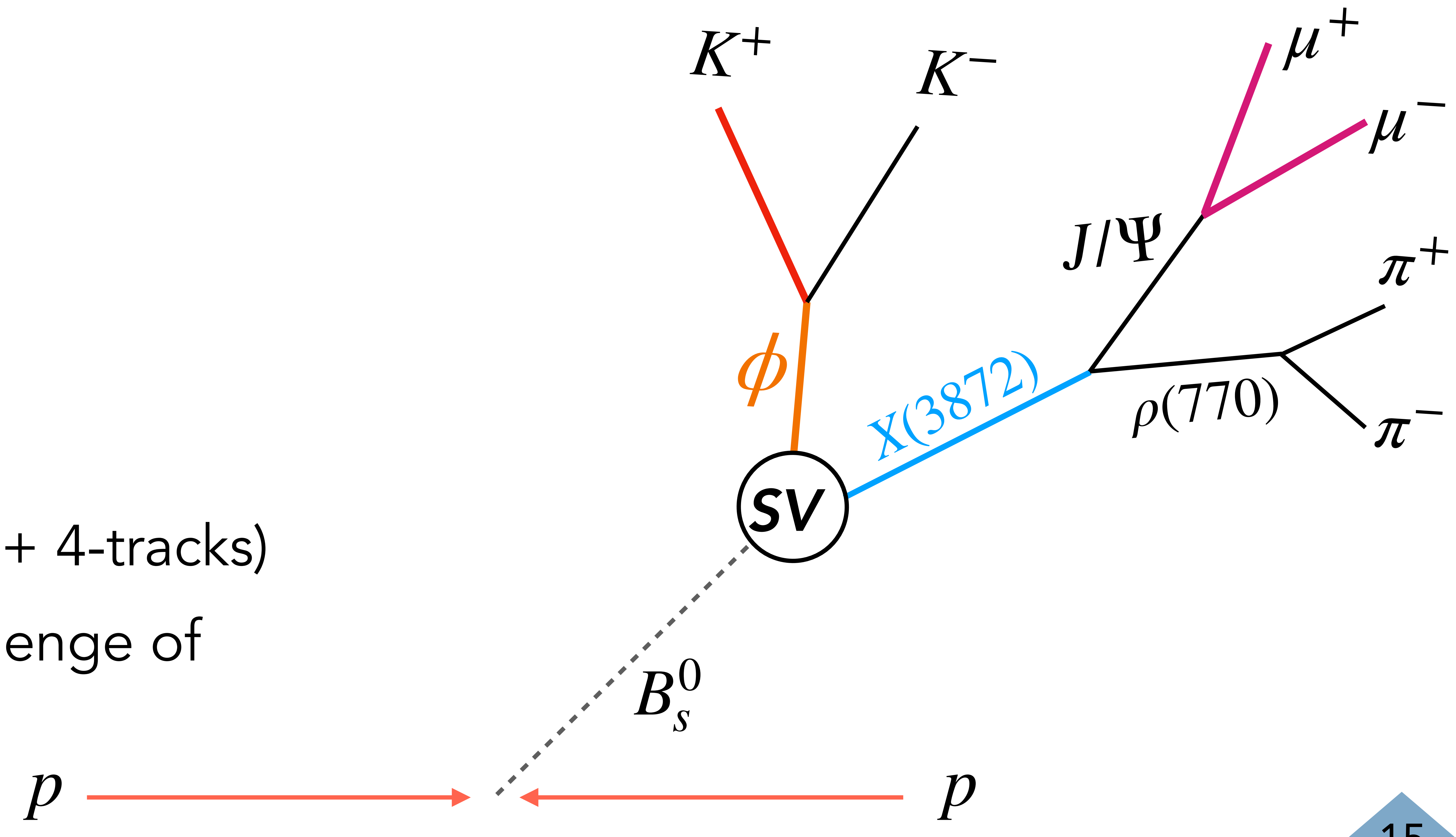


$$Br[B \to X(3872)\ K_s^0] \times Br[X(3872) \to J/\psi\pi^+\pi^-)] = (3.5 \pm 1.9 \pm 0.4)\times 10^{-6}$$

Online selection strategy

HIGH LEVEL TRIGGER selects events with:

- $\mu^+\mu^-$ pair
  - ➜ $p_T(\mu\mu) > 4$ GeV
  - ➜ from the same point + $\mu\mu$-vertex displaced w.r.t. the collision point
  - ➜ $M(\mu\mu) \sim M^{PDG}_{J/\psi}$ within 200 MeV
- one track
  - ➜ $p_T(trk) > 1.2$ GeV
  - ➜ produced at the $\mu\mu$-vertex



