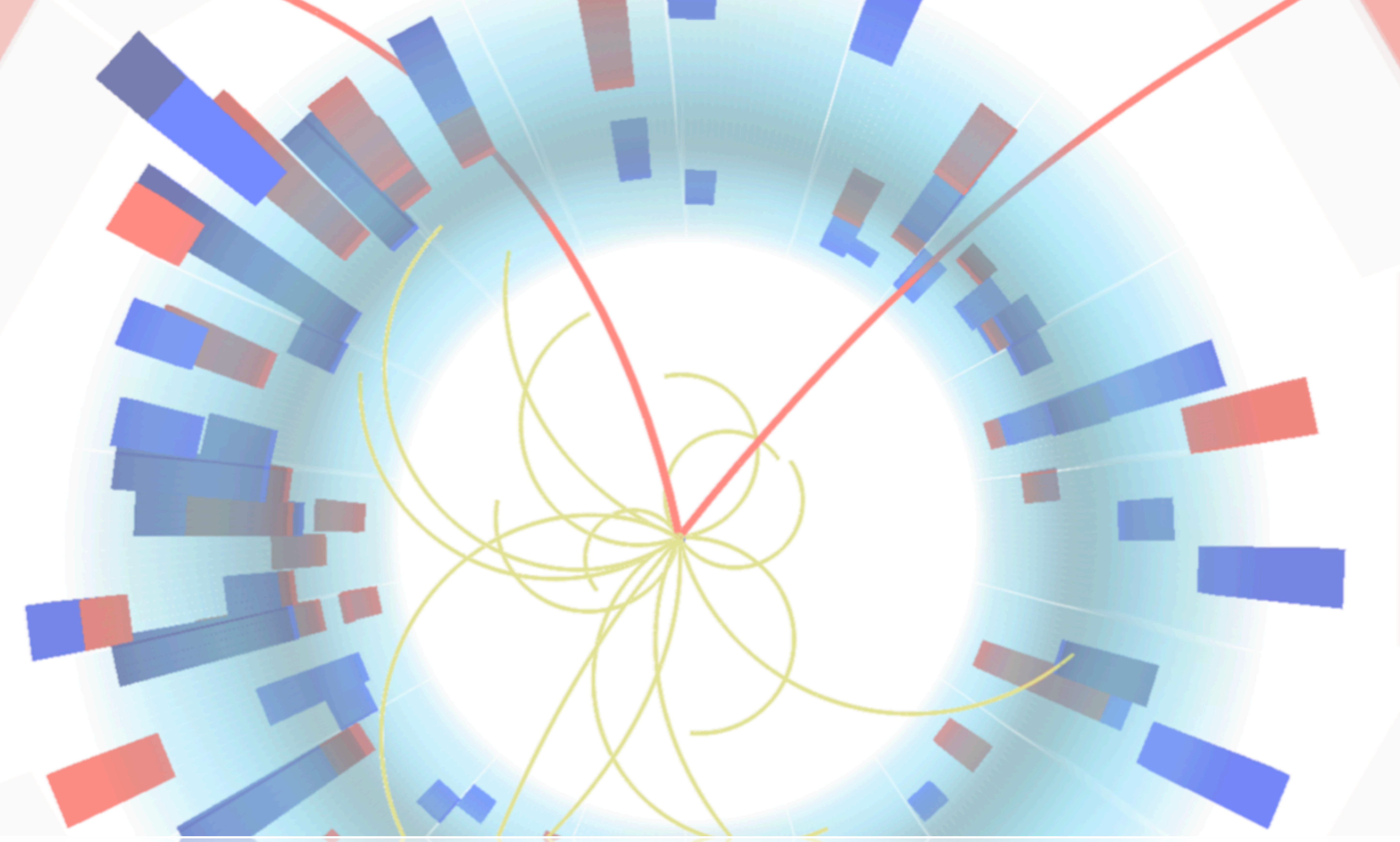


Heavy Flavour & Heavy Ions

Nuno Leonardo (nuno@cern.ch), LIP & IST

EPFL LPHE seminar, Lausanne, December 11th, 2023

LPHE seminar

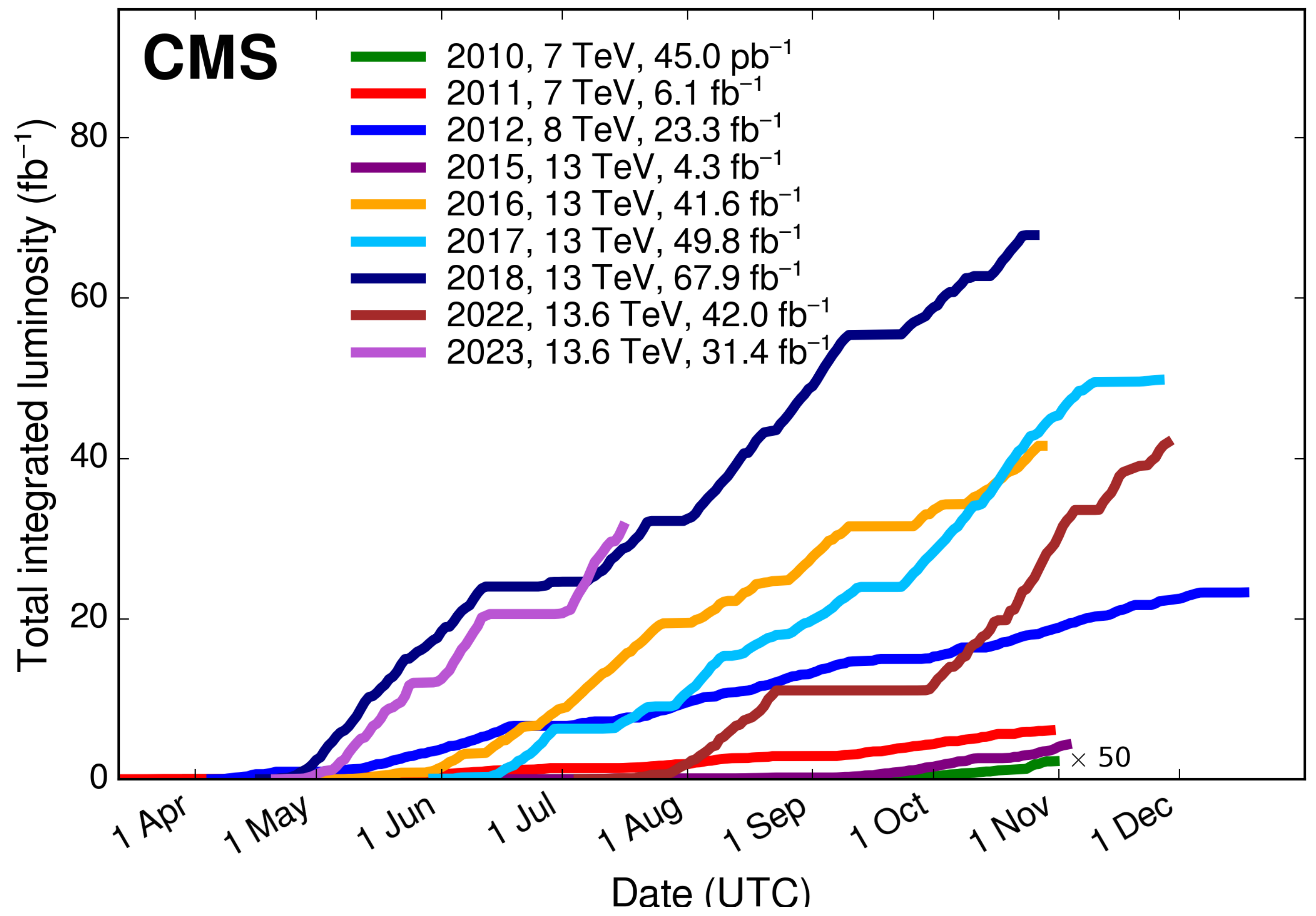
Thanks for Welcoming Me back to EPFL !

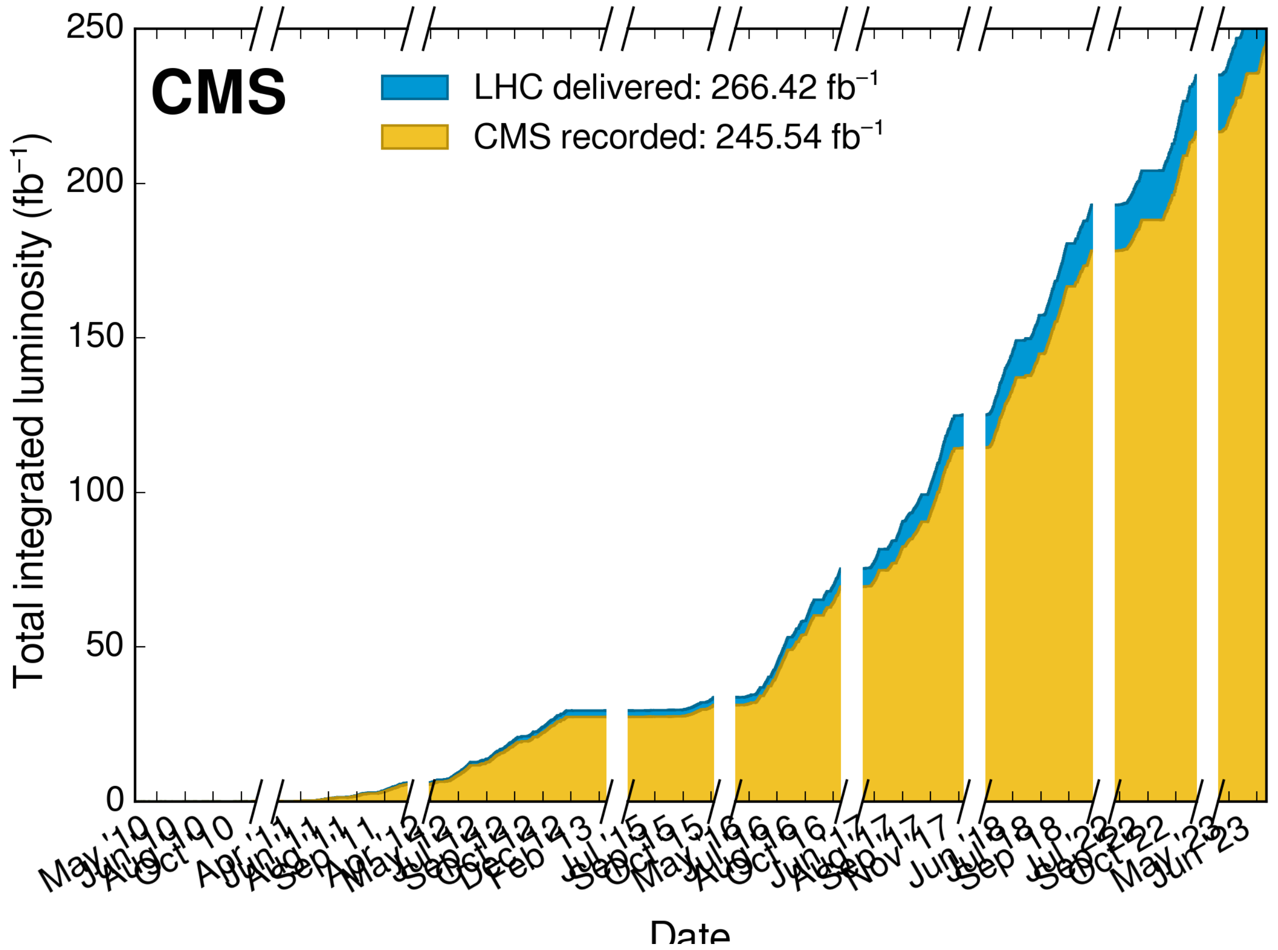
We're now a long way since the start of LHC journey

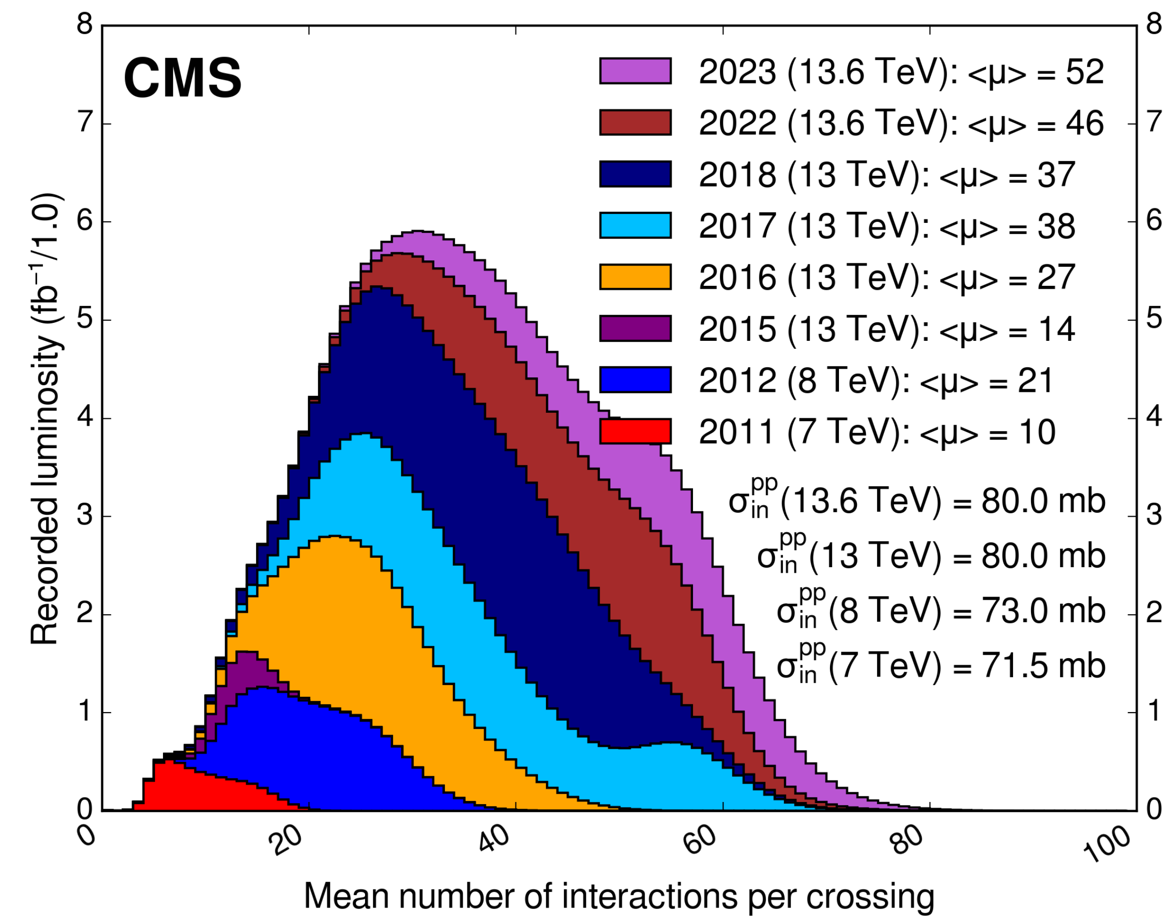
And we're entering the intensity frontier phase

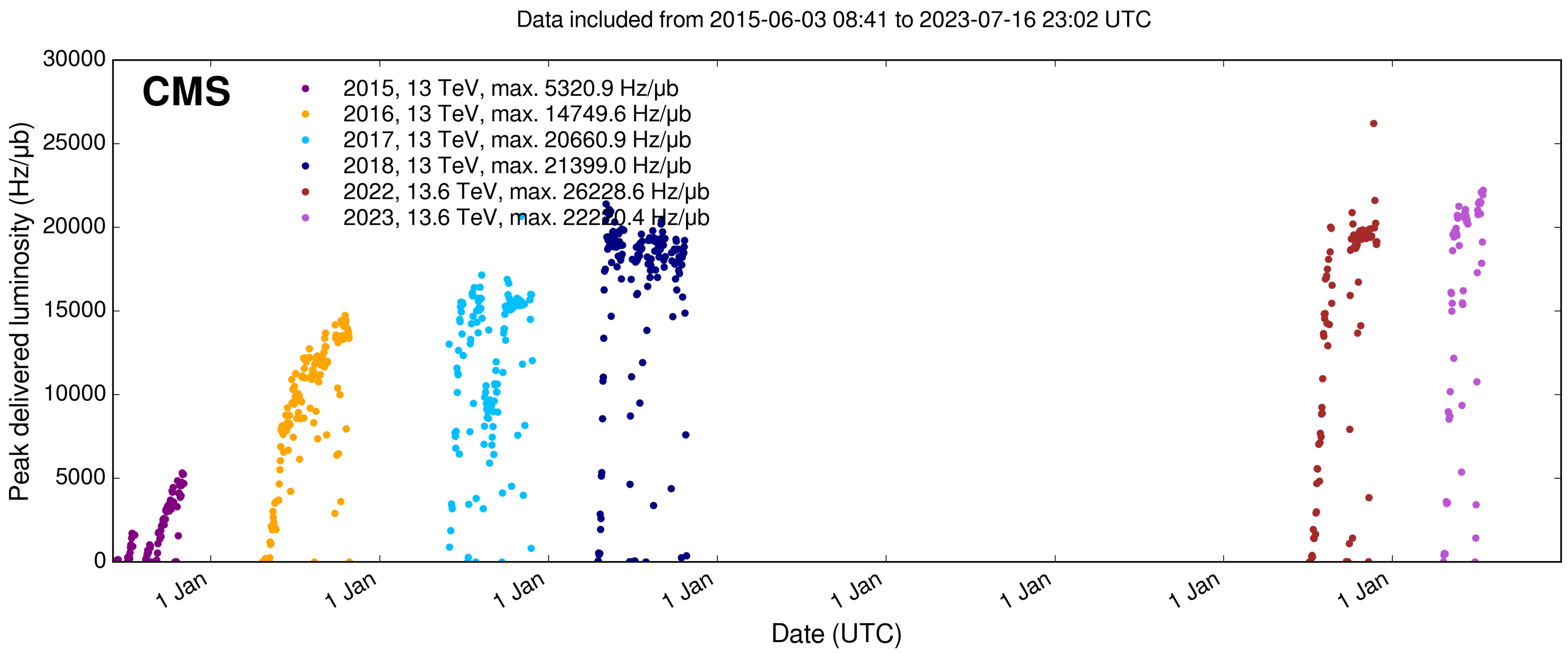
Collecting large, rich data sets

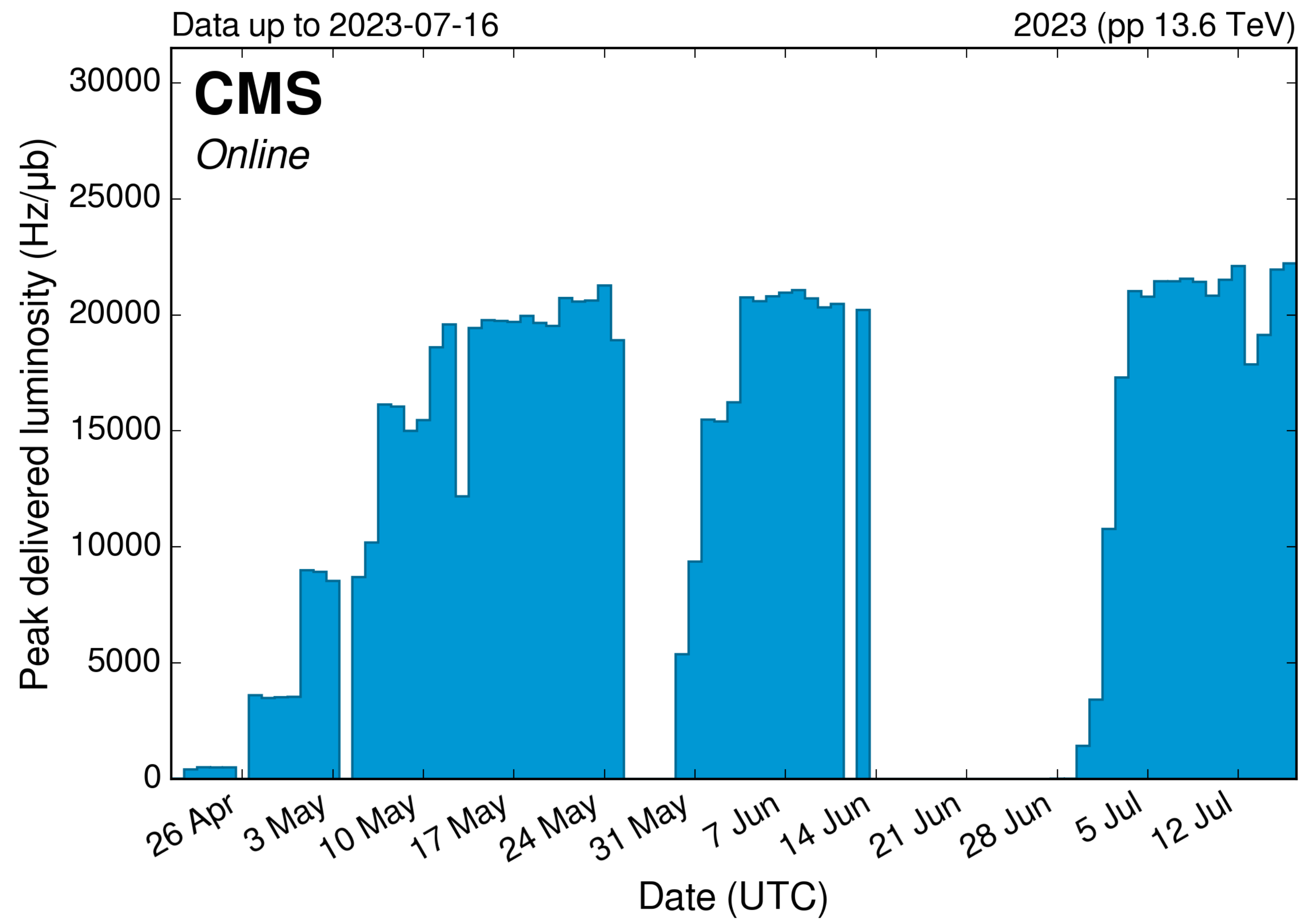
precision measurements
probe new rare processes



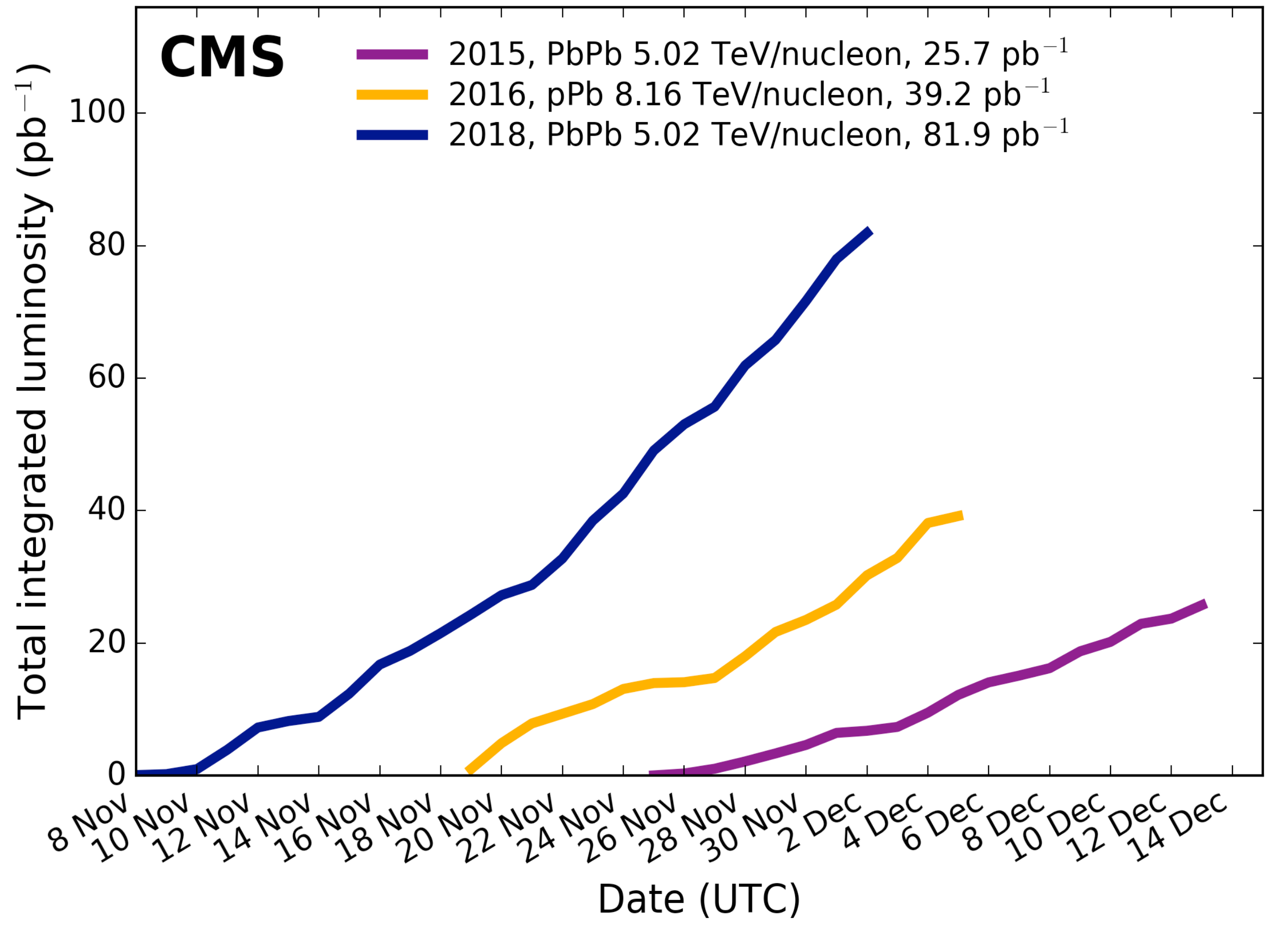


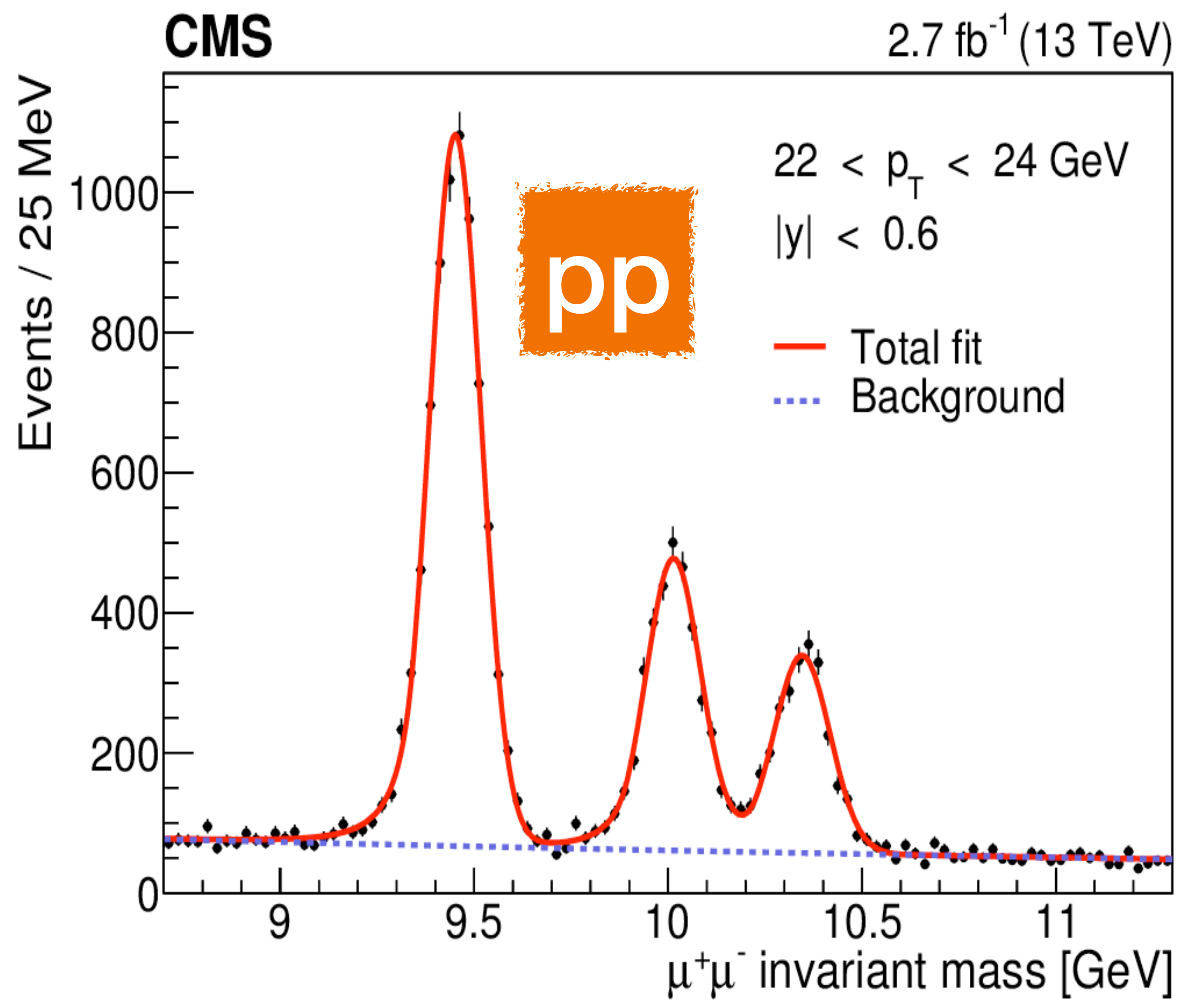


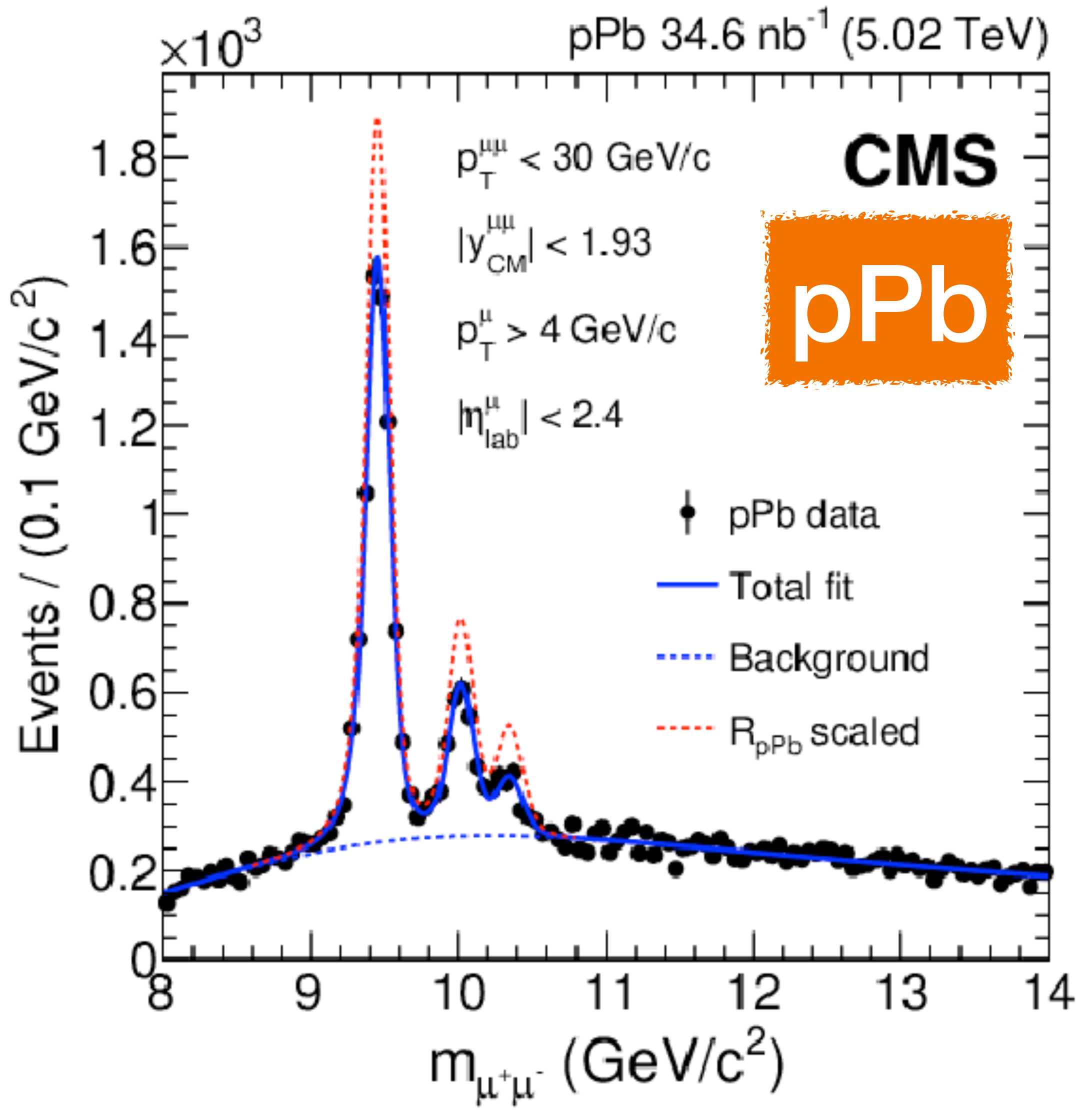


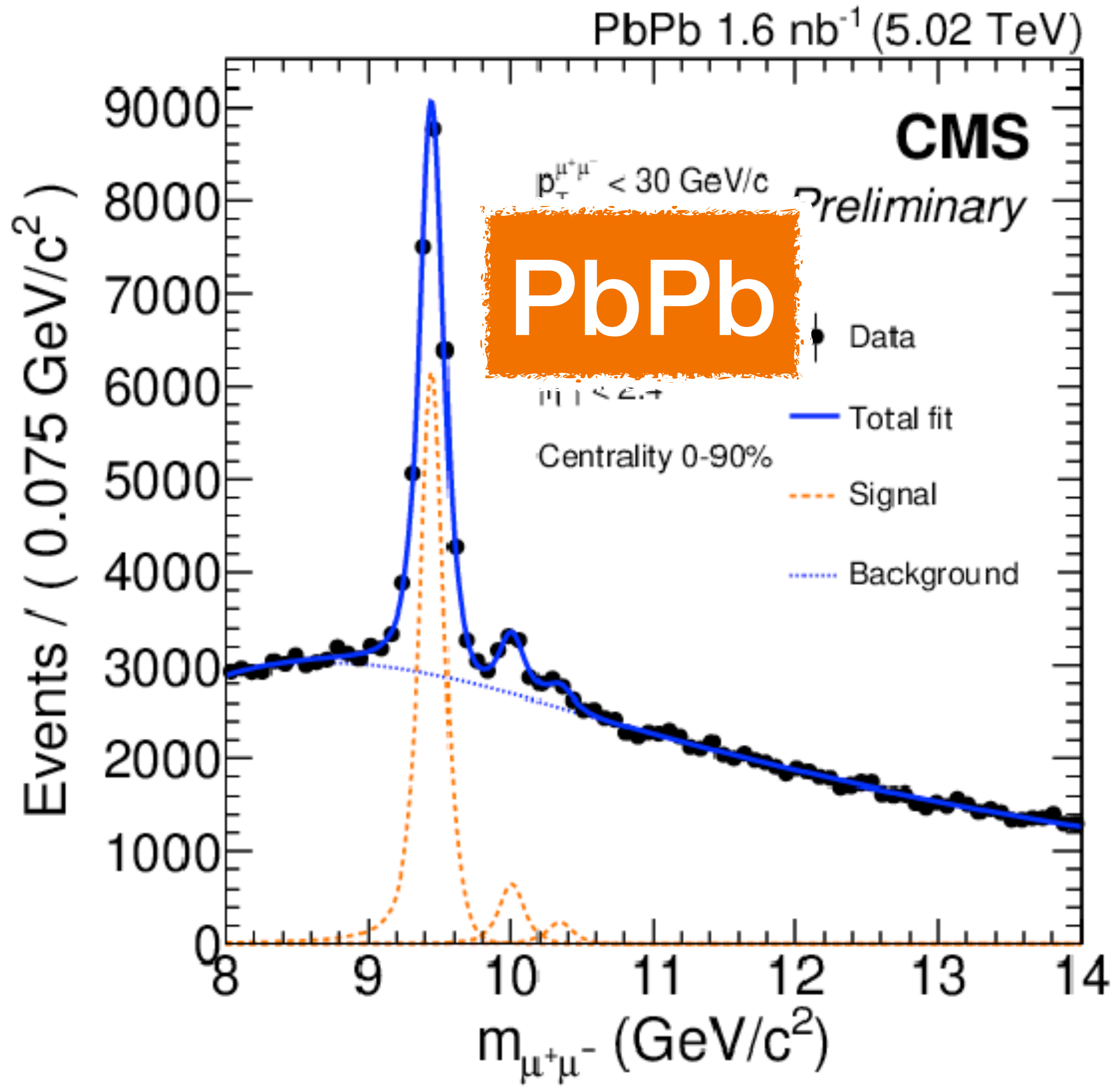


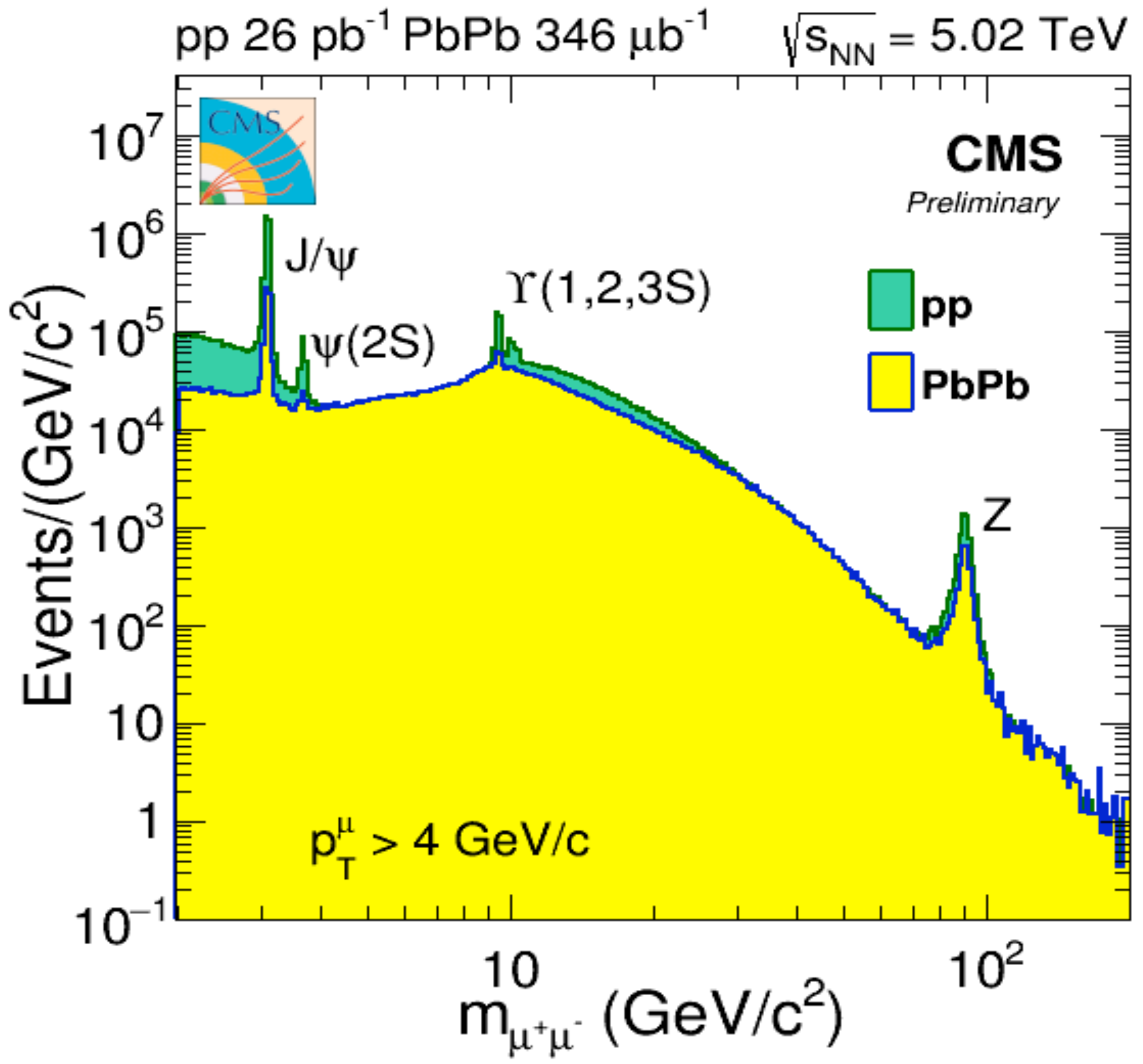
Exploring different collision systems and √s