- Including all the possible combinations ($\mu^+\mu^-$+ 4-tracks)
  - ➜ **combinatorial background**, the main challenge of these analyses

Online selection strategy

Work in progress

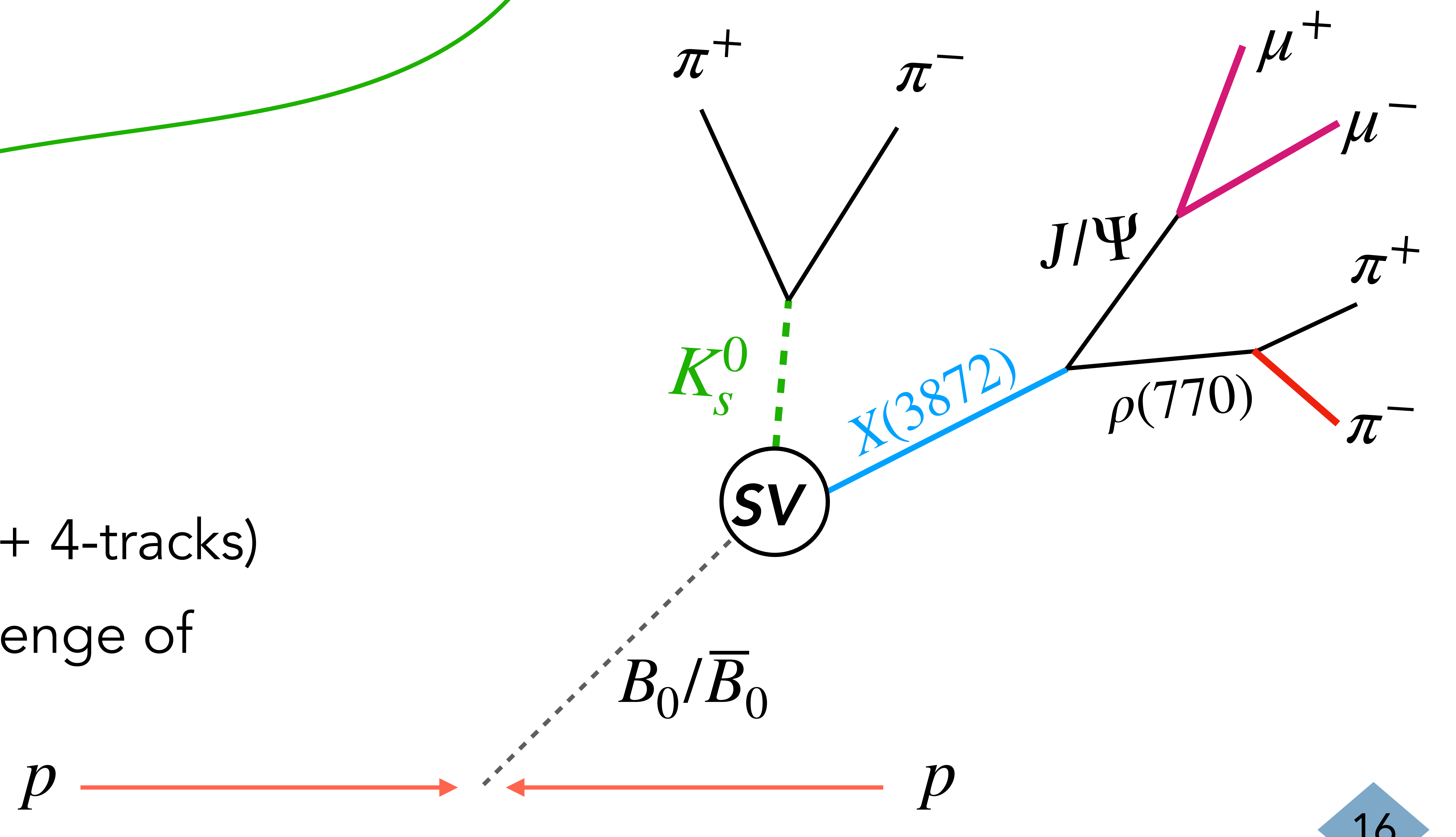
HIGH LEVEL TRIGGER selects events with:

- $\mu^+\mu^-$ pair
  - ➜ $p_T(\mu\mu) > 4$ GeV
  - ➜ from the same point + $\mu\mu$-vertex displaced w.r.t. the collision point
  - ➜ $M(\mu\mu) \sim M^{PDG}_{J/\psi}$ within 200 MeV
- one track
  - ➜ $p_T(trk) > 1.2$ GeV
  - ➜ produced at the $\mu\mu$-vertex

K^0_s can fly for non-negligible distances

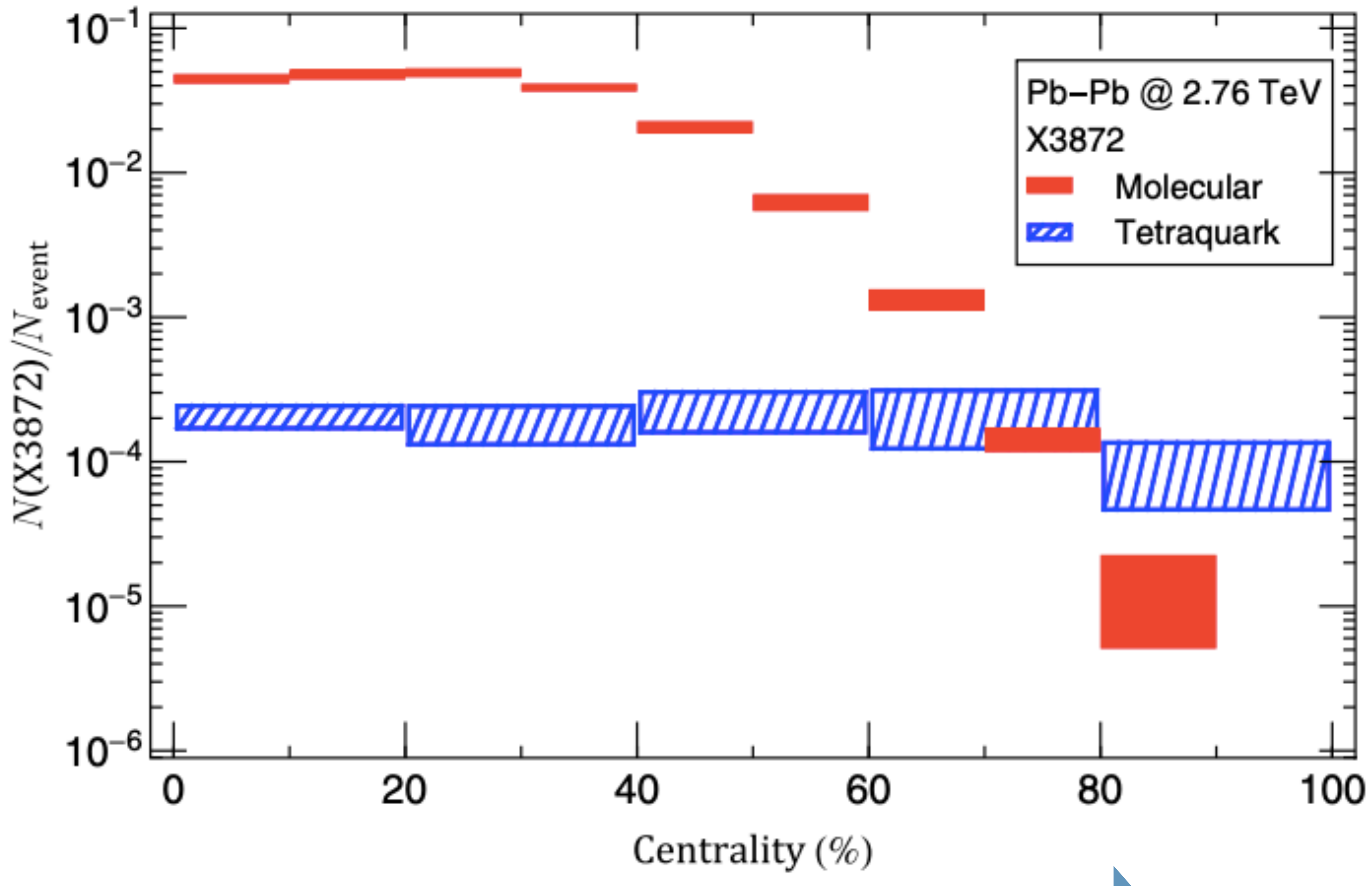
- None of its pions match the $\mu\mu$-vertex
- Pions from $X(3872)$ may be less energetic with $p_T(\pi)$ below threshold