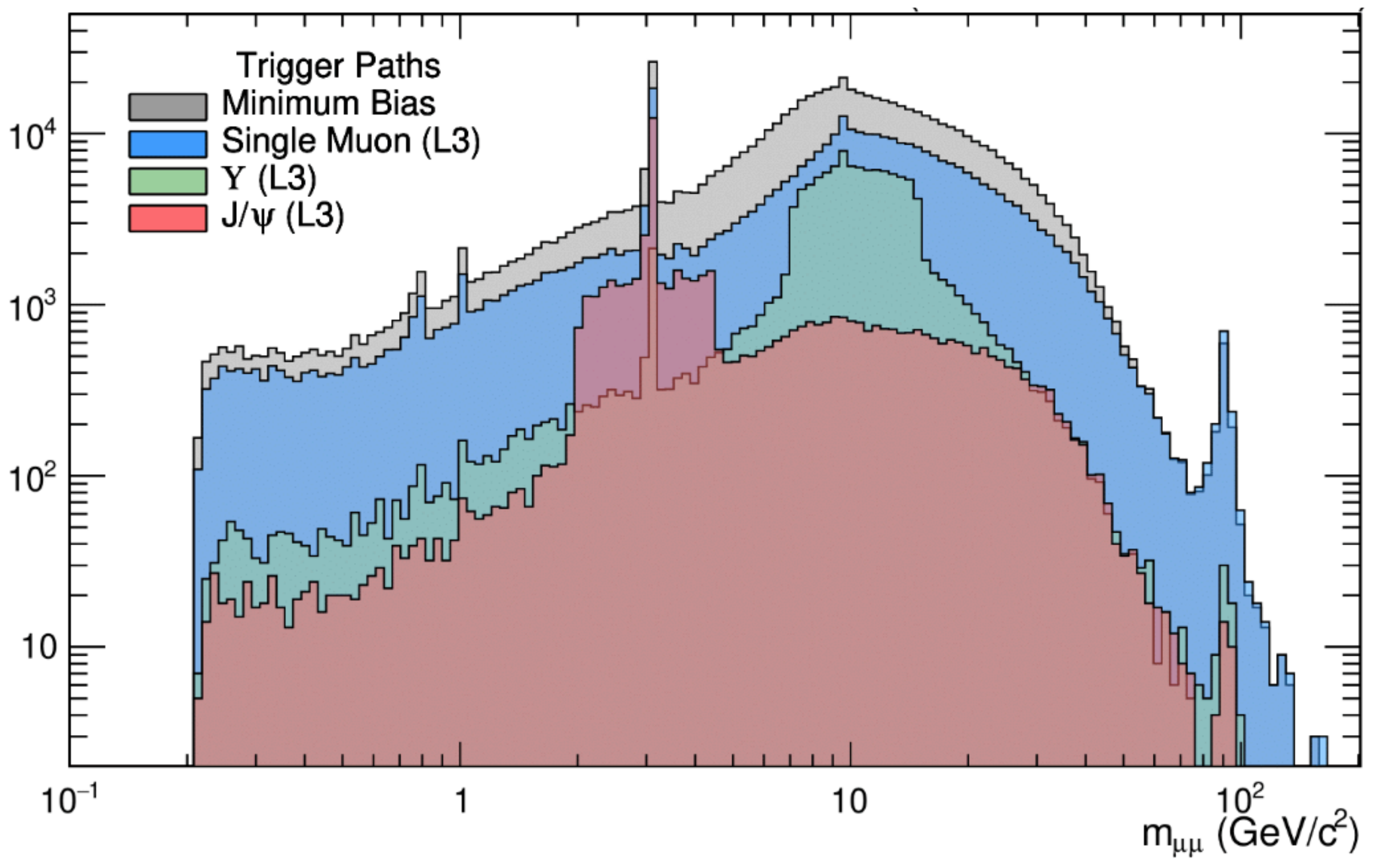


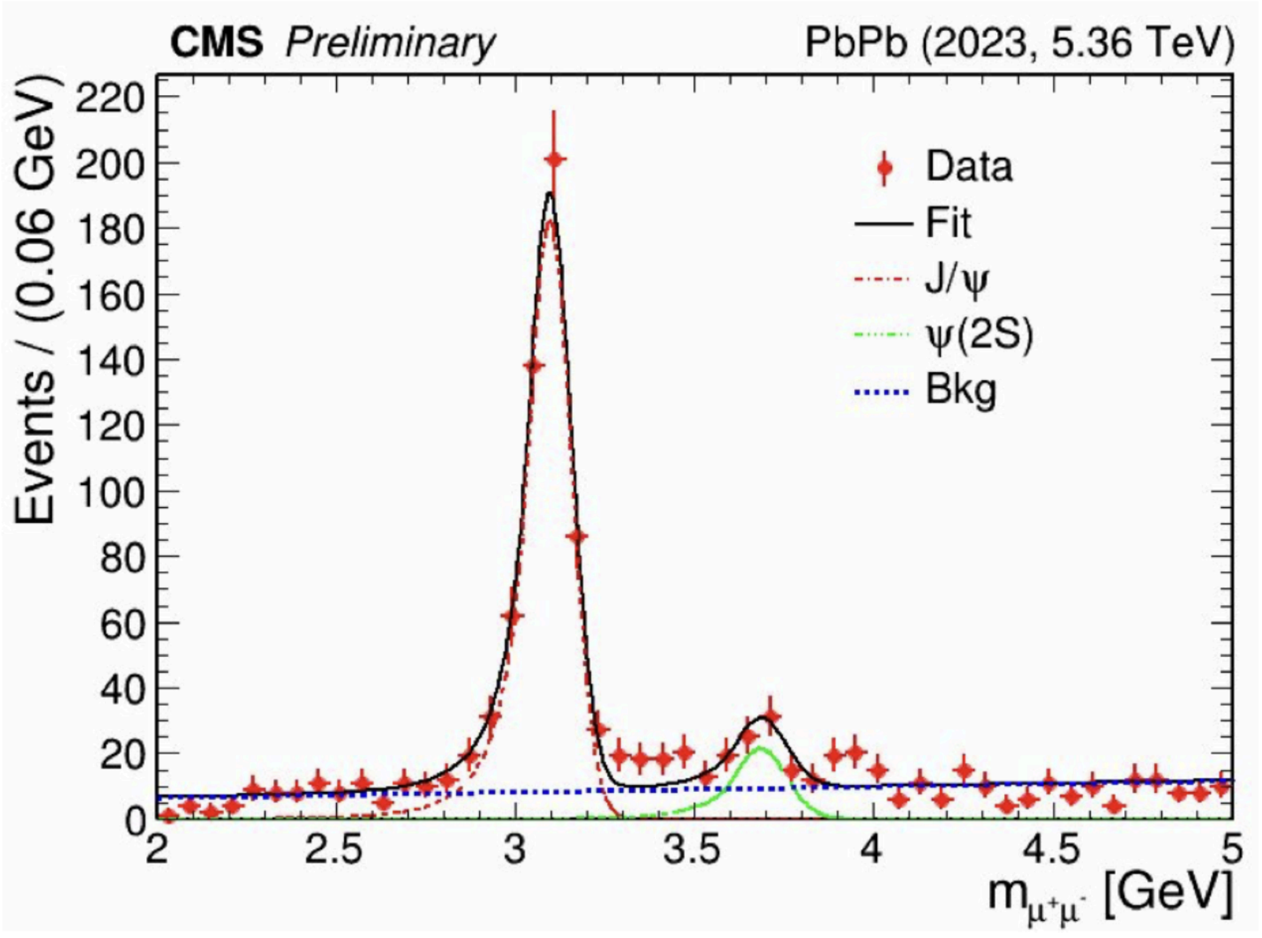




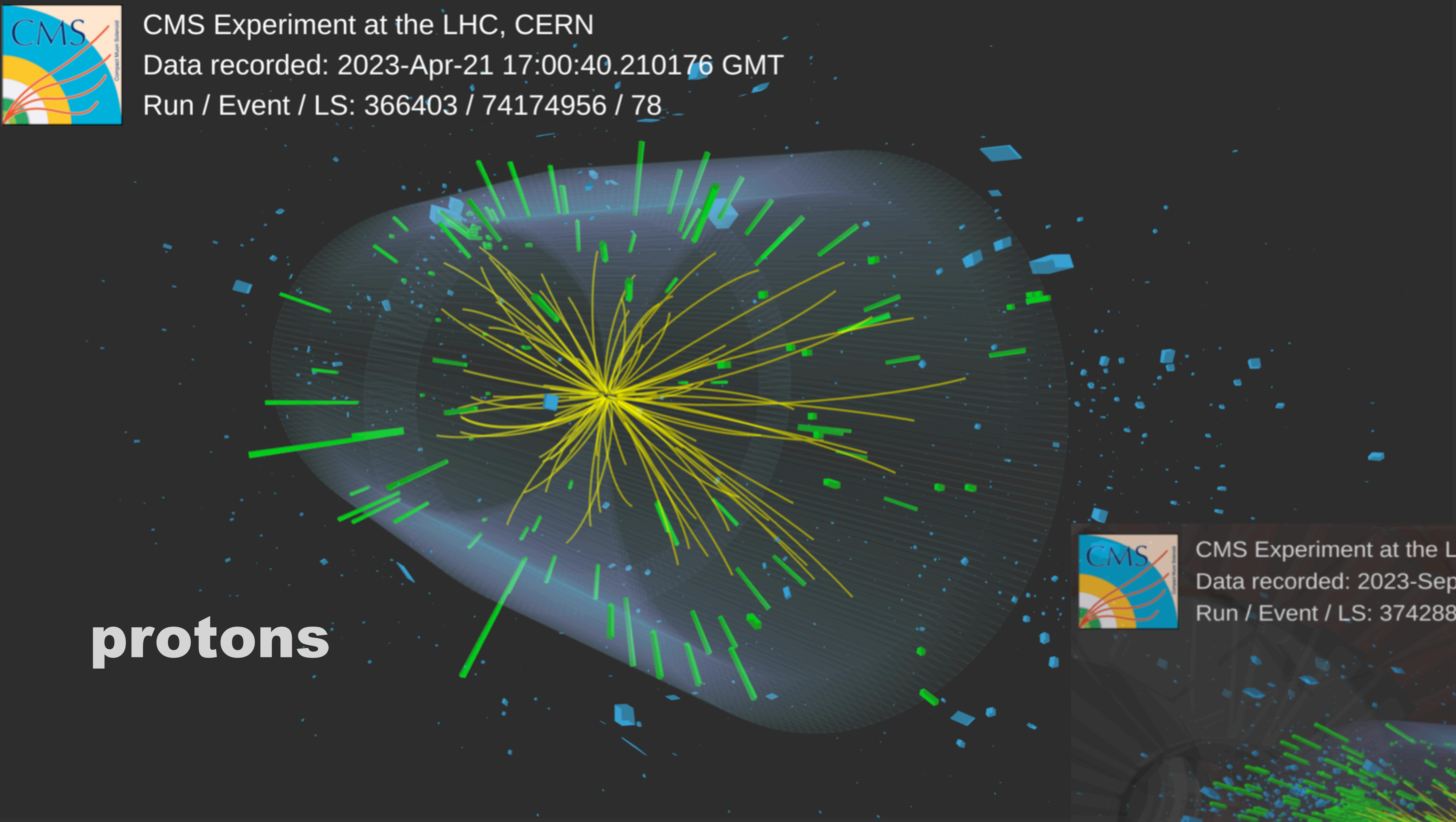




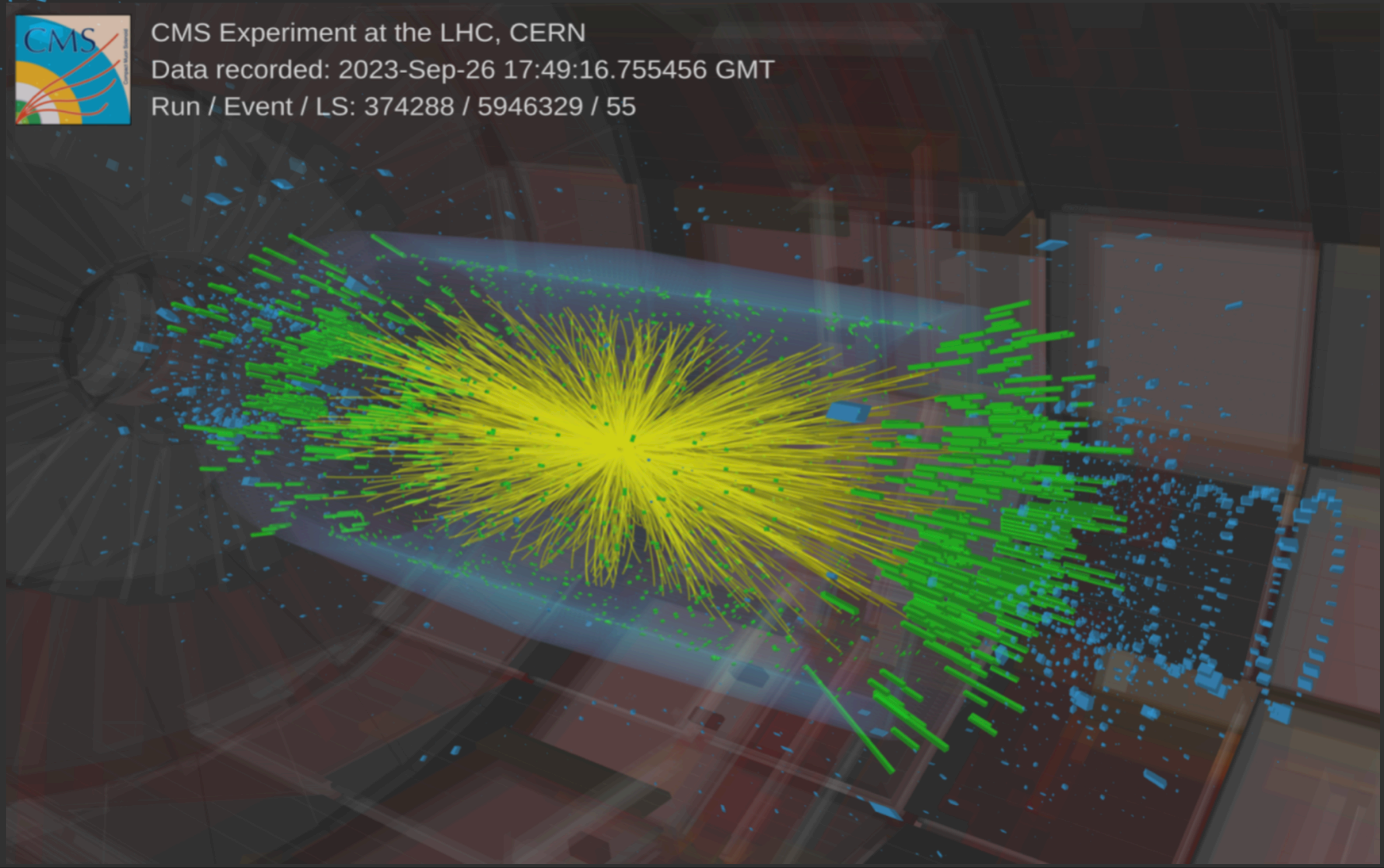




2023



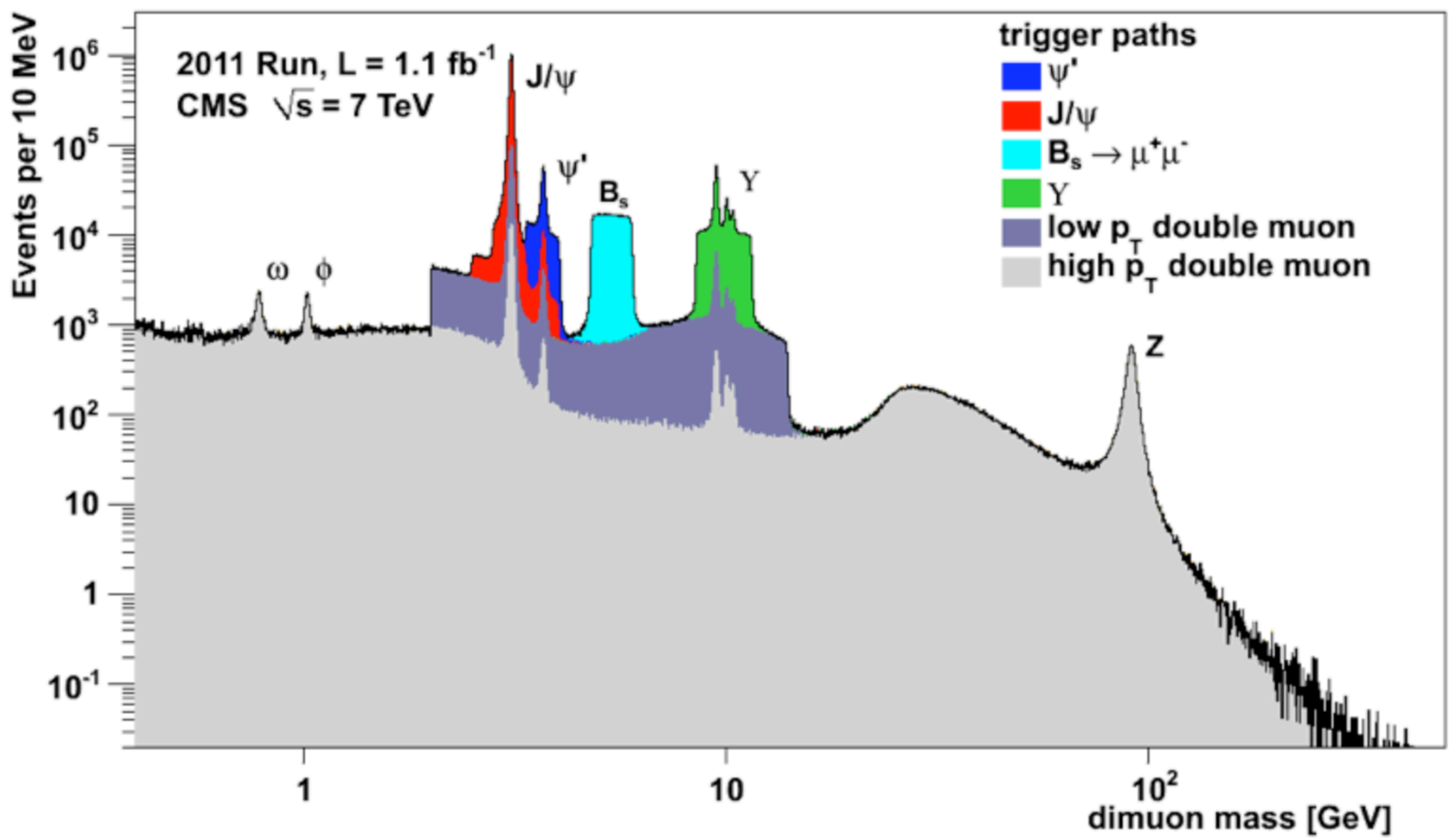
protons



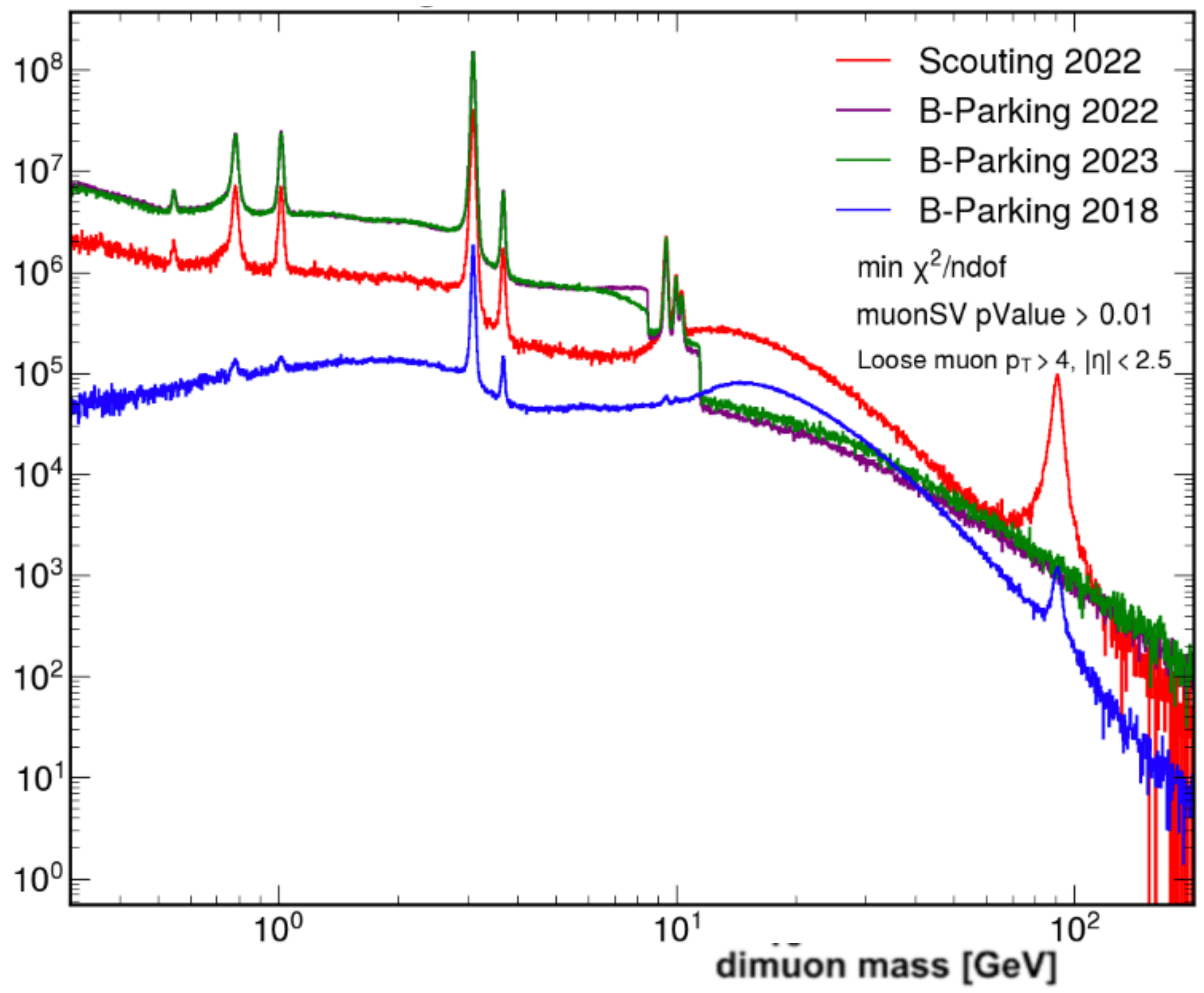
ions

Beyond luminosity

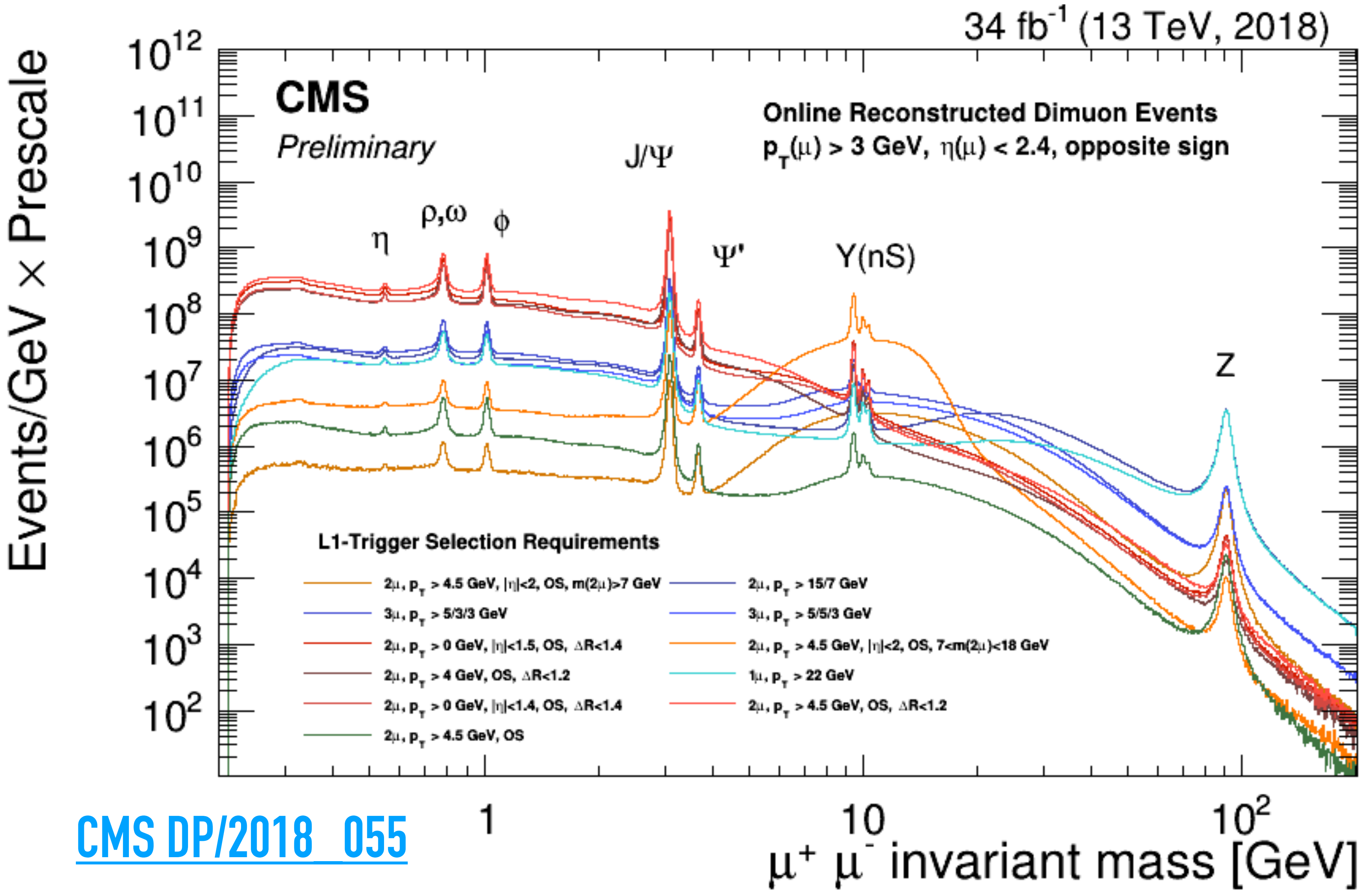
Dedicated trigger algorithms



Novel datataking paradigms



Special data streams: Scouting and Parking



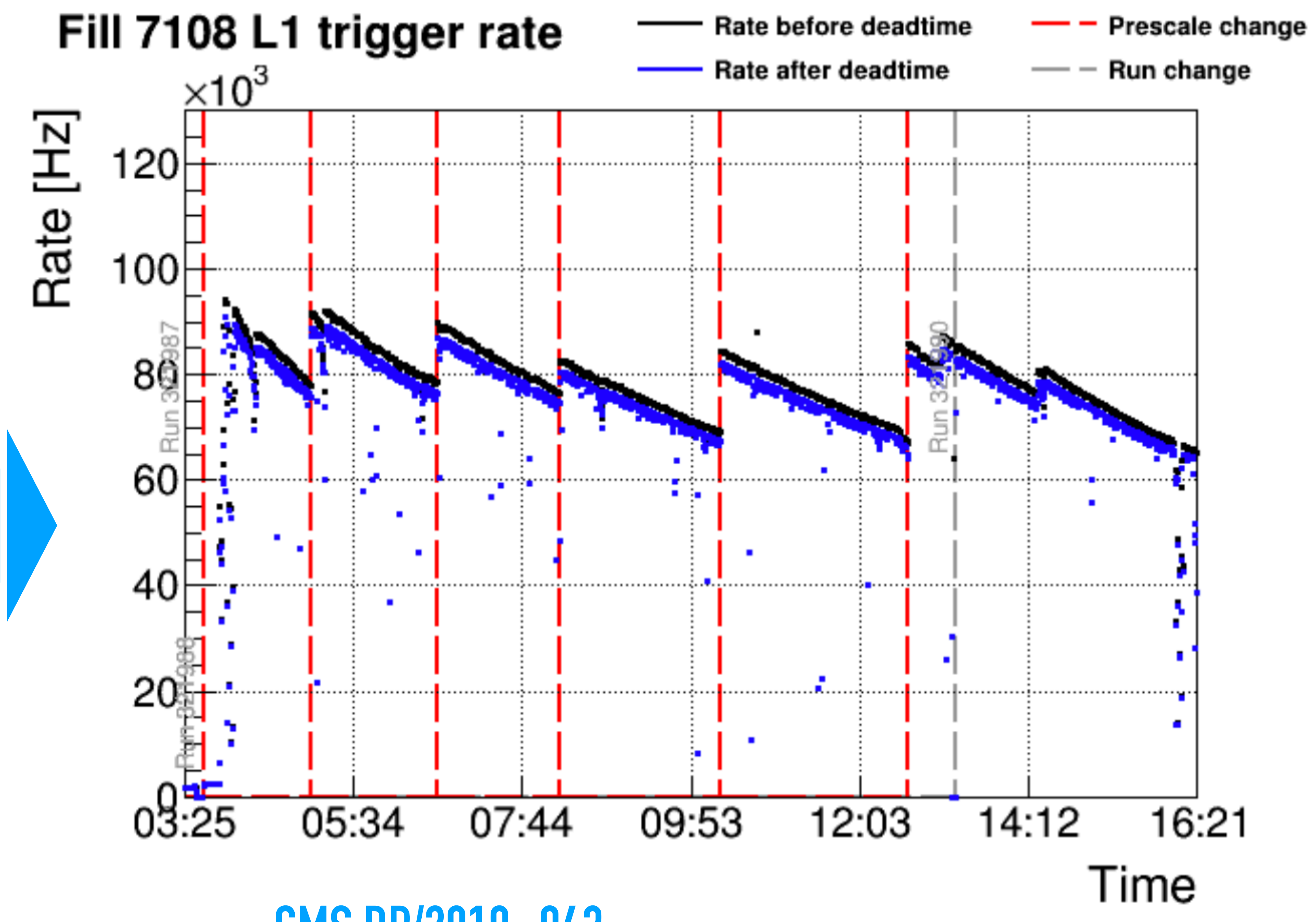
CMS DP/2018_055

Data Scouting

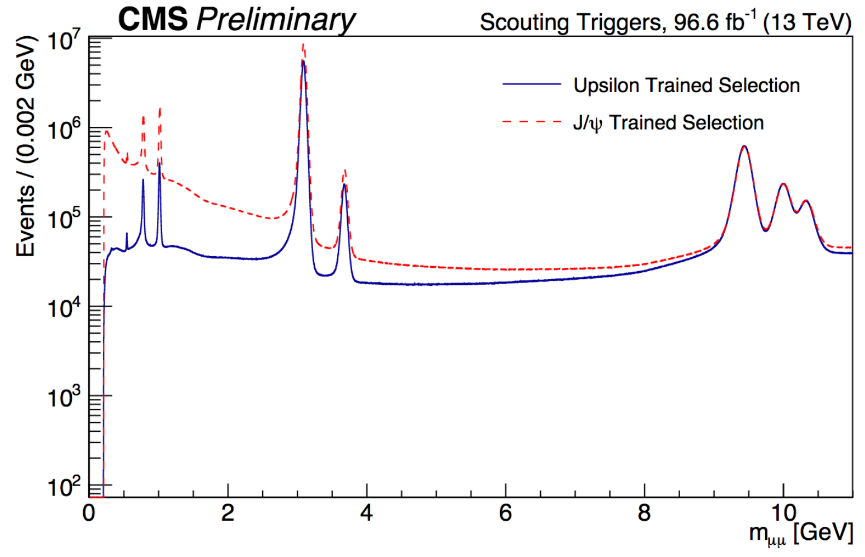
Reduced event content e.g. trigger info only

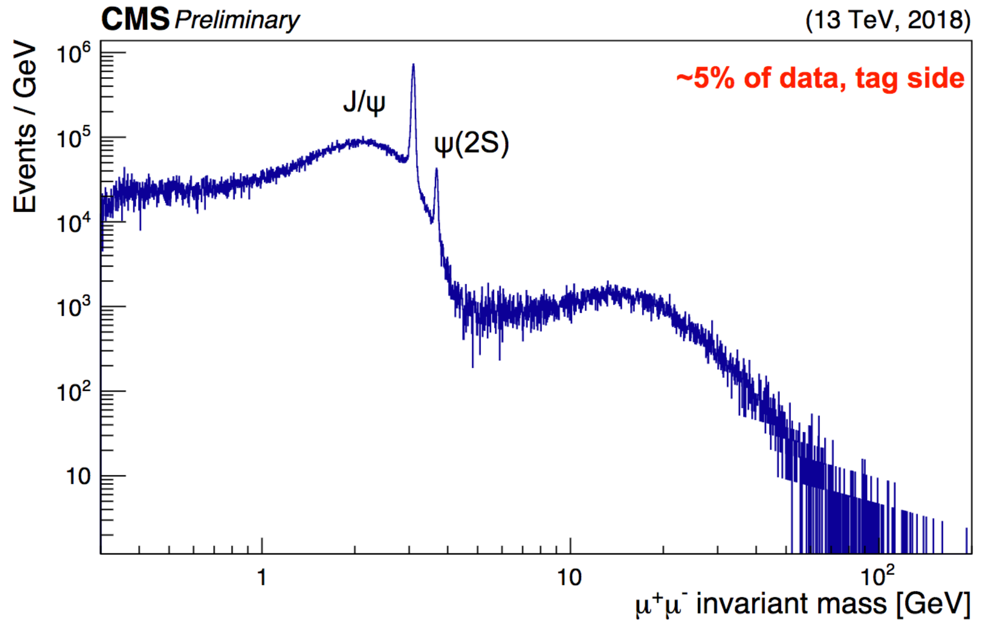
Data Parking

Park RAW data, delayed RECO



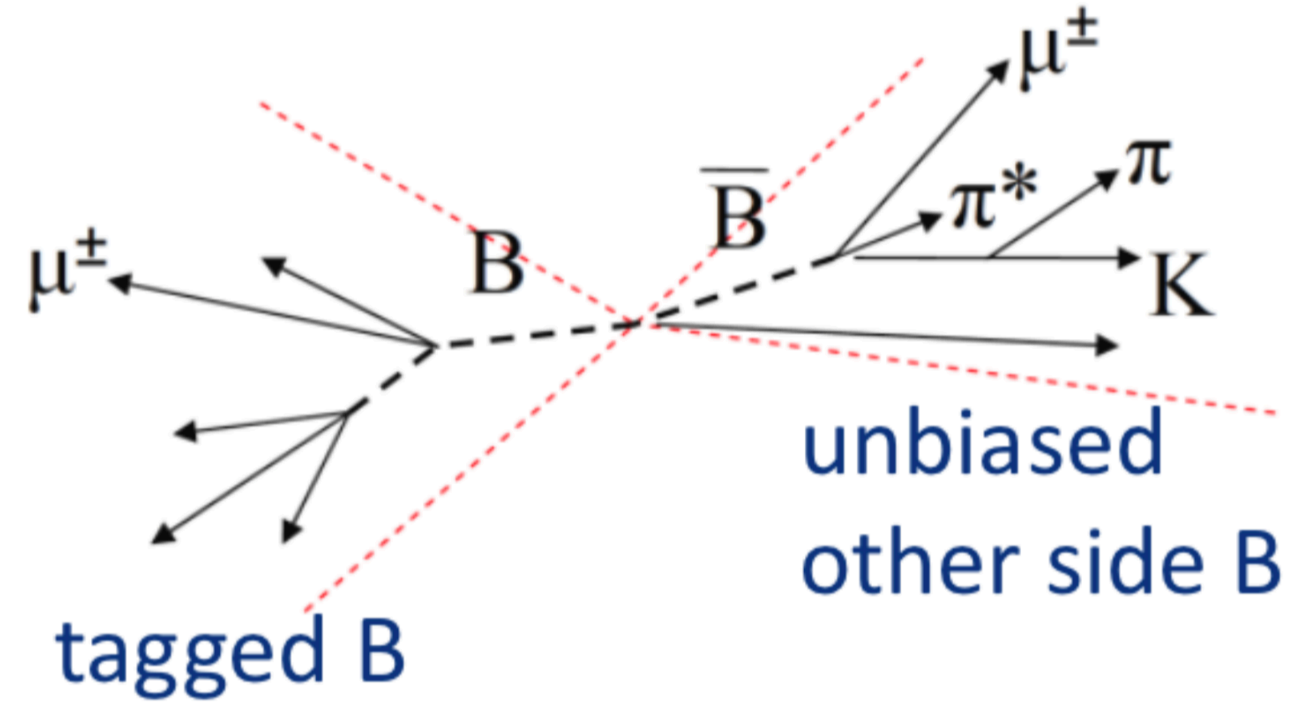
CMS DP/2019_043



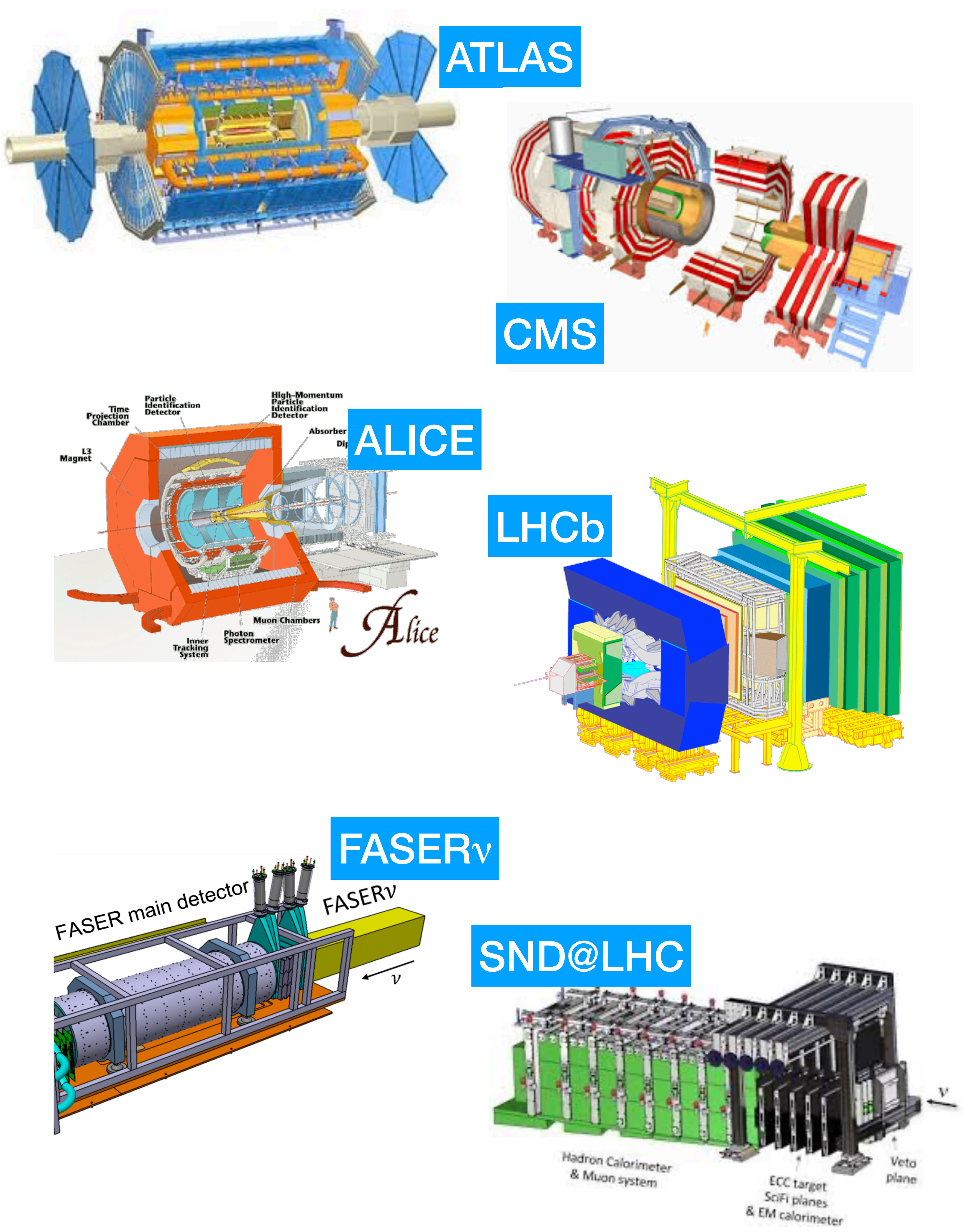


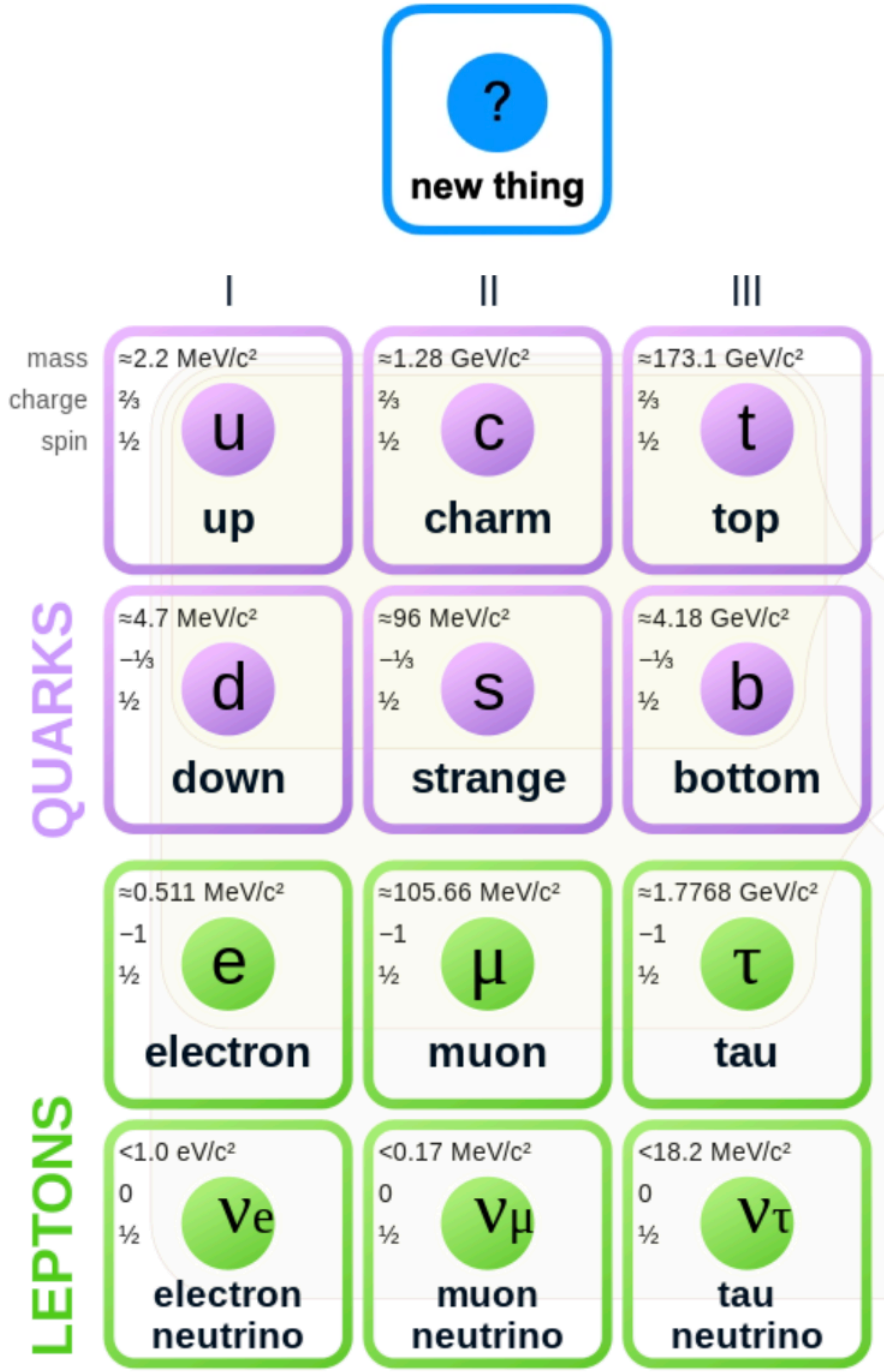
Trigger bandwidth

Event rate	x	Event size	
~ 1 kHz	x	~ 1 MB	= ~ 1 GB/s
increase rate	↩	decrease event size	
5 kHz	x	1.5 kB	= 7.5 MB/s



Flavour @ LHC





Direct search for new particles

Indirect search for new particles

Beauty and charm production

New hadrons and spectroscopy

New and rare decays

Flavour mixing and CKM

Proton and Ion collisions

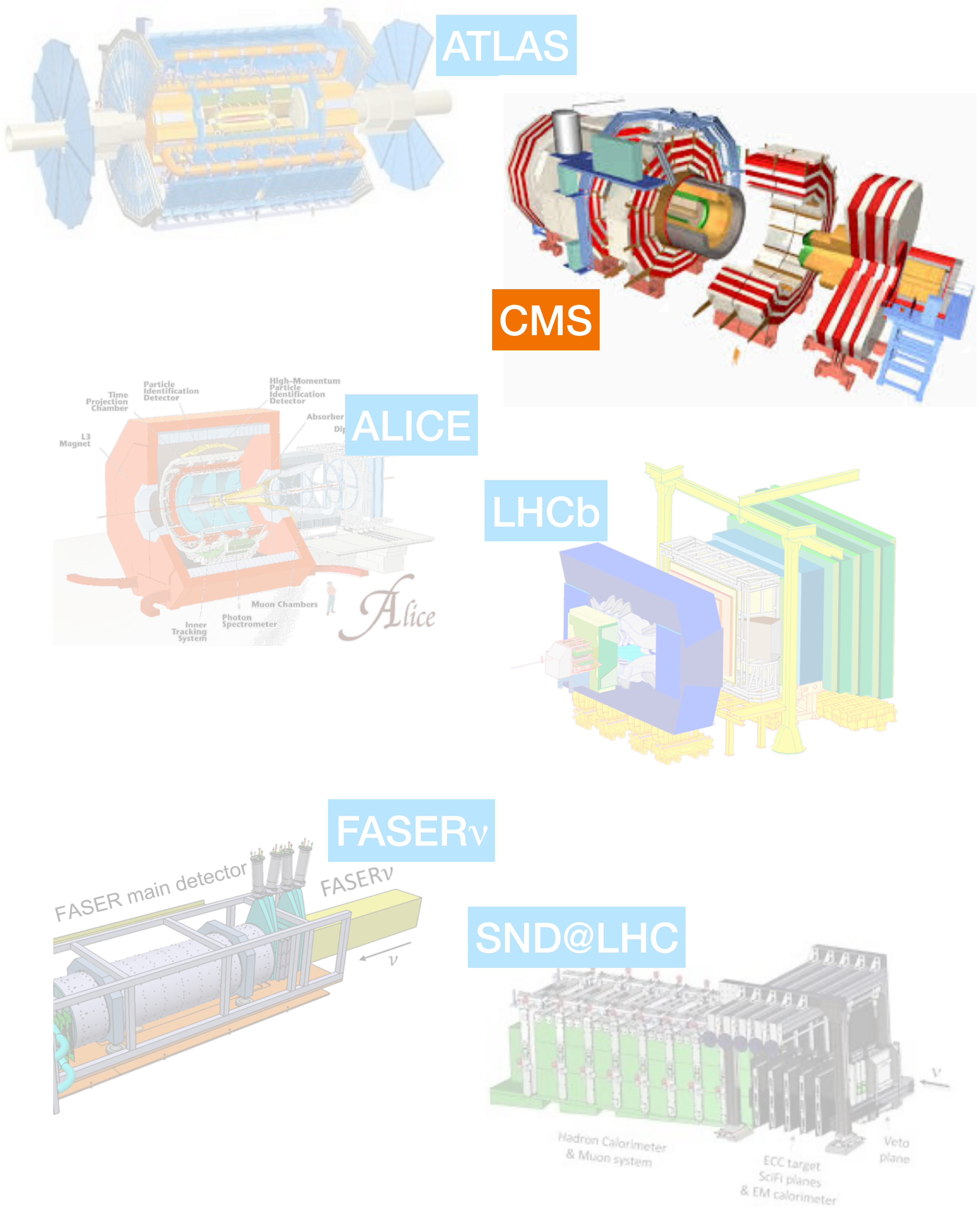
Lepton flavour universality: e vs μ vs τ

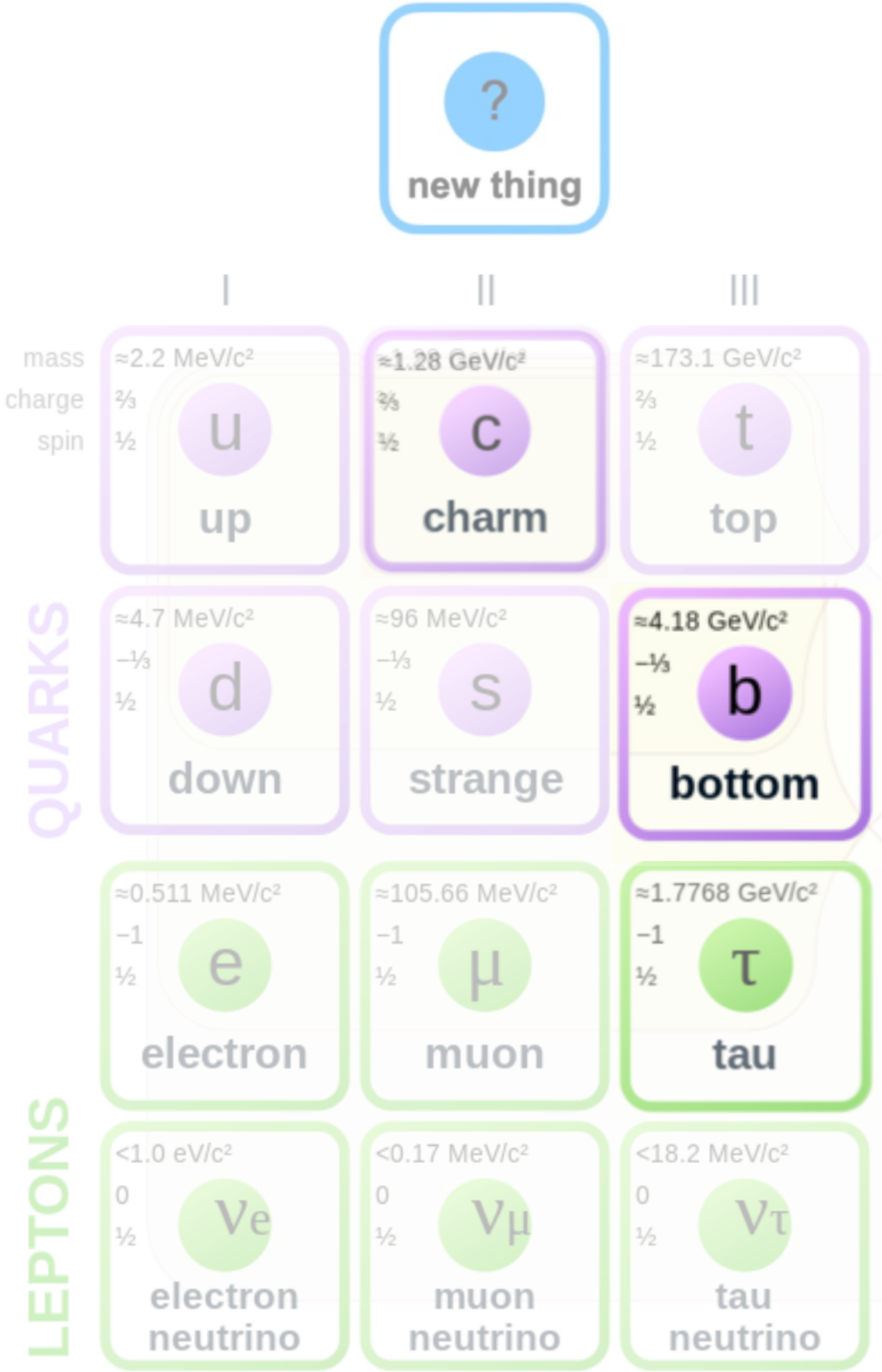
Lepton flavour violation: $\tau \rightarrow \mu\mu\mu$

First neutrino measurements at LHC

Heavy flavour production @high rapidity

Flavour @ CMS





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First neutrino measurements at LHC

Heavy flavour production @high rapidity

Heavy Flavour

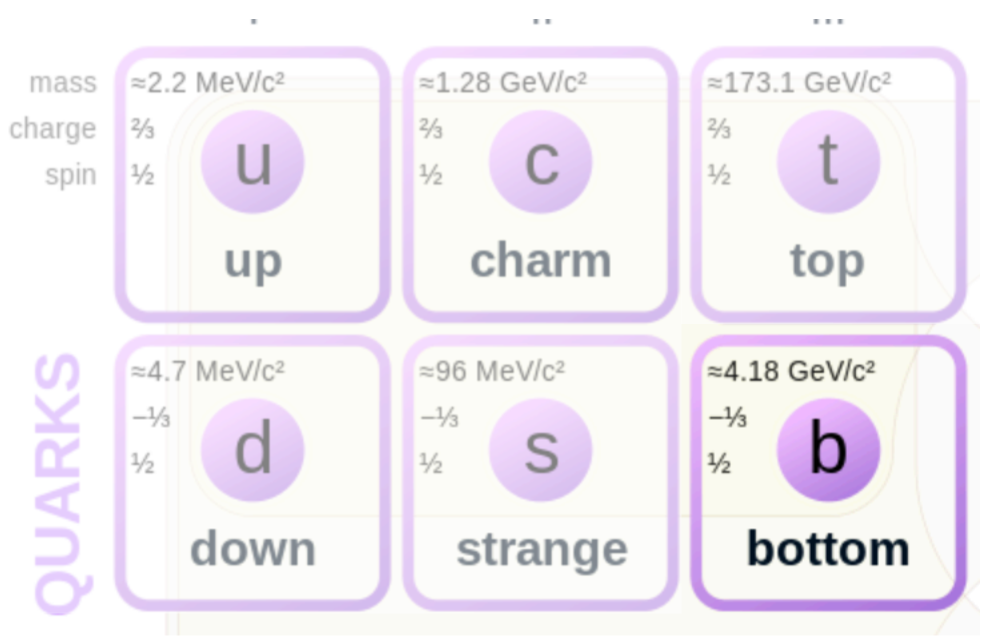
in vacuum

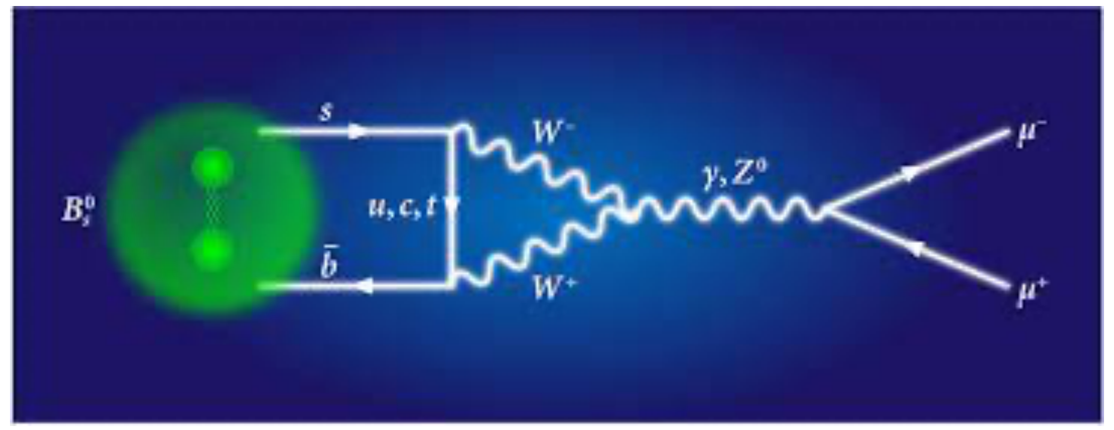
in hot medium

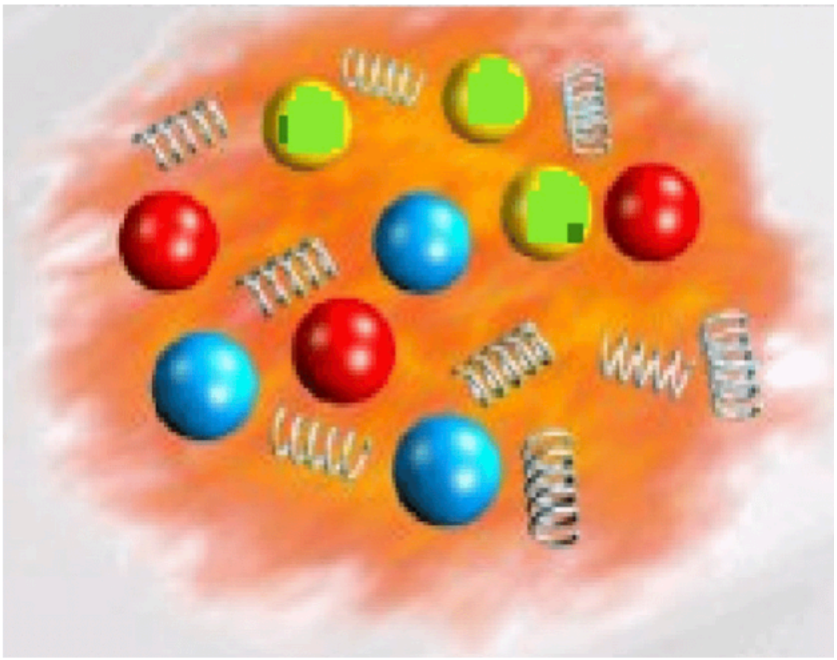
b-quark hadrons

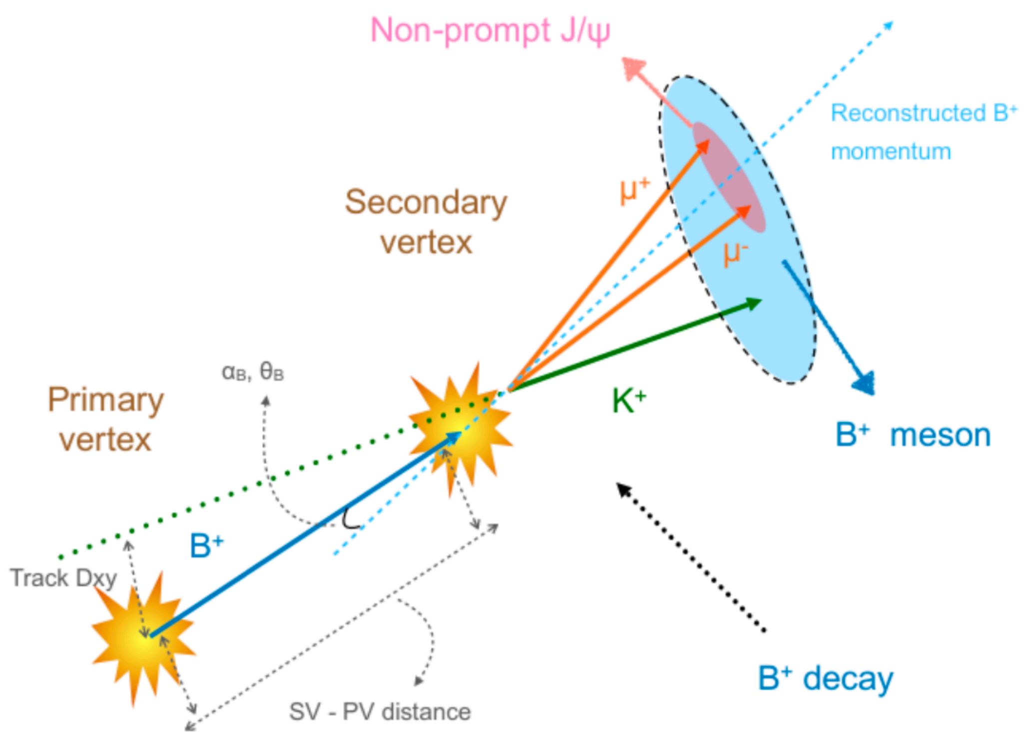
proton-proton collisions

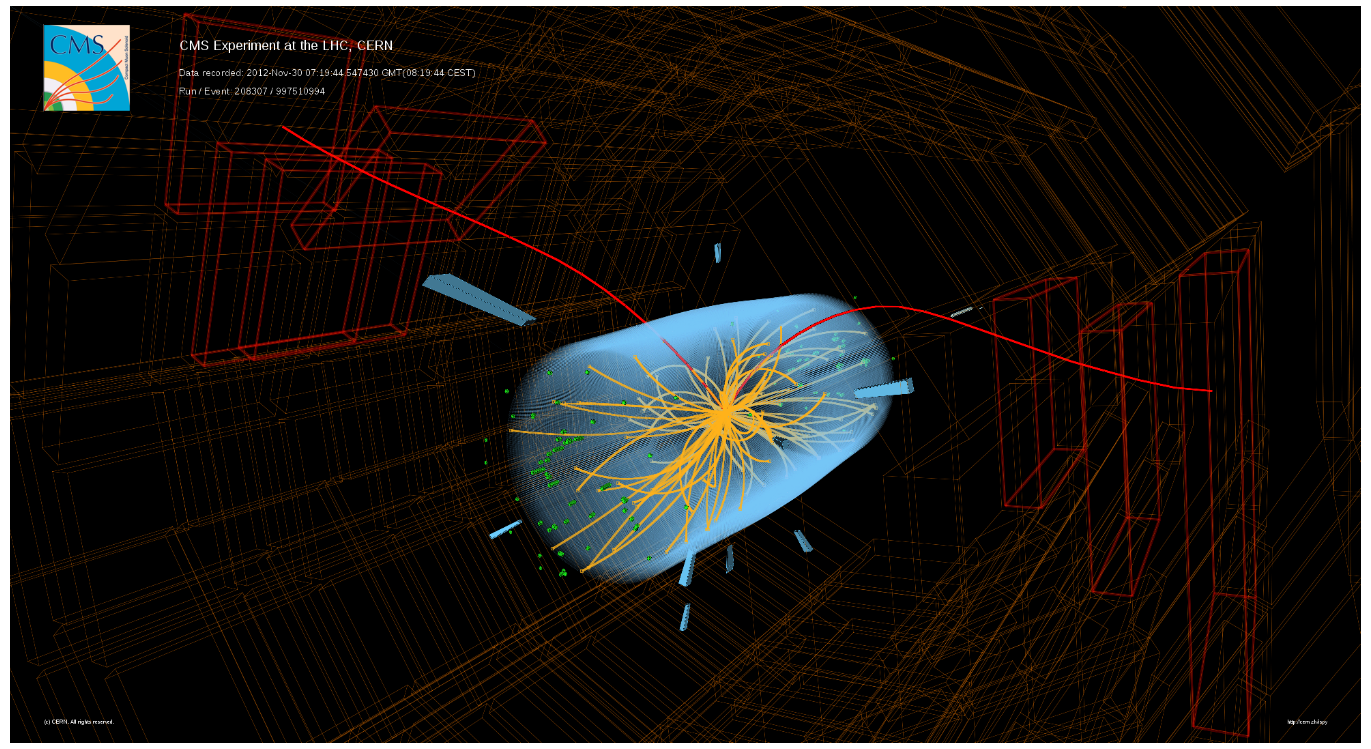
created in UR nuclear collisions

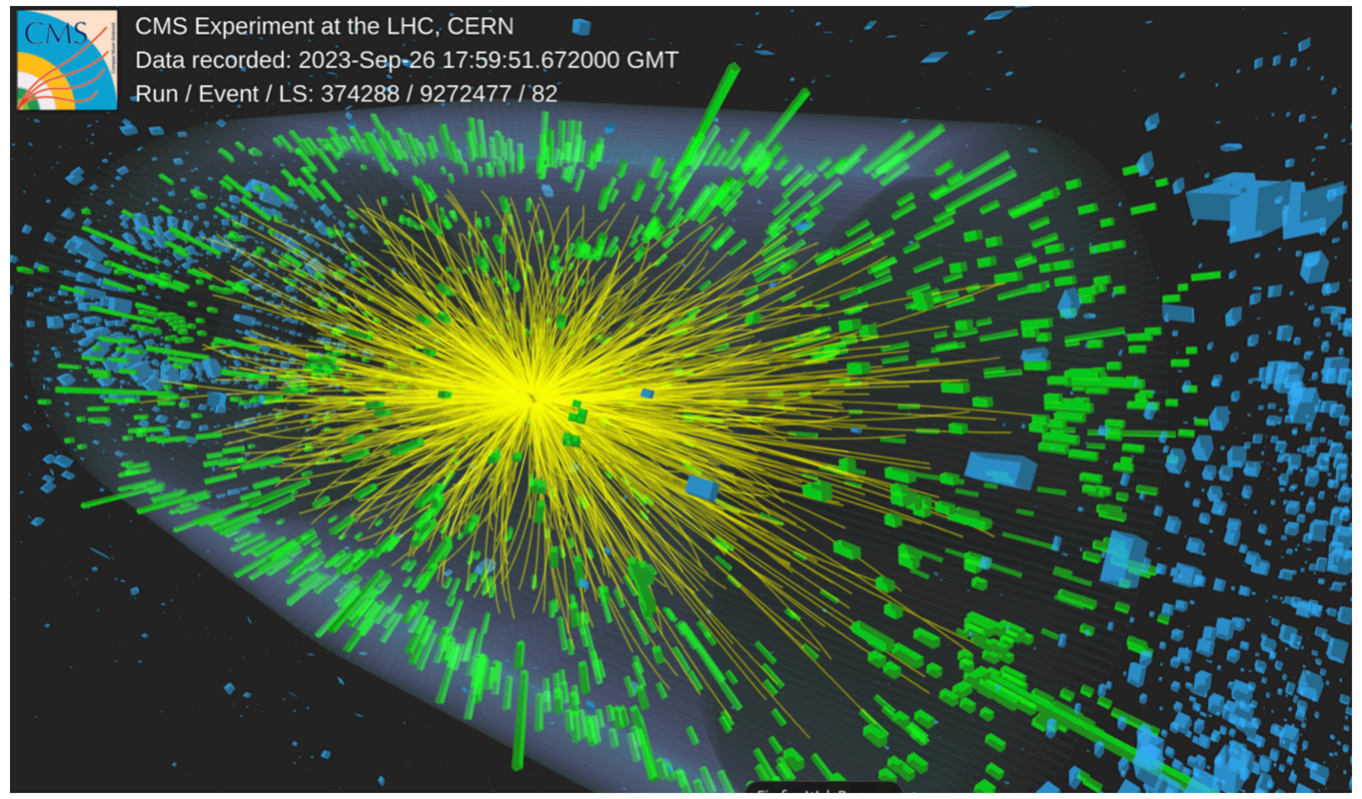






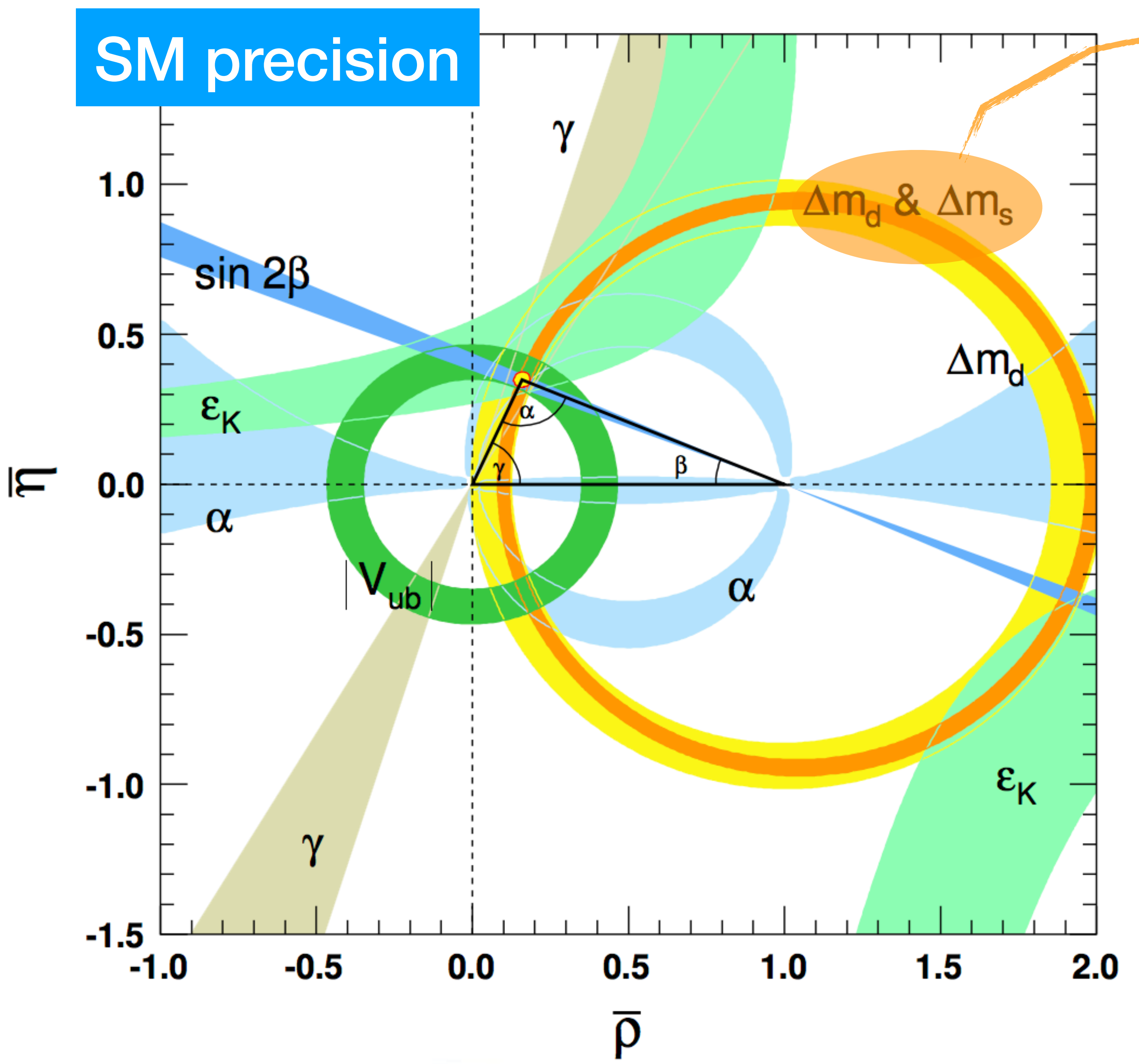


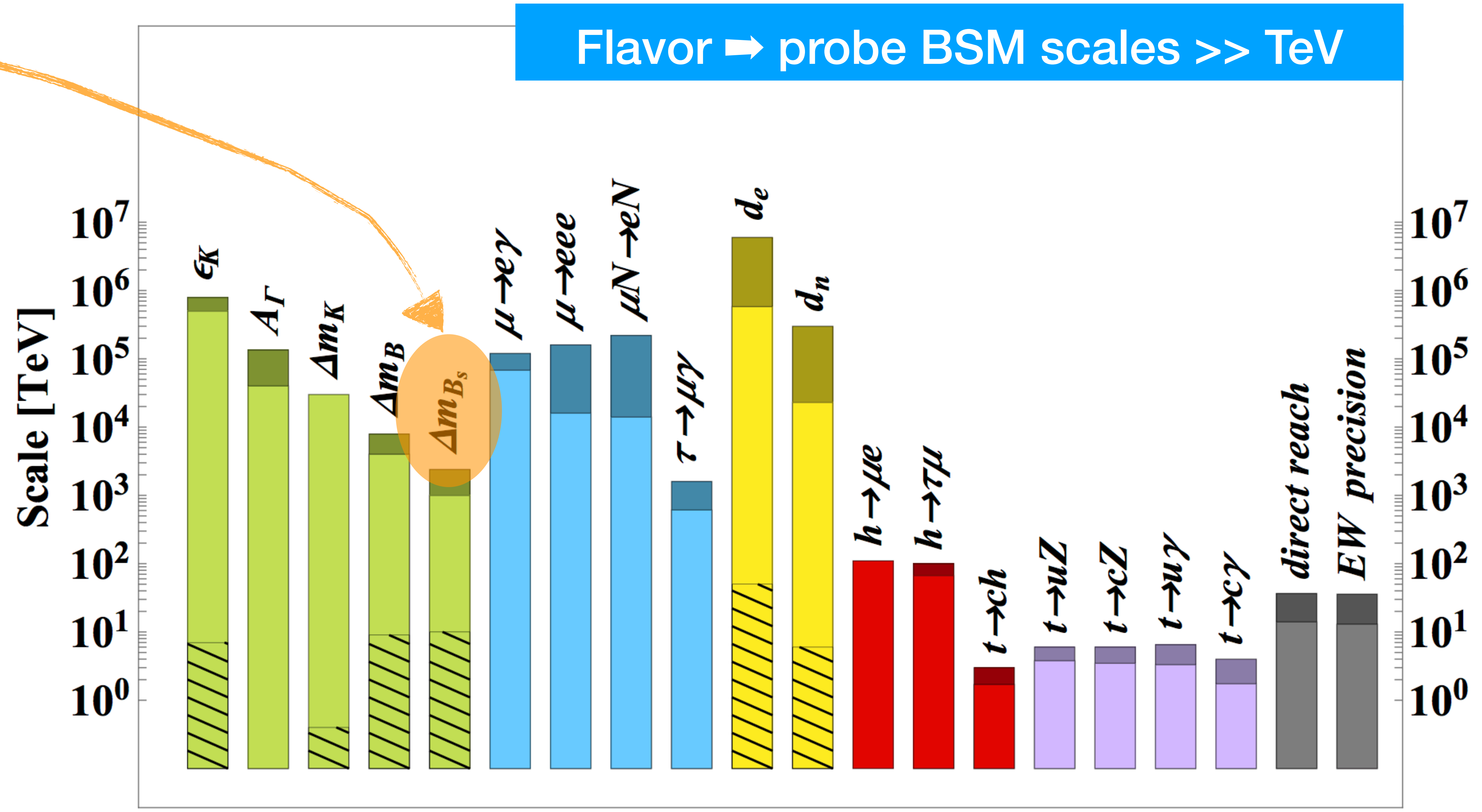




Note: CMS while not designed primarily for either heavy flavour *or* heavy ions, has been consistently making leading contributions to both areas

Flavour = SM precision + BSM search





European Strategy Update

ESPPU 2020

Snowmass 2021

P5 Report 2023

Decipher the Quantum Realm

Explore New Paradigms in Physics

Illuminate the Hidden Universe

Elucidate the Mysteries of Neutrinos

Search for Direct Evidence of New Particles

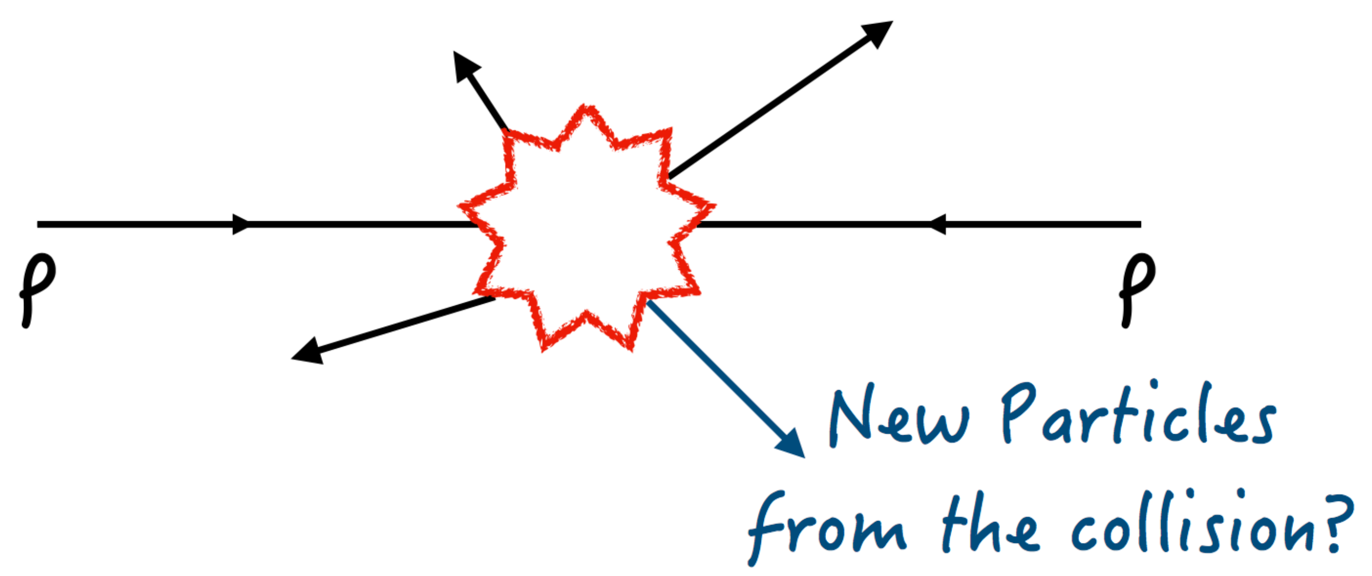
Determine the Nature of Dark Matter

Reveal the Secrets of the Higgs Boson

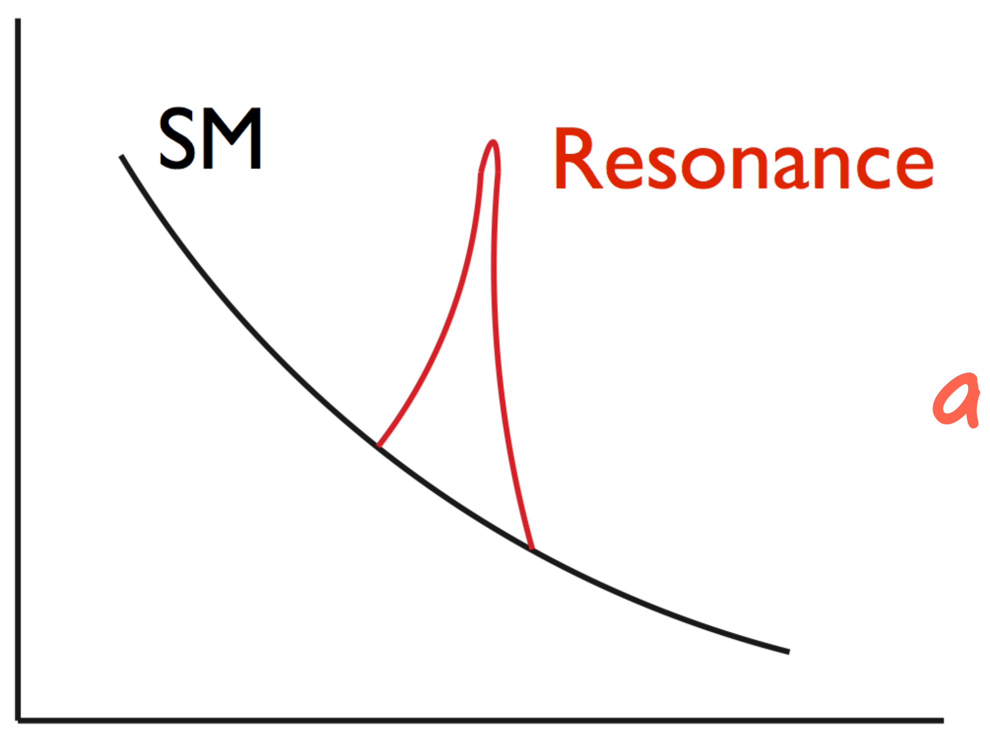
Pursue Quantum Imprints of New Phenomena

Understand What Drives Cosmic Evolution

Direct evidence for NP

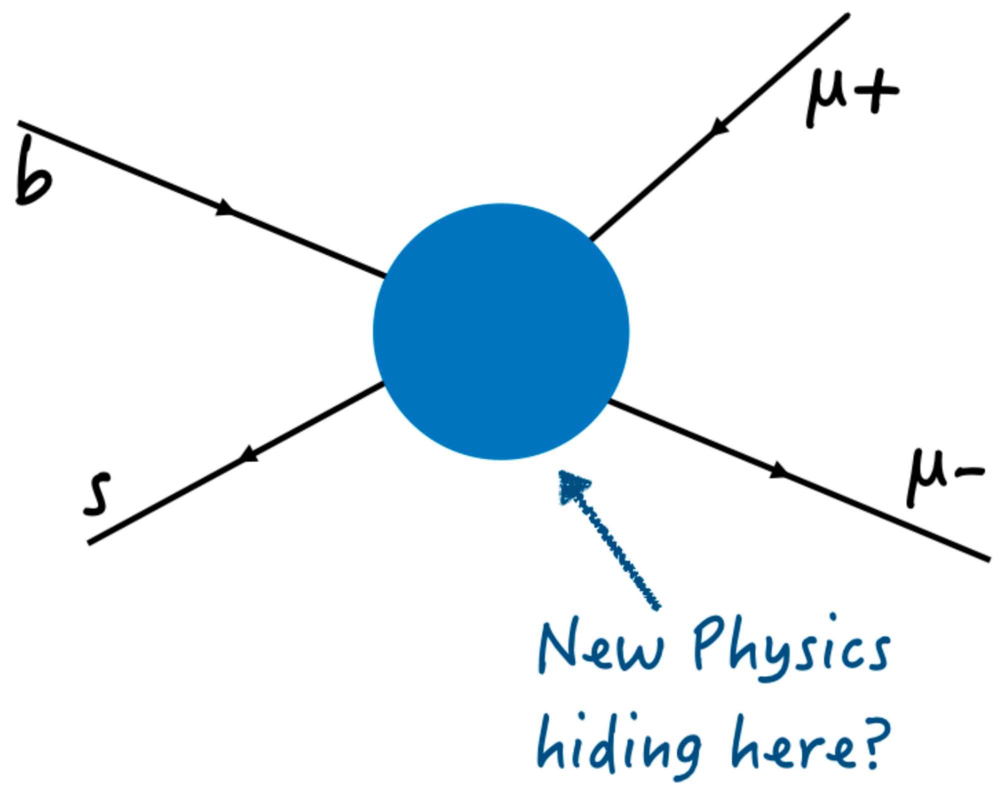


- searching for the decay products of NP particles produced in collision

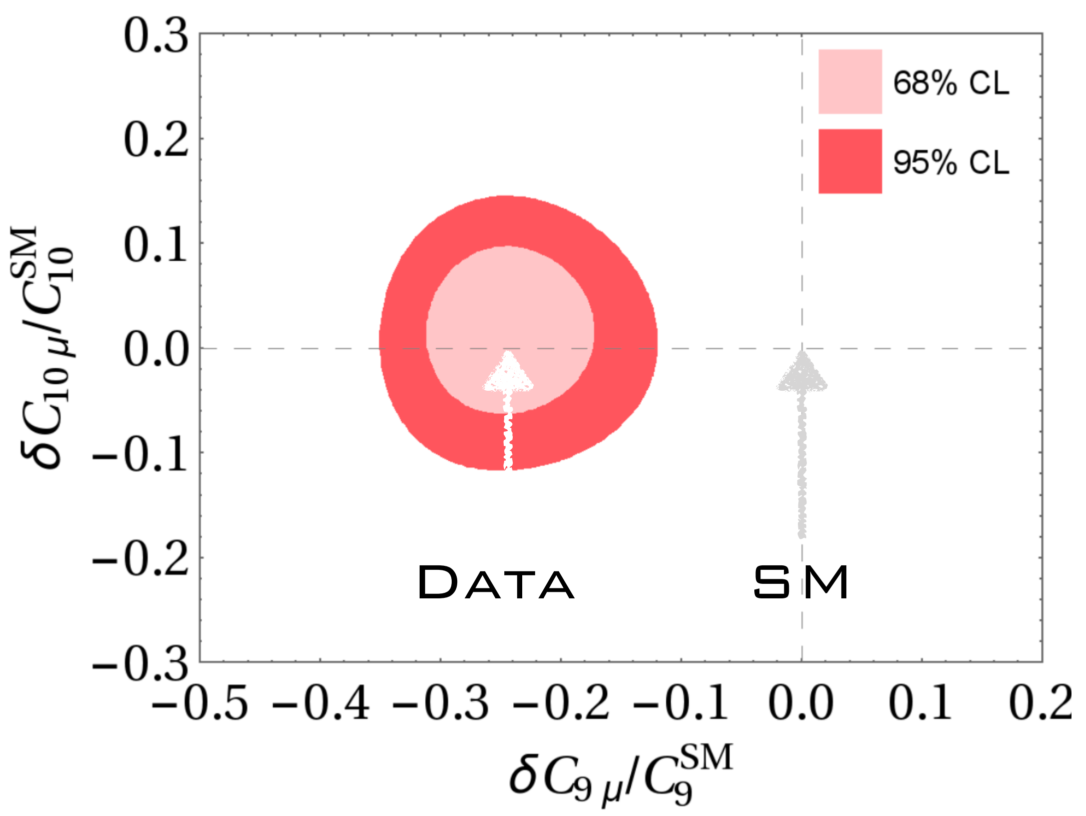


a la Higgs

Quantum **Imprints** of *NP*

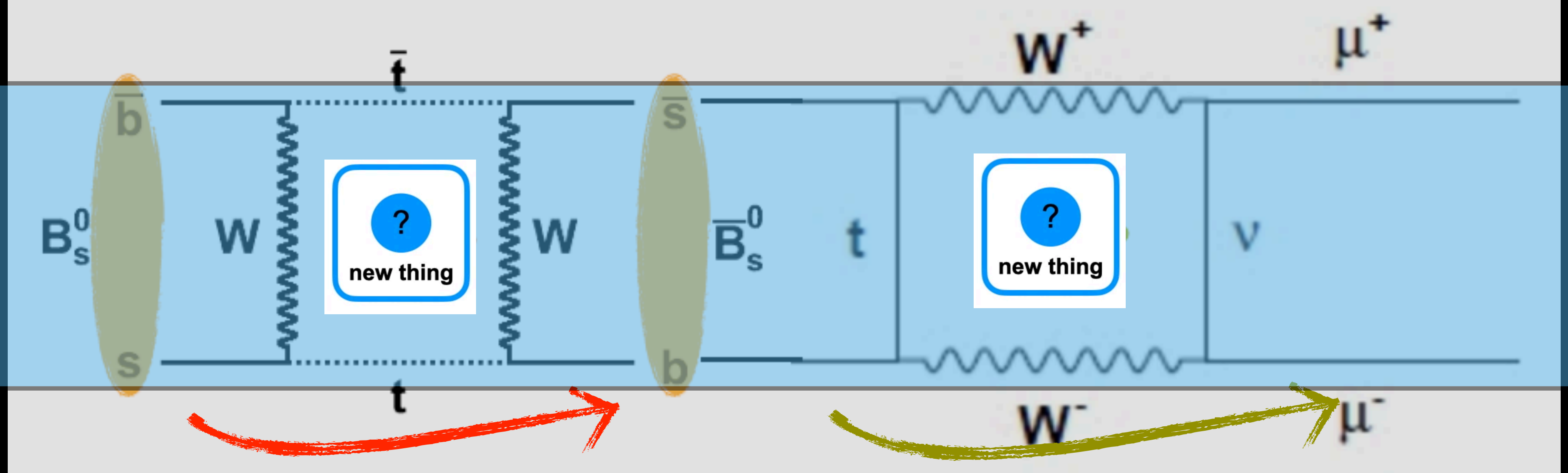


- searching for effects of NP particles running in quantum loops (virtual)



↪ flavour!

B → μμ

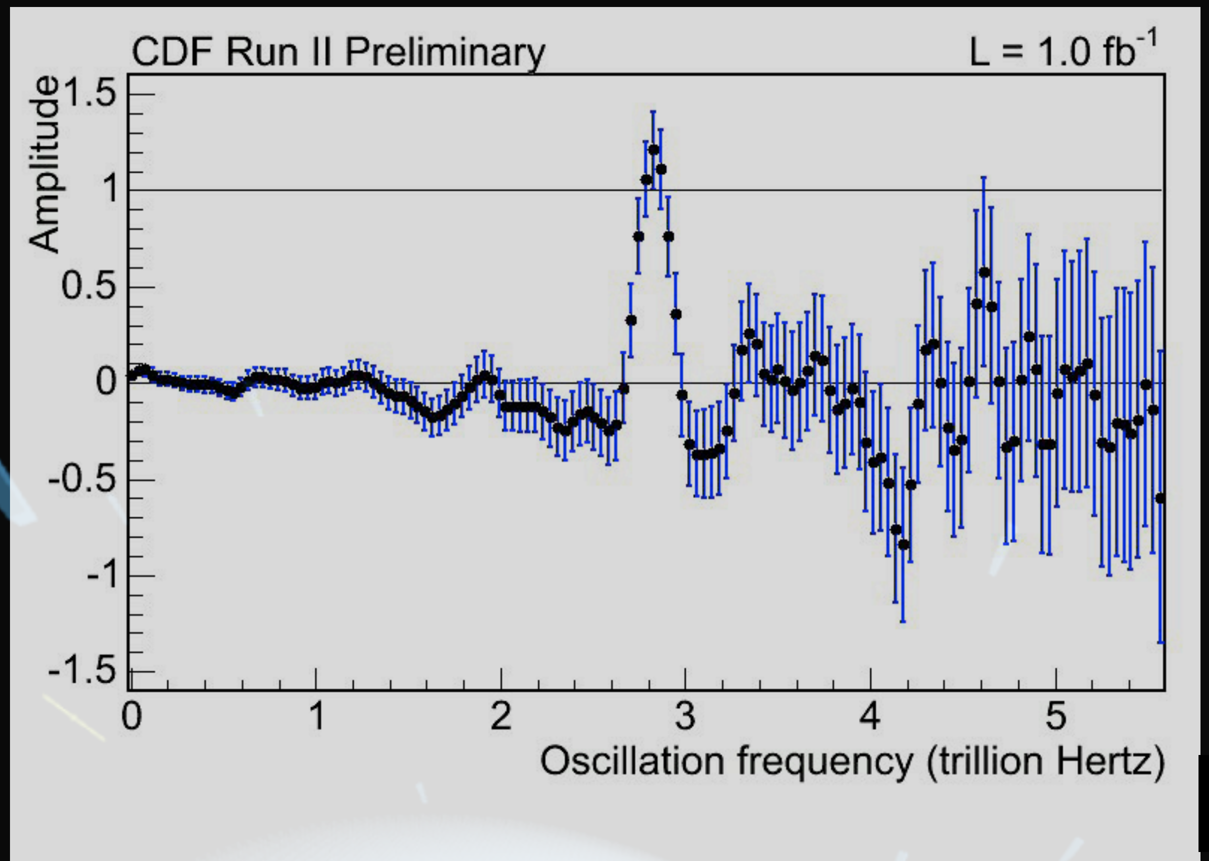


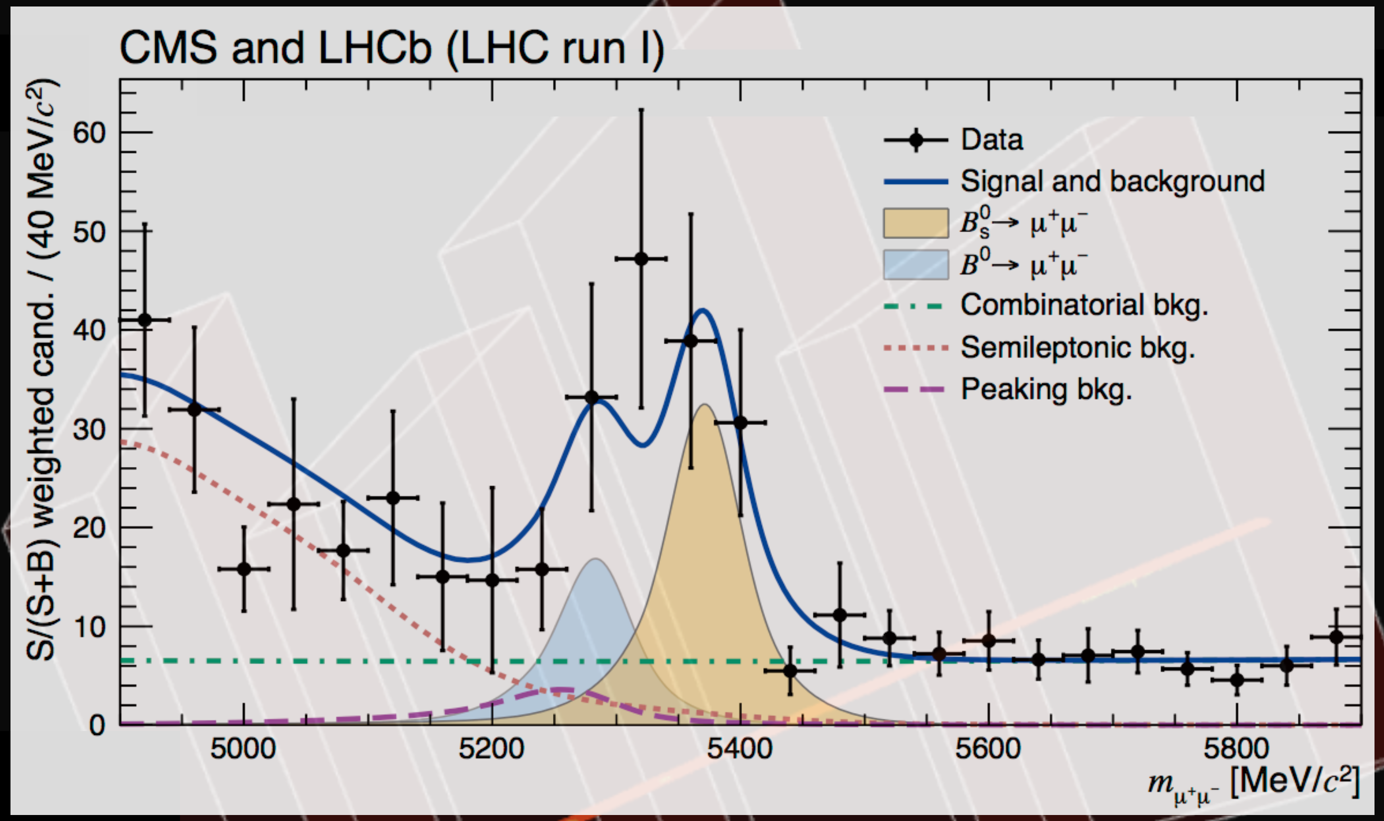
PARTICLE MIXING

RARE DECAY

PRL 97 (2006) 242003, NL thesis

Flavour Oscillations
CDF (2006)





Nature 522 (2015) 68

Flavour-Changing Neutral Current
CMS & LHCb (2015)

ULTRA-RARE DECAY OF A BEAUTIFUL AND STRANGE MESON

B→μμ rare decays

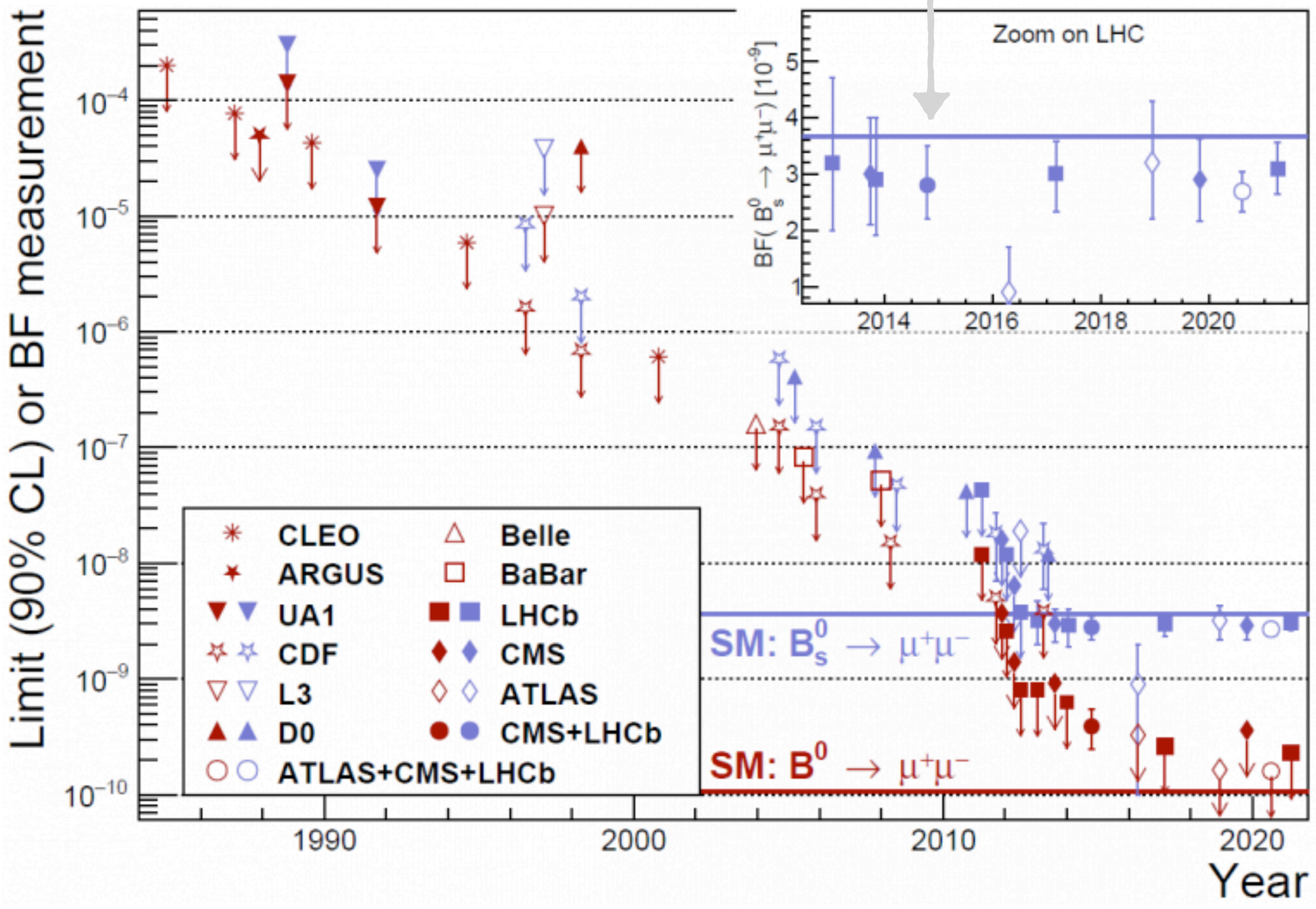
2015

Open Access | Published: 13 May 2015

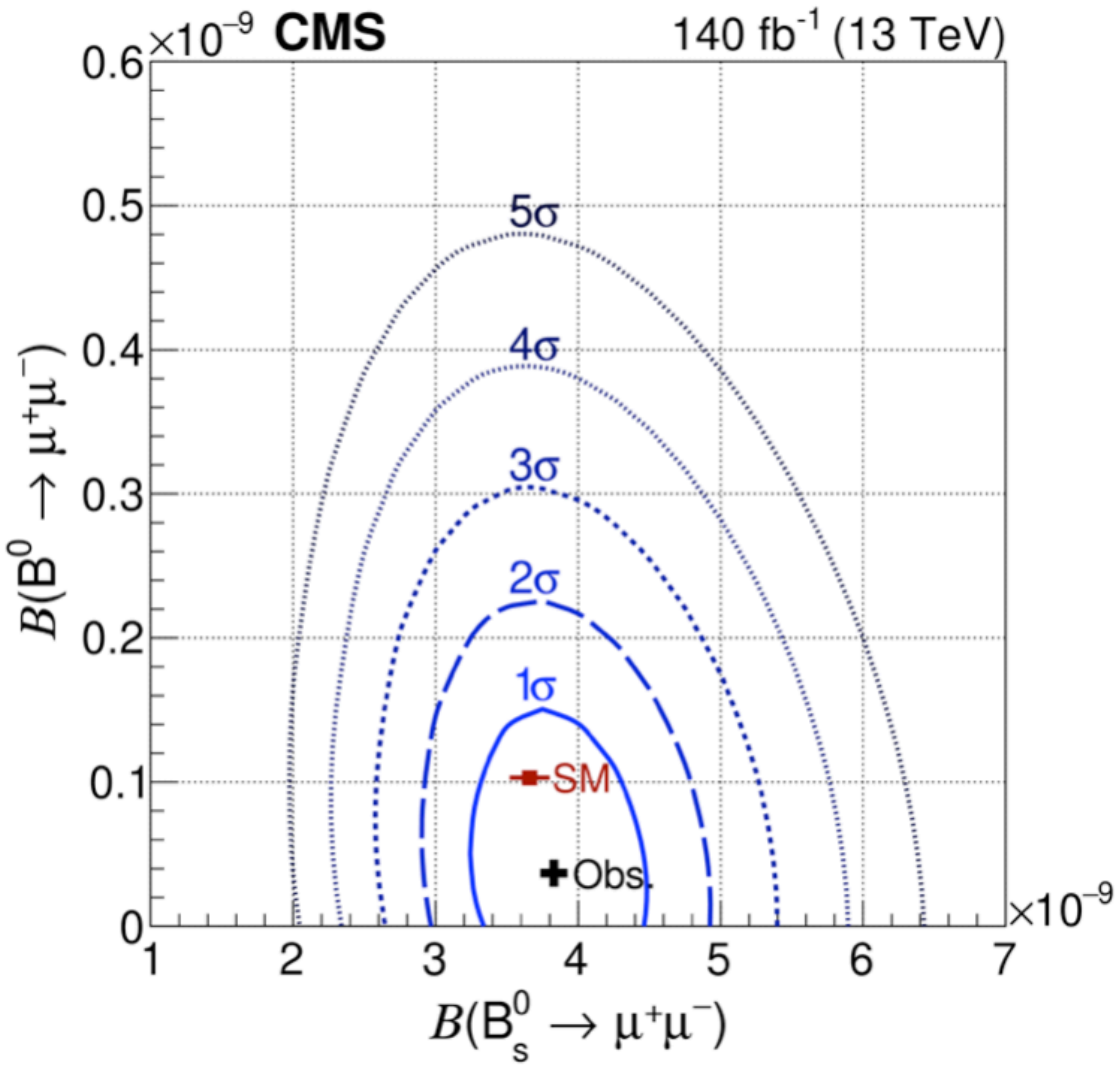
Observation of the rare $B_s^0 \to \mu^+\mu^-$ decay from the combined analysis of CMS and LHCb data

CMS Collaboration & LHCb Collaboration

Nature **522**, 68–72 (2015)



2023



CMS-BPH-21-006

B→μμ branching fractions ↩ hadronization fractions

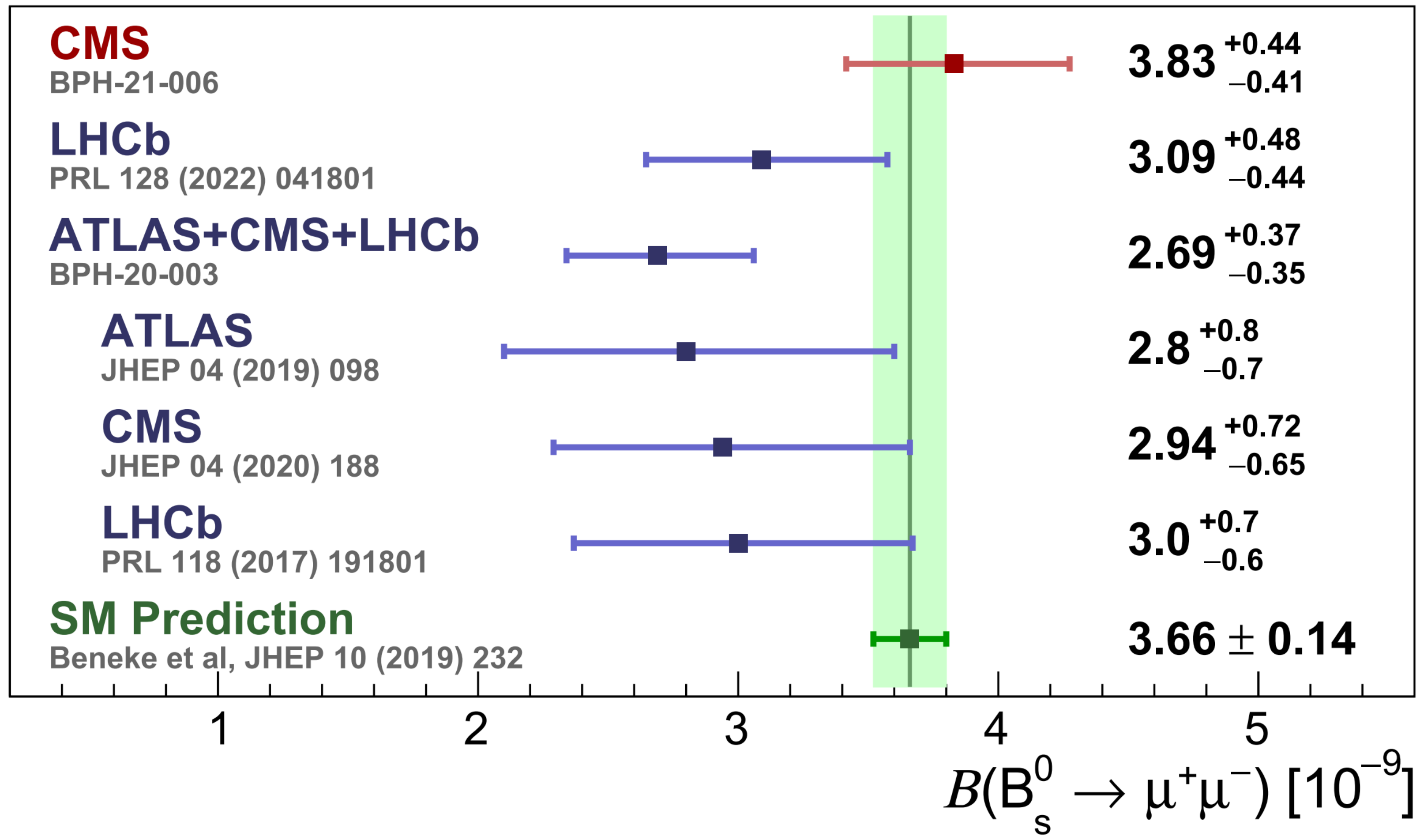
- Branching fractions measured wrt $B^+ \to J/\psi K^+$ or $B_s \to J/\psi\phi$ normalisation channels

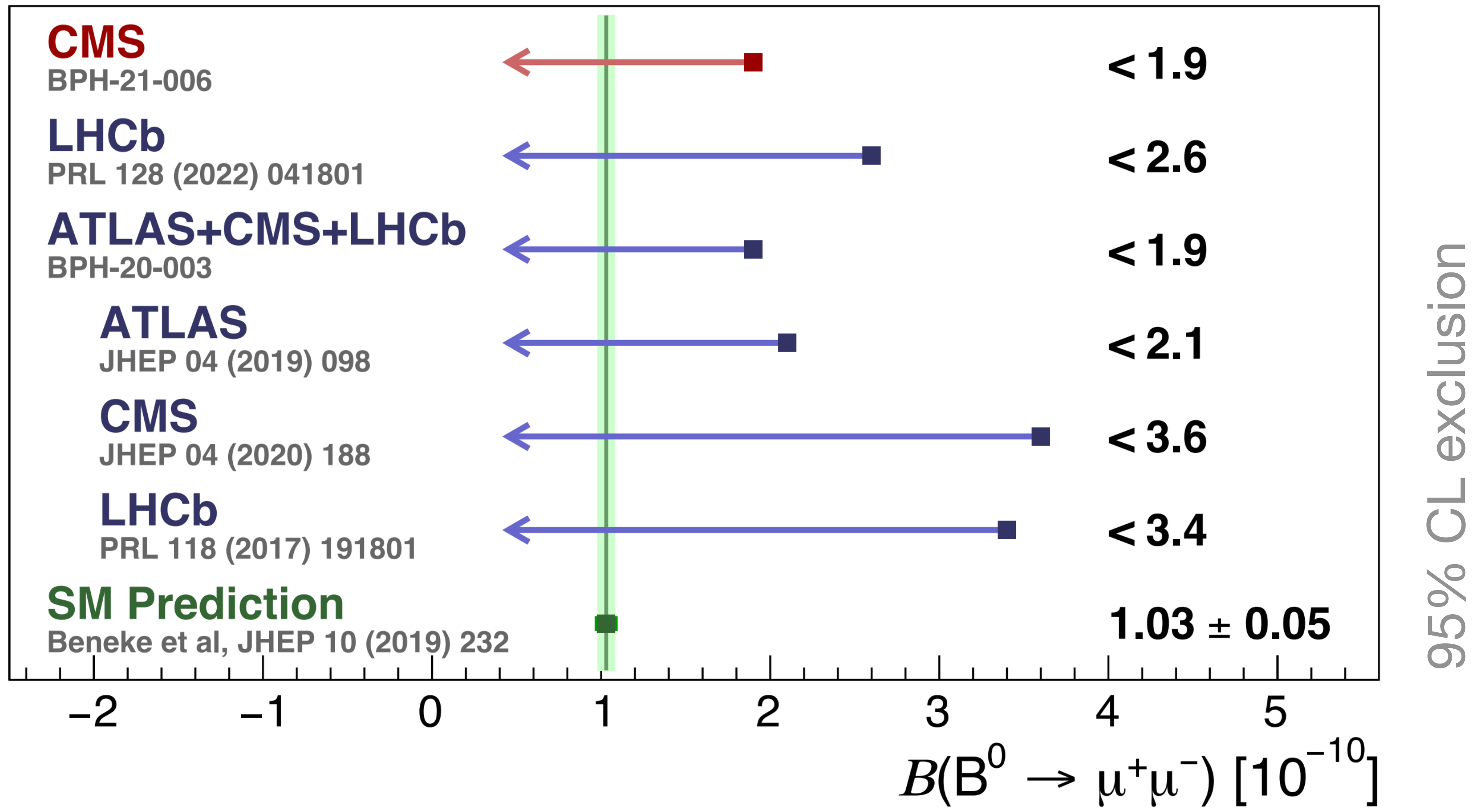
$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = \mathcal{B}(B^+ \to J/\psi K^+) \frac{N_{B^0_s \to \mu^+\mu^-}}{N_{B^+ \to J/\psi K^+}} \frac{\varepsilon_{B^+ \to J/\psi K^+}}{\varepsilon_{B^0_s \to \mu^+\mu^-}} \frac{f_u}{f_s} \quad \Rightarrow \quad \left[3.83^{+0.38}_{-0.36}\,(\text{stat})\,^{+0.19}_{-0.16}\,(\text{syst})\,^{+0.14}_{-0.13}\,(f_s/f_u)\right] \times 10^{-9}$$

$$or \left\{ = \mathcal{B}(B^0_s \to J/\psi\phi) \frac{N_{B^0_s \to \mu^+\mu^-}}{N_{B^0_s \to J/\psi\phi}} \frac{\varepsilon_{B^0_s \to J/\psi\phi}}{\varepsilon_{B^0_s \to \mu^+\mu^-}} \frac{f_s}{f_s} \right\} \quad \Rightarrow \quad \left[3.95^{+0.39}_{-0.37}\,(\text{stat})\,^{+0.27}_{-0.22}\,(\text{syst})\,^{+0.21}_{-0.19}\,(\text{BF})\right] \times 10^{-9}$$

$$\mathcal{B}(B^0 \to \mu^+\mu^-) = \mathcal{B}(B^+ \to J/\psi K^+) \frac{N_{B^0 \to \mu^+\mu^-}}{N_{B^+ \to J/\psi K^+}} \frac{\varepsilon_{B^+ \to J/\psi K^+}}{\varepsilon_{B^0 \to \mu^+\mu^-}} \frac{f_u}{f_d} \quad \Rightarrow \quad \left[0.37^{+0.75}_{-0.67}\,(\text{stat})\,^{+0.08}_{-0.09}\,(\text{syst})\right] \times 10^{-10}$$