- Including all the possible combinations ($\mu^+\mu^-$+ 4-tracks)
  - ➜ **combinatorial background**, the main challenge of these analyses

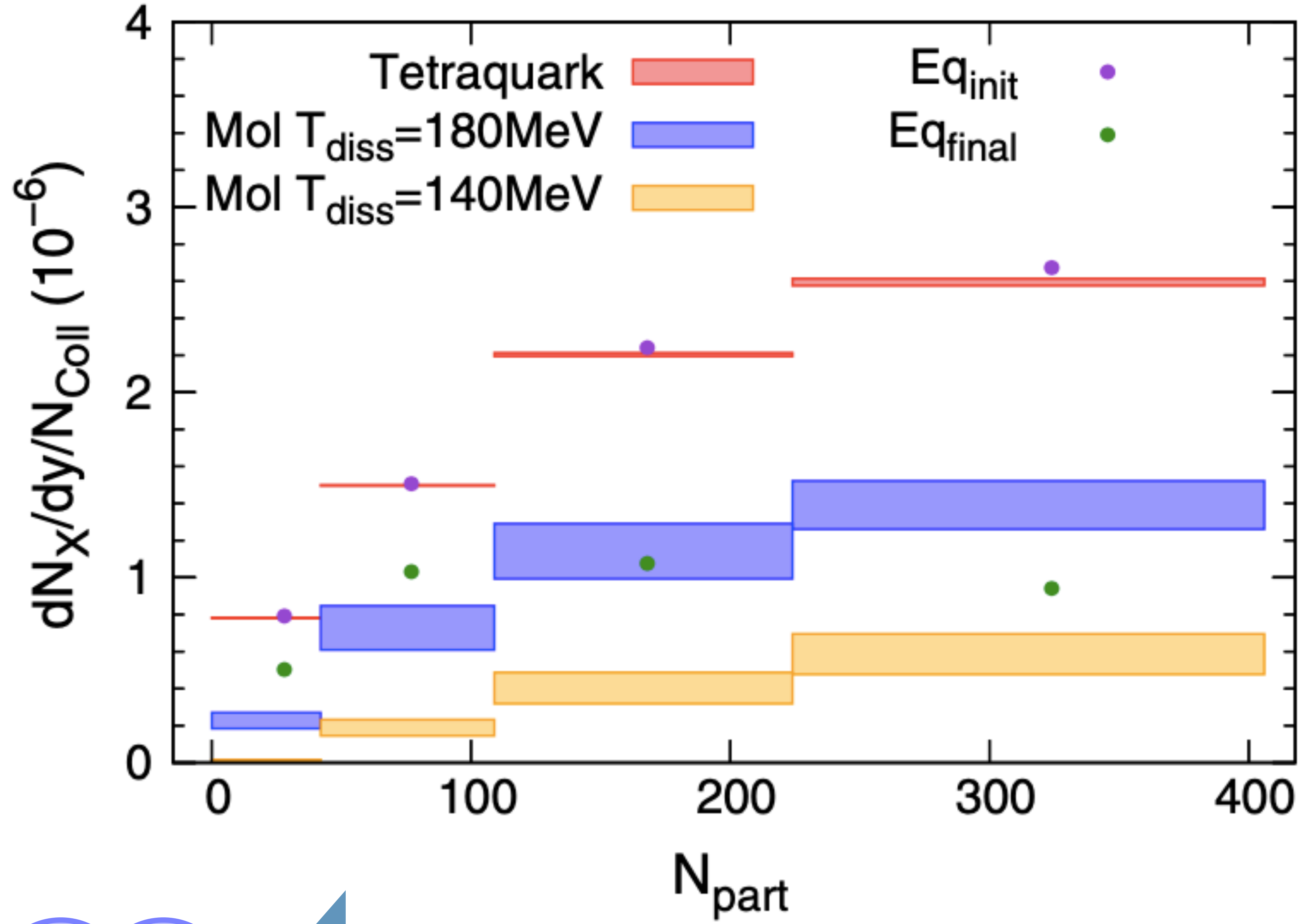


$X(3872)$ production in heavy ions collisions

10.1103/PhysRevLett.126.012301



arXiv:2006.09945



Multiphase transport model **AMPT**

- $N_{MOLECULE} > N_{TETRAQUARK}$
- molecular production drops in peripheral collisions

TAMU transport model

- $N_{MOLECULE} > N_{TETRAQUARK}$
- loose-molecule has larger interaction rate and dissociates