CMS-BPH-21-006

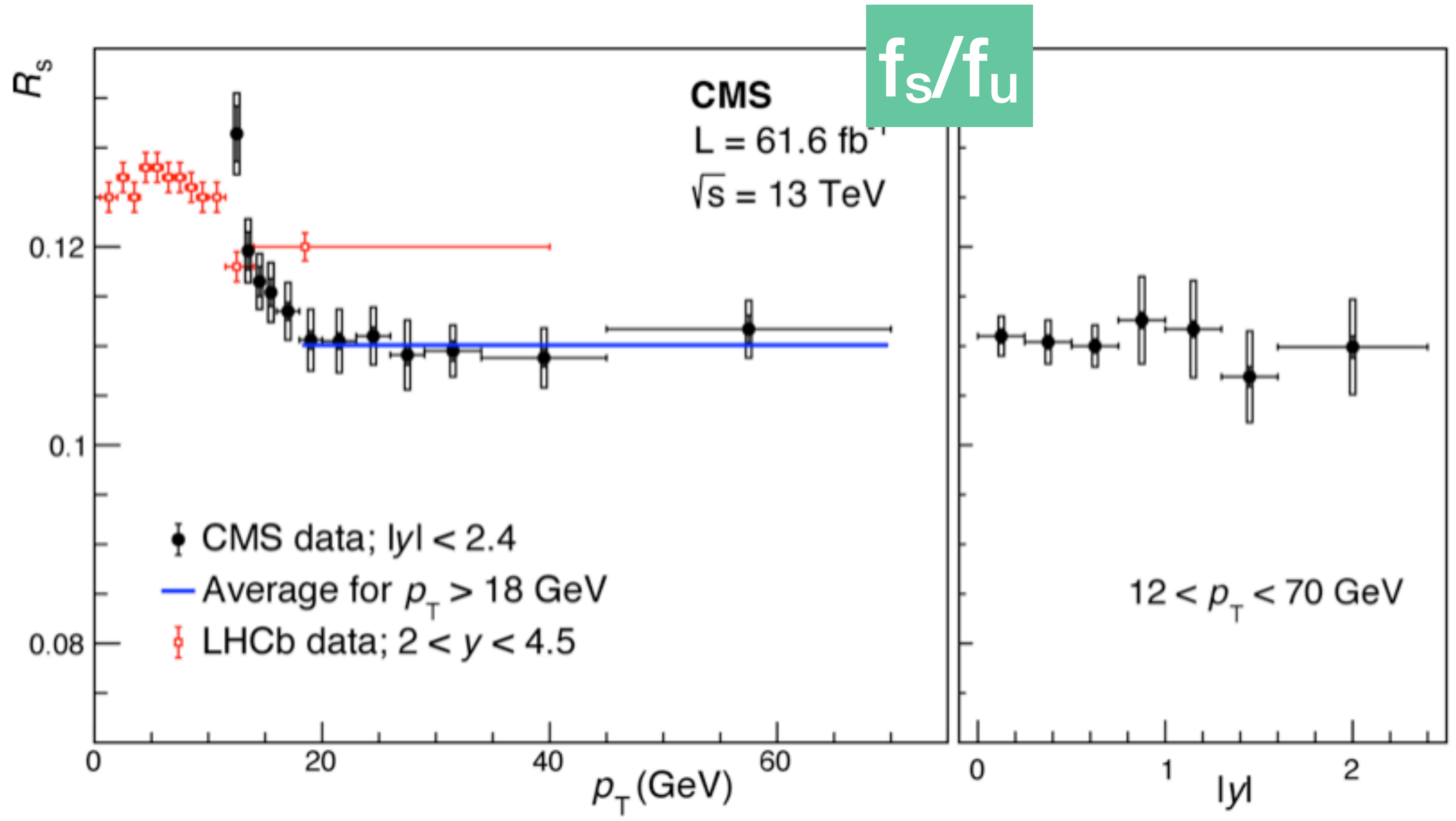


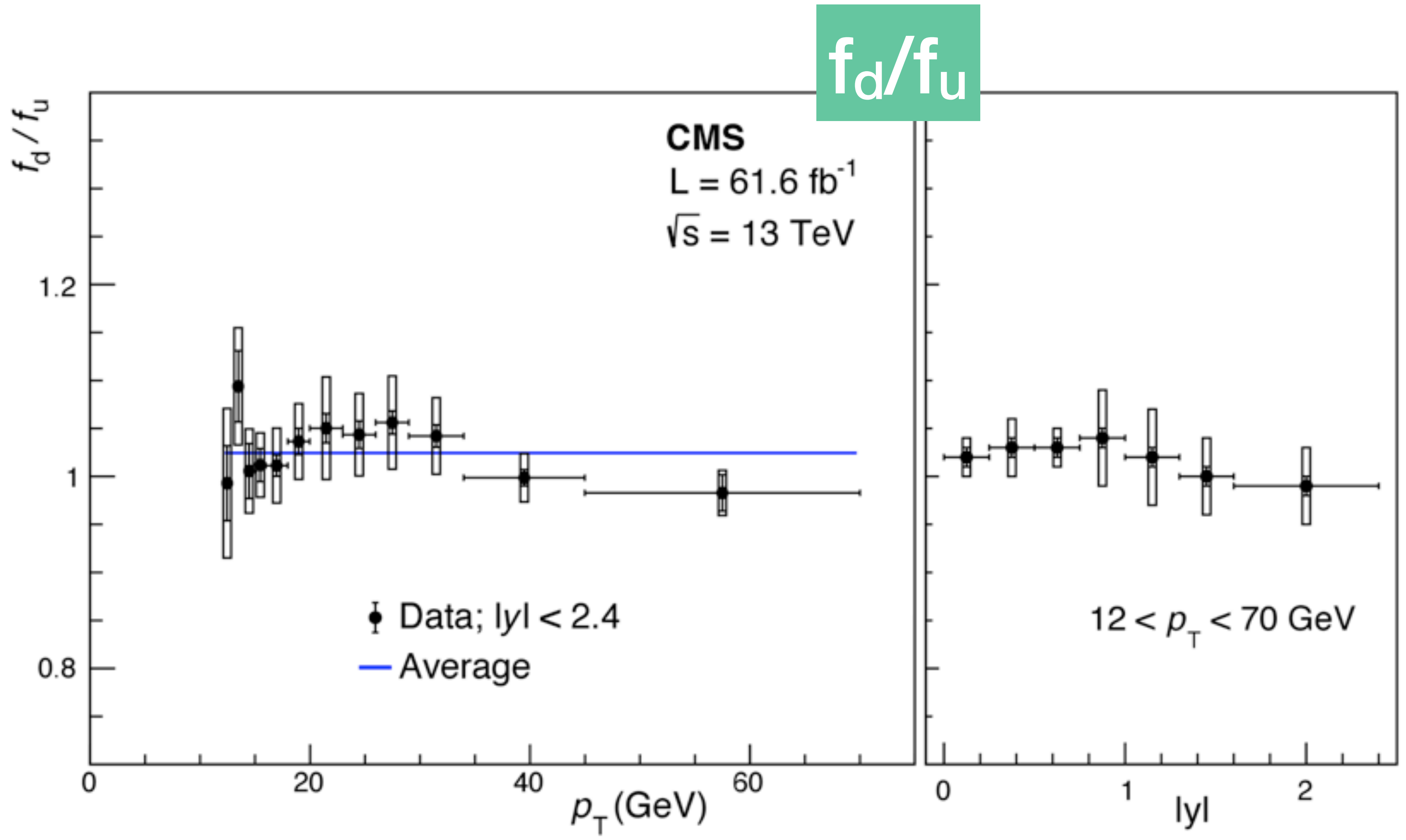


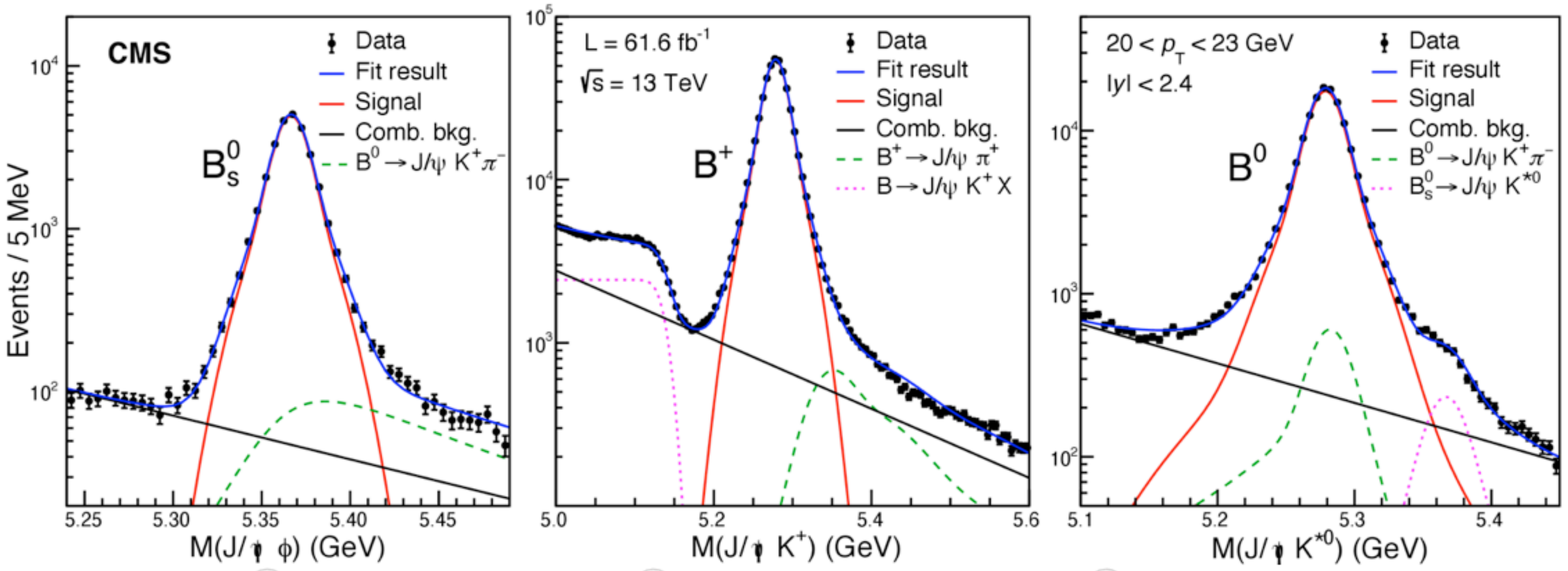
b-quark hadronization fractions

[CMS-BPH-21-001]

- production fractions assessed using
  - $B_s \to J/\psi\phi$, $B^+ \to J/\psi K^+$, $B^0 \to J/\psi K^{*0}$
- measure the dependence of the ratios on p_T, y
  - LHCb reported dependence on p_T, at low p_T (<20GeV)
- CMS confirms p_T dependence of f_s/f_u
  - which becomes asymptotically constant for p_T>20GeV
- no dependence observed with B rapidity
- f_d/f_u compatible with unit (isospin symmetry)





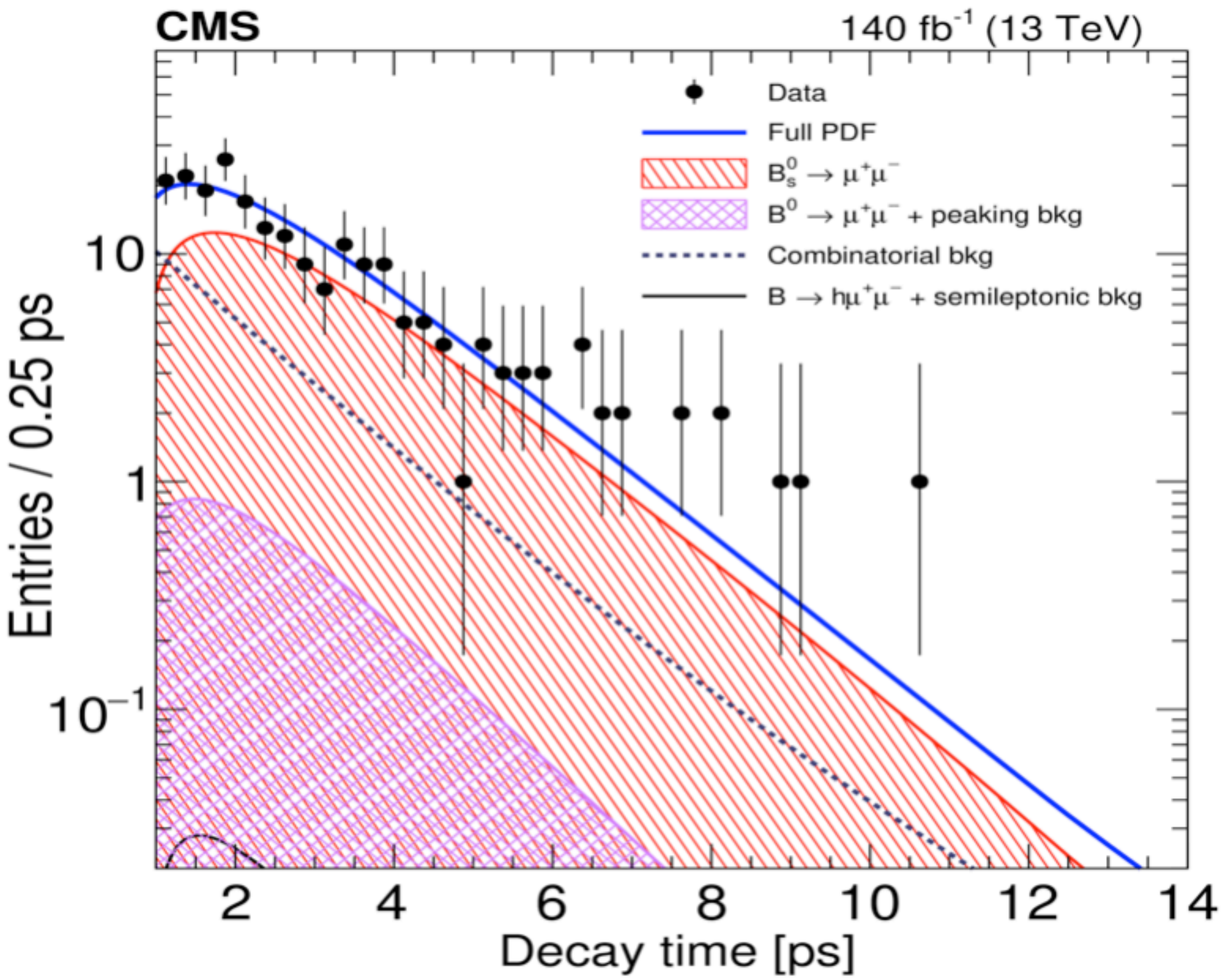


$B_s \to \mu\mu$ effective lifetime

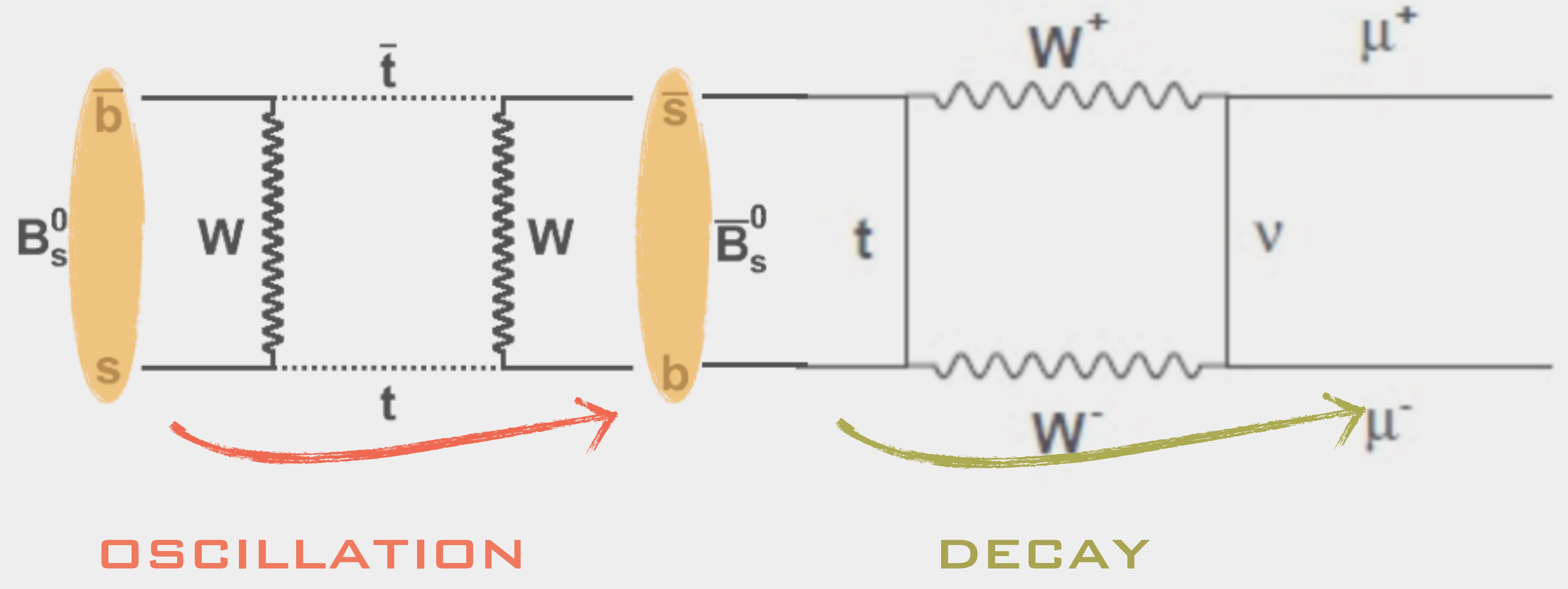
- $\tau(B_s \to \mu\mu)$ has **added sensitivity** to BSM
  - in SM with absence of CP violation only the heavy eigenstate B_H decays into dimuon

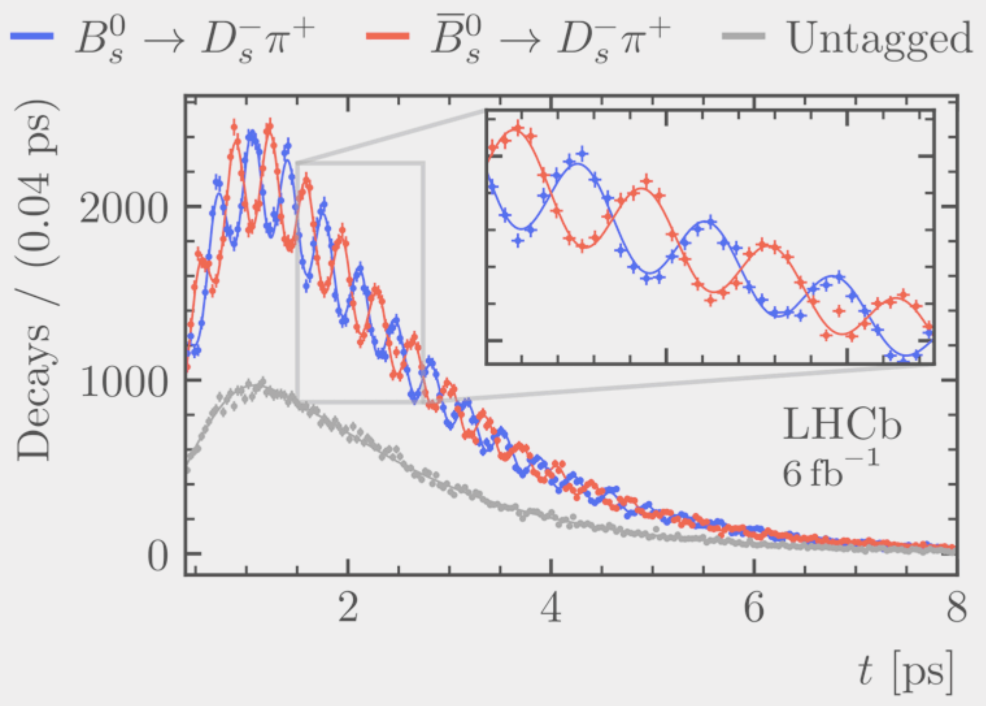
$$\tau = 1.83\,^{+0.23}_{-0.20}\,(\mathrm{stat})\,^{+0.04}_{-0.04}\,(\mathrm{syst})\ \mathrm{ps}$$

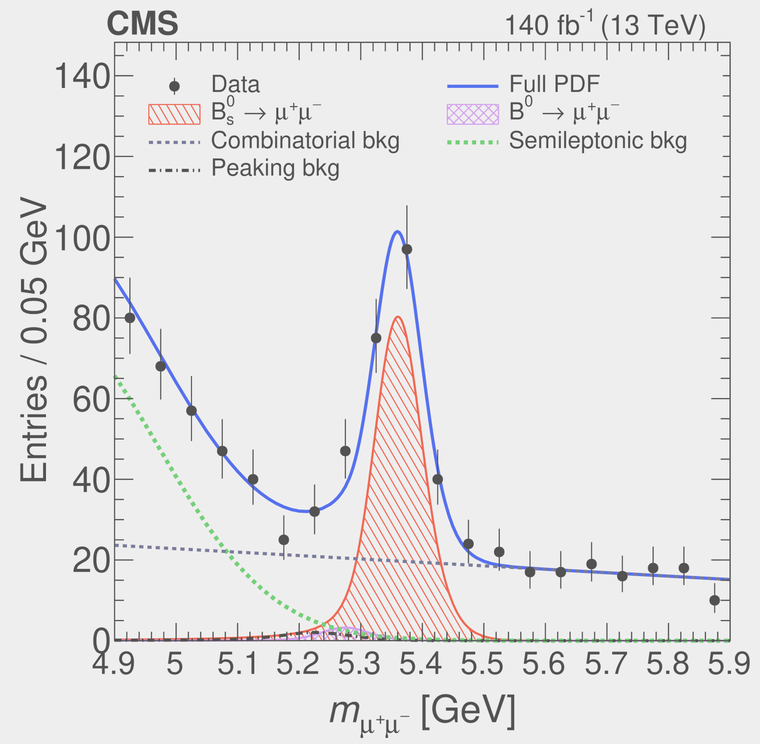
$$\tau_H = 1.624 \pm 0.009\ \mathrm{ps}$$
$$\tau_L = 1.429 \pm 0.007\ \mathrm{ps}$$

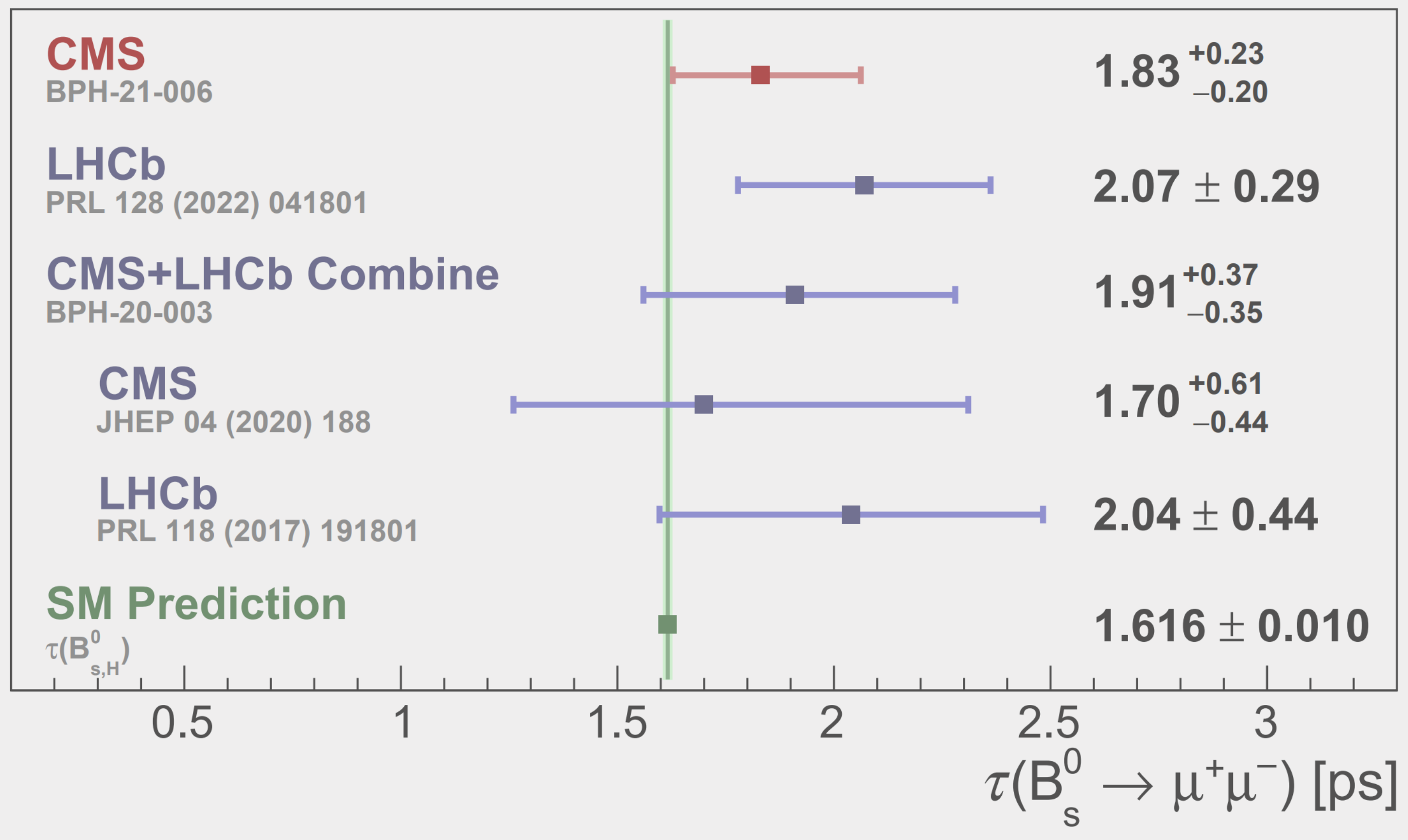


CMS-BPH-21-006



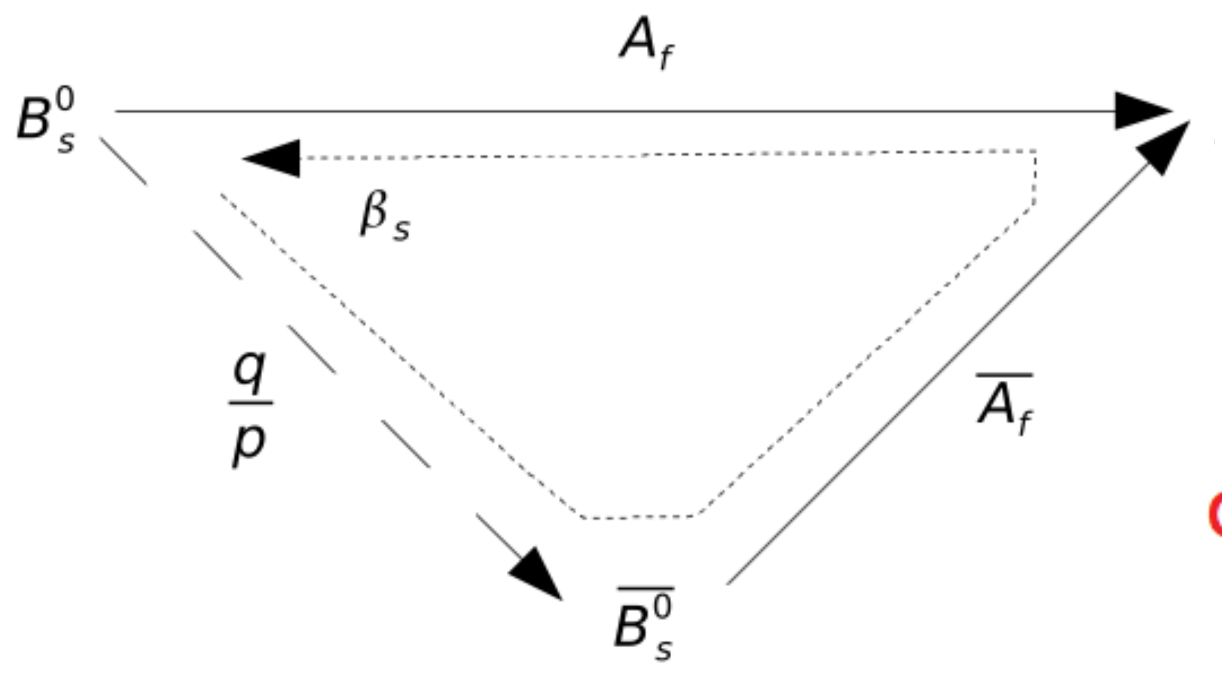




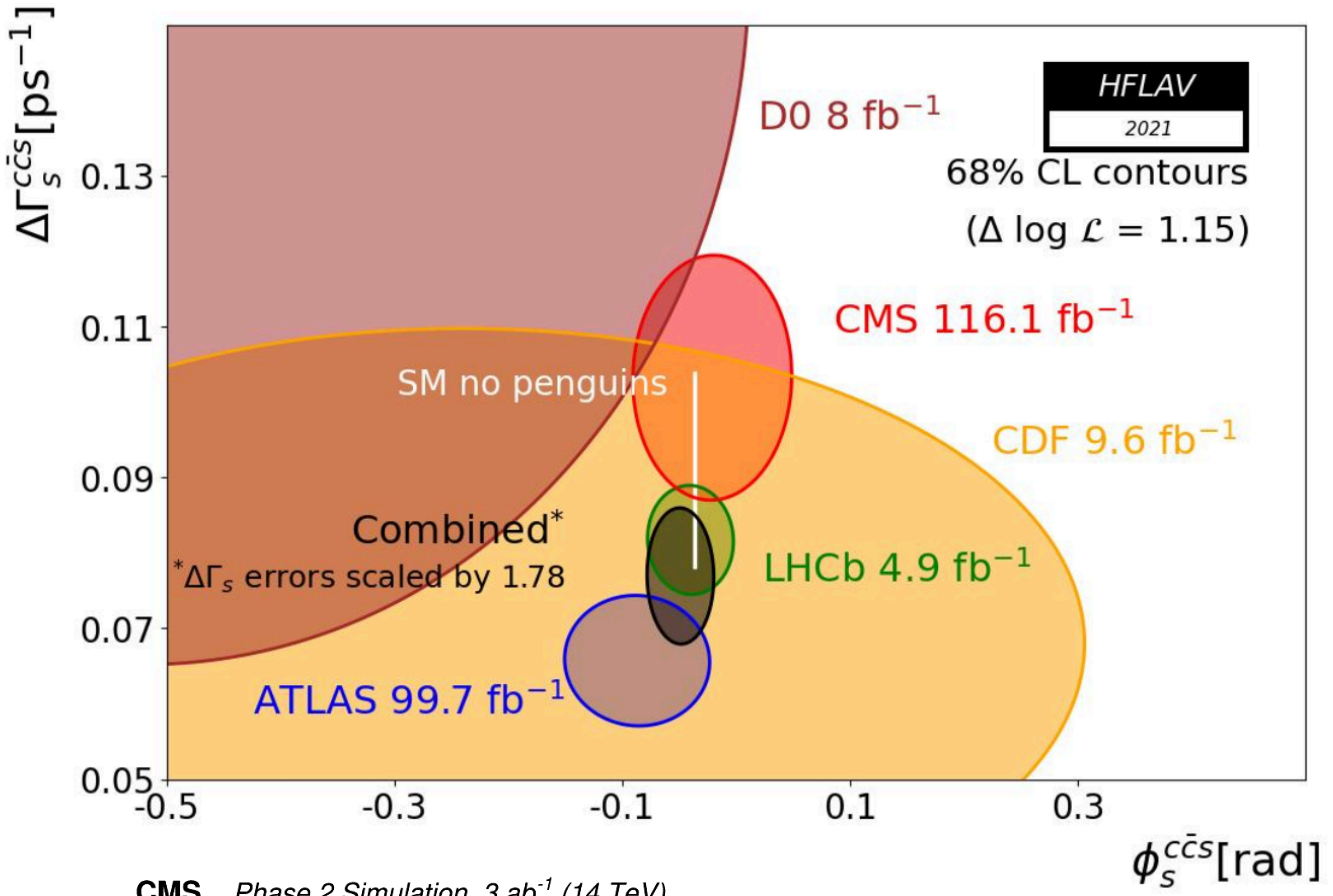


B_s mixing phase and CP violation

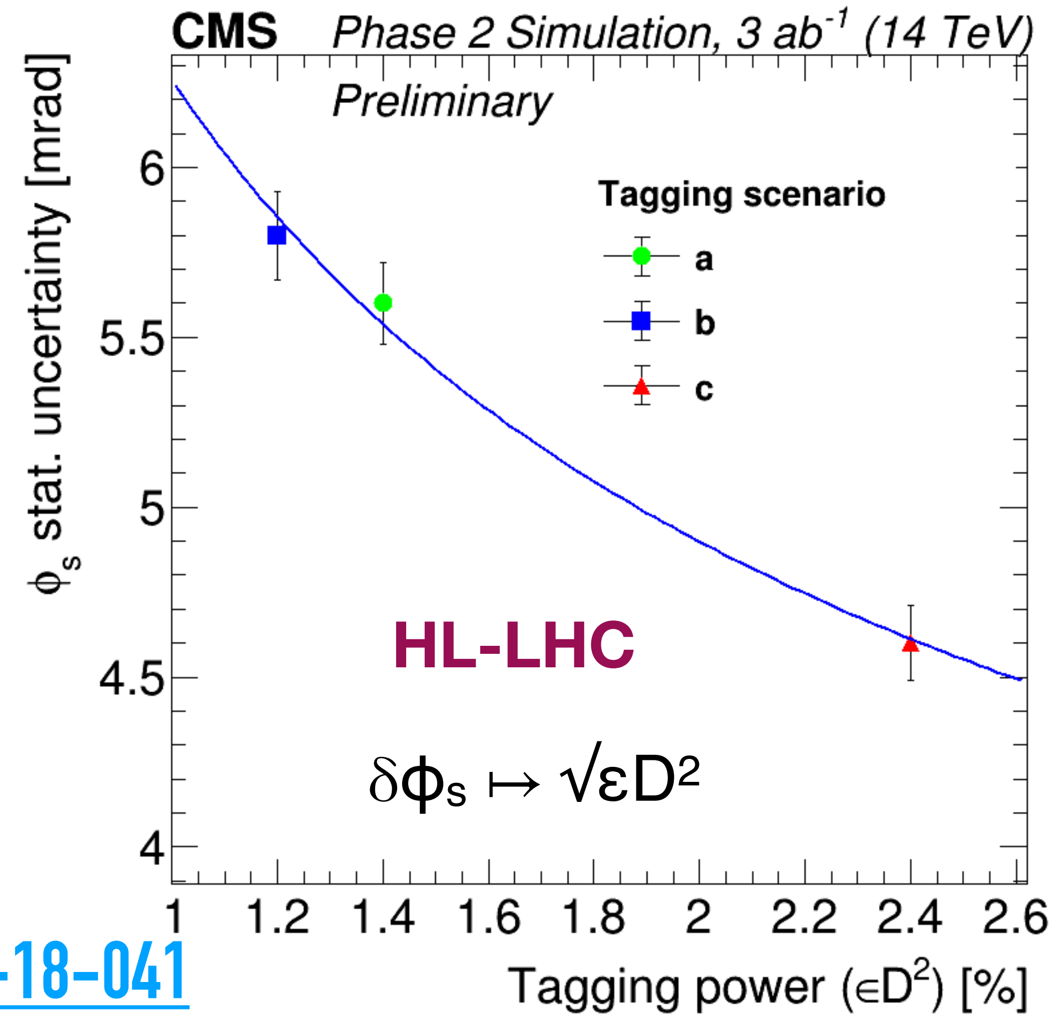
- probe CPV in interference of decay with and without flavour mixing



$\phi_s = \phi_s^{SM} + \phi_s^{NP}$



- using high statistics modes, $B_s \to J/\psi KK$
- developments in flavour tagging
  - optimization of opposite-side flavour algorithms: soft lepton, muon, jet
  - development of same side tagging



↪ Current developments point to improvements in tagging power twice as large as in previous HL-LHC estimates!

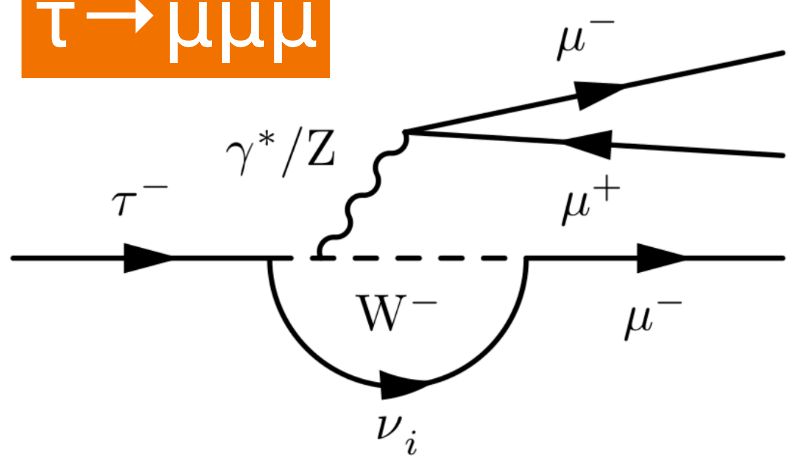
CERN-THESIS-2023-279 CMS-FTR-18-041

Searching for flavour violations

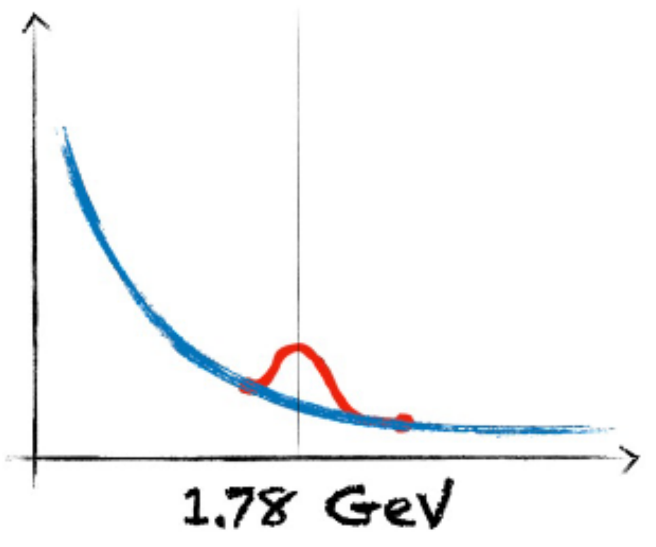
CLFV | charged lepton flavour violation

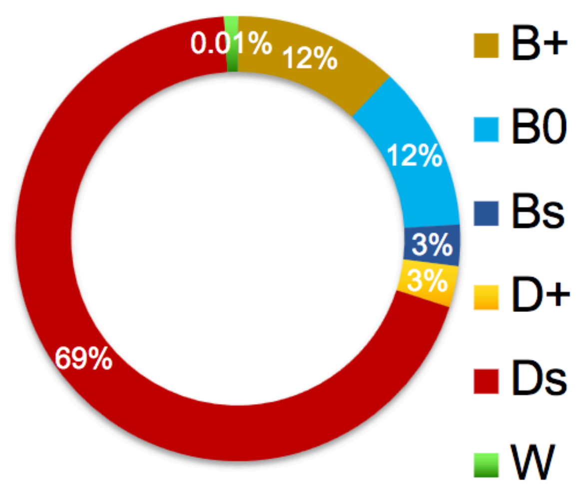
- clean final state, searched for at various colliders
- normalisation $D_s \to \phi\pi$; source: B,D→τ

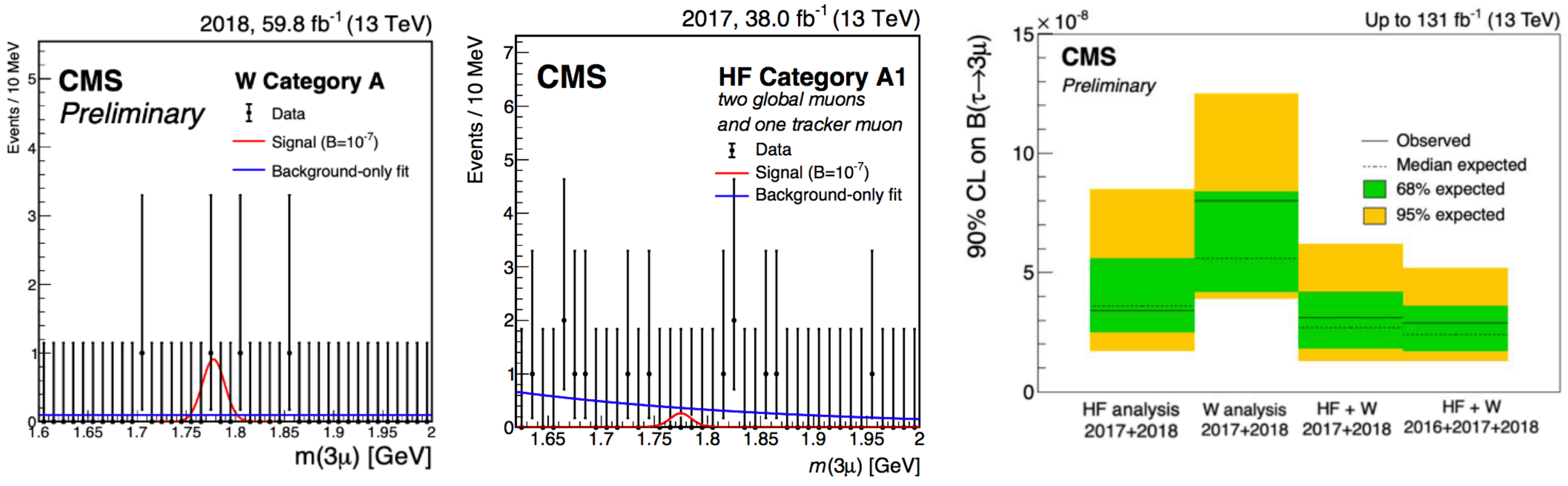
τ→μμμ



CMS-BPH-21-005



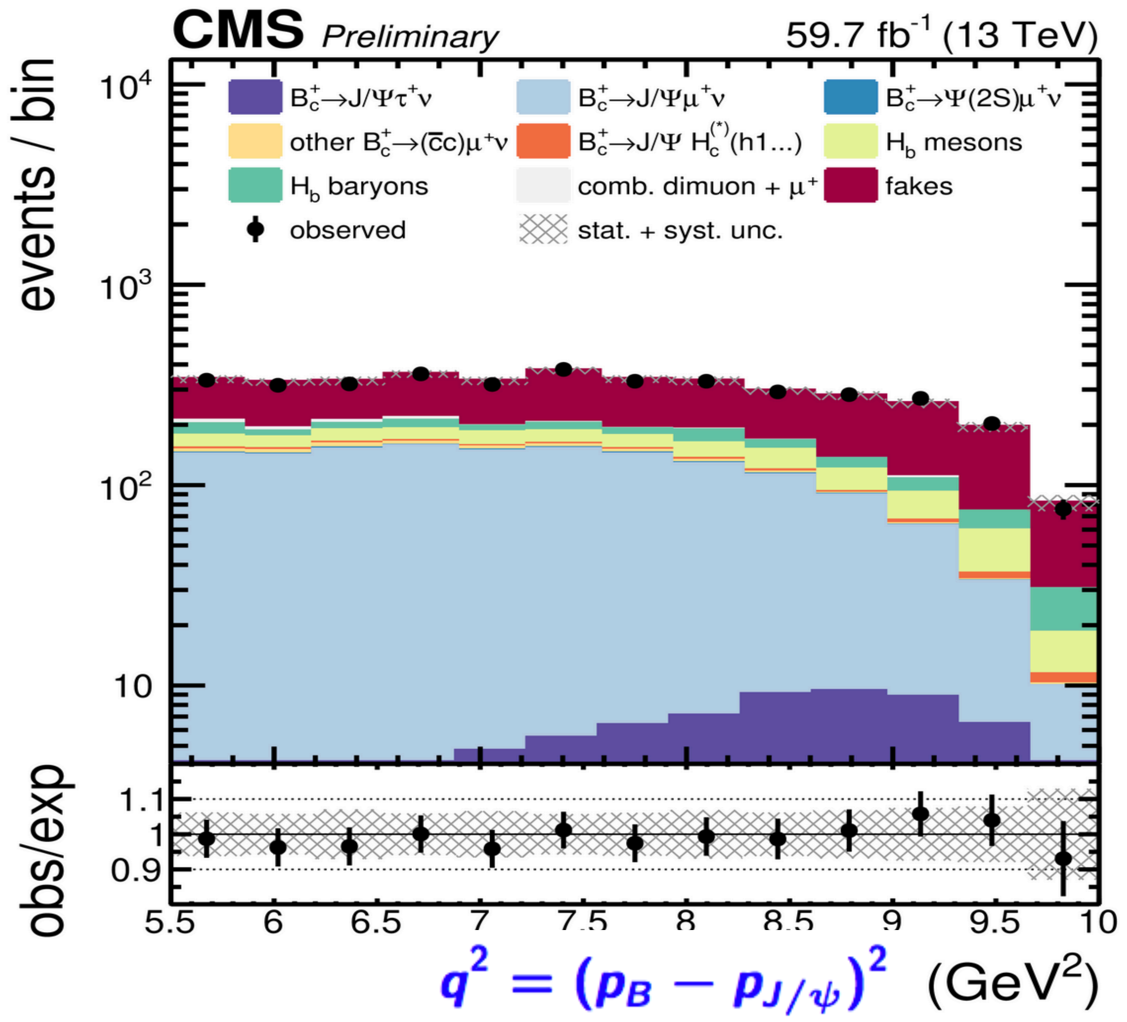




observed (expected) upper limit @ 90% CL **B(τ→3μ) < 2.9 (2.4) x 10^{-8}**

comparable to world best UL (90%CL) set by Belle at 2.1 x 10^{-8}

LFUV | lepton flavour universality violation



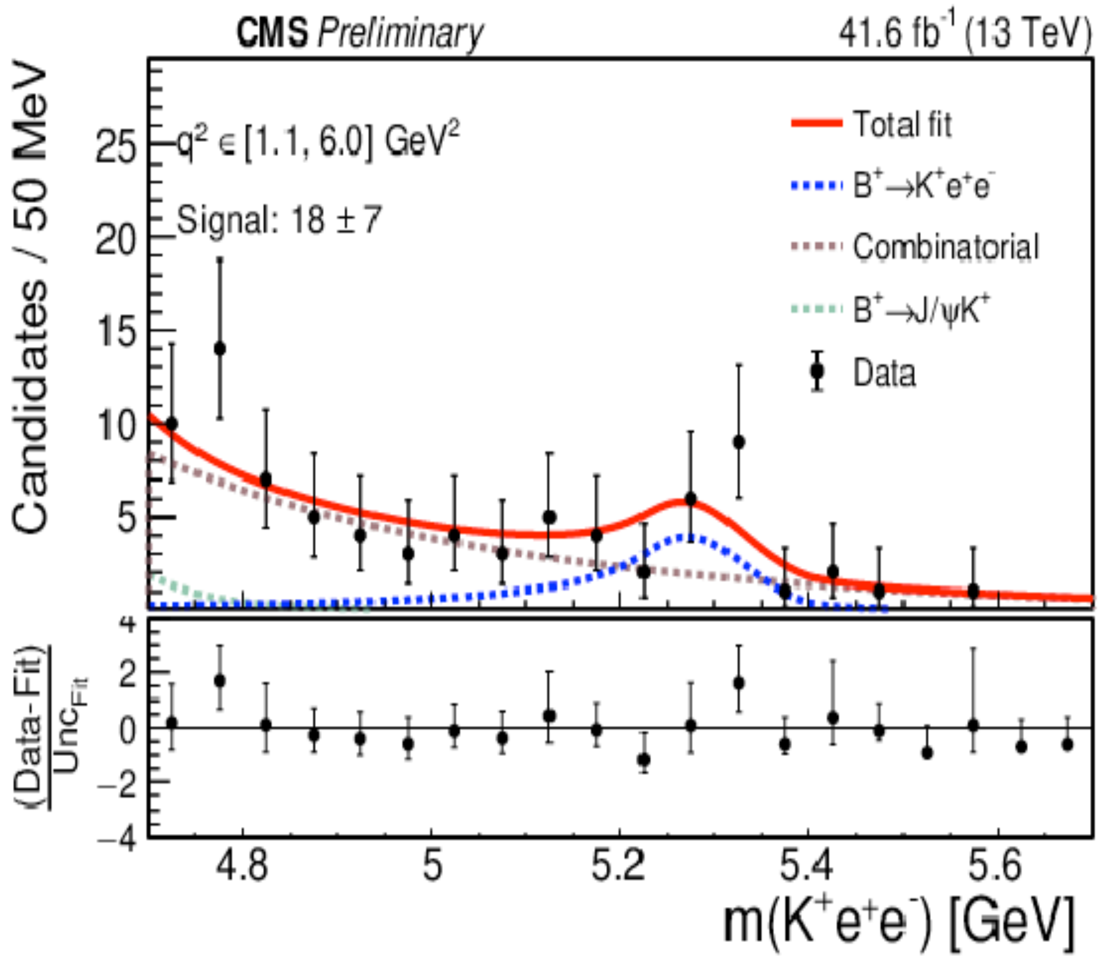
$B_c \to J/\psi l\nu$ τ vs μ

$$R(J/\psi) = \frac{\mathcal{B}(B_c^+ \to J/\psi\tau^+\nu_\tau)}{\mathcal{B}(B_c^+ \to J/\psi\mu^+\nu_\mu)}$$

$$= 0.17 \pm 0.33$$

SM 0.2582(38)

CMS-BPH-22-012 CMS-BPH-22-005



B+→K+ ll μ vs e

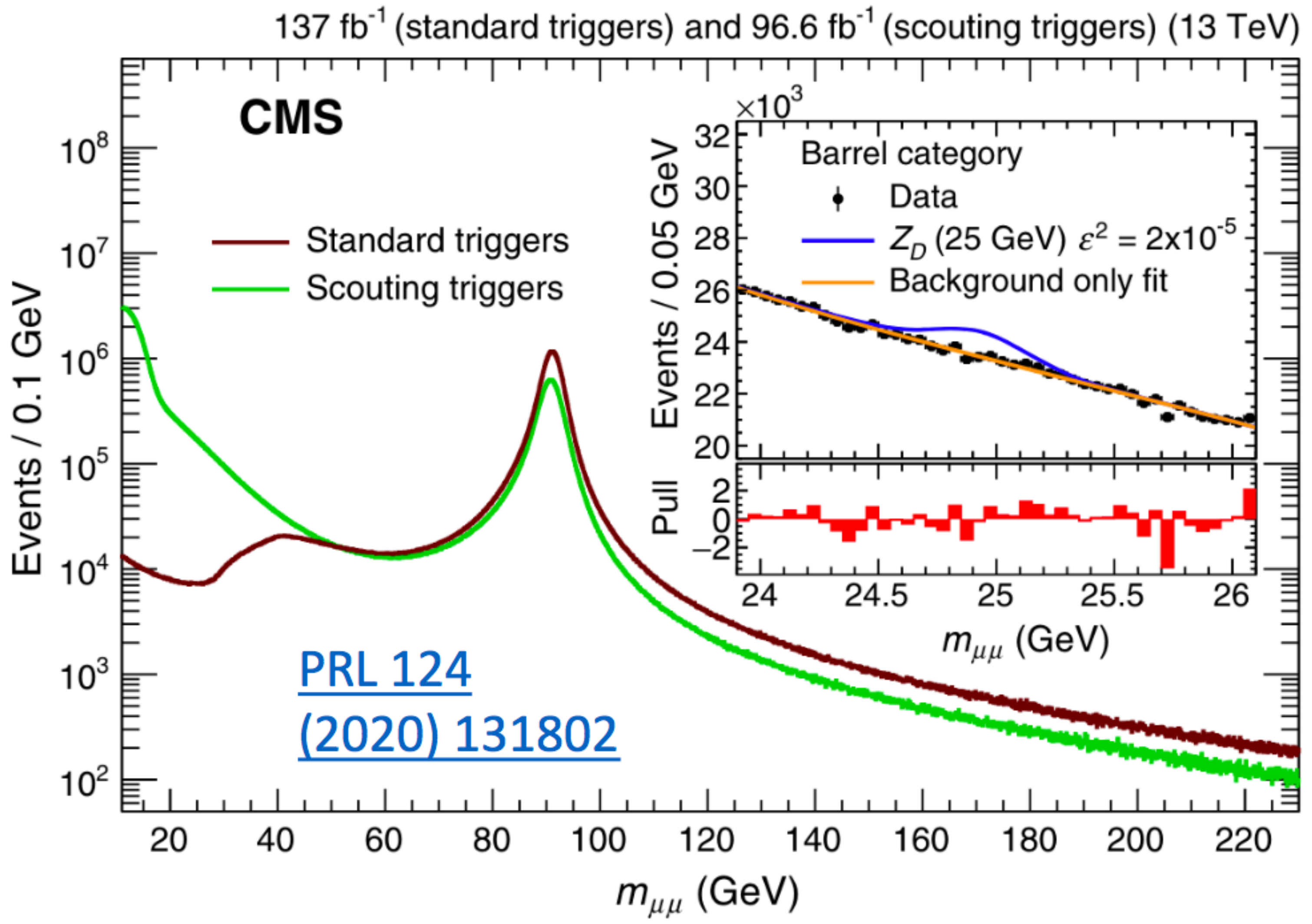
$$R_K = \frac{BF(B \to \mu\mu K)}{BF(B \to eeK)}$$

$R_K = 0.78^{+0.46}_{-0.23}$ (stat) $^{+0.09}_{-0.05}$ (syst)

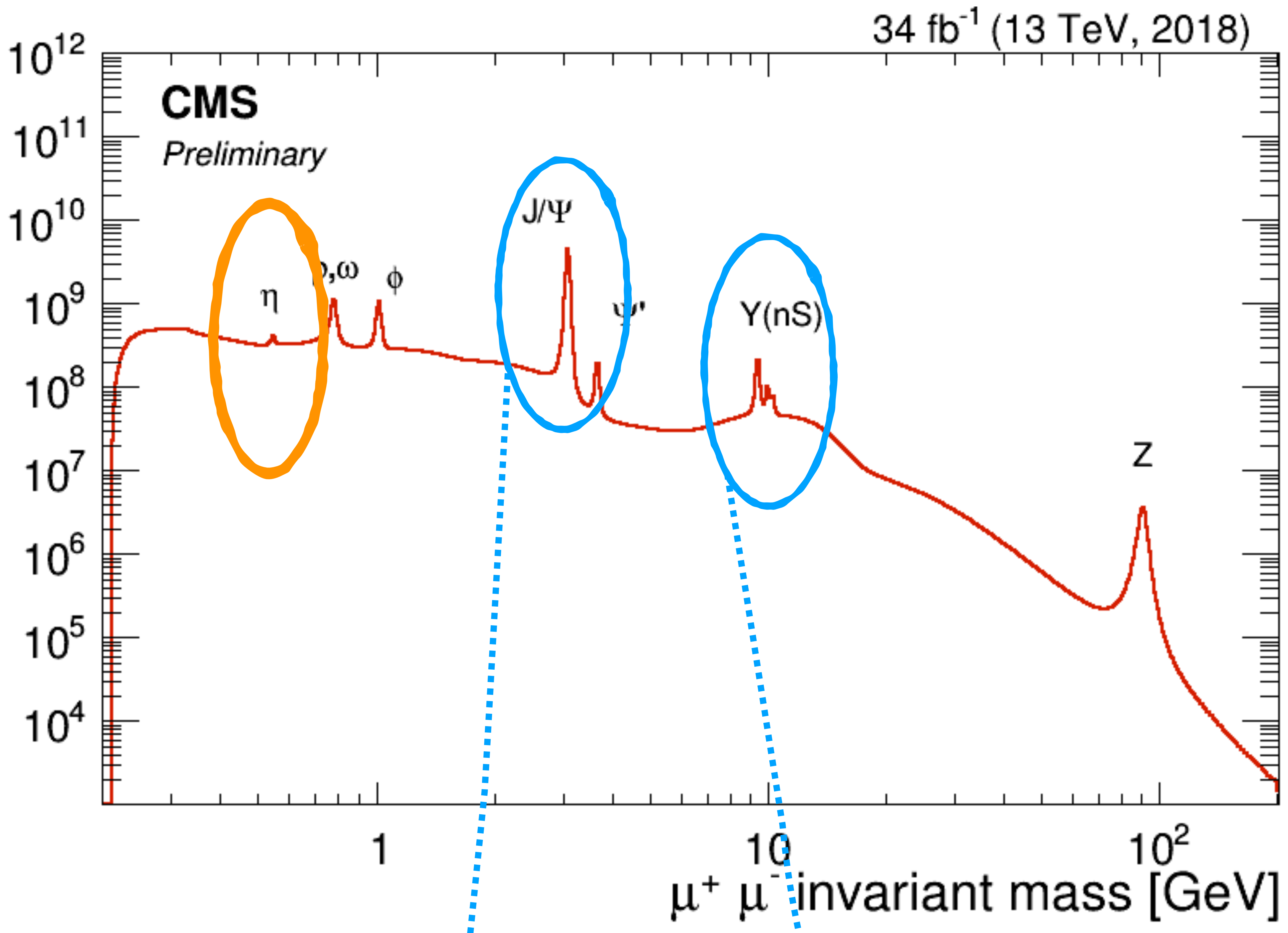
↪ **uses 2018 parked data**

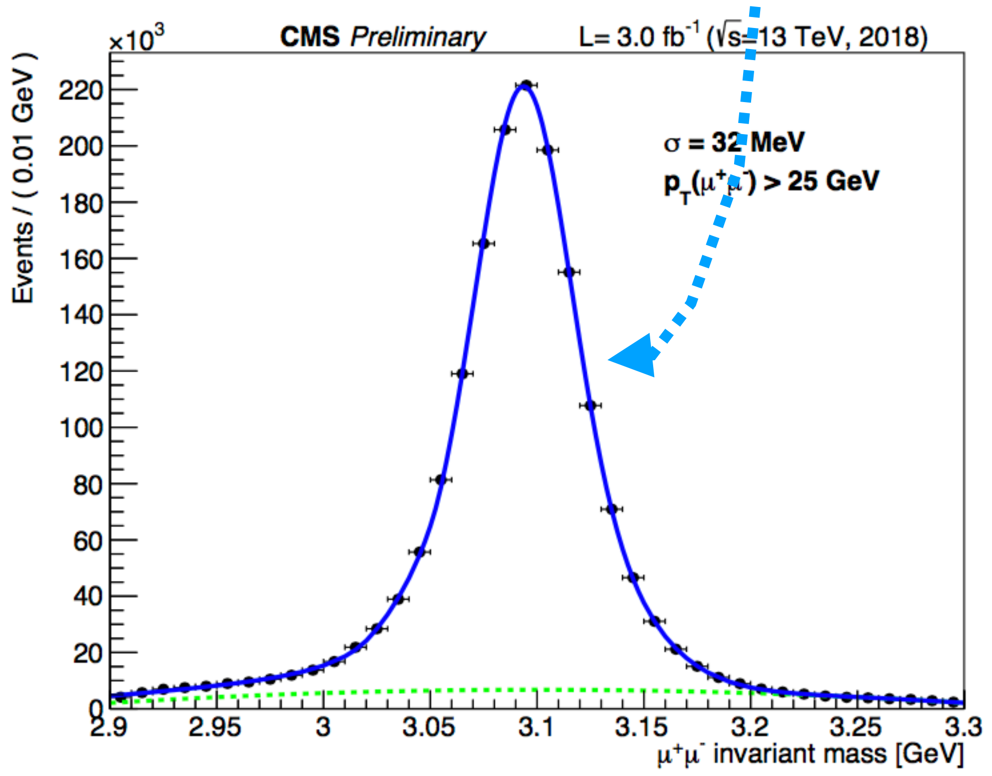
The dimuon spectrum

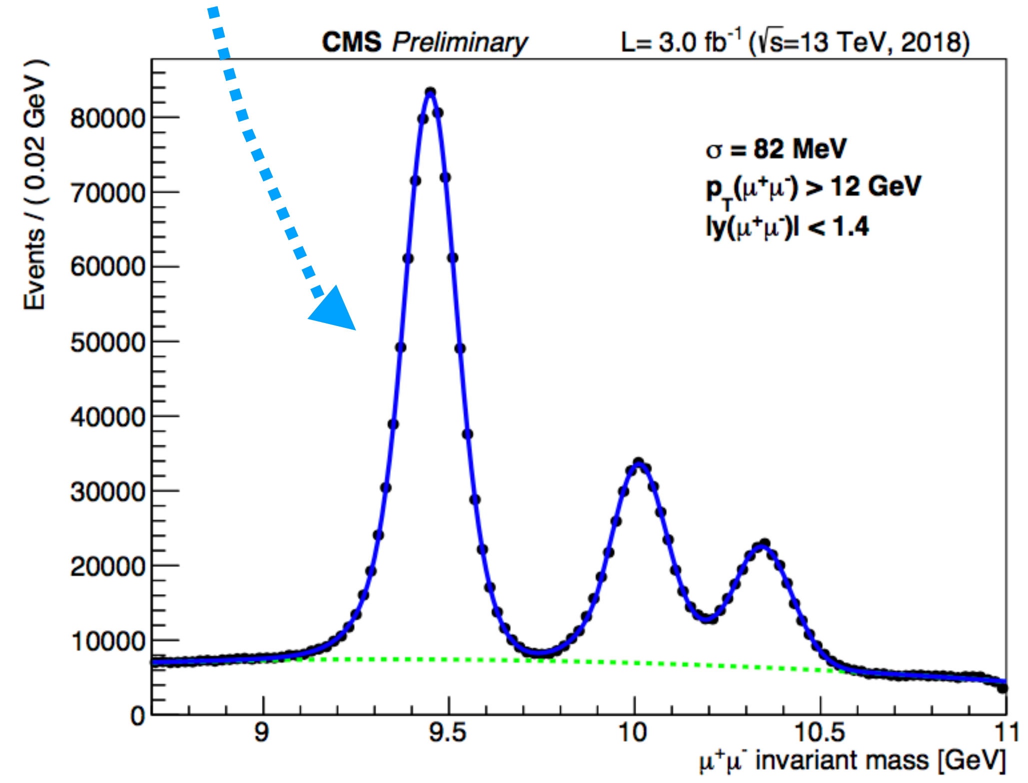
- Standard dimuon triggers
  - provide access to bulk of HF final states
- **Parking data**
  - facilitate access to non-muonic channels
- **Scouting** dimuon triggers
  - high-rate triggers (5x) with HLT-only information
  - $p_T(\mu)$>3GeV, no mass cut (low mass resonances)



PRL 124 (2020) 131802



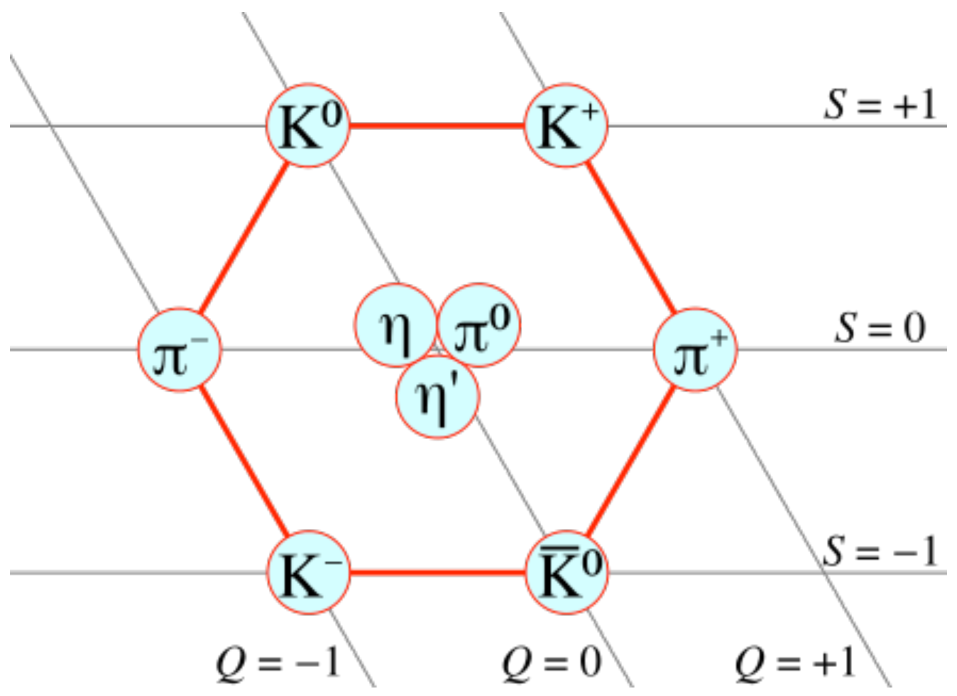


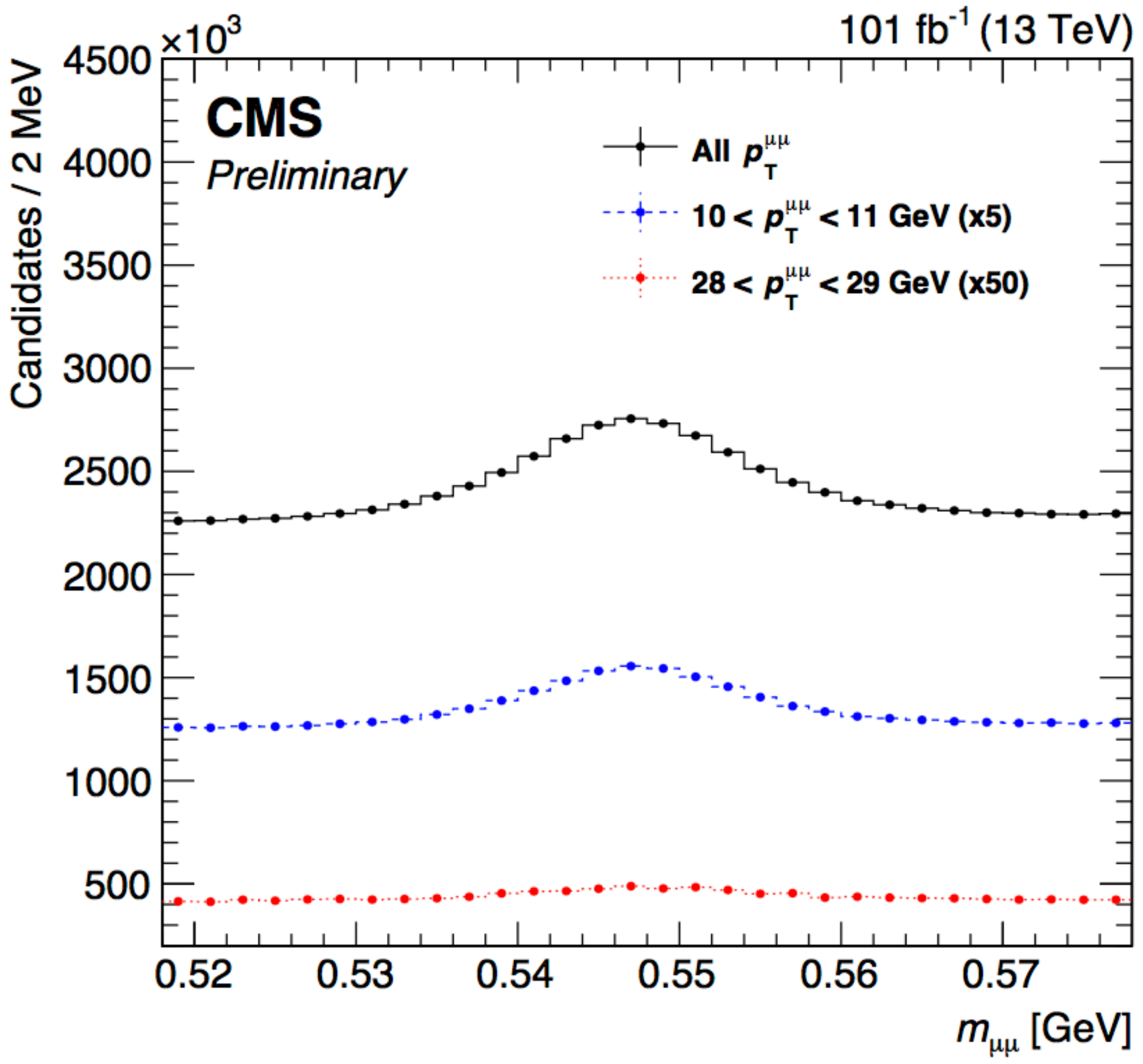


CMS-DP-2018-03

Observation of rare η decay

- observation of the double-Dalitz **η→μμμμ** decay
  - first **positive observation** employing **scouting** data in CMS
- studies allow precision tests of SM and sensitive to BSM
  - test low-energy QCD, hadronic contribution to $(g\text{-}2)_\mu$, search new light particles



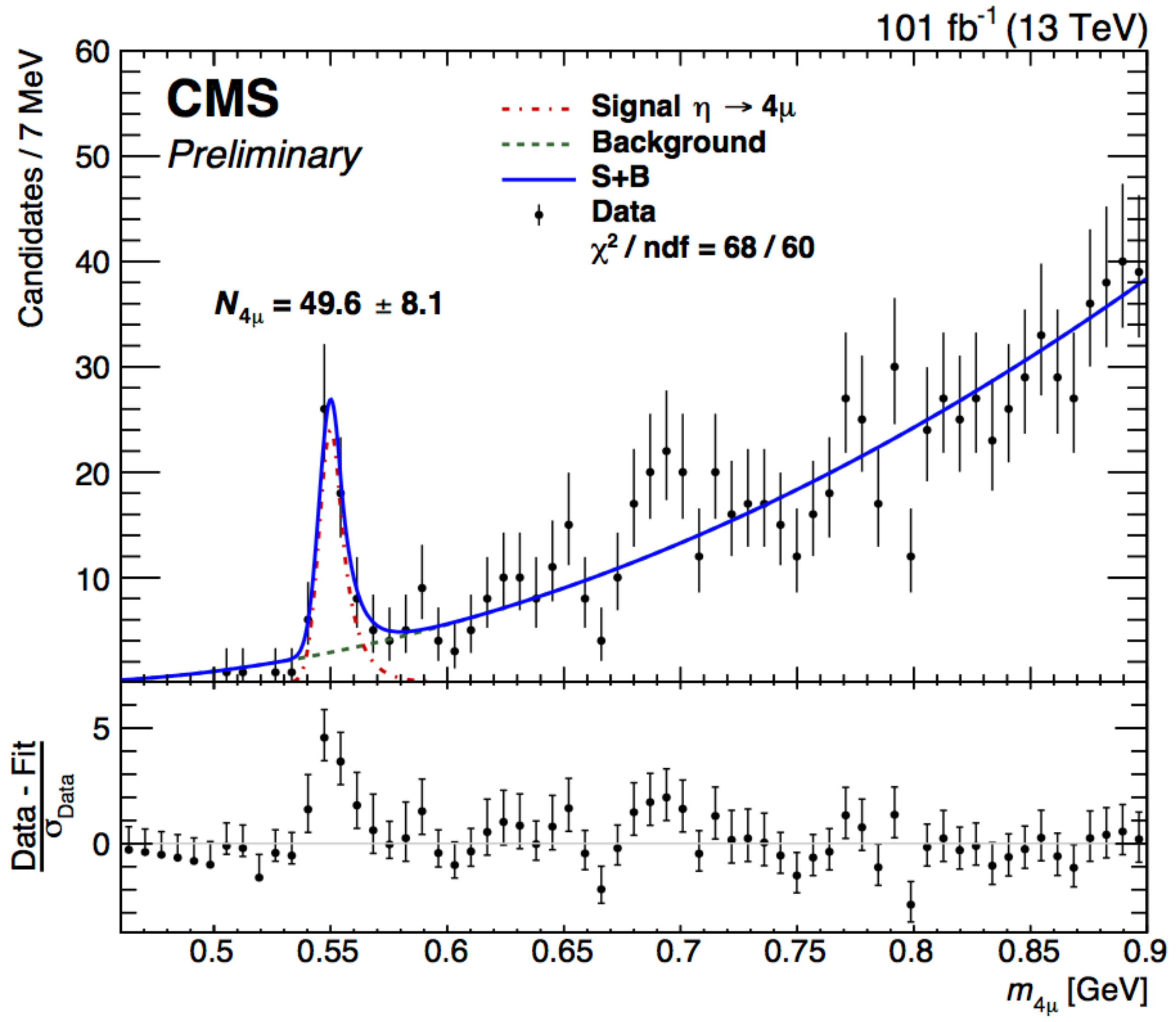


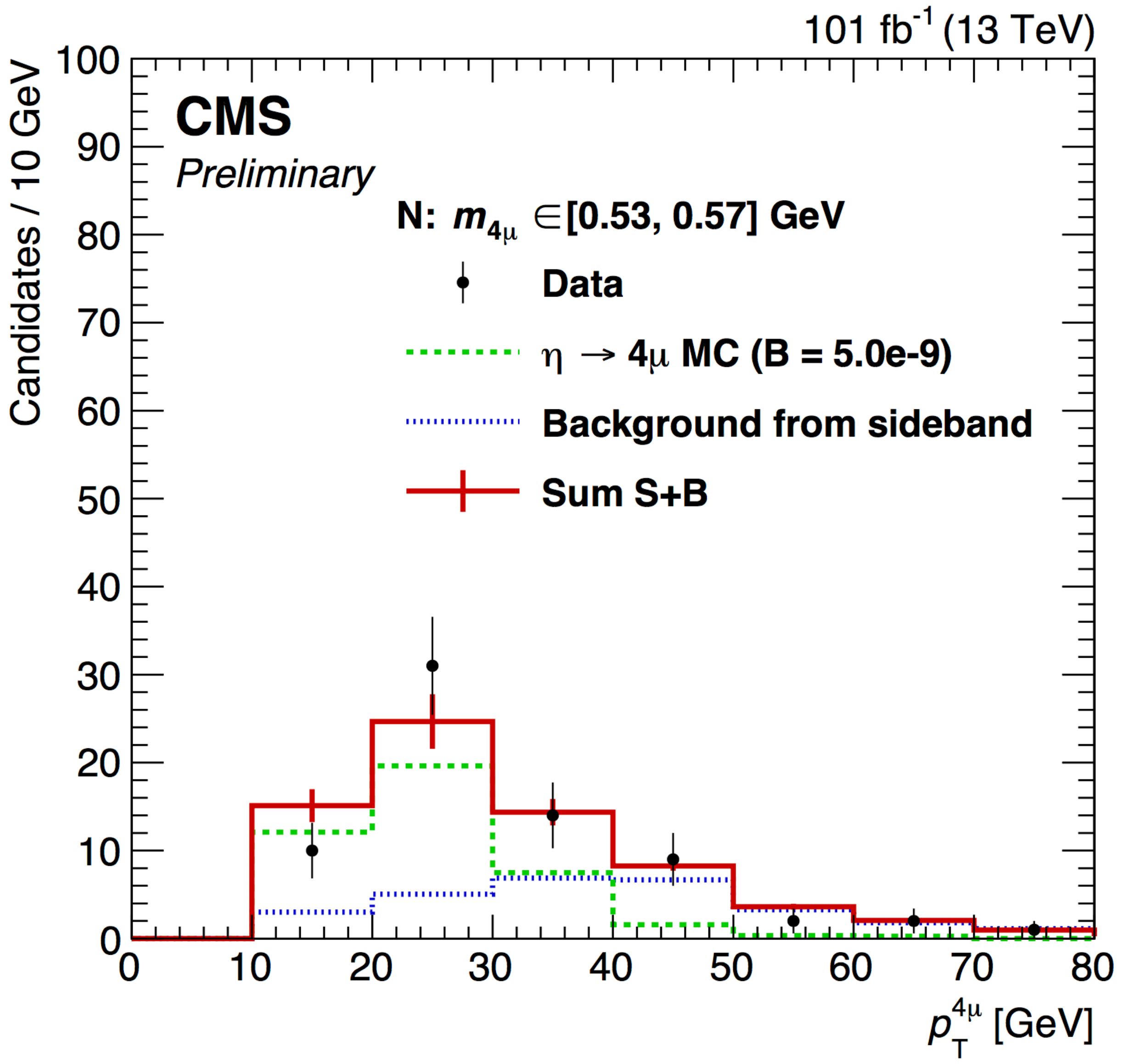
$B(\eta \to \mu\mu)$ =

5.8(0.8)×10^{-6}

$N_{\mu\mu} \approx 4.5 \cdot 10^6$

$N_\eta \approx 10^{12}$





$$\frac{B_{4\mu}}{B_{2\mu}} = \frac{N_{4\mu}}{\sum_{i,j} N_{2\mu}^{i,j} \frac{A_{4\mu}^{i,j}}{A_{2\mu}^{i,j}}} = (0.9 \pm 0.1\,(\text{stat}) \pm 0.1\,(\text{syst})) \times 10^{-3}$$

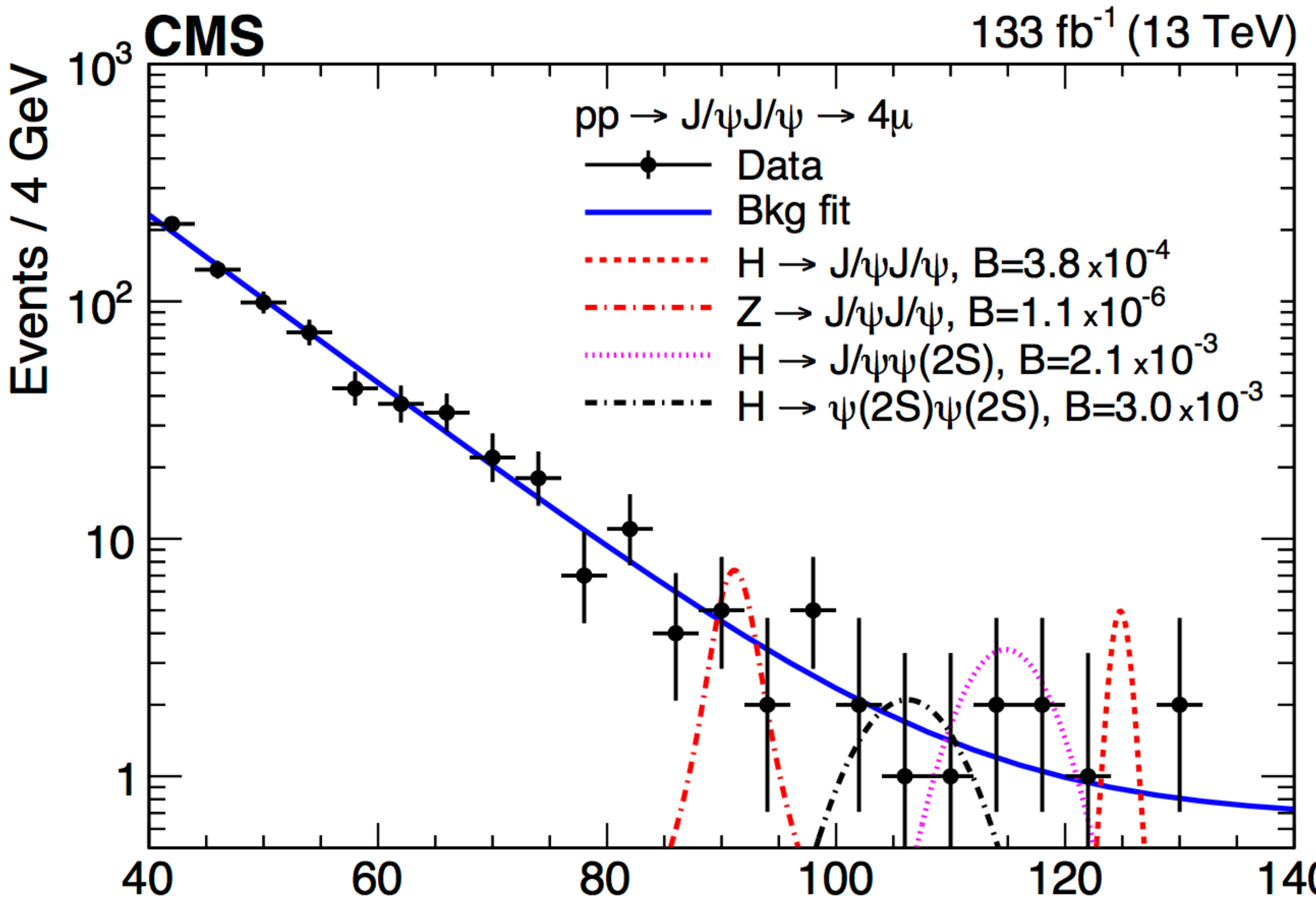
$$\mathcal{B}(\eta \to 2\mu) = (5.8 \pm 0.8) \times 10^{-6}$$

$$\mathcal{B}(\eta \to 4\mu) = (5.0 \pm 0.8\,(\text{stat}) \pm 0.7\,(\text{syst}) \pm 0.7\,(\mathcal{B})) \times 10^{-9}$$

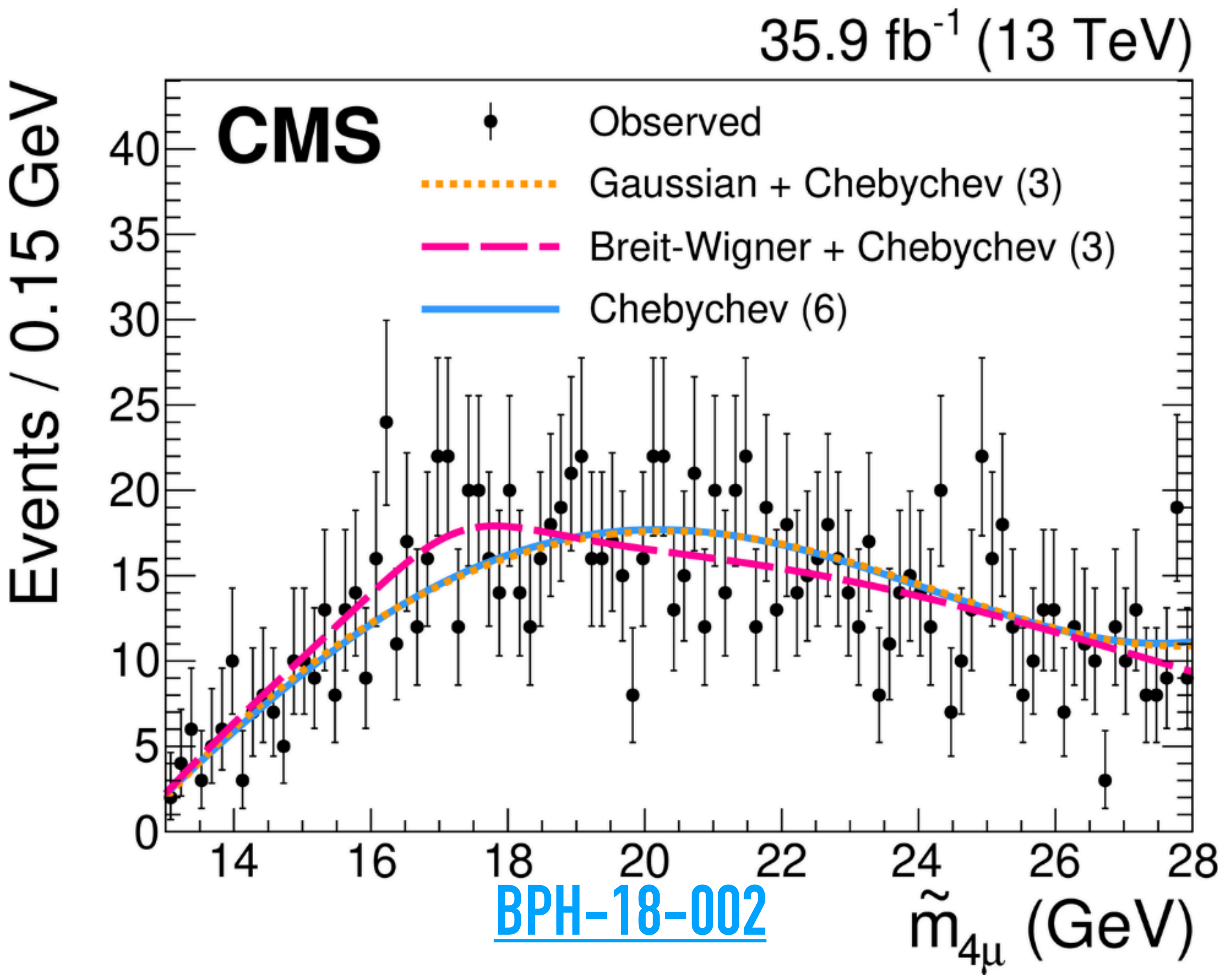
CMS-BPH-22-003

Di-quarkonium mass spectrum

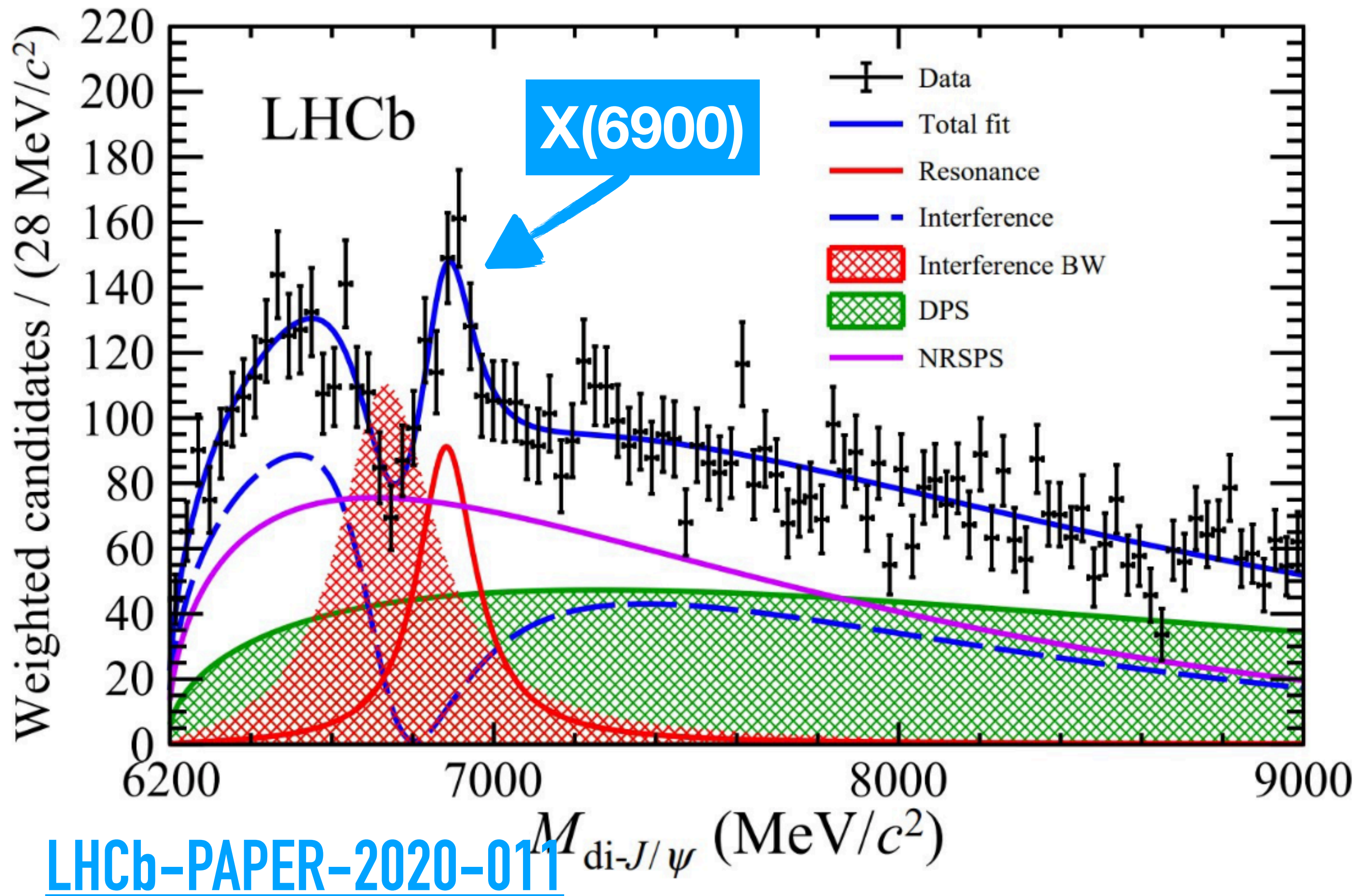
- final states with multiple quarkonia provide clean and robust canvas for searches
  - at both low- and high p_T
- first new structure reported by LHCb in 2020 in J/ψ J/ψ mass spectrum
  - narrow structure near the kinematic threshold, denoted **X(6900)**
- all-heavy tetra-quark candidate
  - after several doubly-heavy exotic candidates, this all-heavy possibility raises particular interest
  - the X(6900) peak is compelling, but proper understanding of J/ψJ/ψ mass spectrum remains uncertain



HIG-20-008

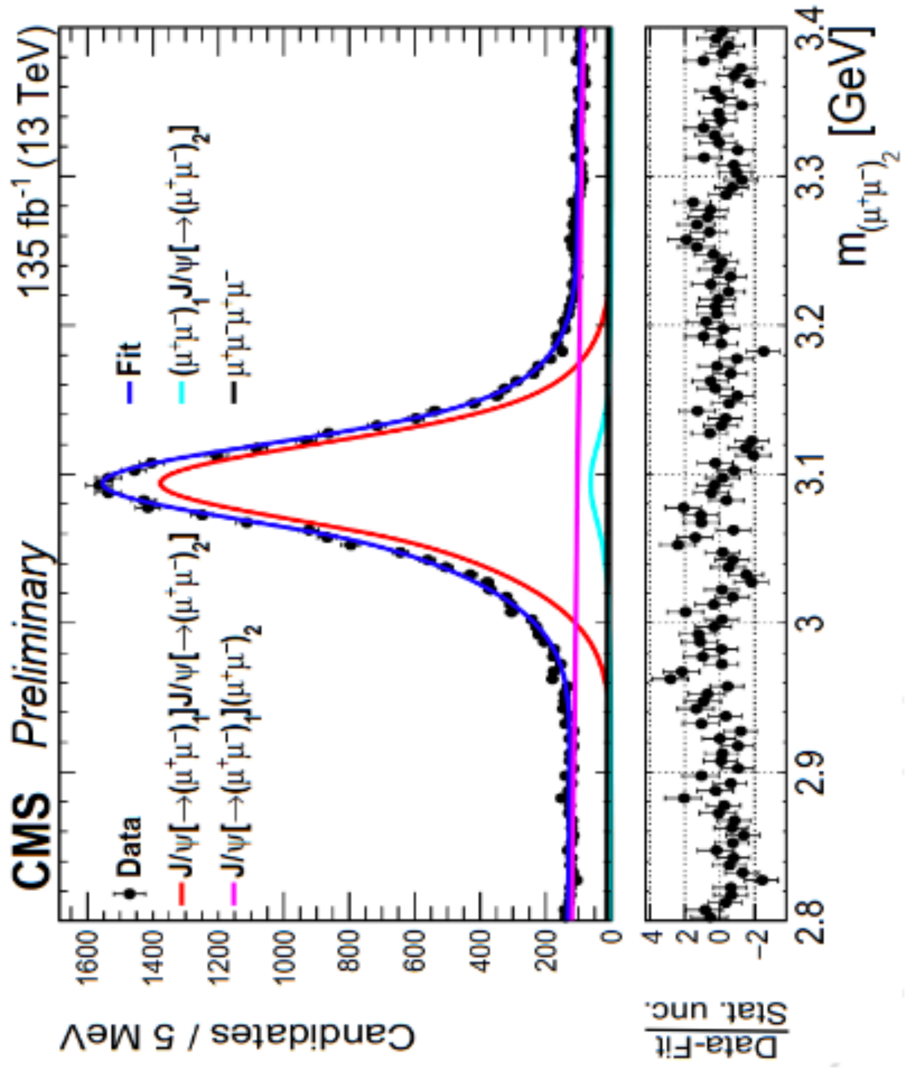


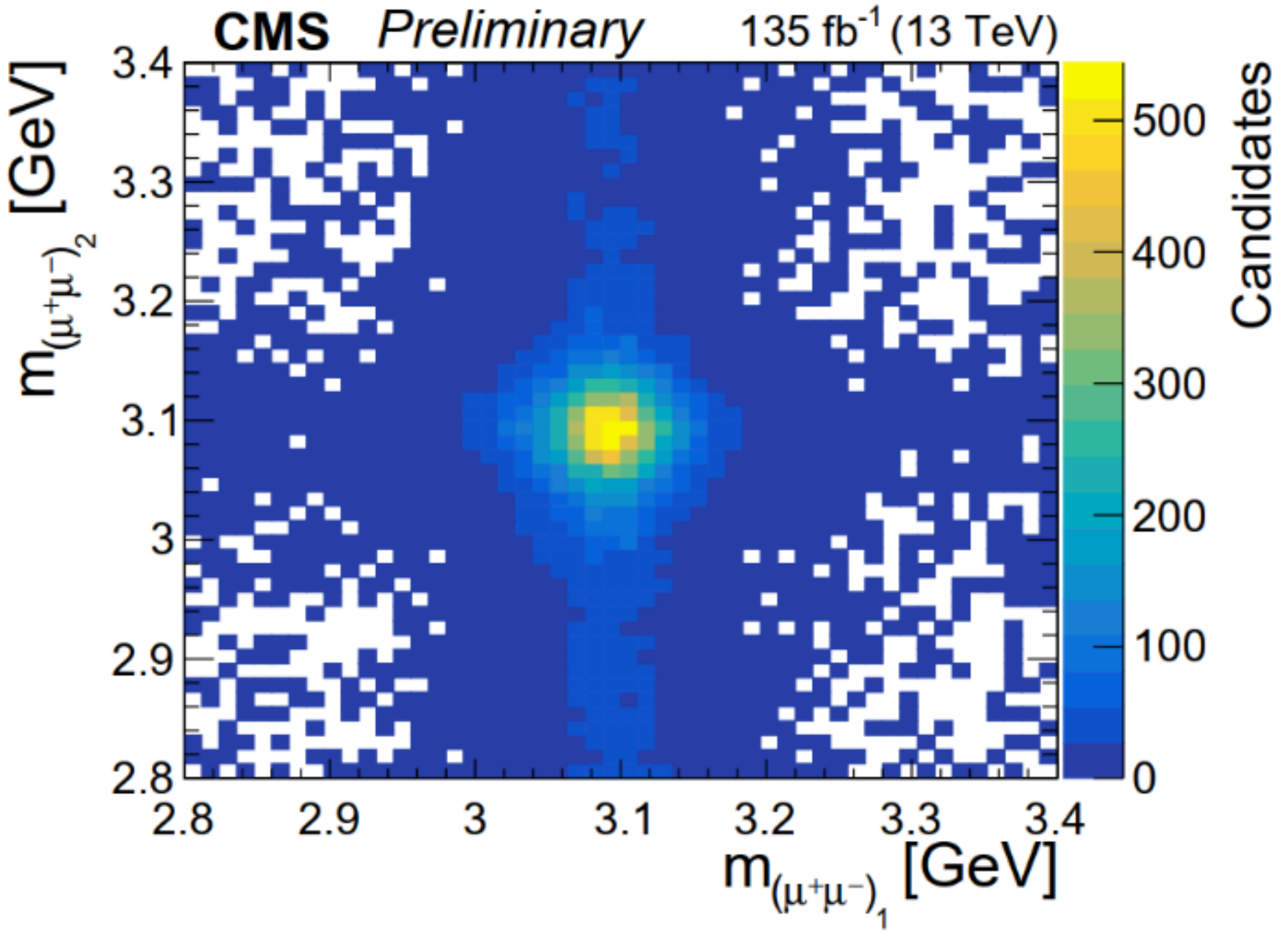
BPH-18-002

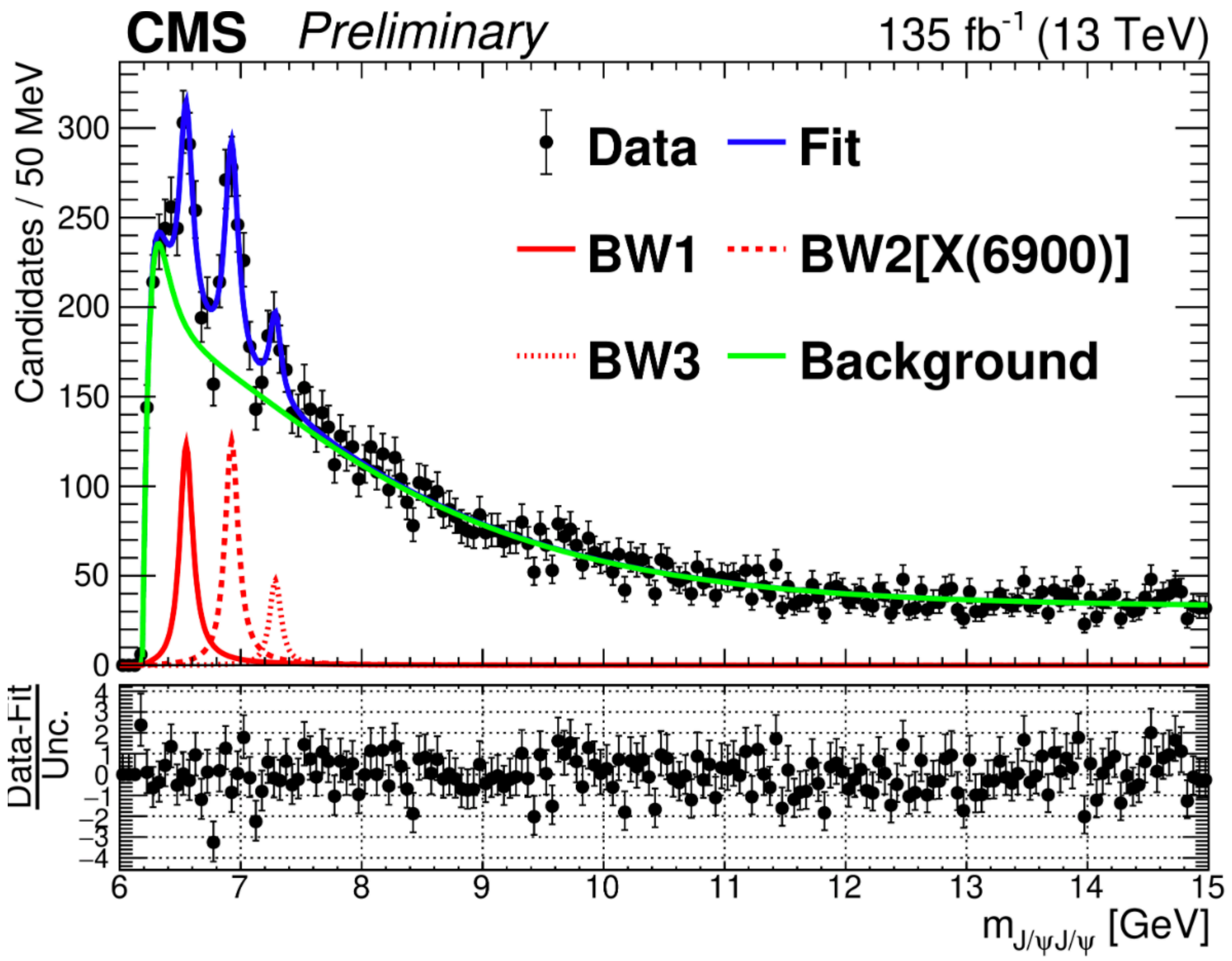


LHCb-PAPER-2020-011

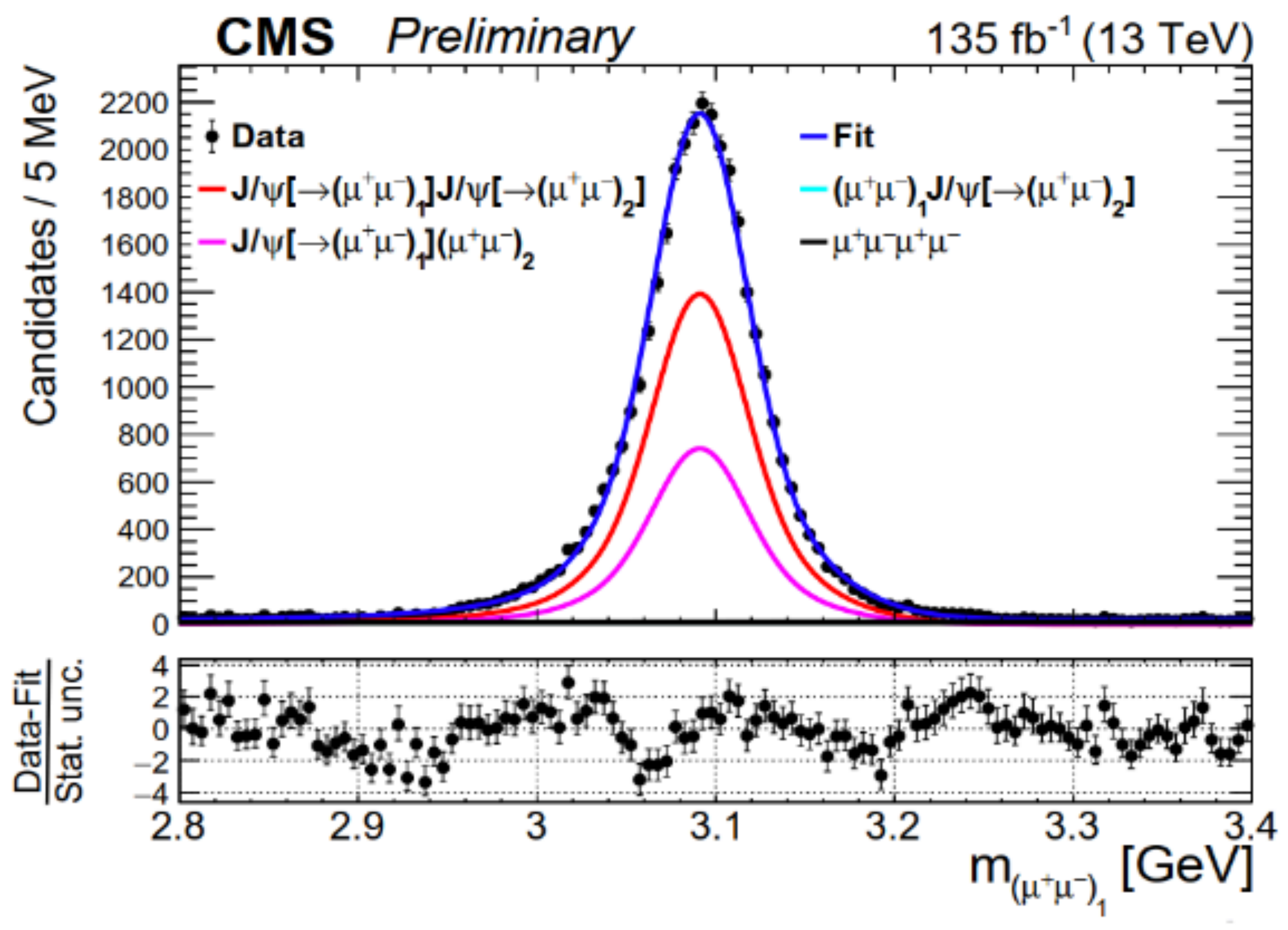
Probing the J/ψJ/ψ (→μμμμ) mass spectrum





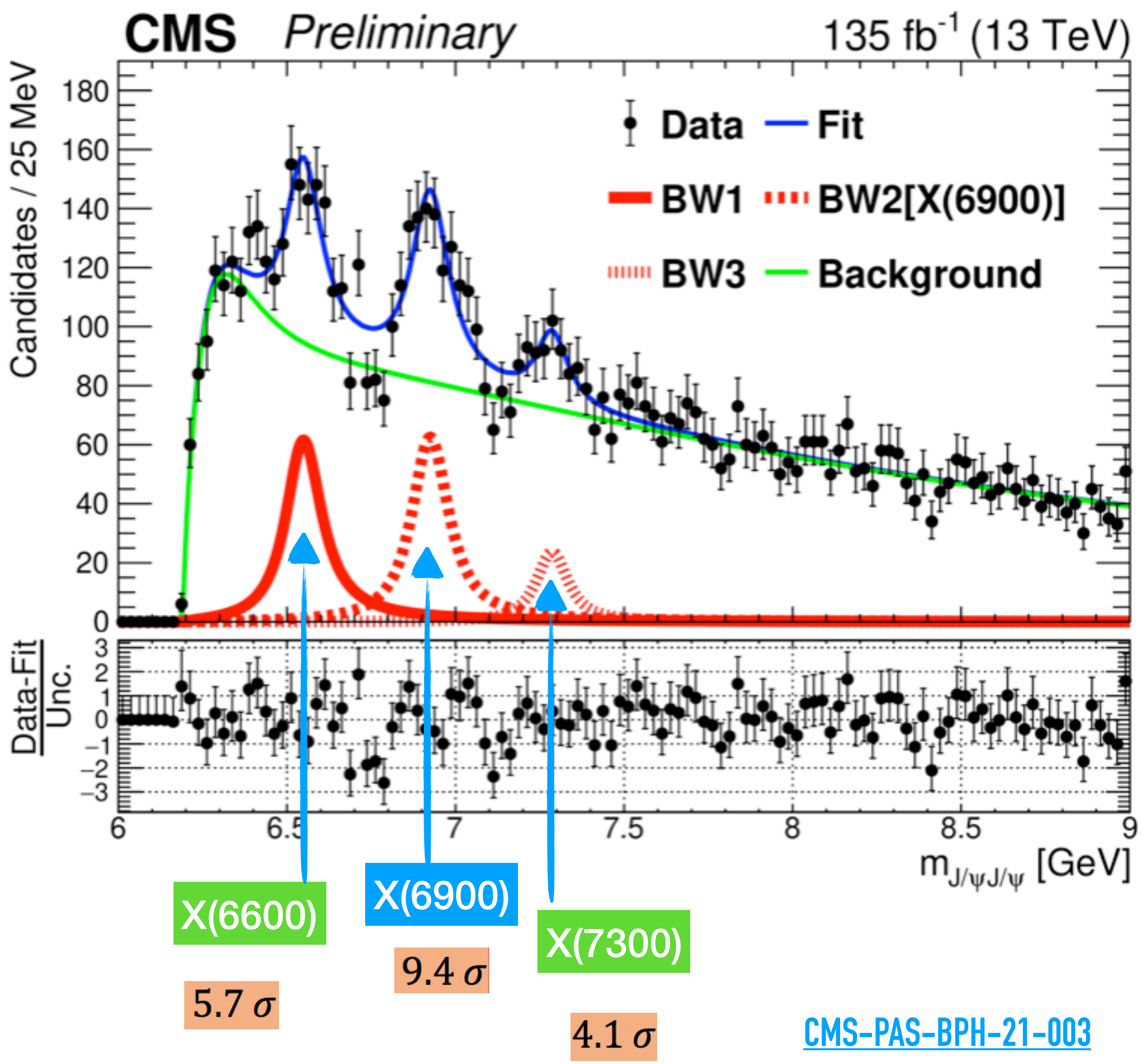


$J/\psi J/\psi \rightarrow (\mu\mu)_1(\mu\mu)_2$

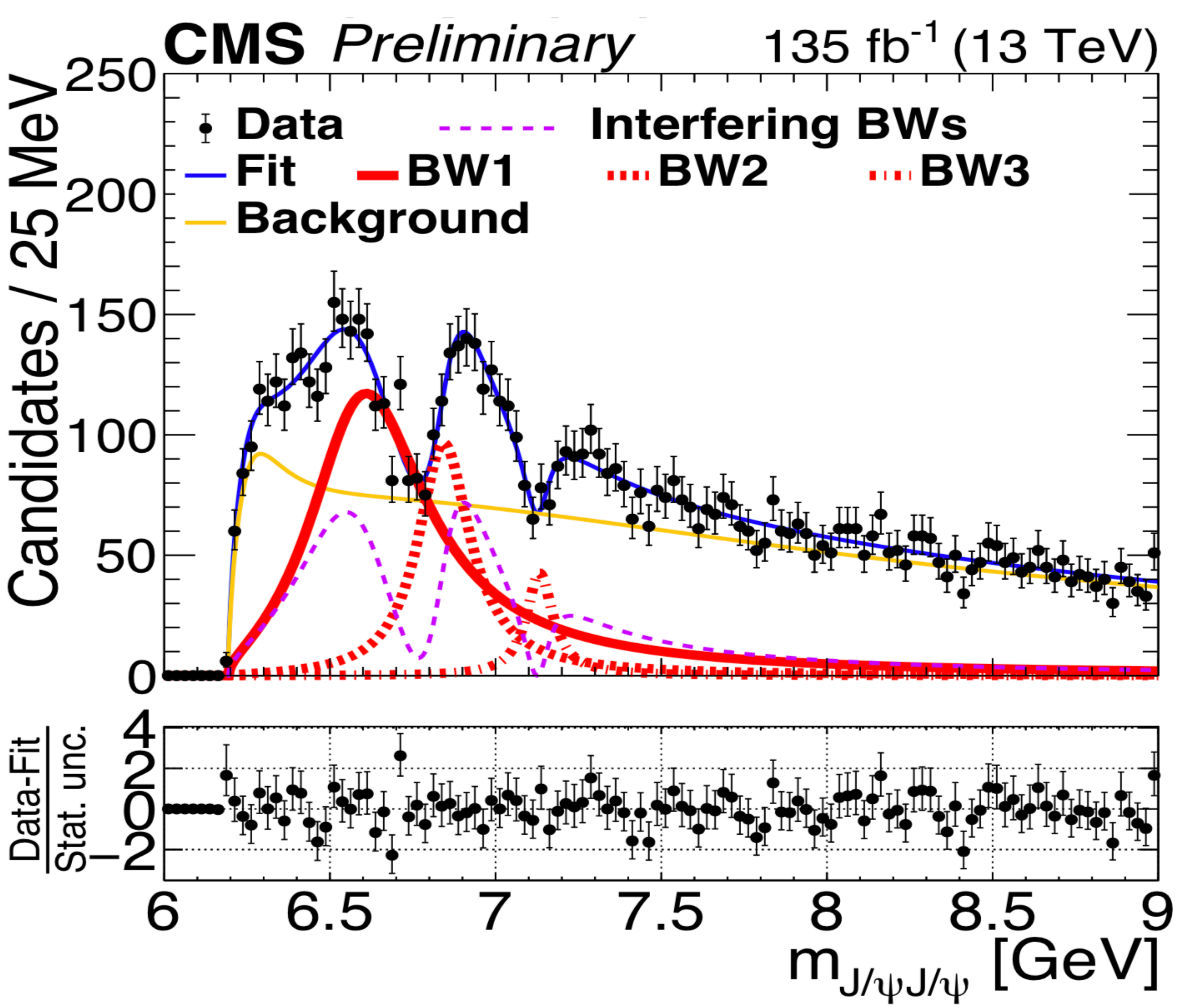


- 2016+2017+2018 data (135 fb^{-1})
- trigger: 3μ, one pair around m(J/ψ)
- blind region: 6.2-7.8 GeV
- require 4μ vertex prob. > 0.5%
- obtain ~1500 J/ψ pairs after selection

Observation of new structures in *m(J/ψJ/ψ)*



CMS-PAS-BPH-21-003

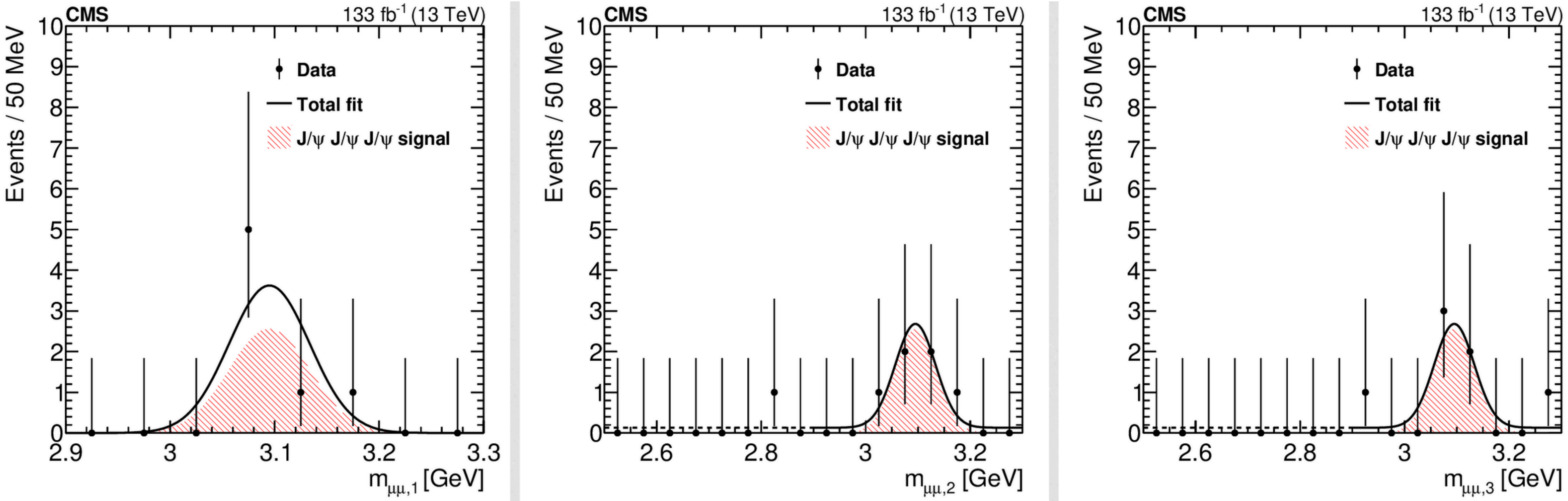


- X(6900) **confirmed**, compatible with LHCb
  - plus two new structures detected

Observation of triple *J/ψ* production

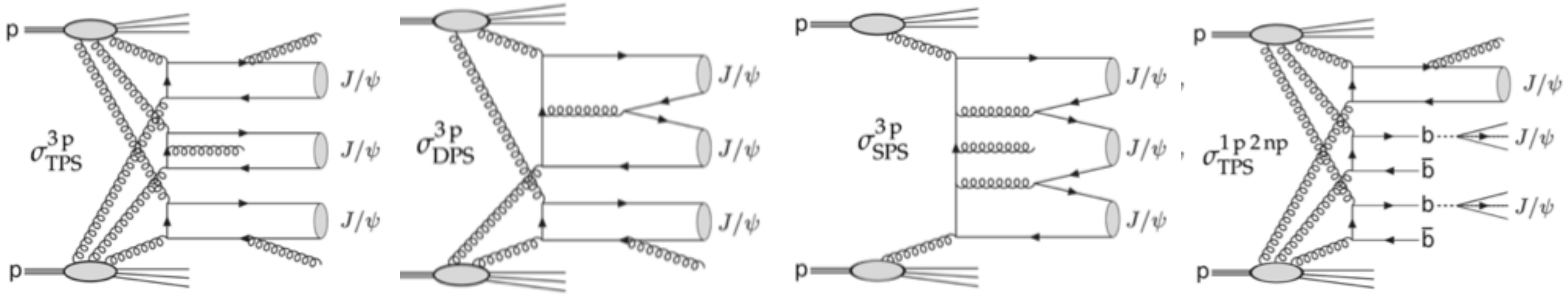
- signal observed with 5.5σ
- measure fiducial cross section

For all muons	$p_T > 3.5\,\text{GeV}$ for $\lvert\eta\rvert < 1.2$ $p_T > 2.5\,\text{GeV}$ for $1.2 < \lvert\eta\rvert < 2.4$
For all J/ψ mesons	$p_T > 6\,\text{GeV}$ and $\lvert y\rvert < 2.4$ $2.9 < m_{\mu^+\mu^-} < 3.3\,\text{GeV}$

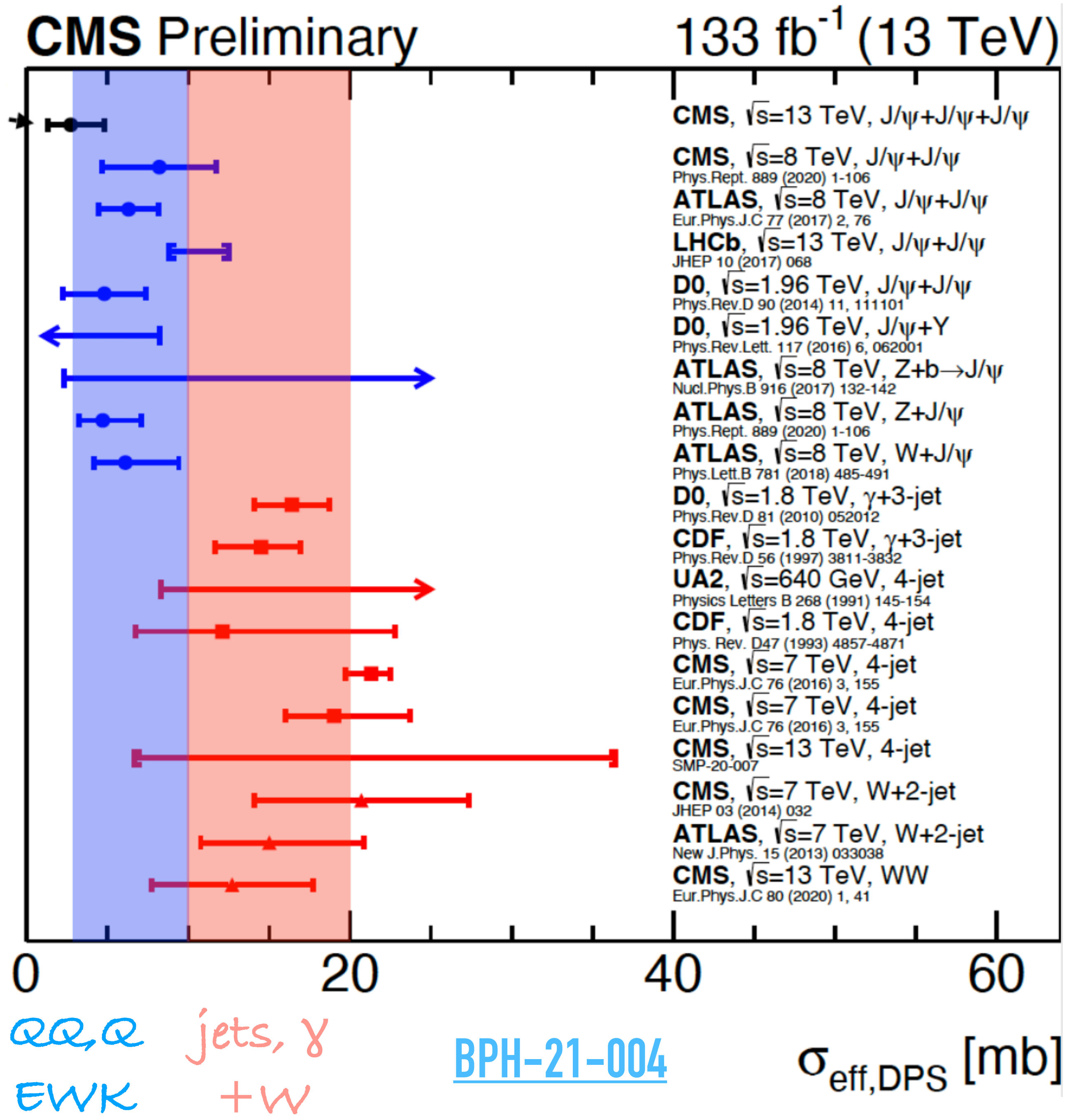


$$\sigma(\mathrm{pp} \rightarrow \mathrm{J}/\psi\,\mathrm{J}/\psi\,\mathrm{J}/\psi\,\mathrm{X}) = N_{\mathrm{sig}}^{3\mathrm{J}/\psi} / (\epsilon\,\mathcal{L}_{\mathrm{int}}\,\mathcal{B}^3_{\mathrm{J}/\psi\rightarrow\mu^+\mu^-}) \Rightarrow 272^{+141}_{-104}\,(\mathrm{stat}) \pm 17\,(\mathrm{syst})\,\mathrm{fb}$$

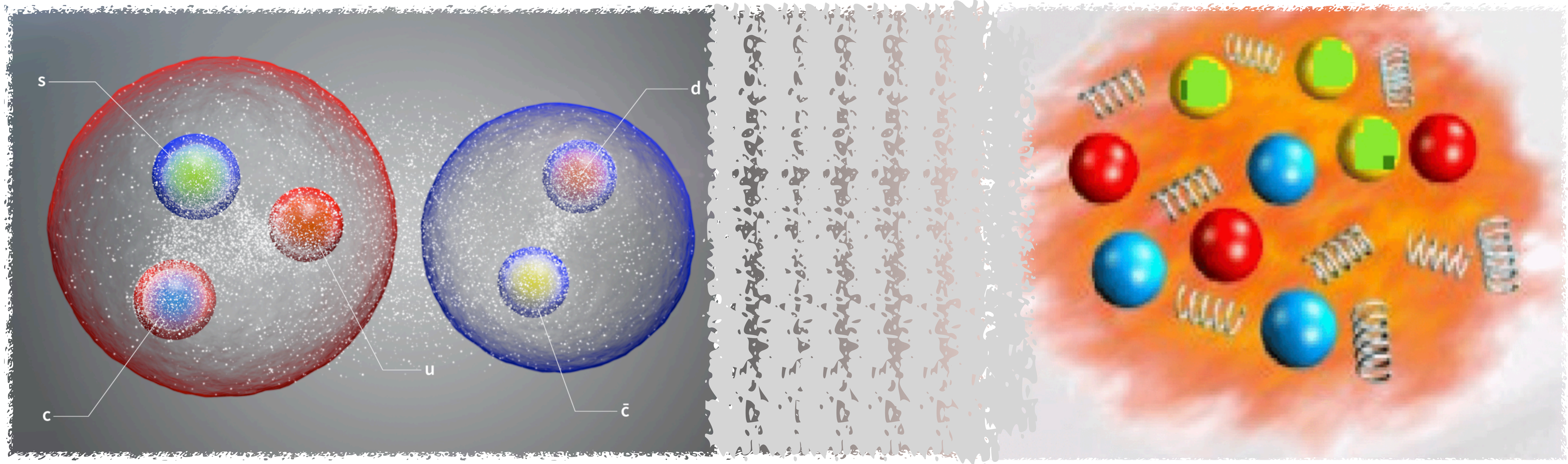
- allows to probe multiple-parton scattering

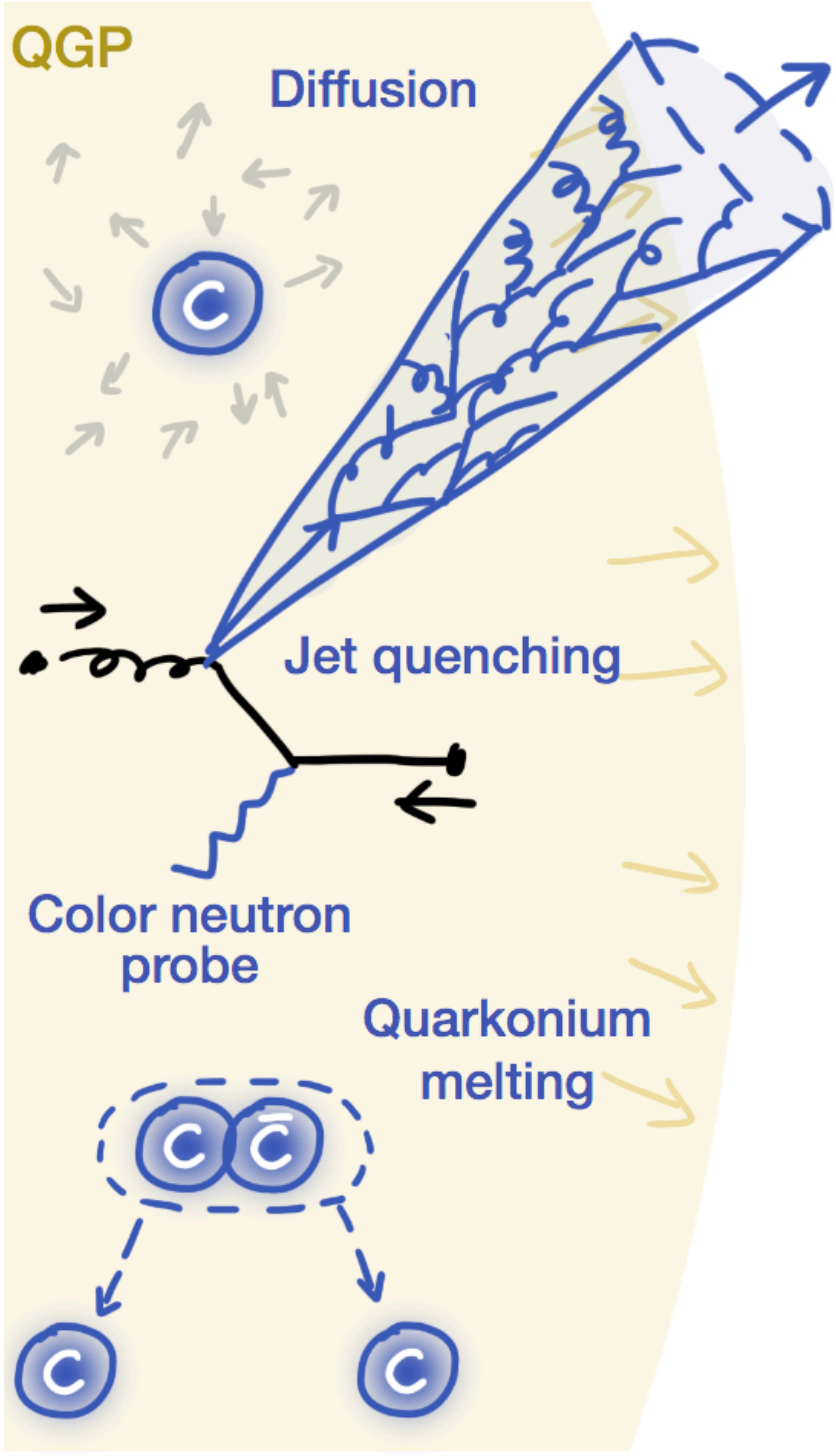


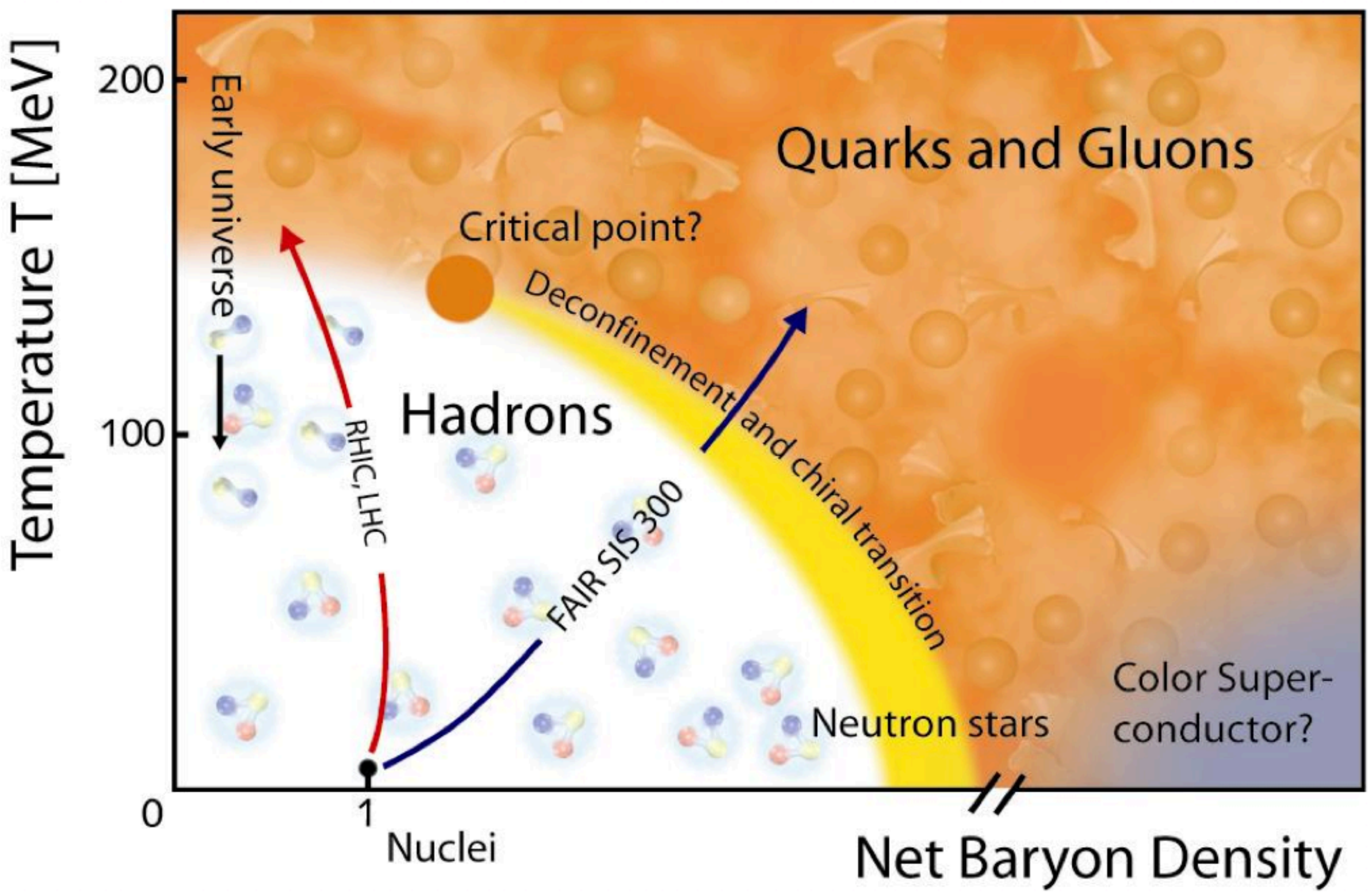
- assuming SPS factorization: $\sigma_{eff,DPS} = 2.7^{+1.4}_{-1.0}(exp)^{+1.5}_{-1.0}(theo)\,mb$



And now, into a hot, deconfined medium







➡ at large energy densities, QCD predicts the existence of a deconfined state of quarks and gluons -- the quark gluon plasma (QGP)

- reproduced in heavy ion collisions

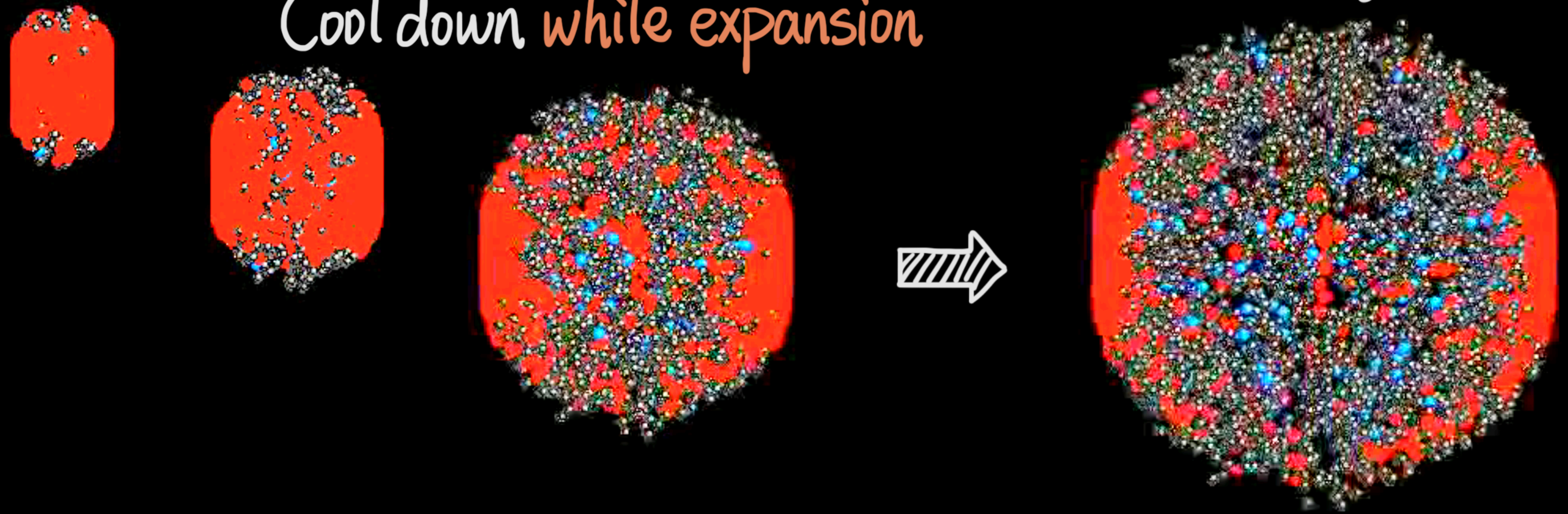
Before collisions (two pancakes of nucleons)

Collisions (the harder, the earlier)

QGP emergence (tons of soft scatterings)

Cool down while expansion

Hadronization



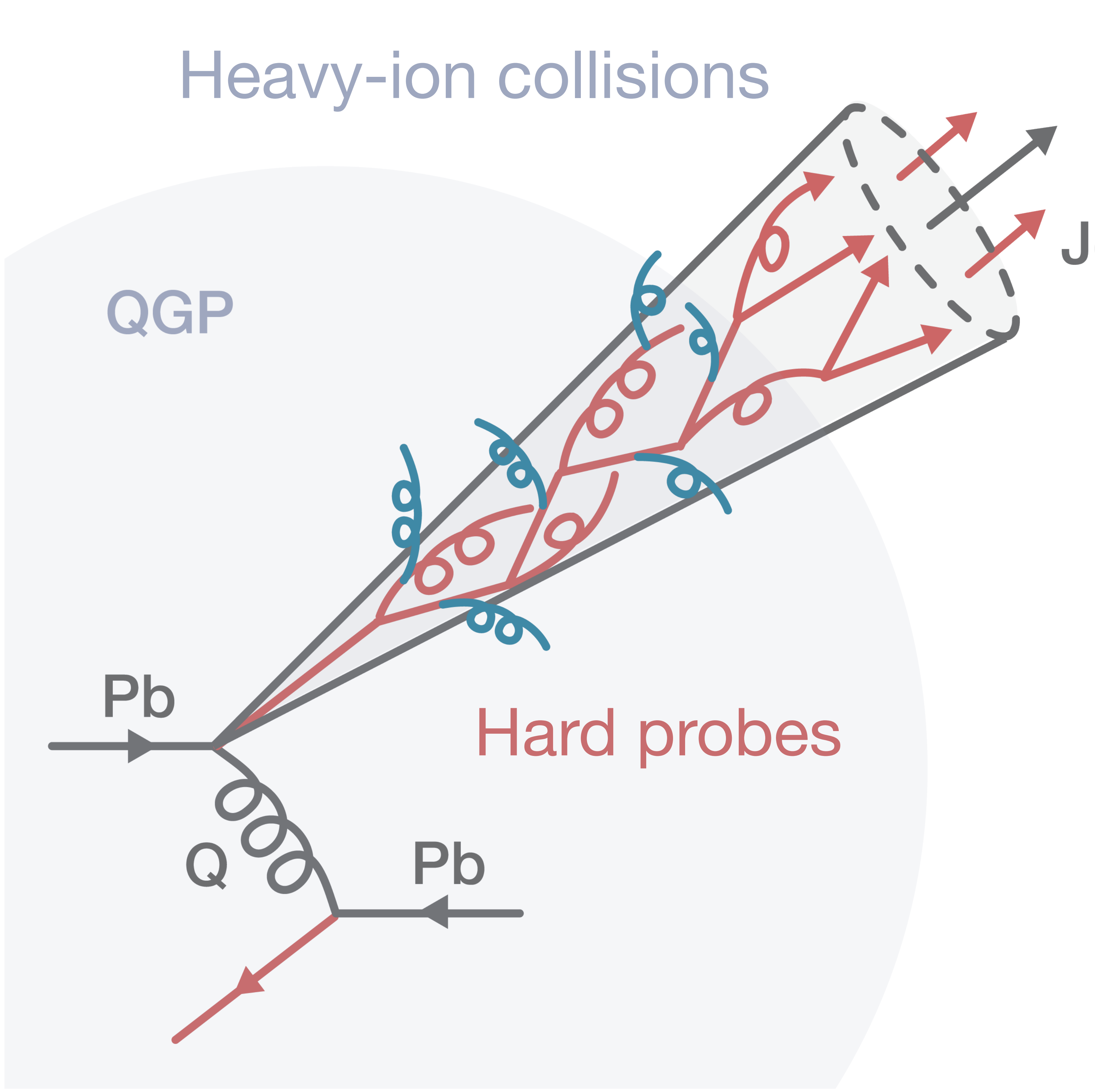
Quark Gluon Plasma

Baryons

Mesons

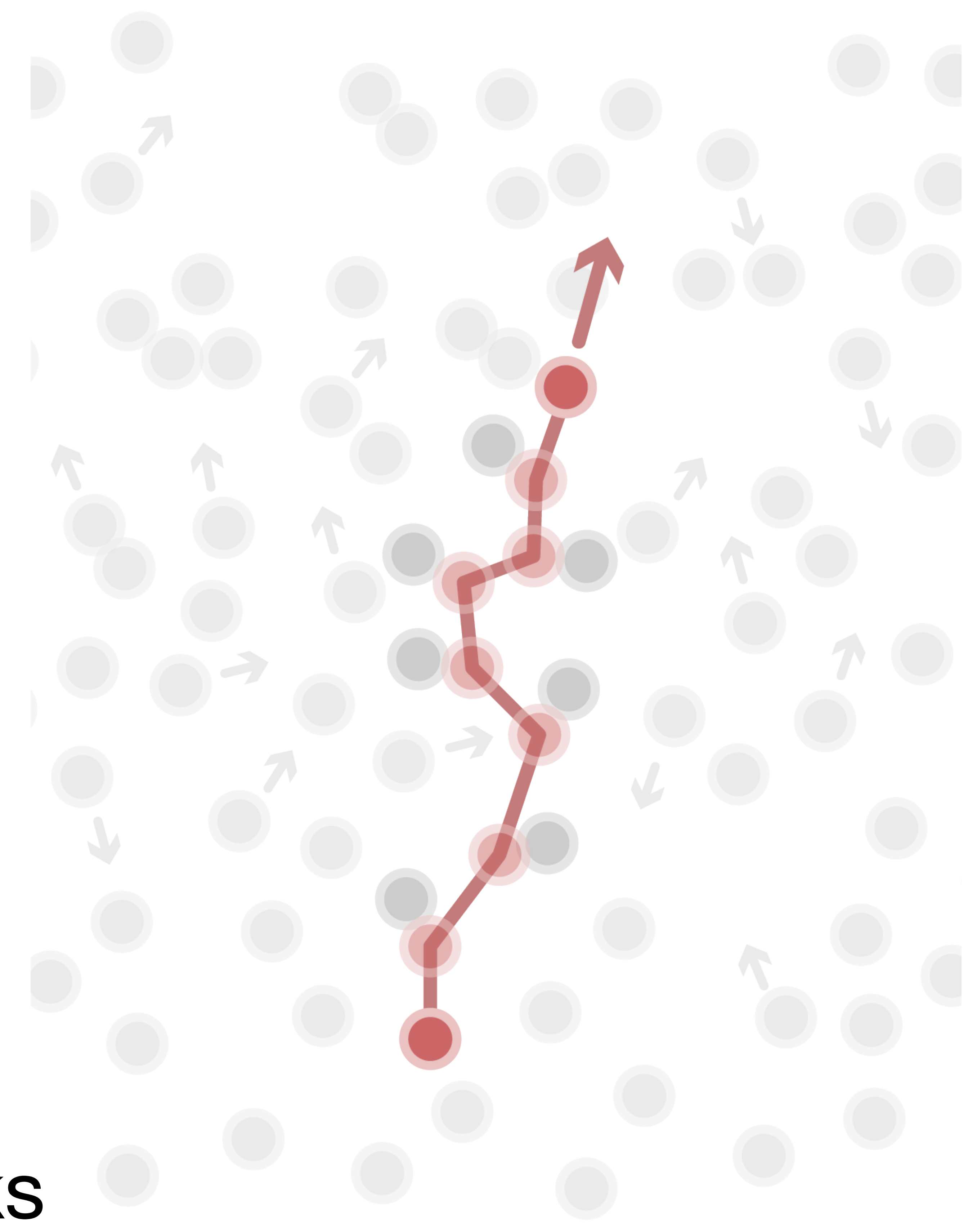
CREDITS: J. WANG

Hard Probes of QGP ⟶ Heavy Flavour HPs



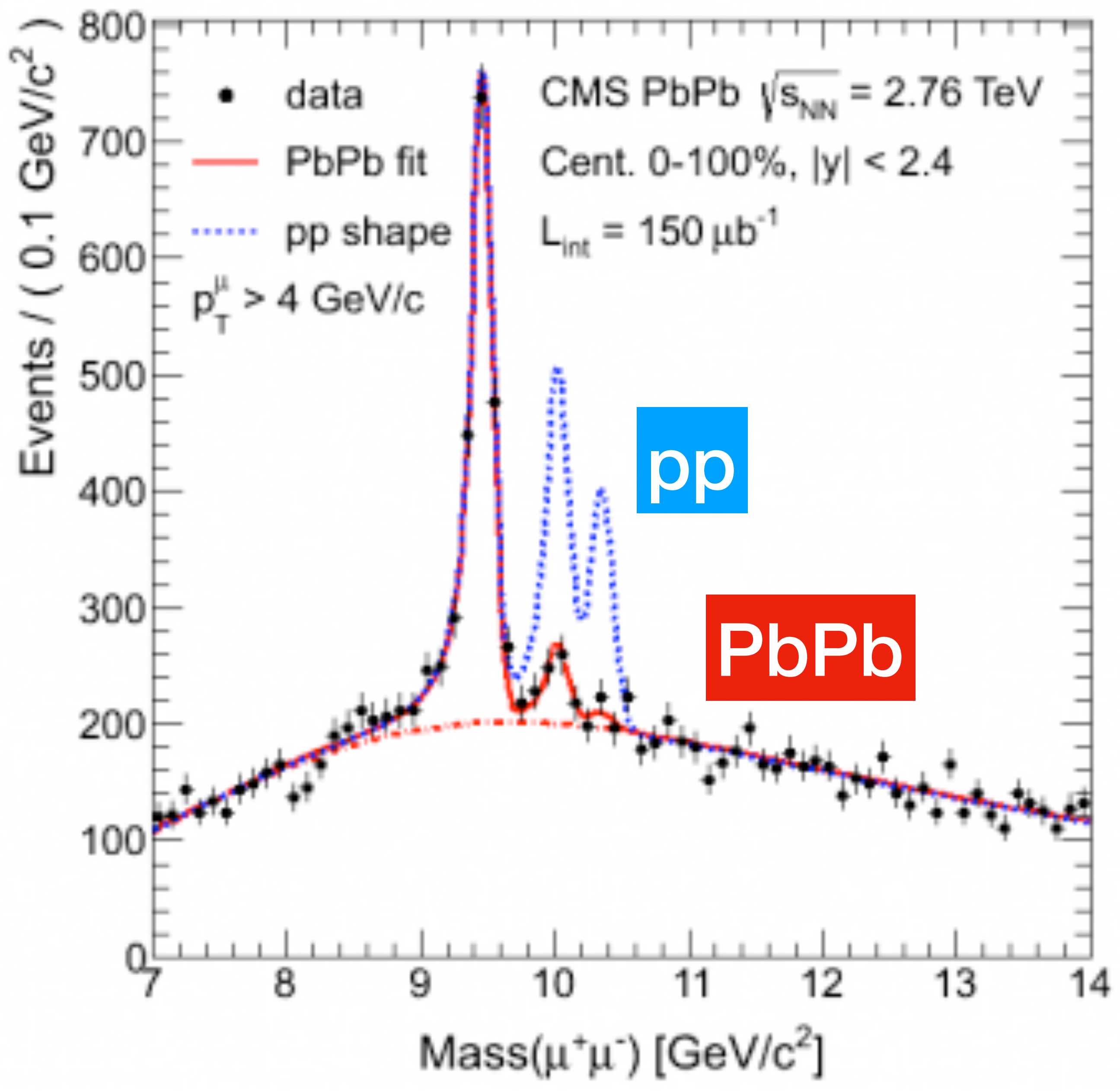
Hard probes
"X-ray" QGP

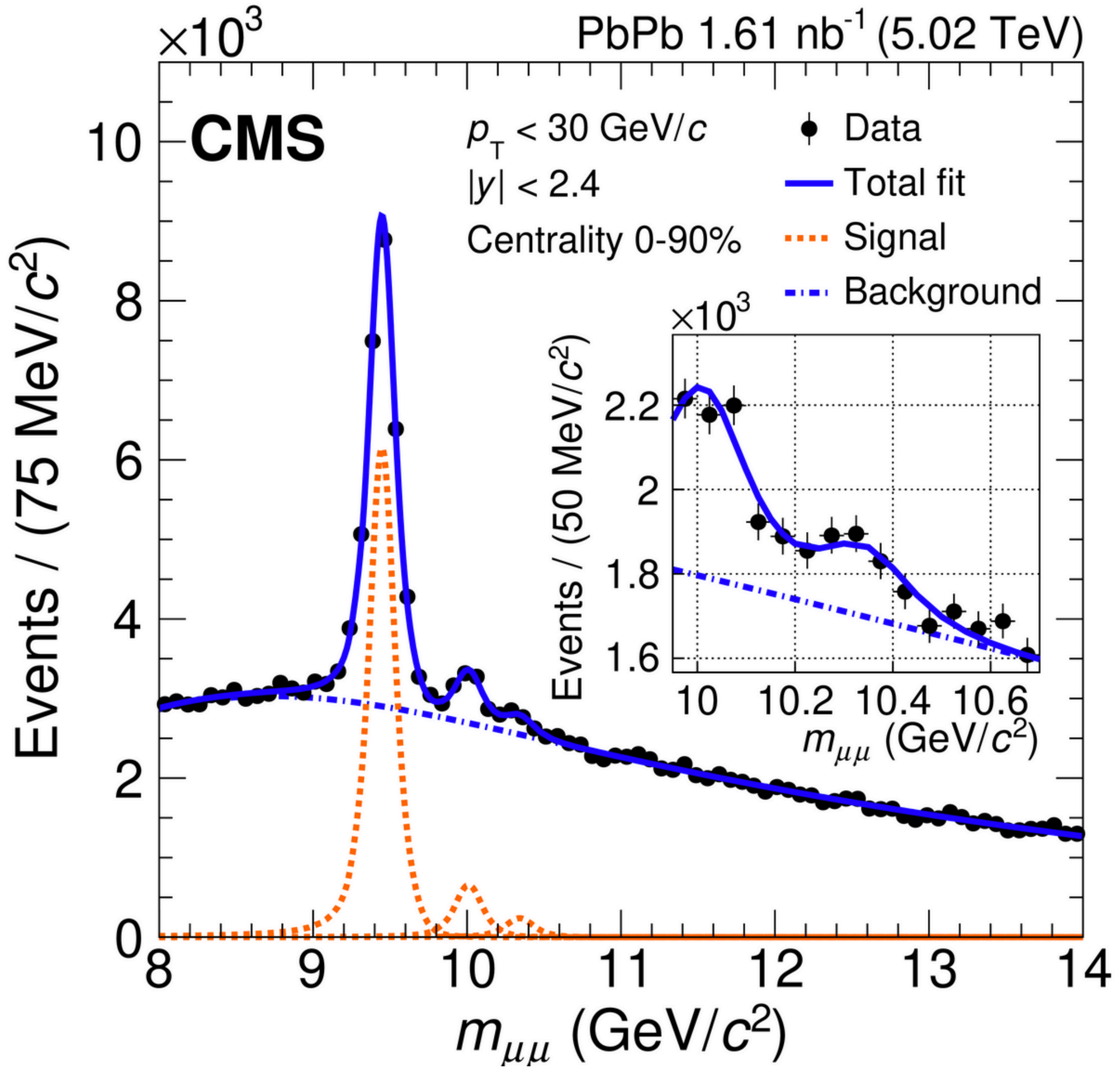
- Hard (large Q) ➜ high p_T particles
- Produced at early stage
  - $\tau \sim 1/Q \sim 1/m_Q$
  - access to short lifetime processes
- Initial production calculable with pQCD
  - $m_Q \gg \Lambda_{QCD}$
- Rarely produced in medium
  - $m_Q \gg T_{QGP}$
  - clean probe, e.g. study hadronization
- Interactions w/ QGP heavy ≠ light quarks
  - $m_Q \gg m_q$

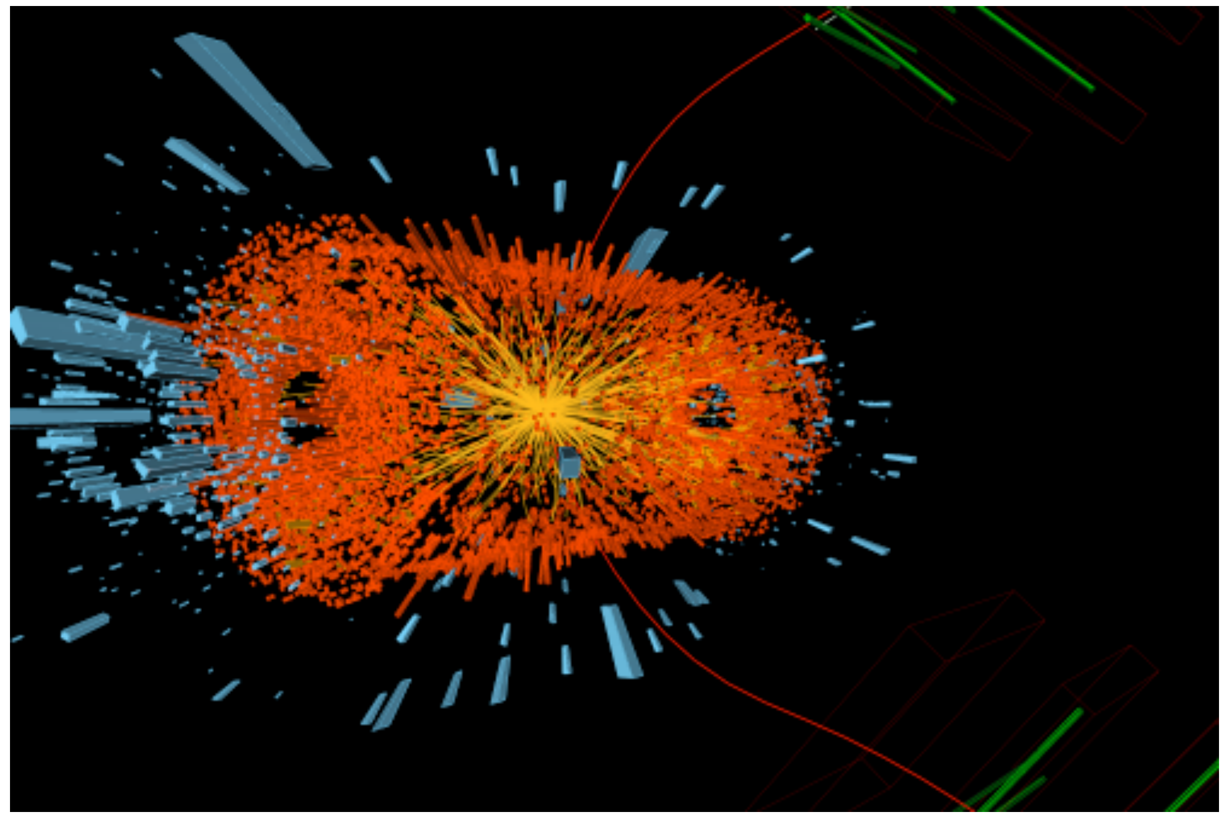


Heavy quark diffusion in QGP

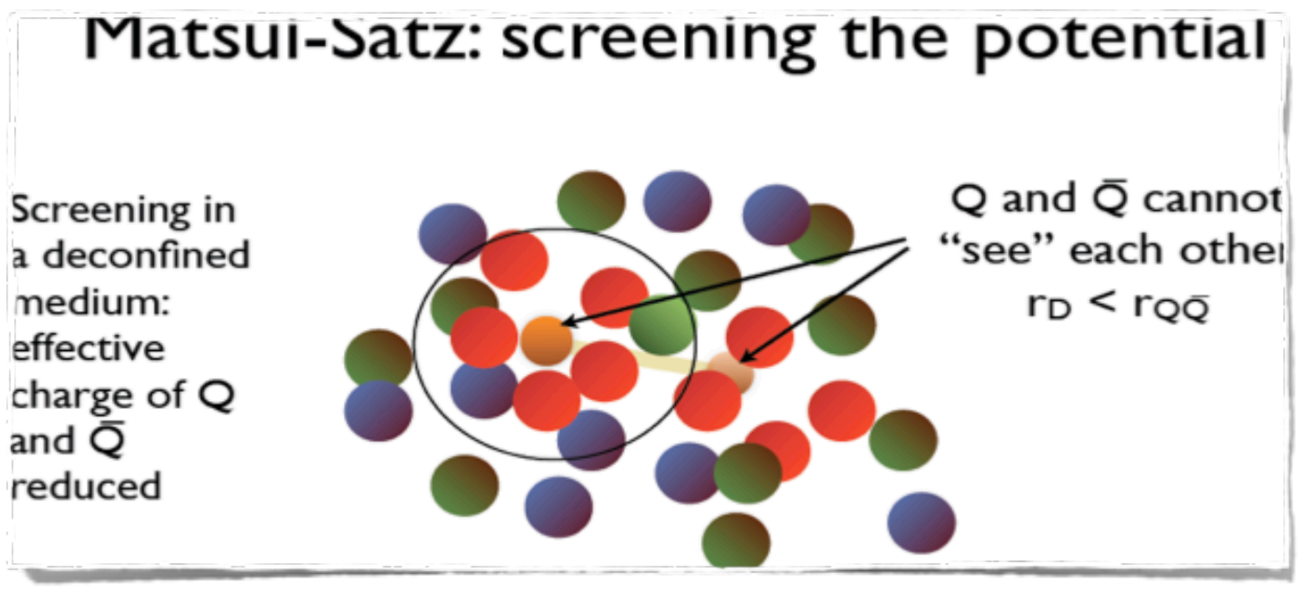
Upsilon suppression







HIN-11-011 HIN-21-007

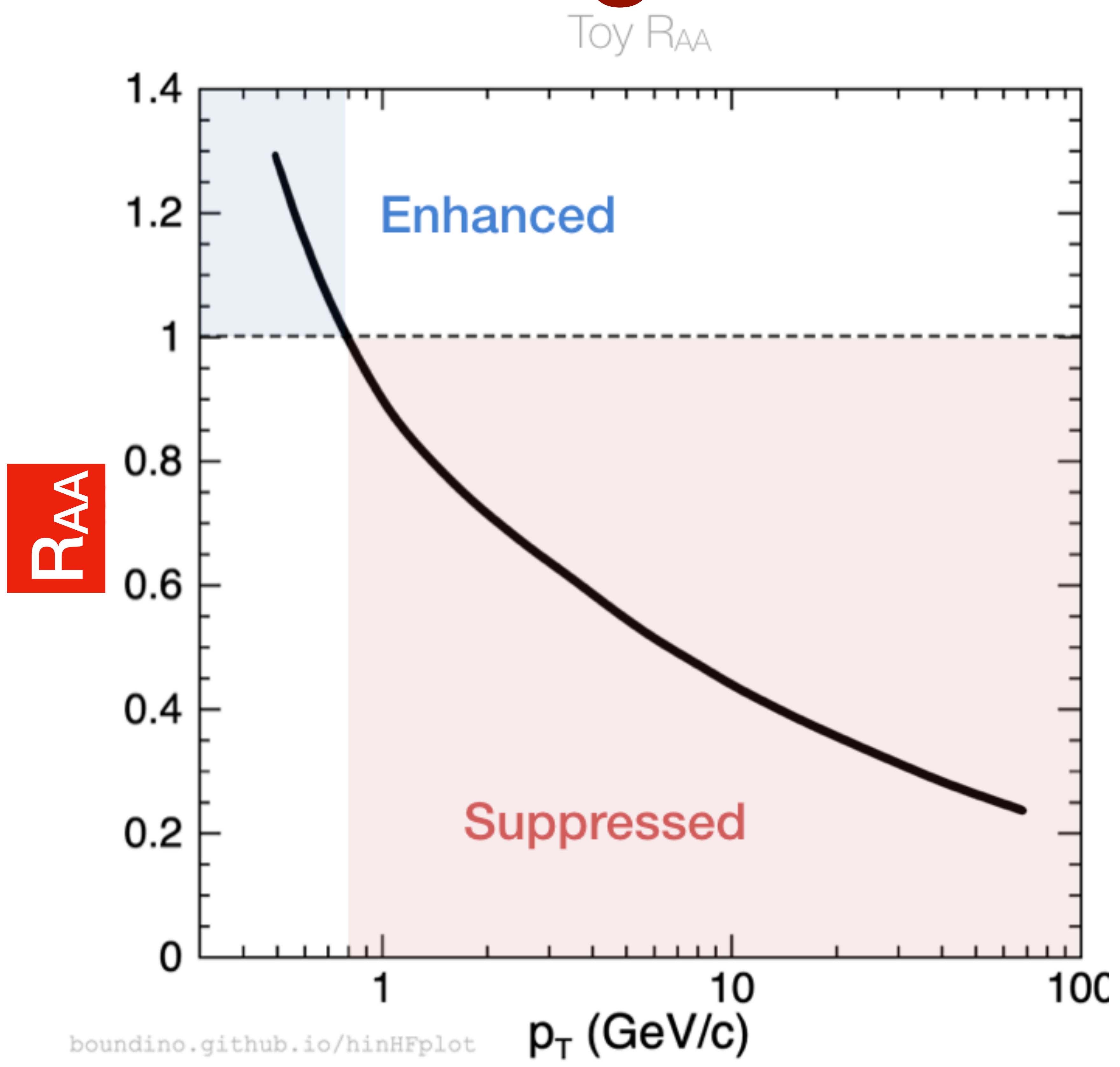


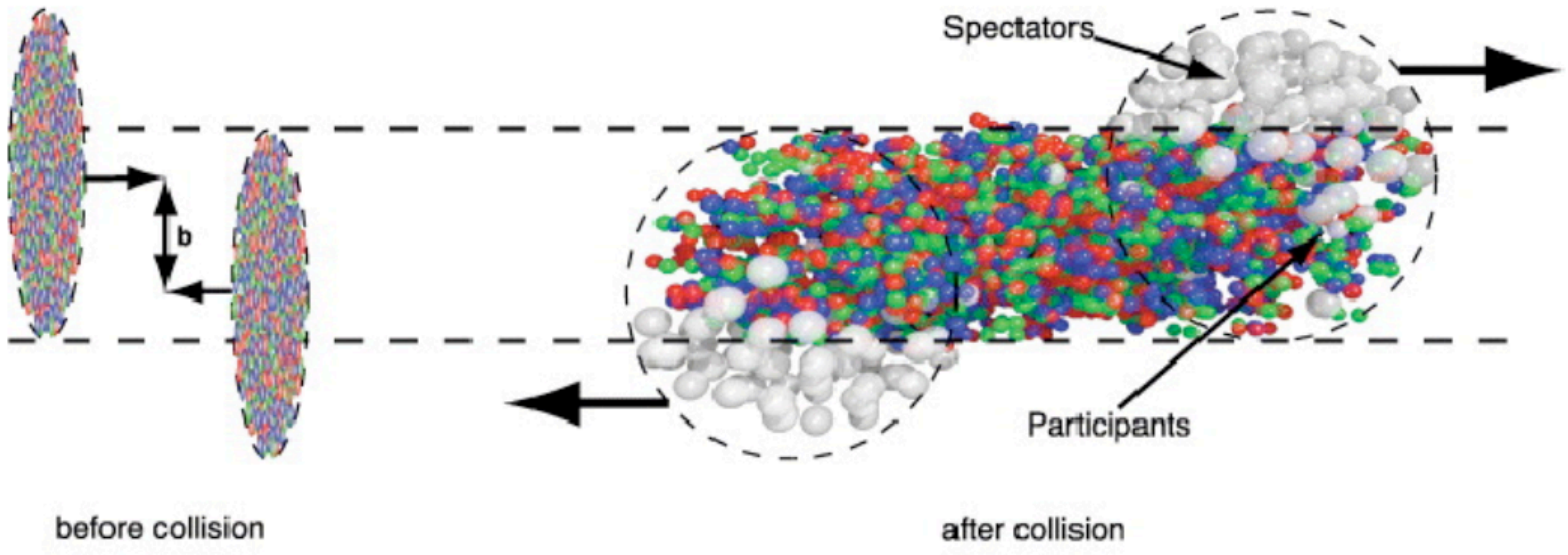
- out of the three Υ(nS) states
  - the excited states Υ(2S), Υ(3S) are suppressed wrt ground state Υ(1S)
- when comparing PbPb vs pp collisions

$$\frac{\Upsilon(2S)/\Upsilon(1S)|_{PbPb}}{\Upsilon(2S)/\Upsilon(1S)|_{pp}} = 0.21 \pm 0.07\,(\text{stat.}) \pm 0.02\,(\text{syst.})$$

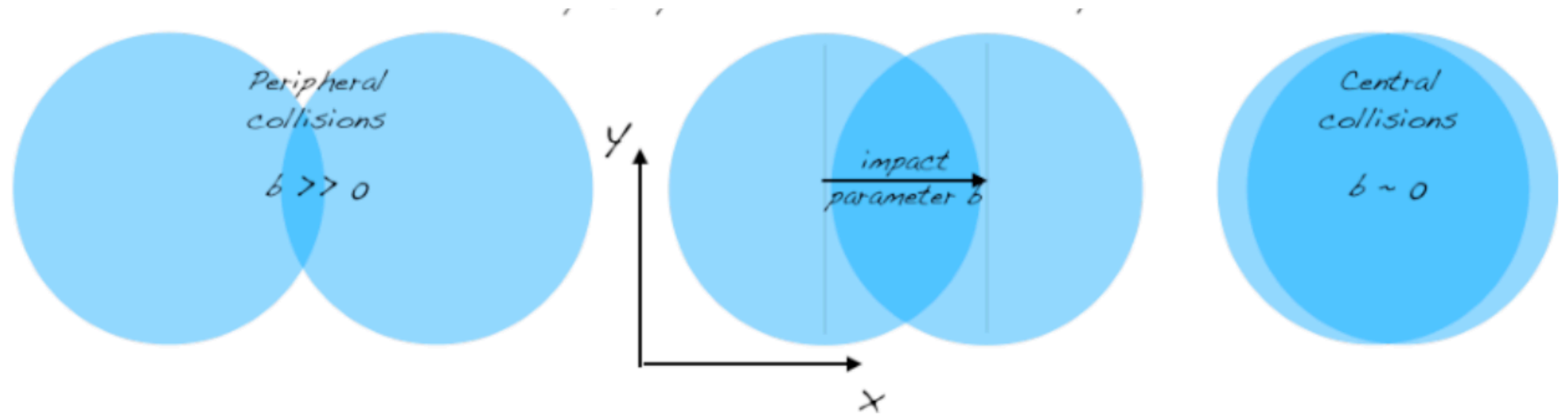
- ↪ quarkonium states melt, ie are dissociated in the QGP
- the melting occurs sequentially
  - least bound stated are more melted than tightly bound states

Measuring the medium effects (schematics)





Centrality of the collision ↔ N_{part} (# of participants)



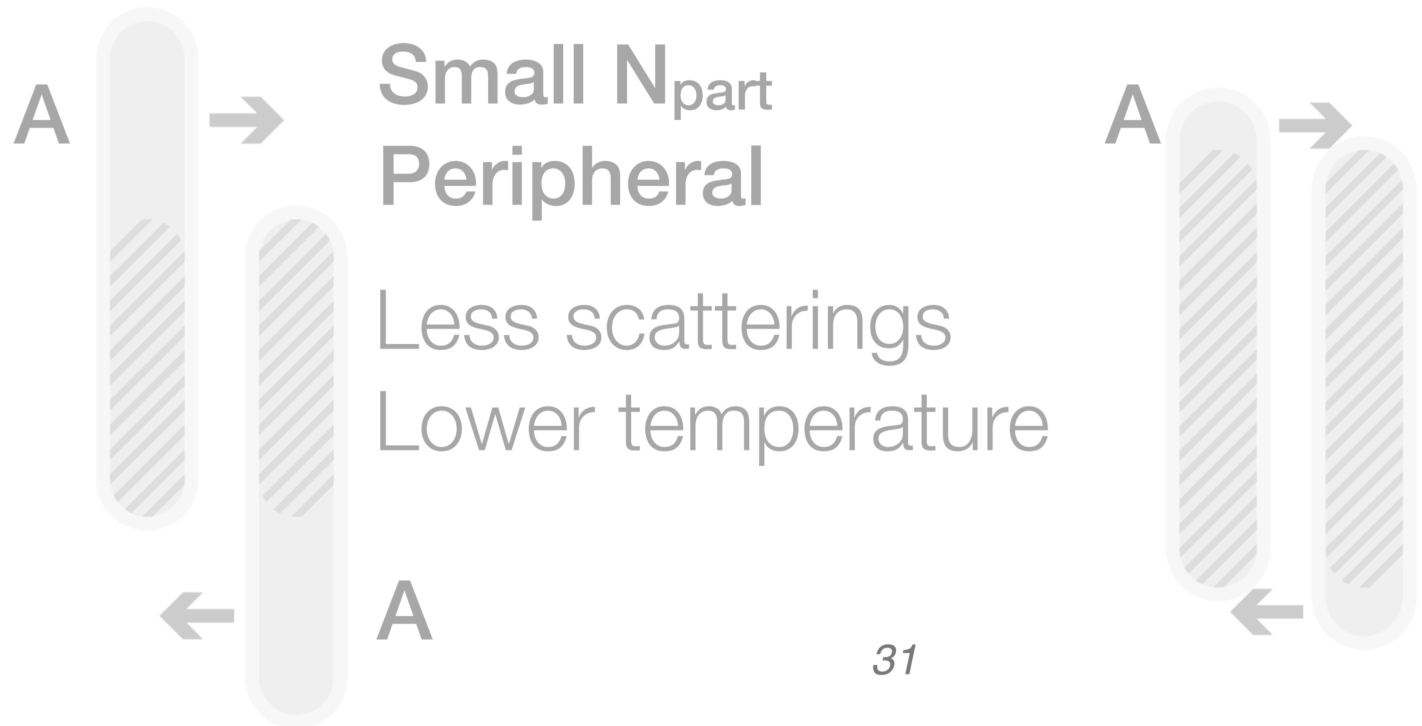
Nuclear modification factor R_{AA}

R_{AA} =1: superposition of nucleon-nucleon collisions

$$R_{AA} = \frac{dN_{AA}/dp_T}{T_{AA} d\sigma_{pp}/dp_T}$$

← Heavy-ion

← pp



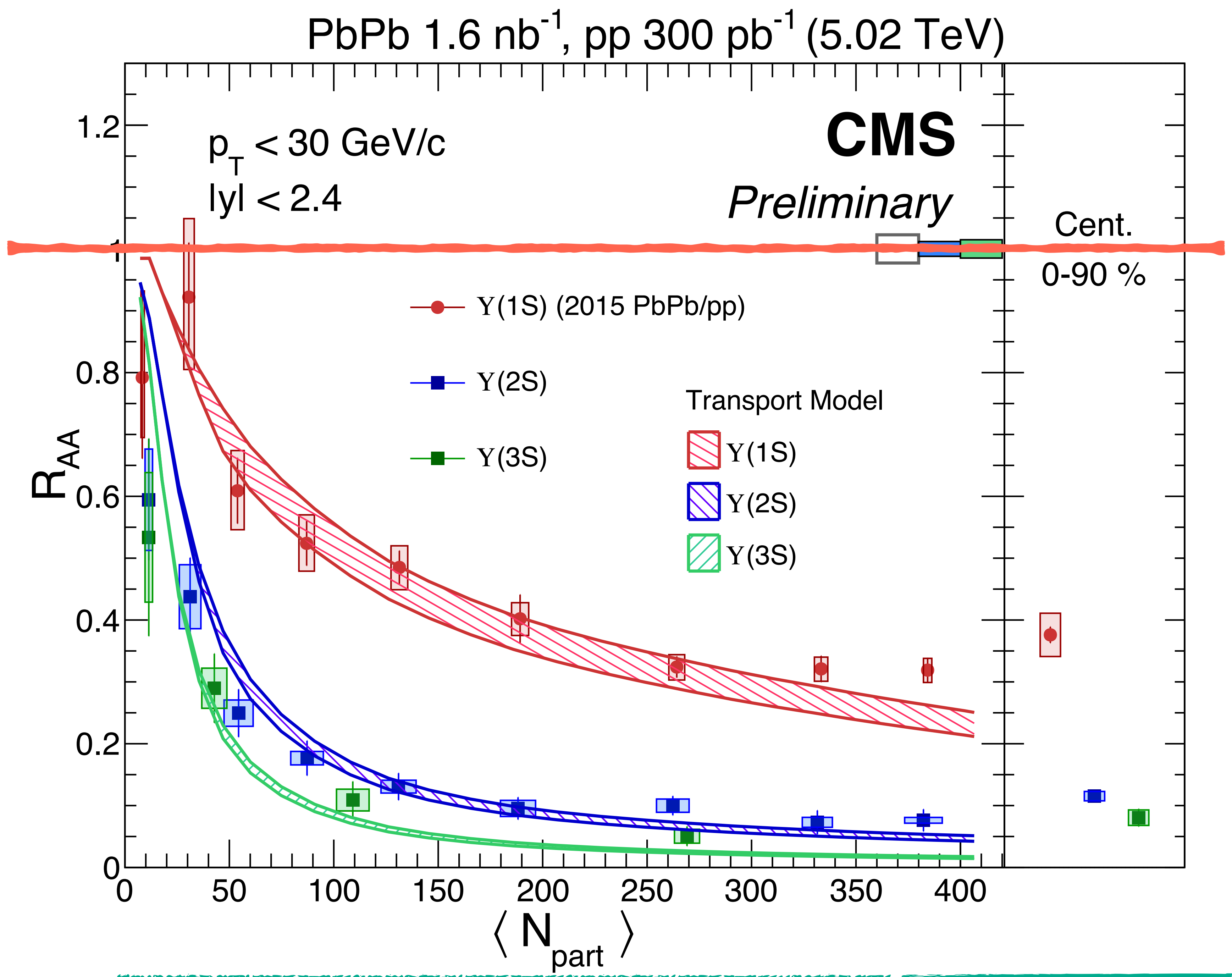
Small N_{part}
Peripheral

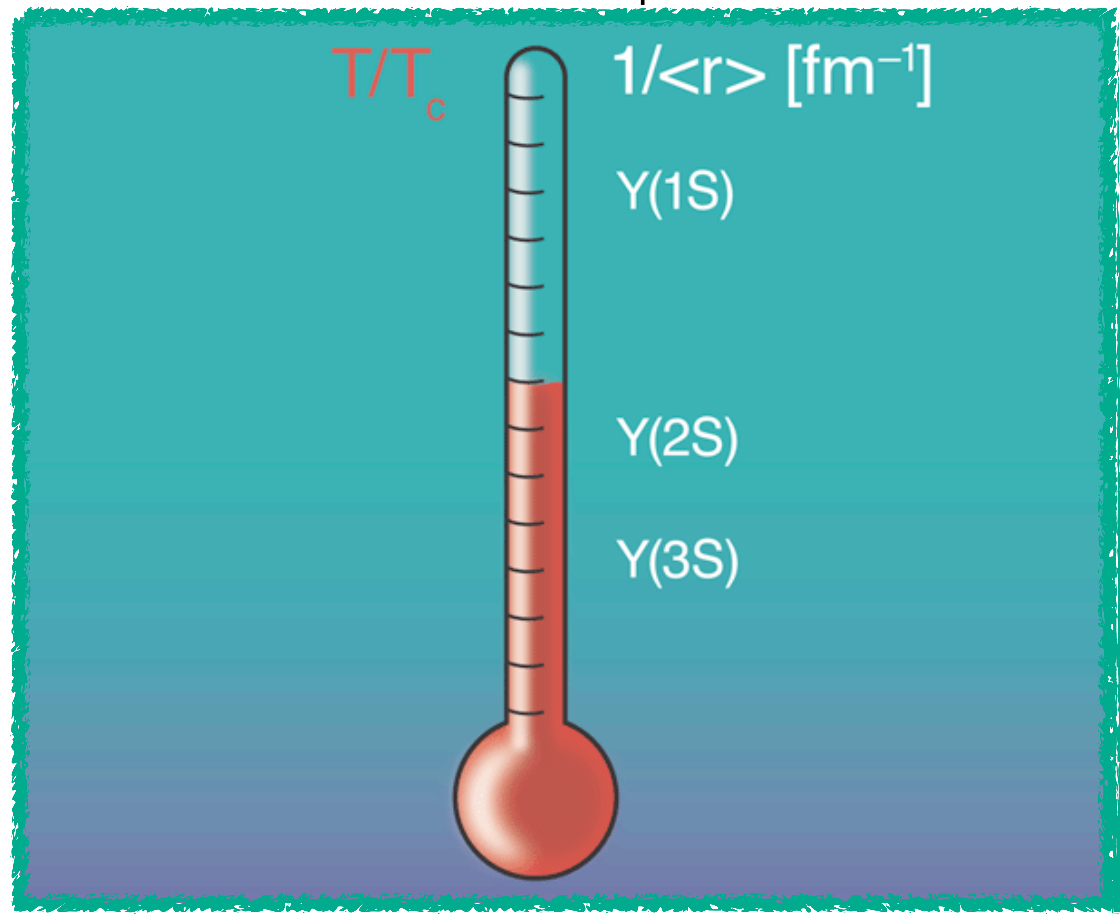
Less scatterings
Lower temperature

Large N_{part}
Central

More scatterings
Higher temperature

Particles melt in the QGP, sequentially

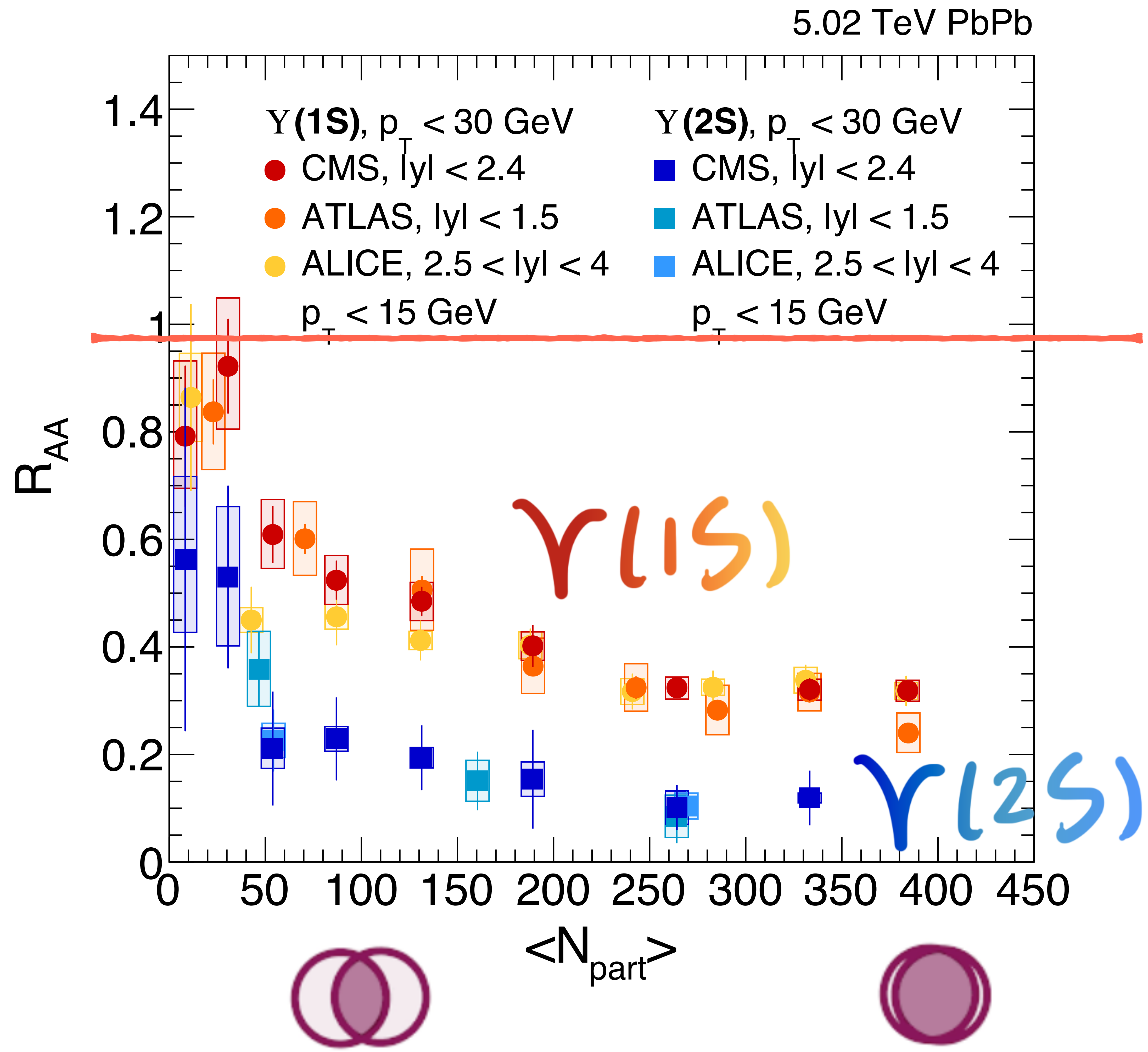




Sequential melting

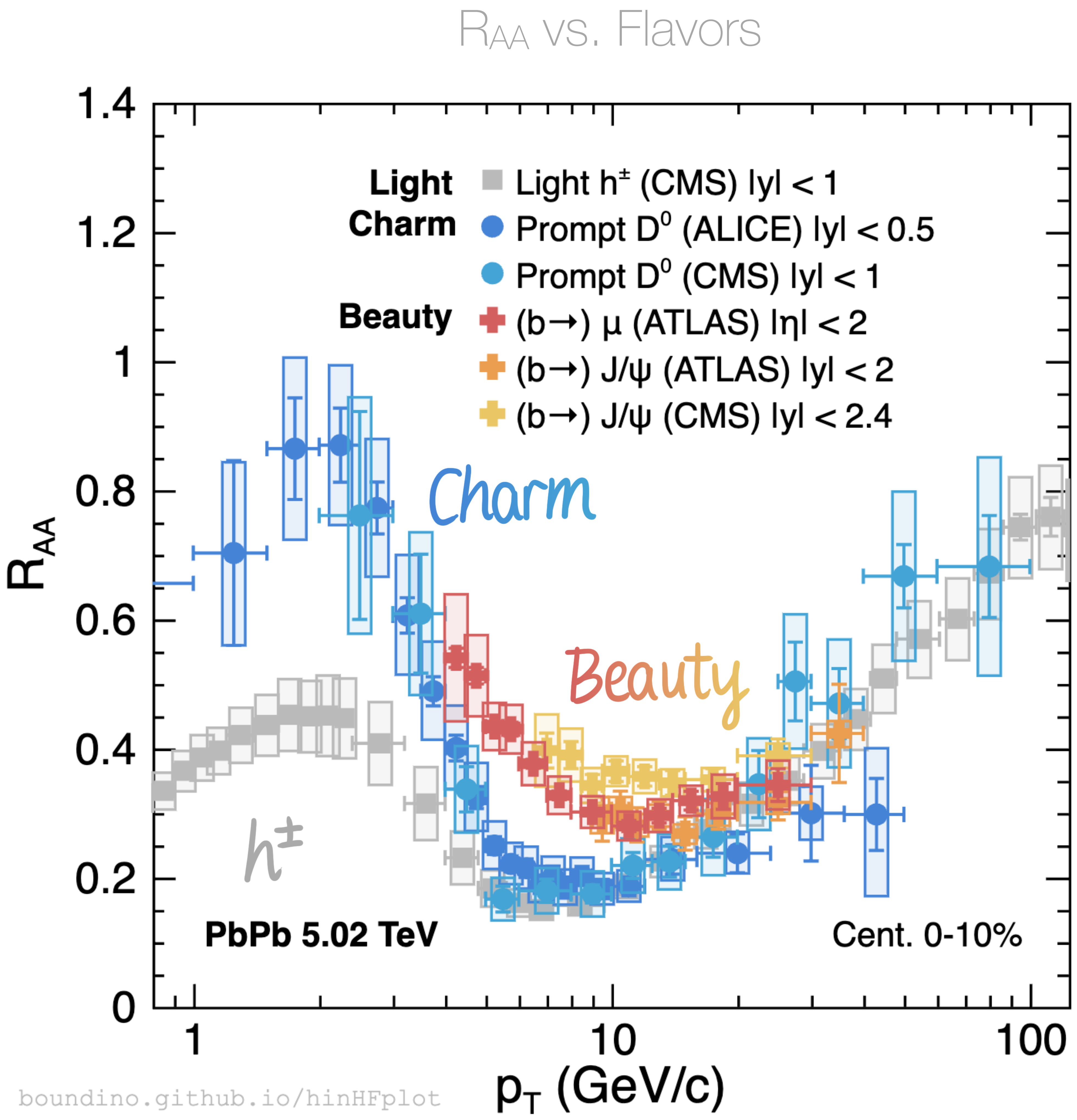
⬇

Thermometer of the QGP



PLB 822 (2021) 136579 arXiv:2205.03042 PLB 790 (2019) 270

Particles loose energy in QGP, sequentially

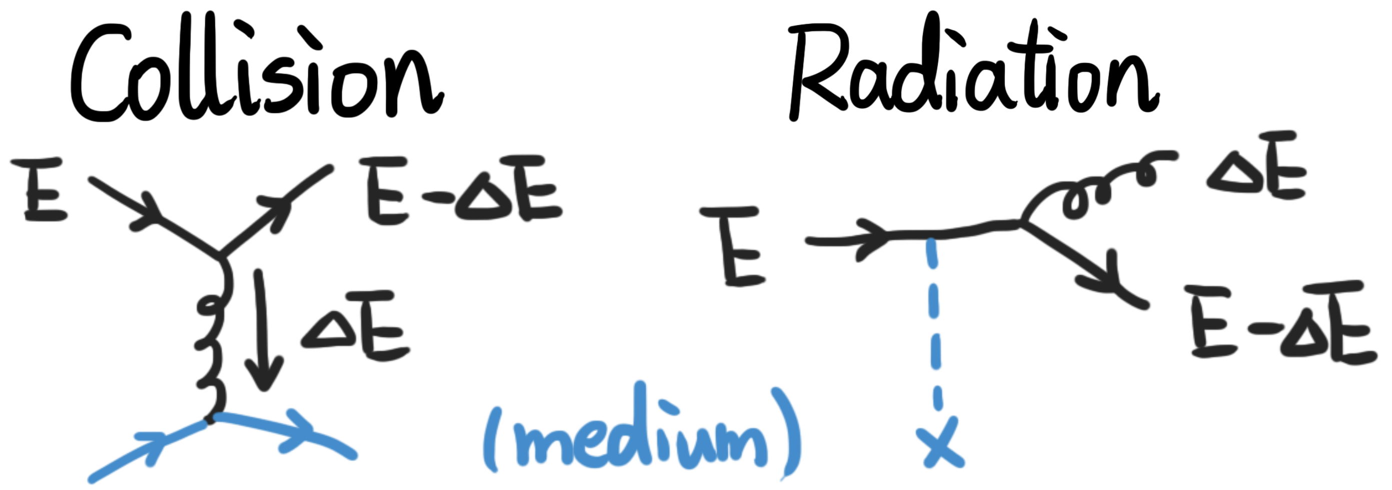


JHEP 04 (2017) 039

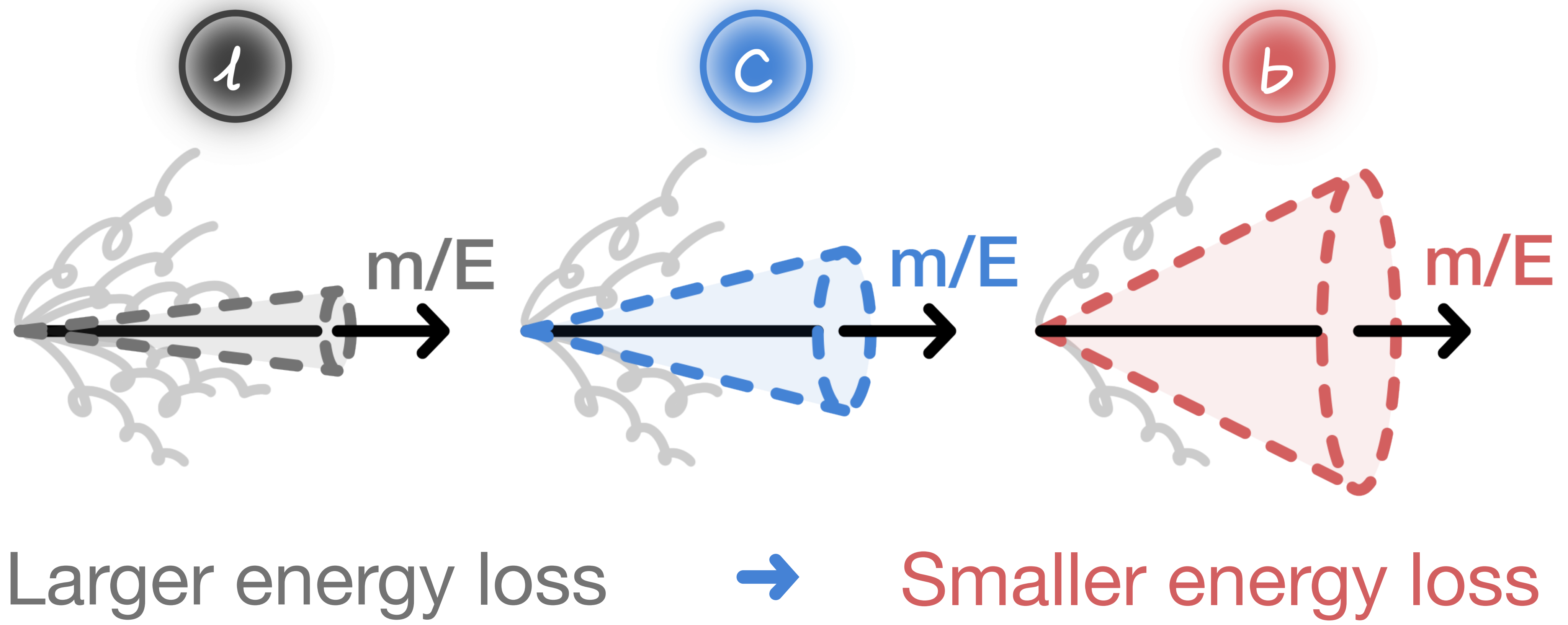
PLB 829 (2022) 137077

EPJC 78 (2018) 509

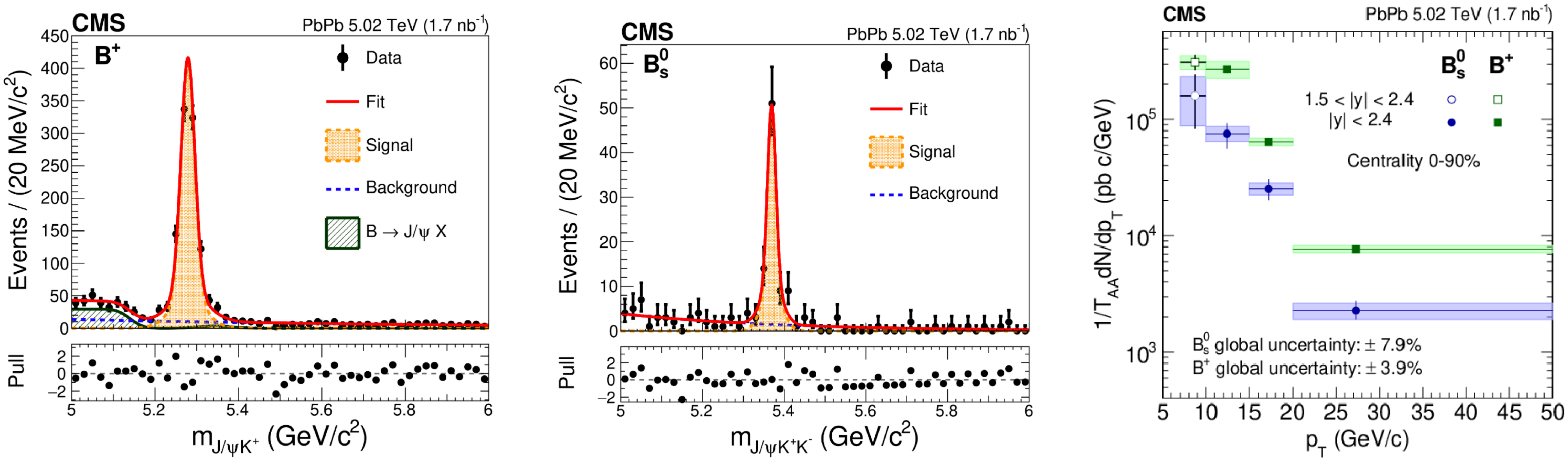
EPJC 78 (2018) 762



- Dead cone effect
  - Radiation is suppressed inside $\theta < m/E$
  - Energy loss $\Delta E_l > \Delta E_c > \Delta E_b$



Exclusive reconstruction, for 1st time in ion collisions



HIN-19-011

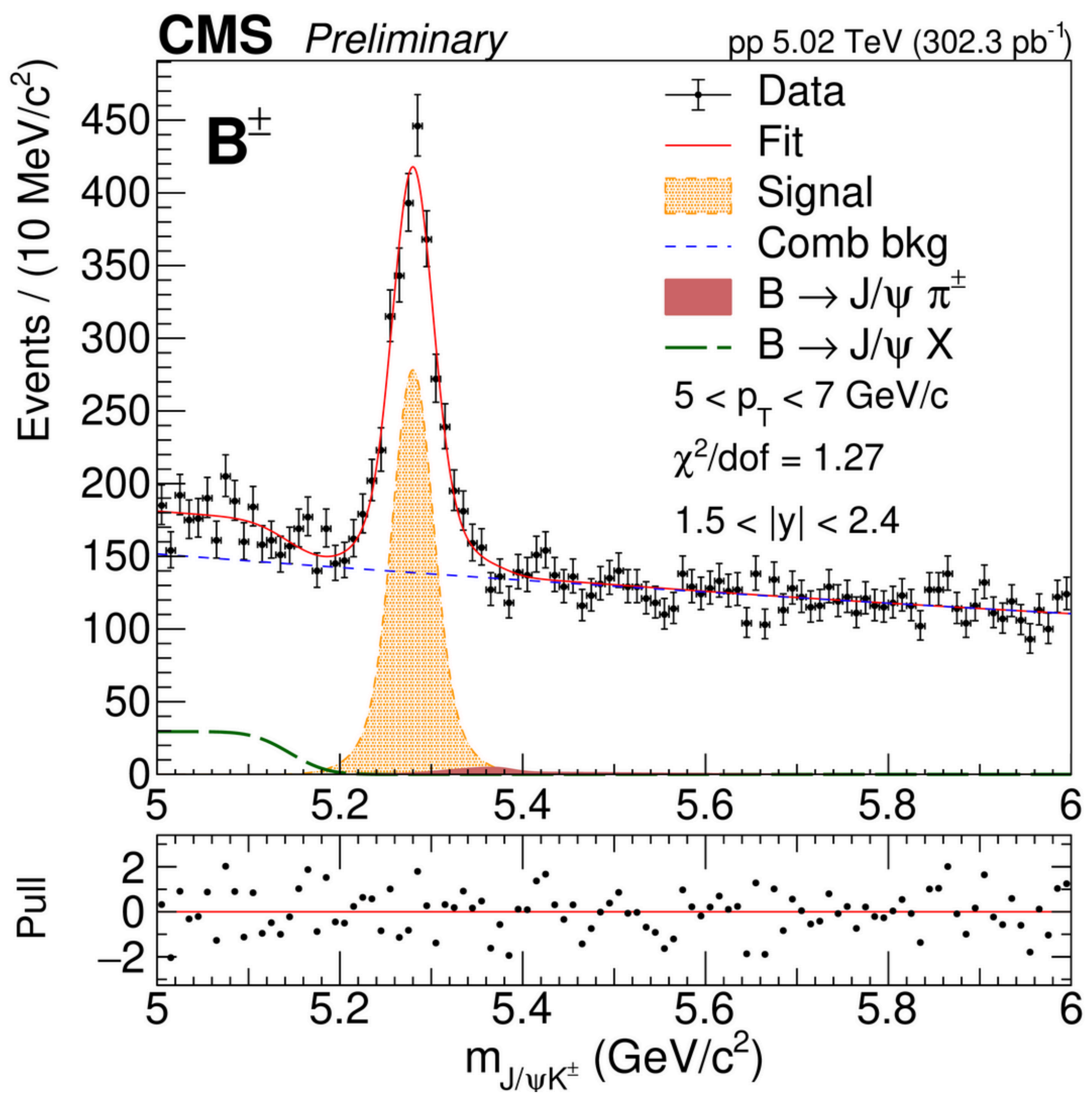
- with CMS we have observed for the first time B mesons in nuclear collisions
- through full reconstruction of their decays: eg $B_s \to J/\psi\phi$, $B^+ \to J/\psi K^+$
- higher precision (ordinates and abcissae) + allows to probe flavour dependencies

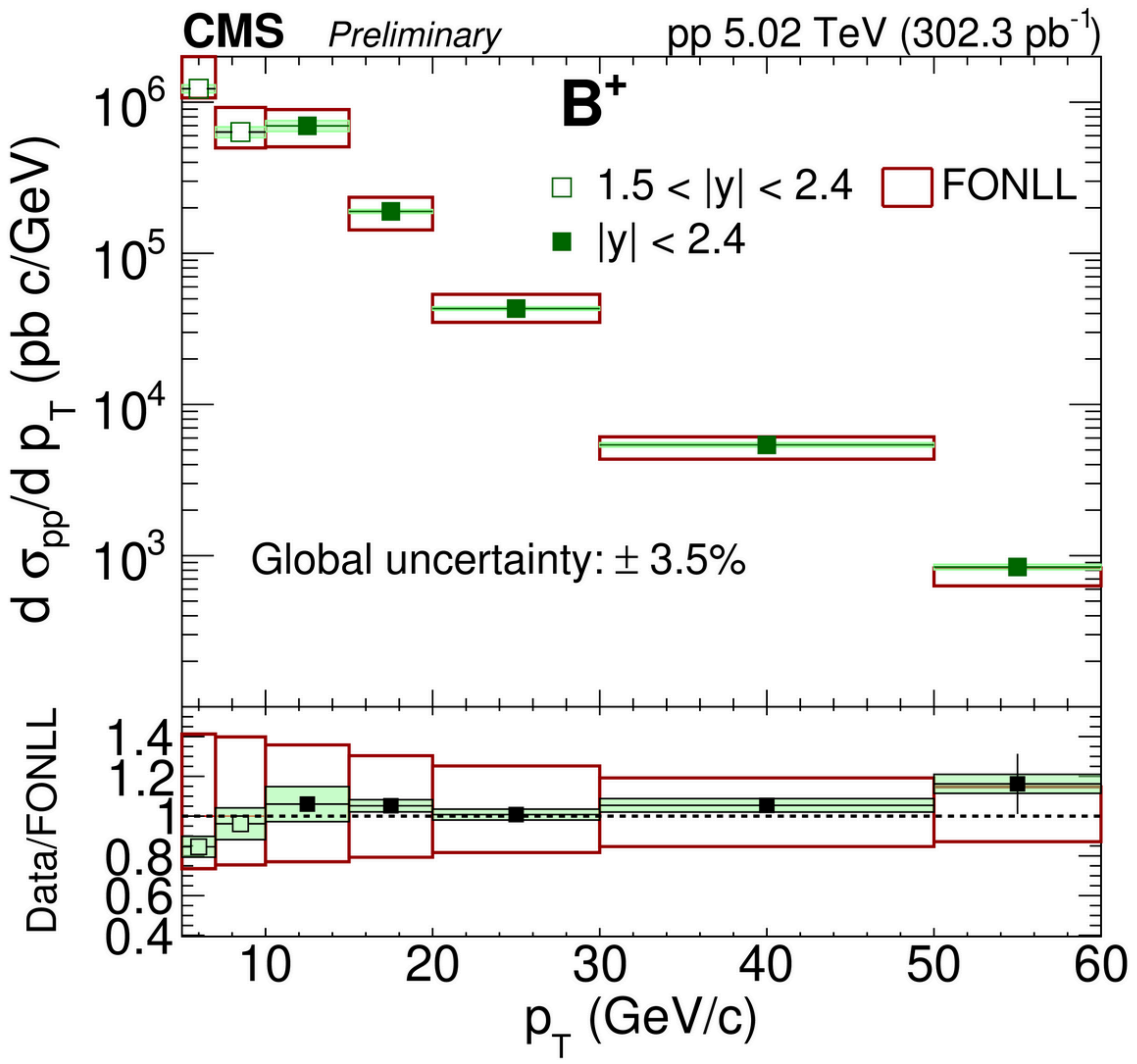
and in small systems, too, pp and pPb (references)

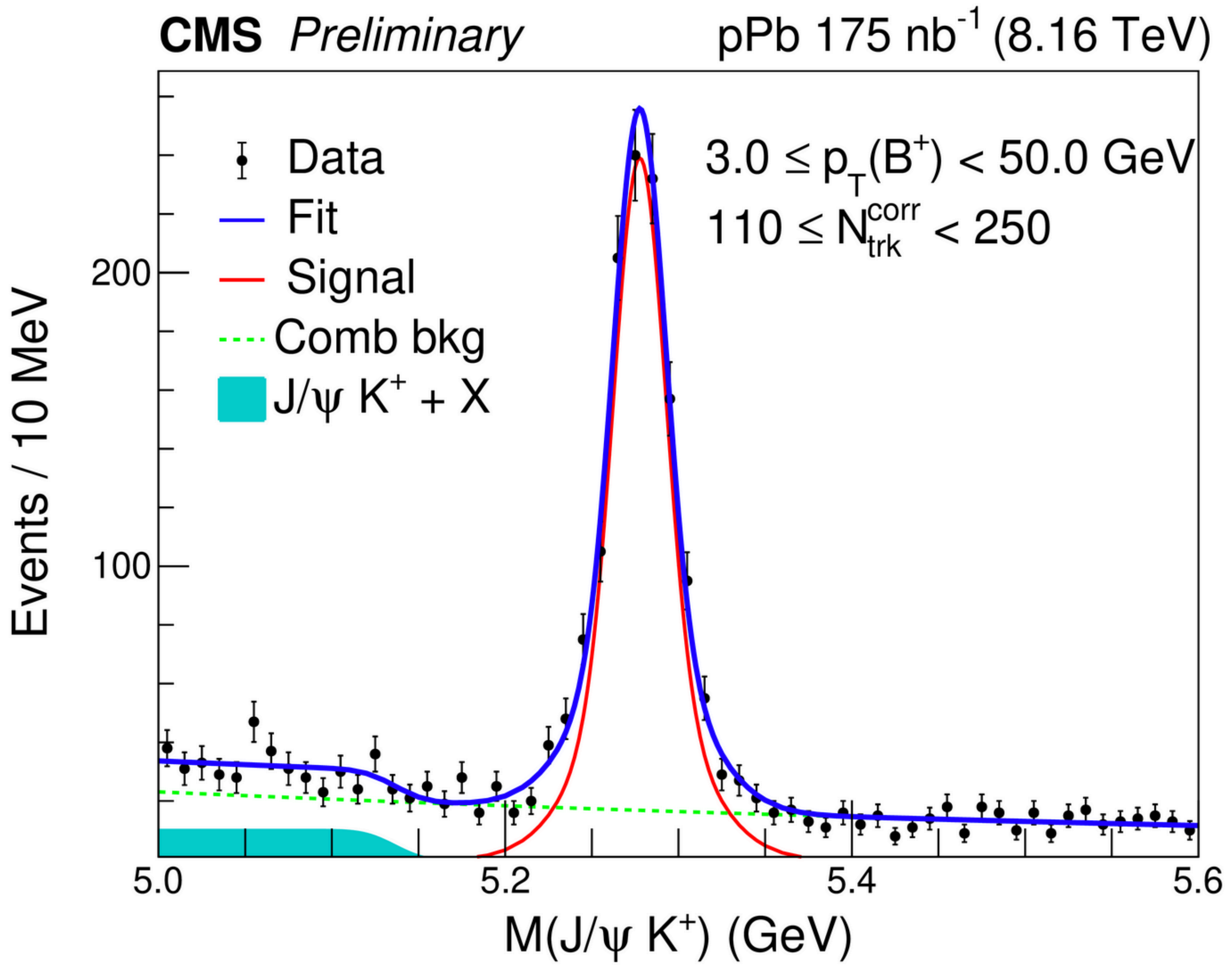
$B^+ \to J/\psi K^+$

HIN-21-014

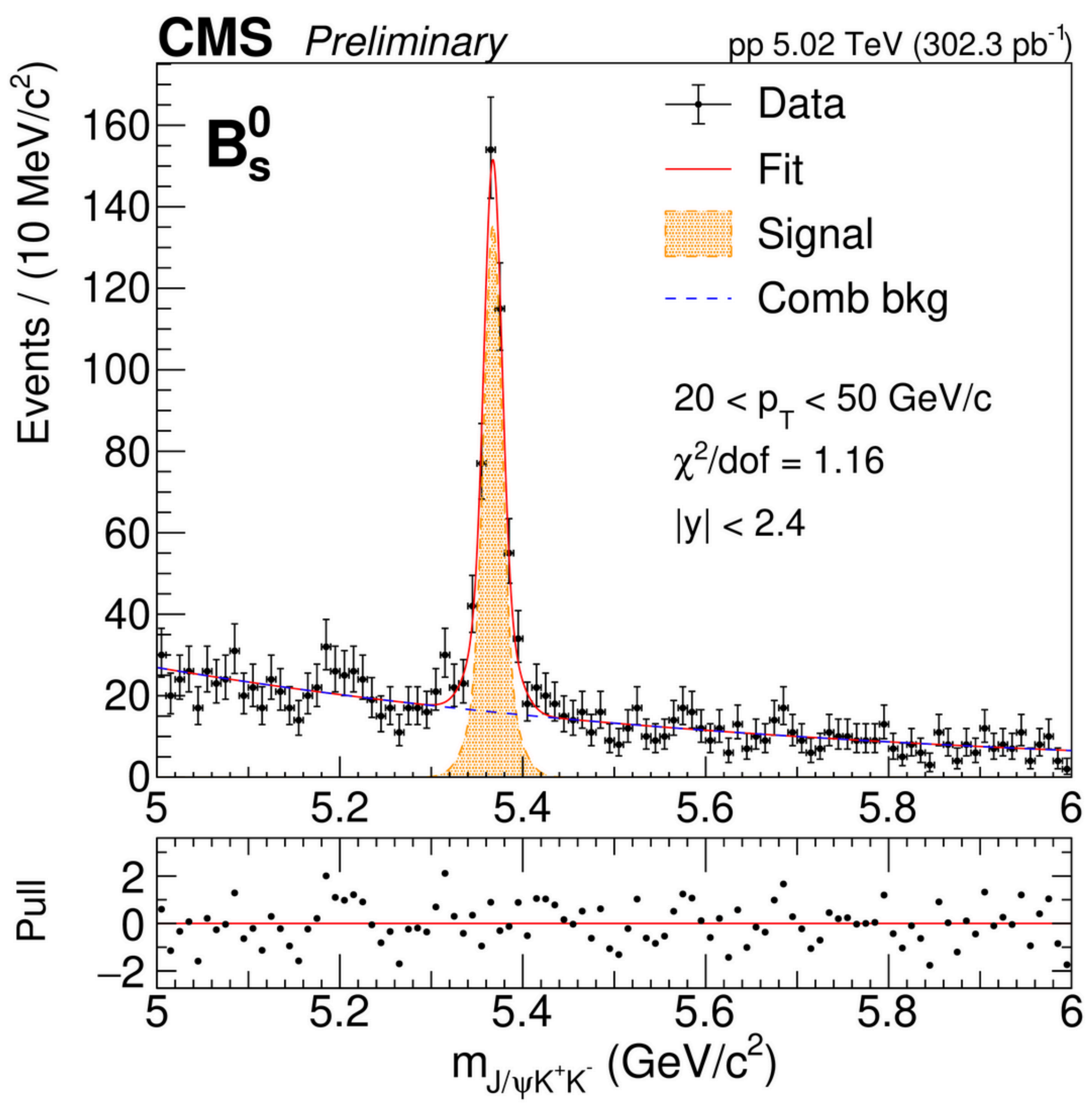
$B_s \to J/\psi \phi$

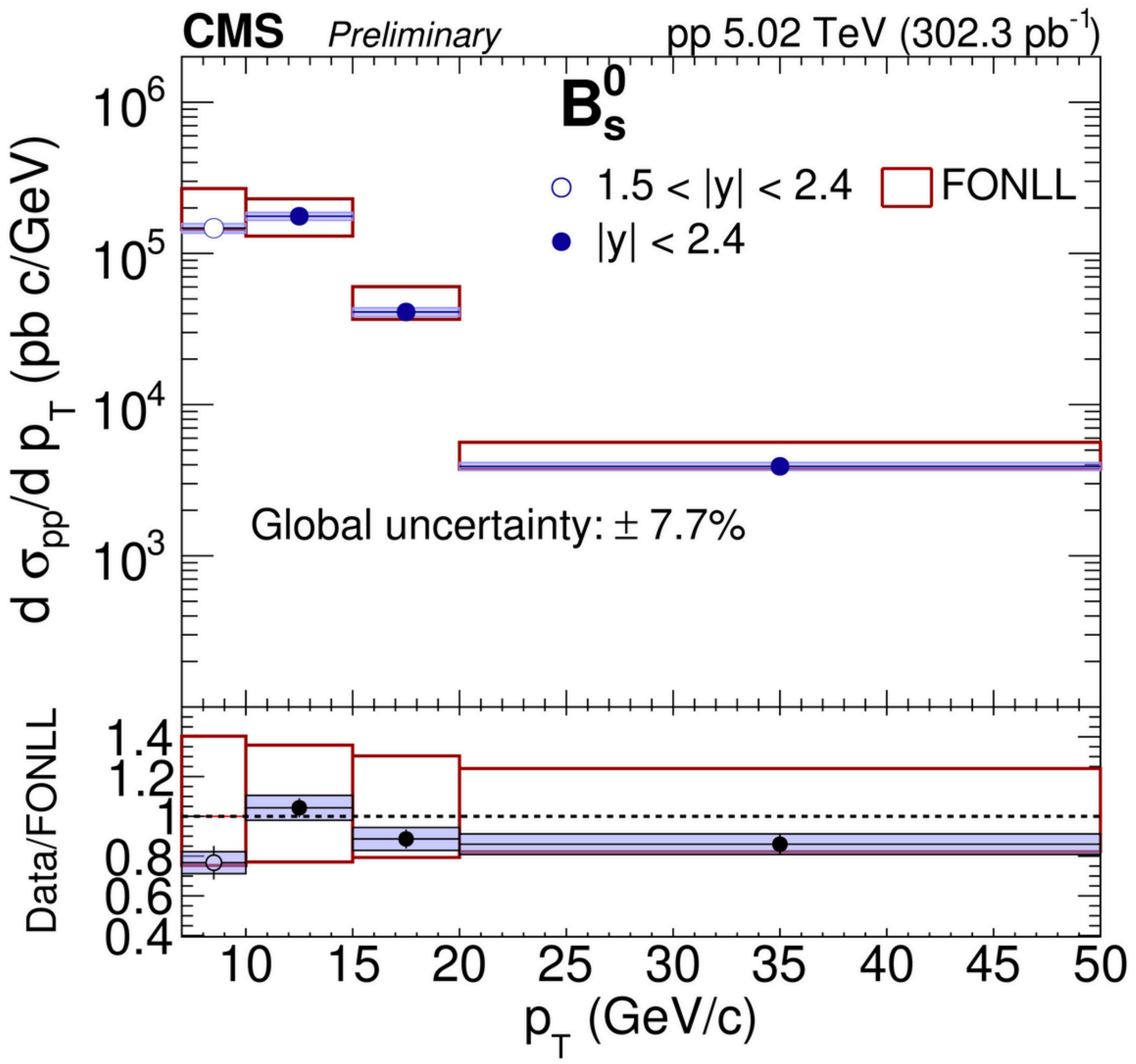


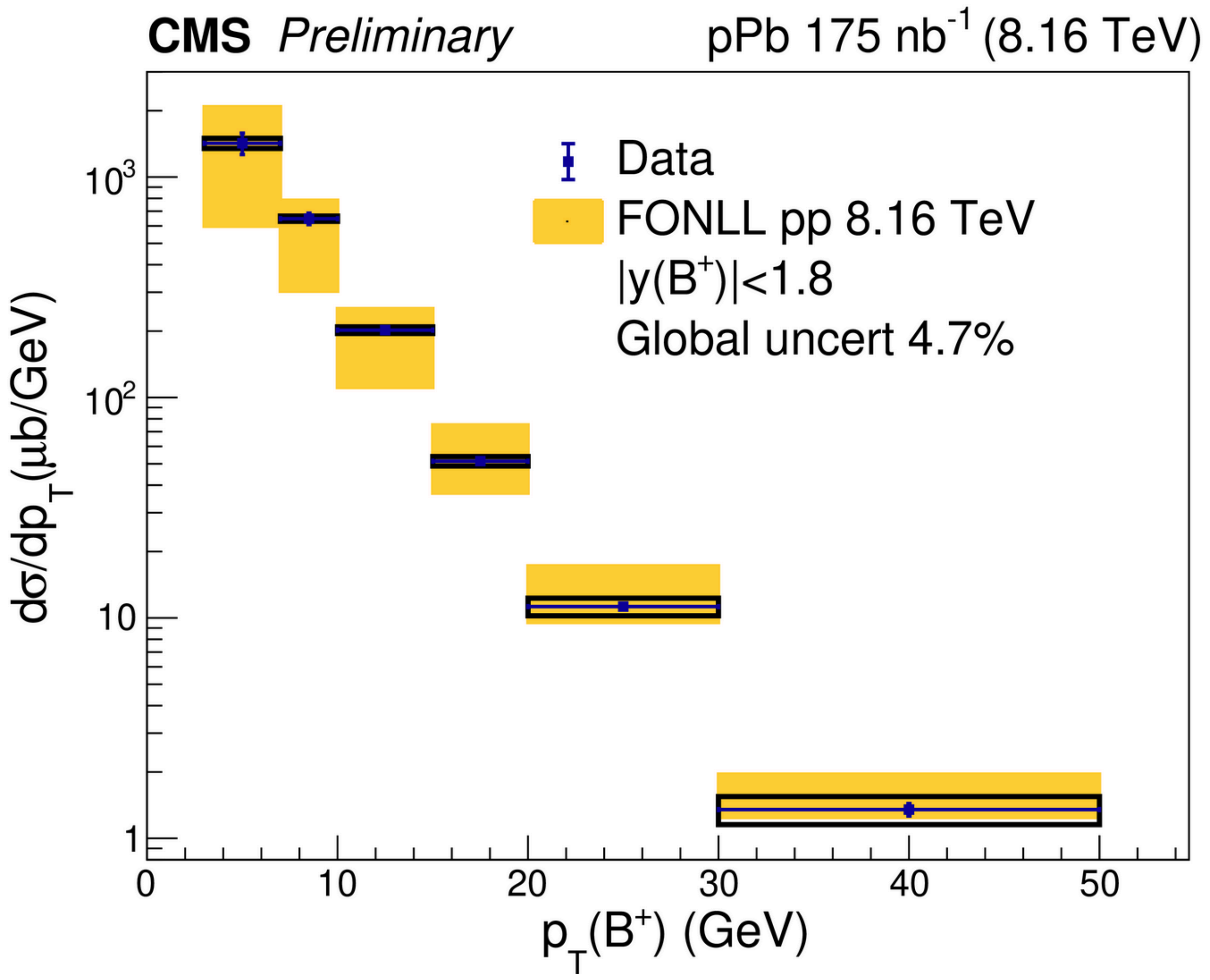




HIN-22-001

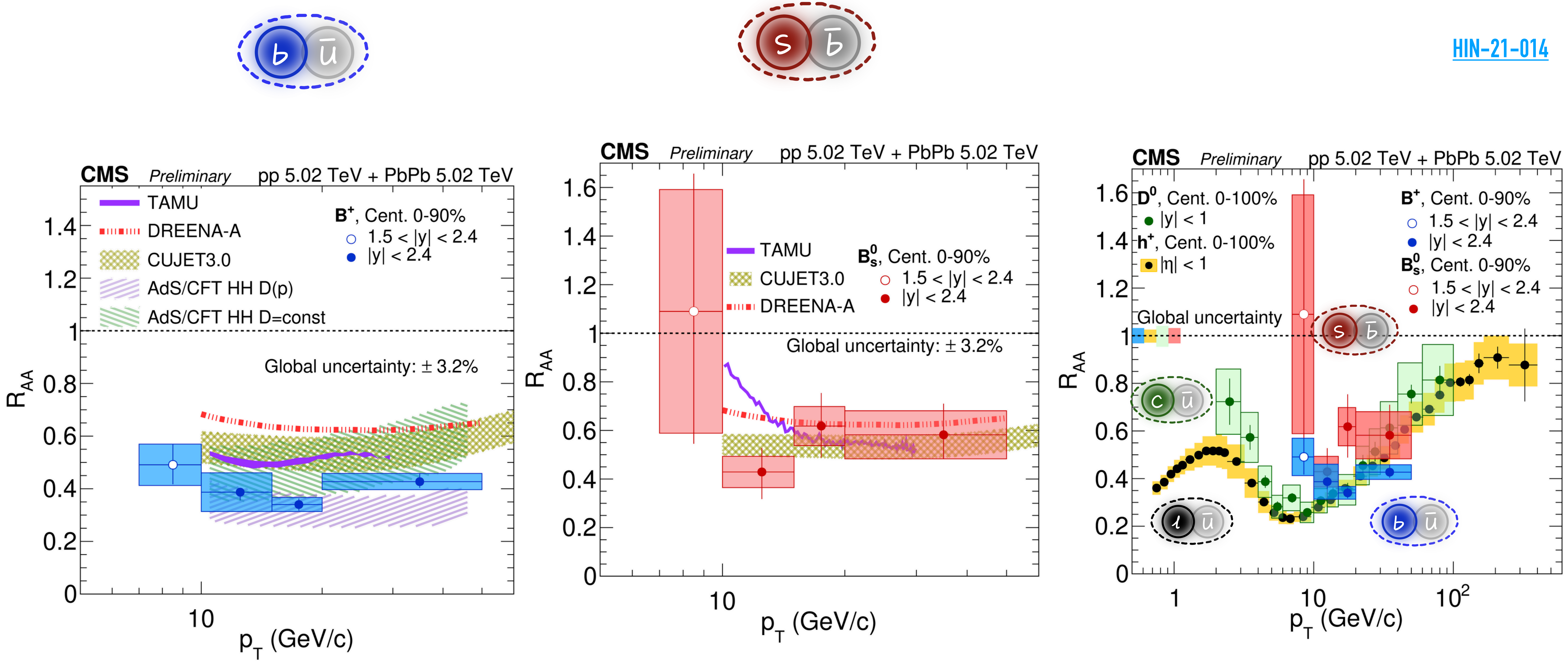




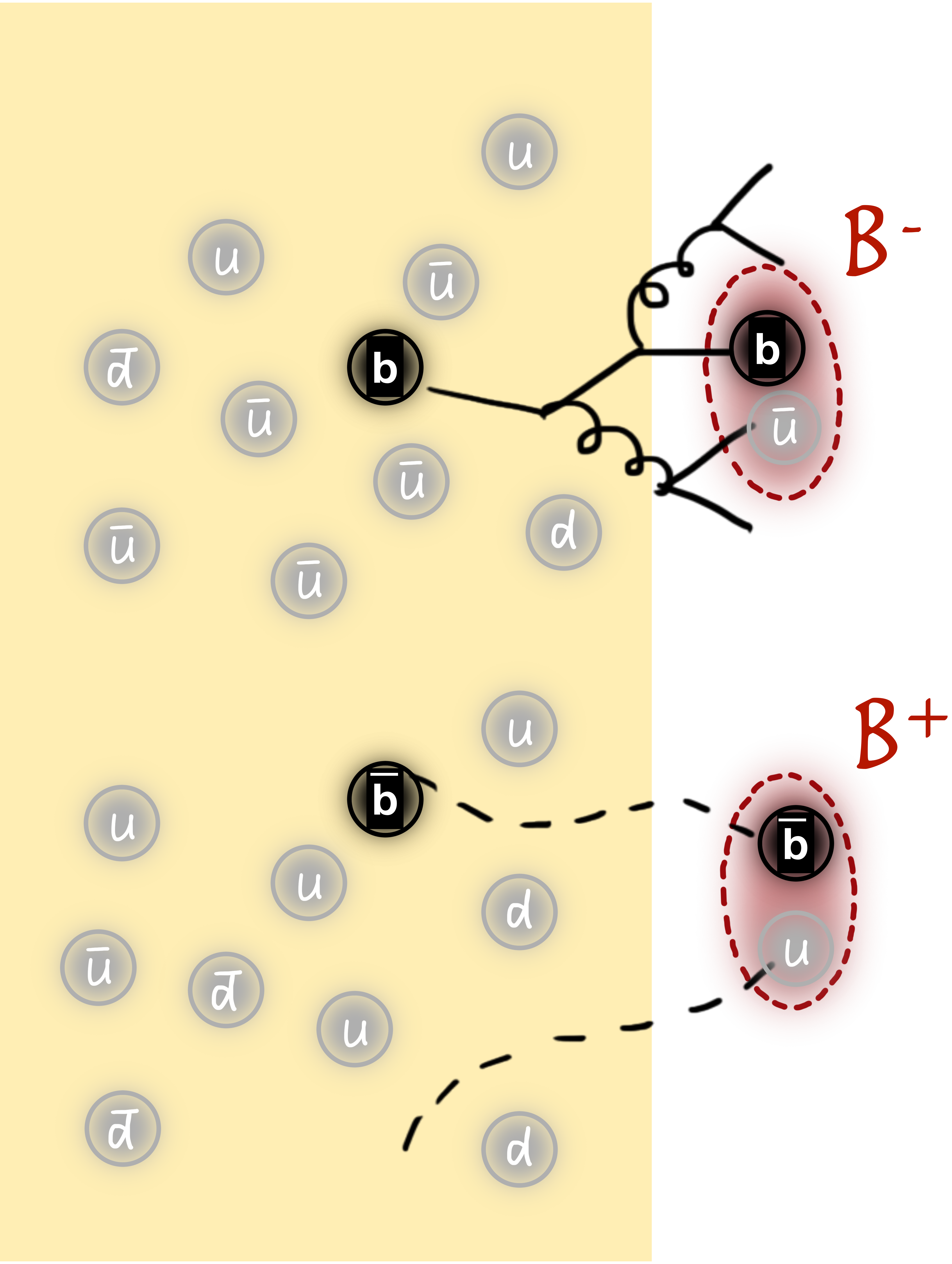


B mesons' nuclear modification factors

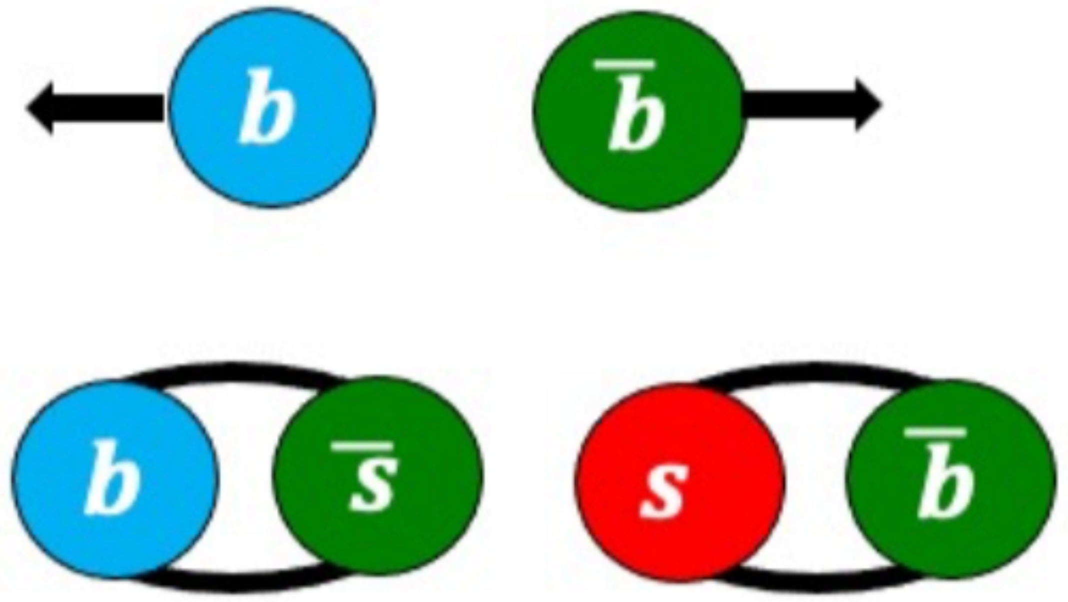
HIN-21-014



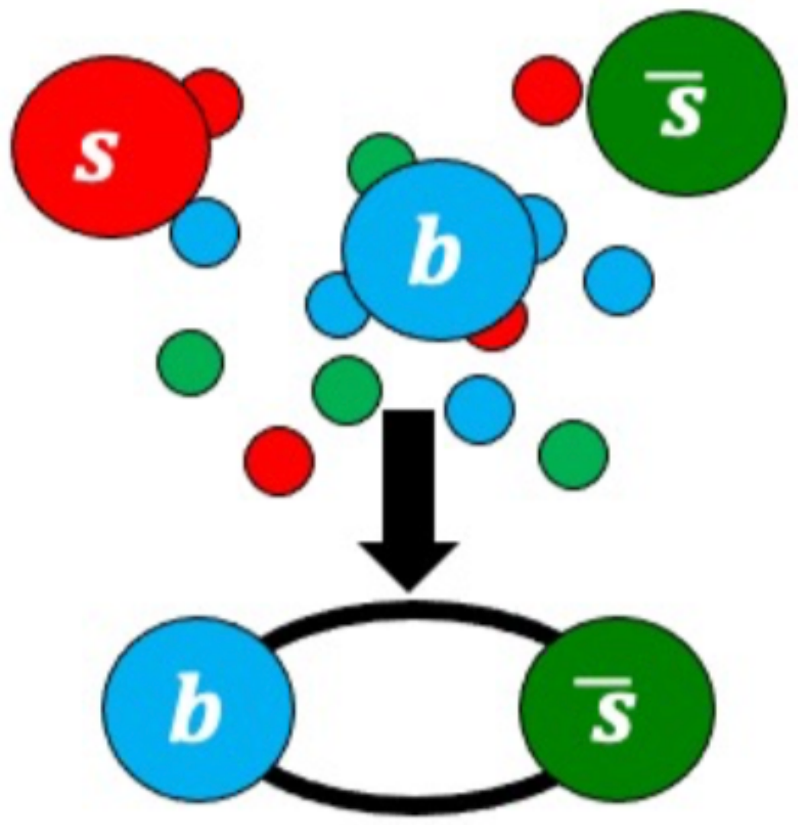
Hadronization



Fragmentation
(high p_T)

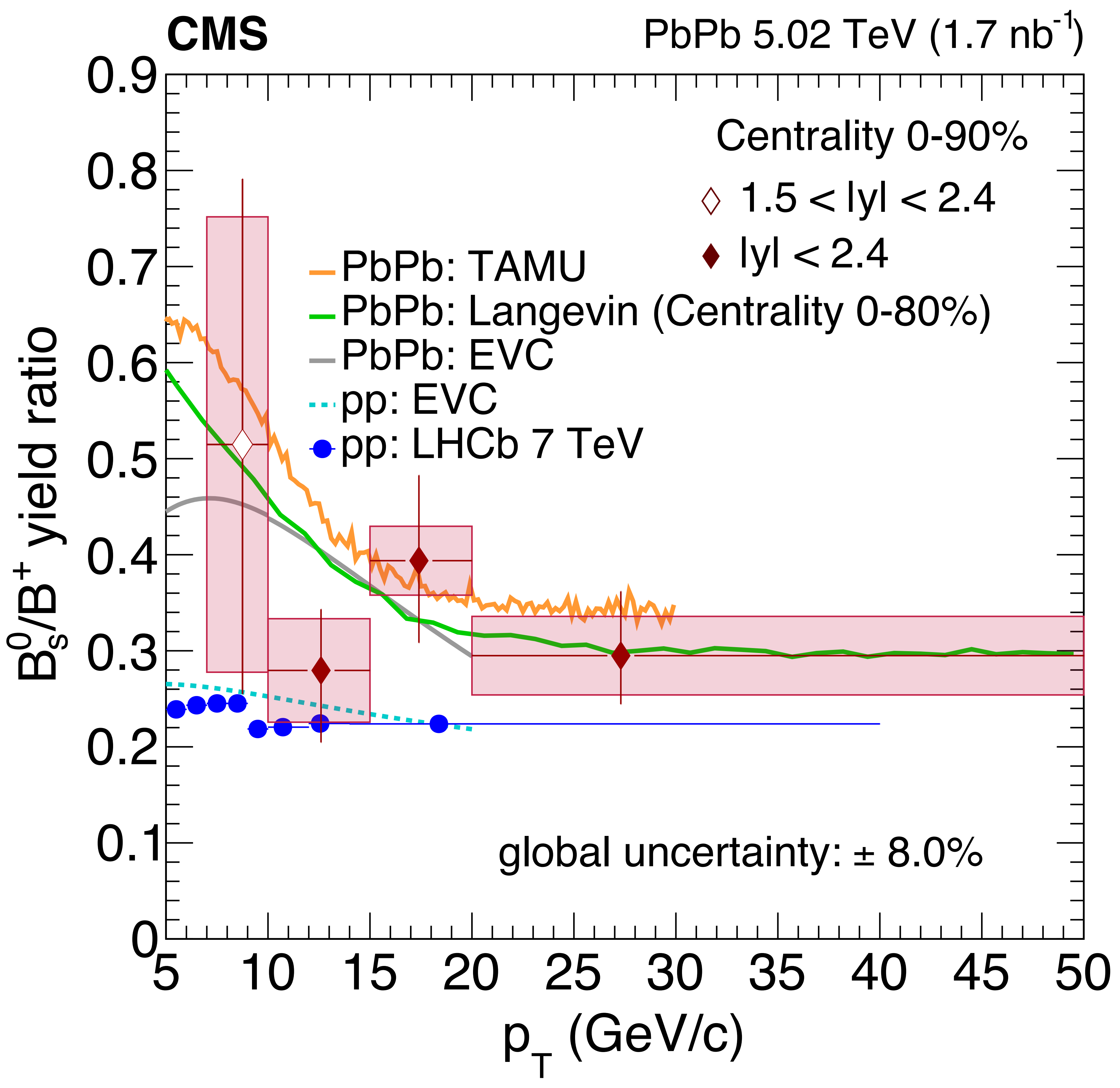


Coalescence
(low p_T)



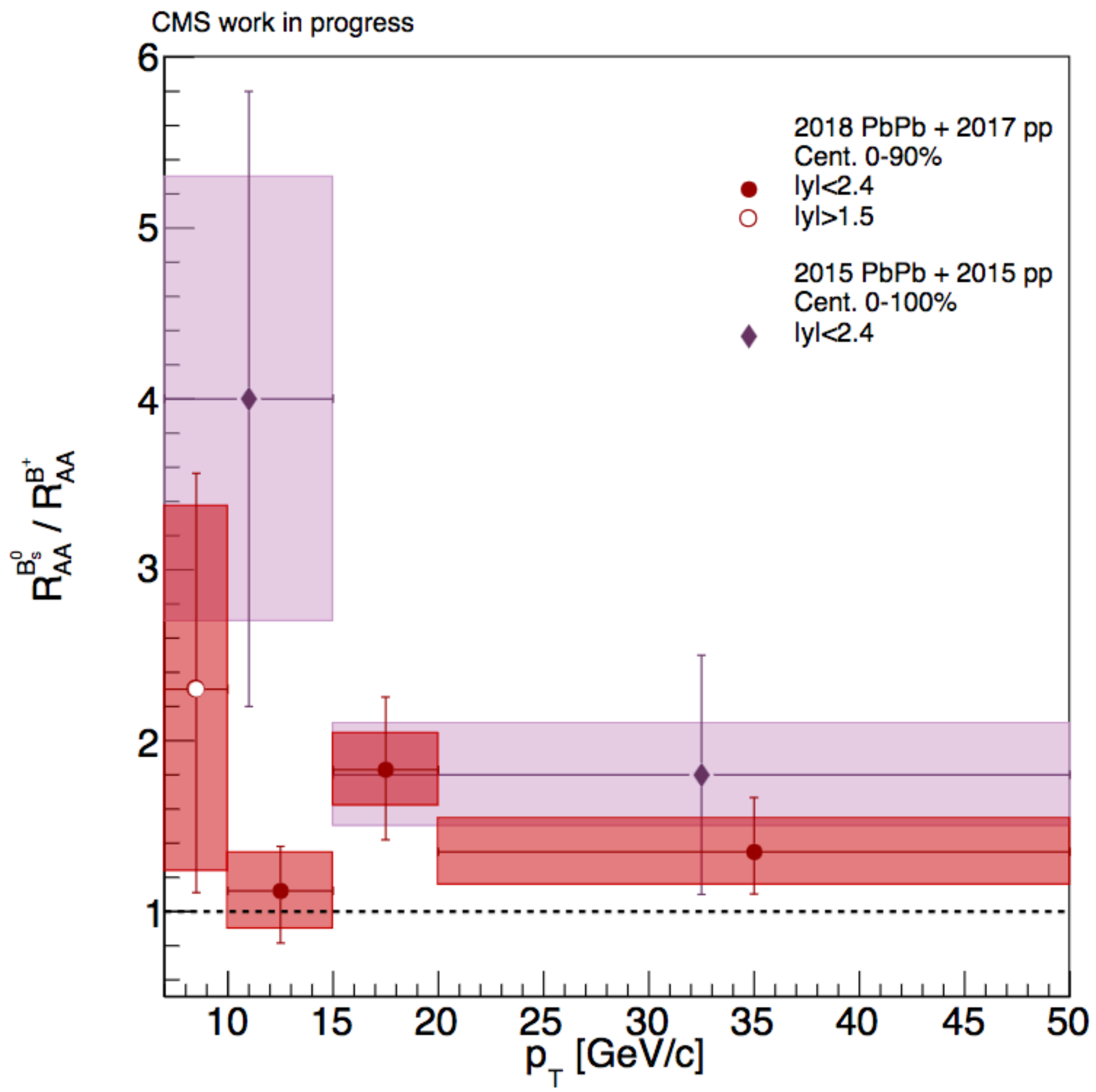
B_s/B_u hadronization fractions, in medium

B_s/B^+ σ ratio in PbPb



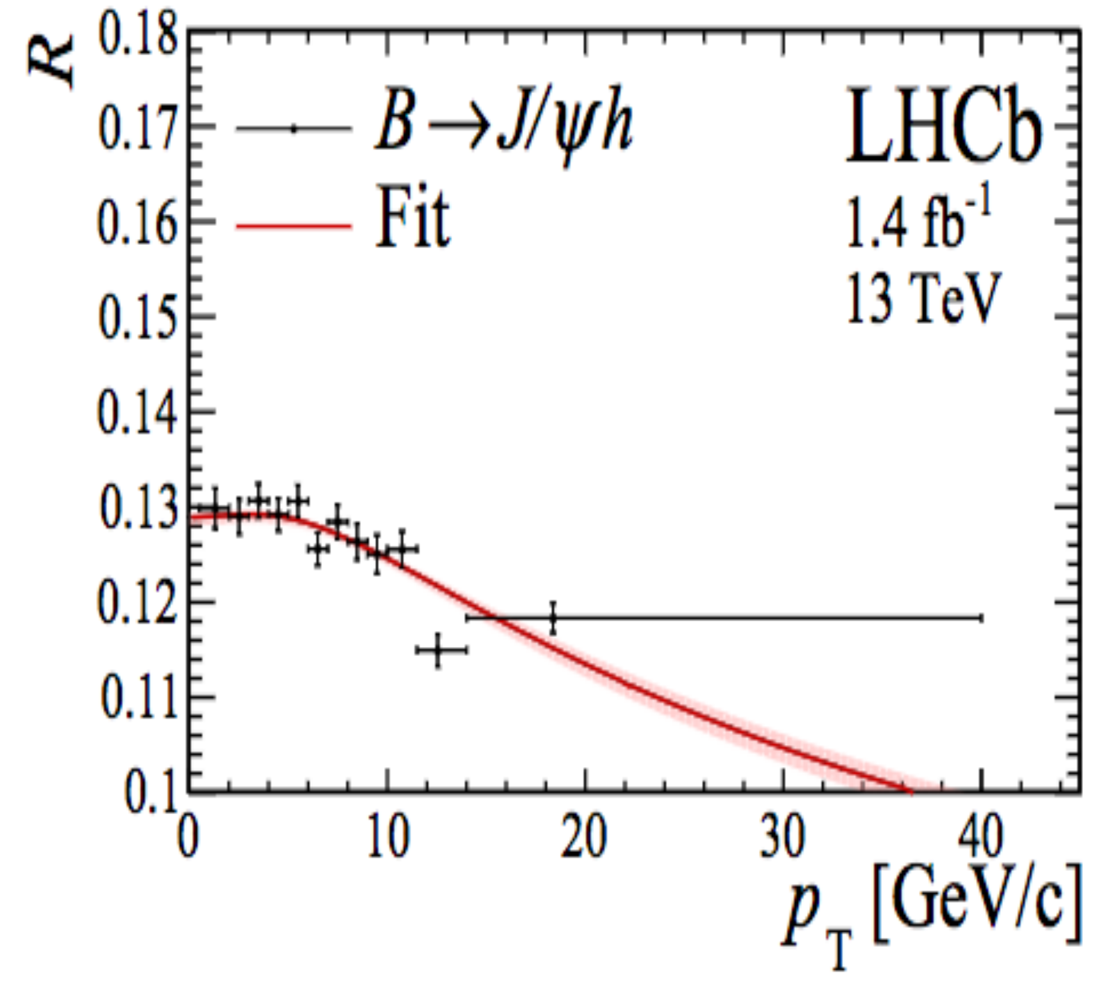
HIN-19-011 CERN-THESIS-2019-256

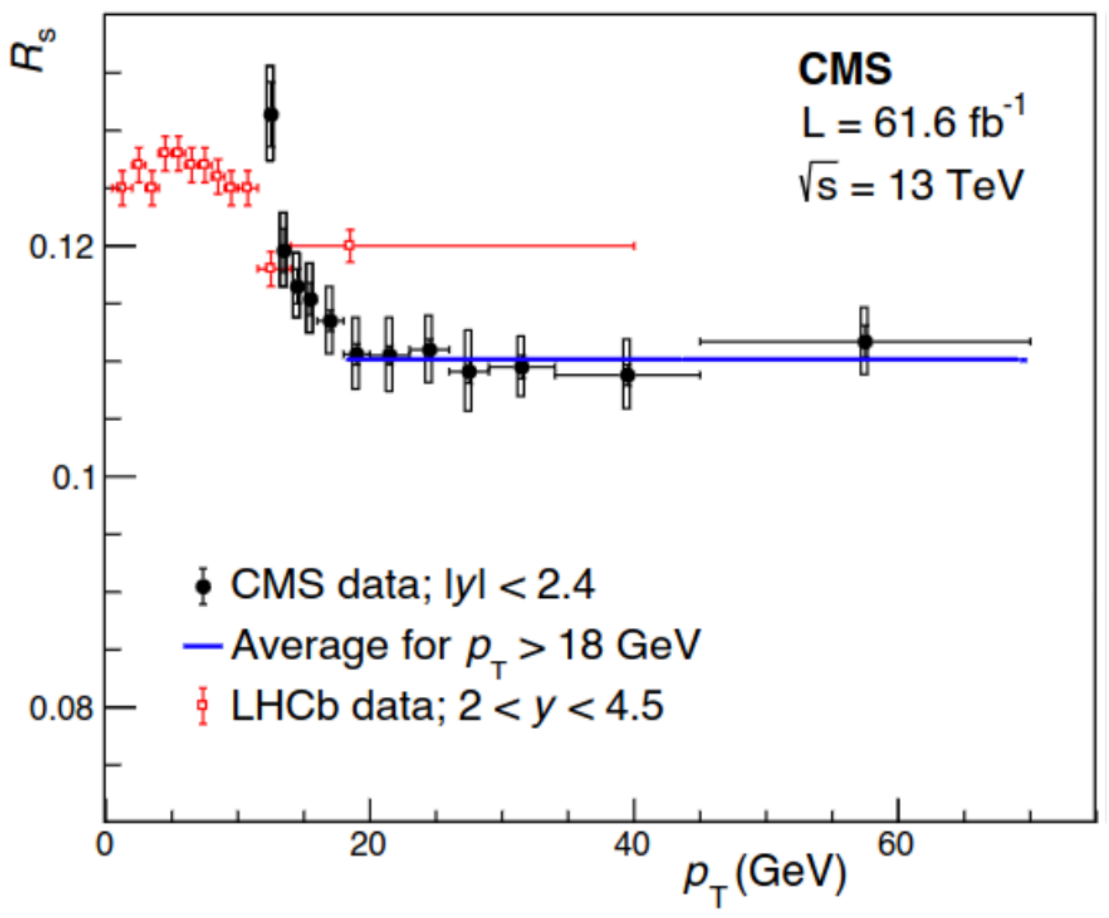
B_s/B^+ R_{AA} (PbPb/pp) ratio

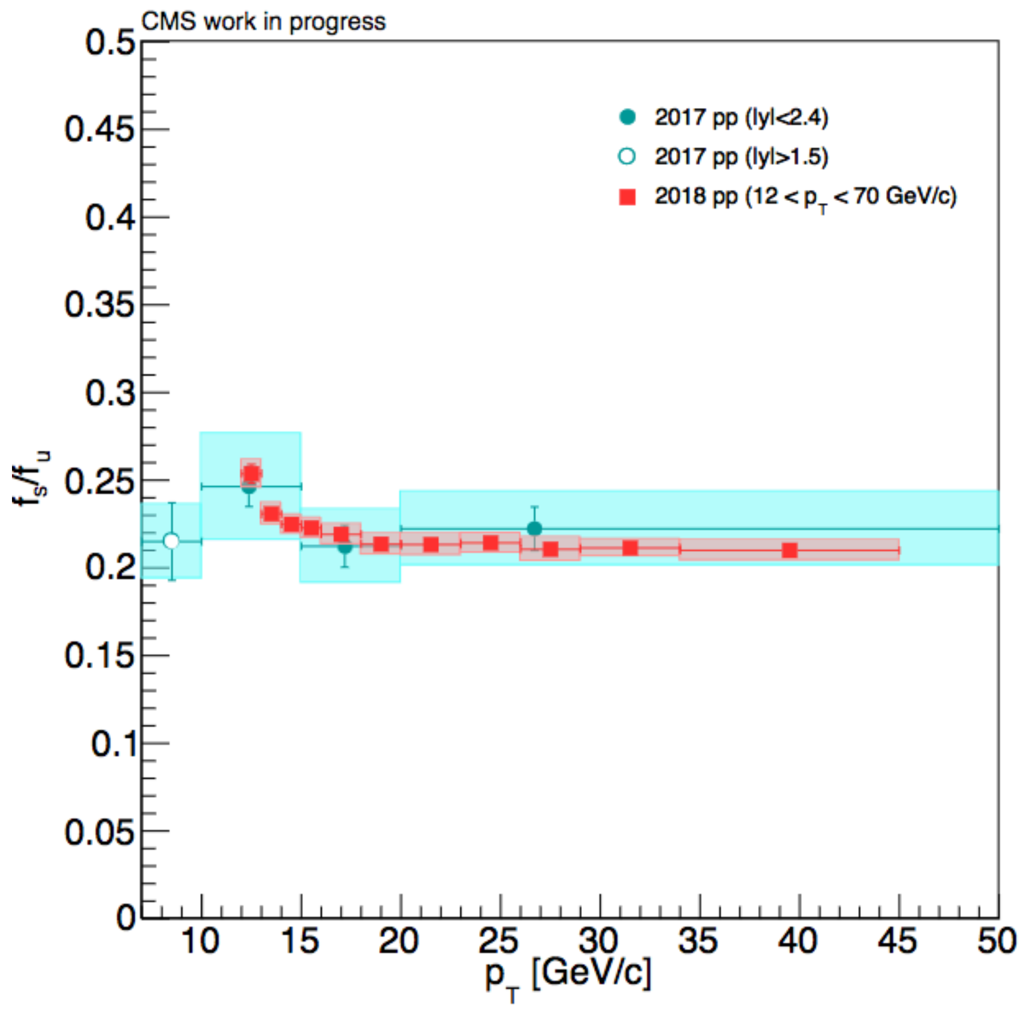


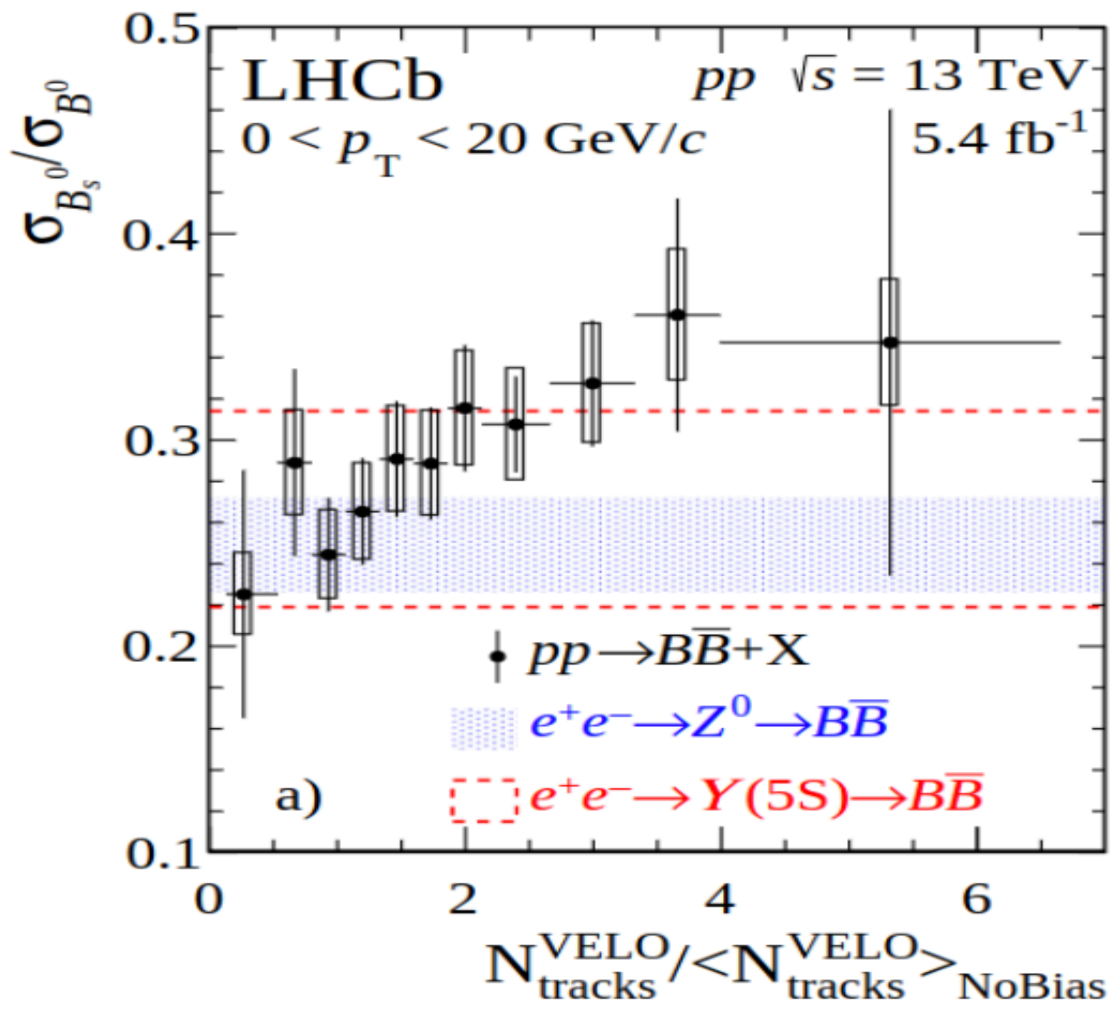
CERN-THESIS-2023-064

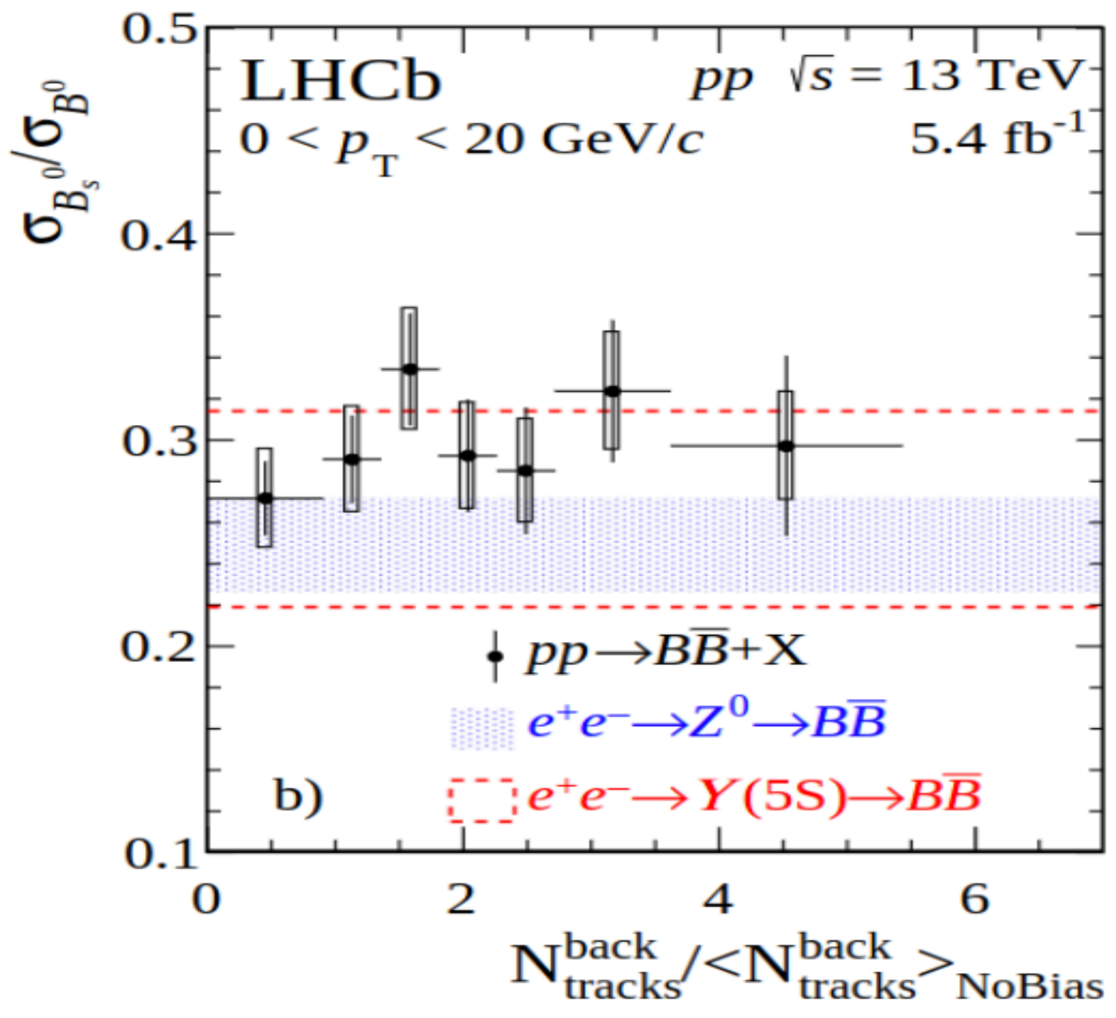
B_s/B_u hadronization fractions, in vacuum

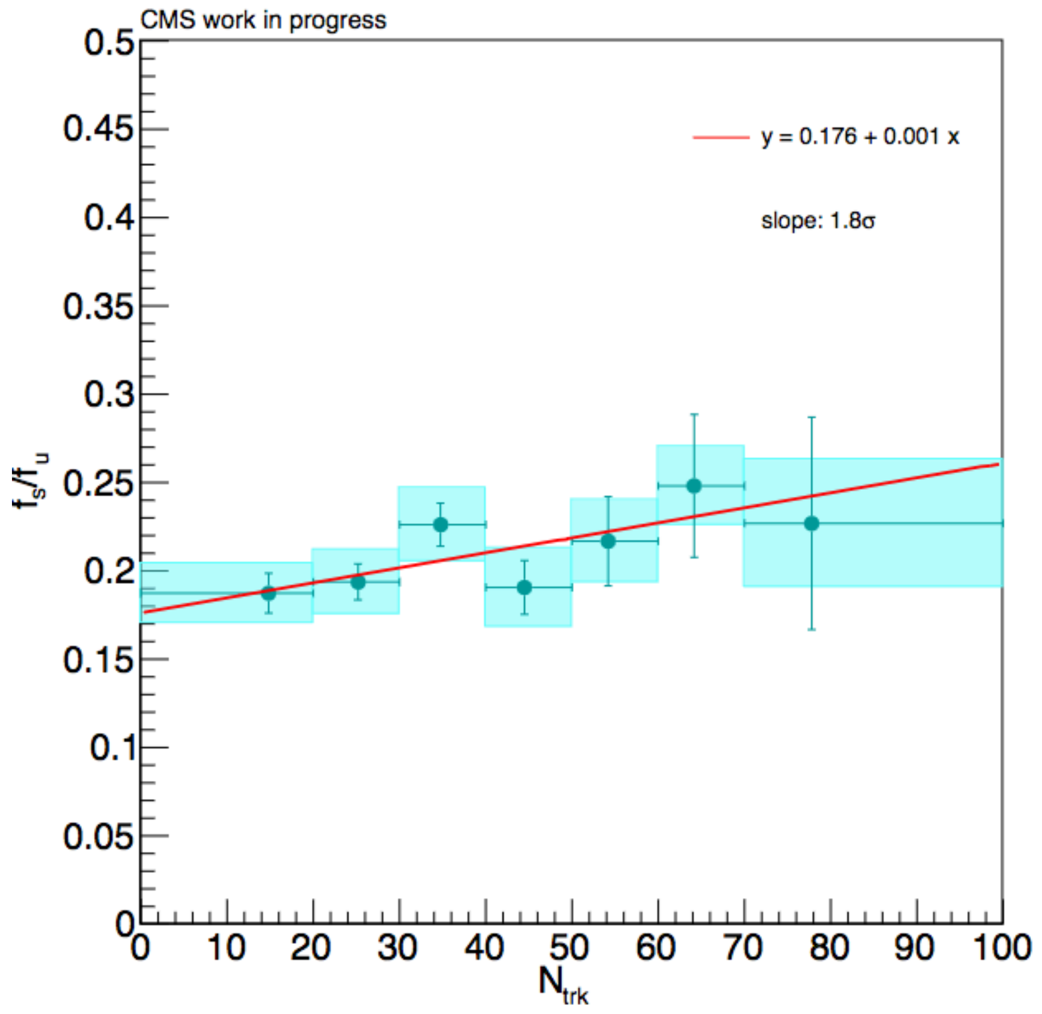












vs p_T

- non-universality of hadronization fractions

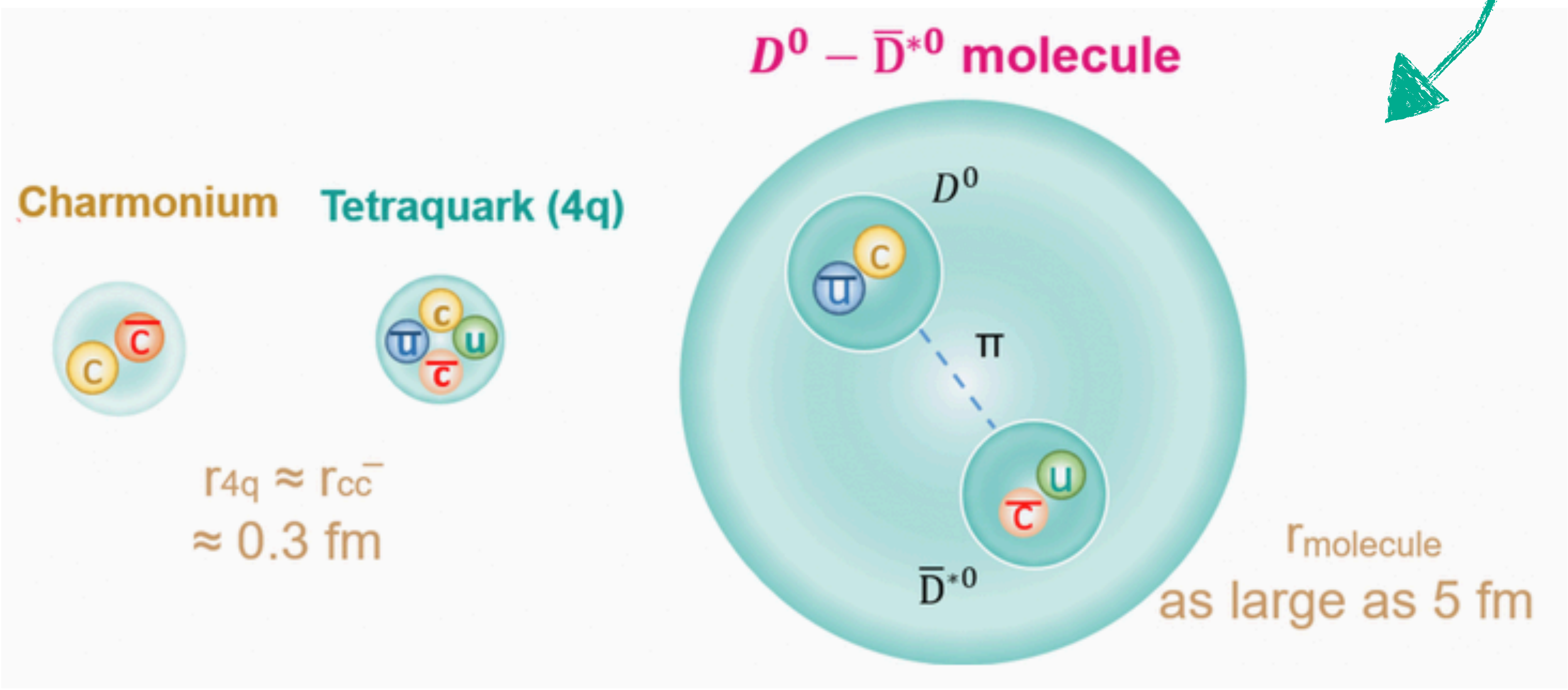
vs multiplicity

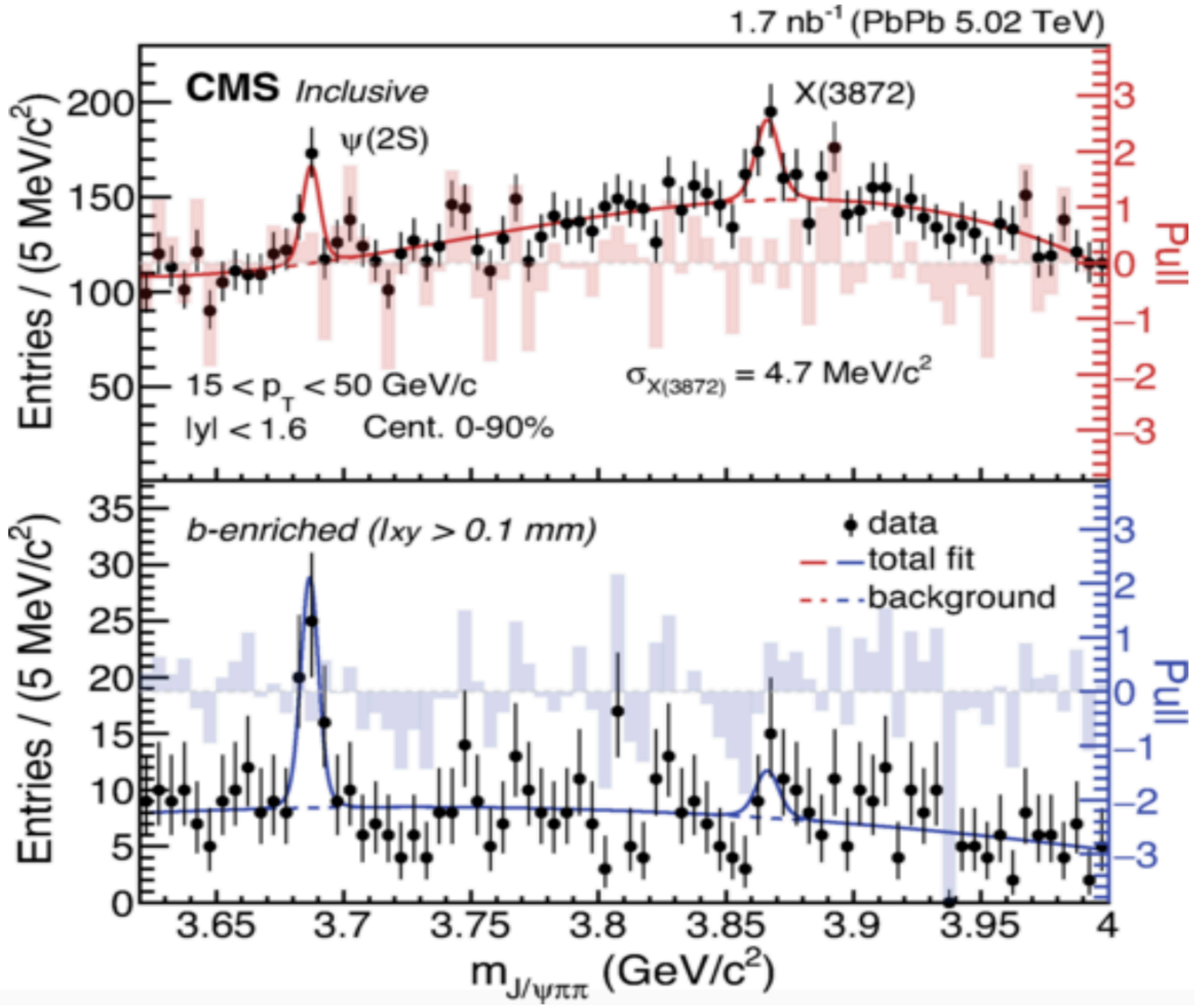
- environment plays a role in quark hadronization
- compatible with coalescence effects at high N_{trk} and low p_T

arXiv:2103.06810 2204.13042 CMS-BPH-21-001 CERN-THESIS-2023-282

Exotic hadron in hot medium

- **evidence** (4σ) for the production of the exotic hadron X(3872) in PbPb data
- facilitates a novel way to improve understanding of
  - properties of the medium
  - **nature** of exotic hadrons



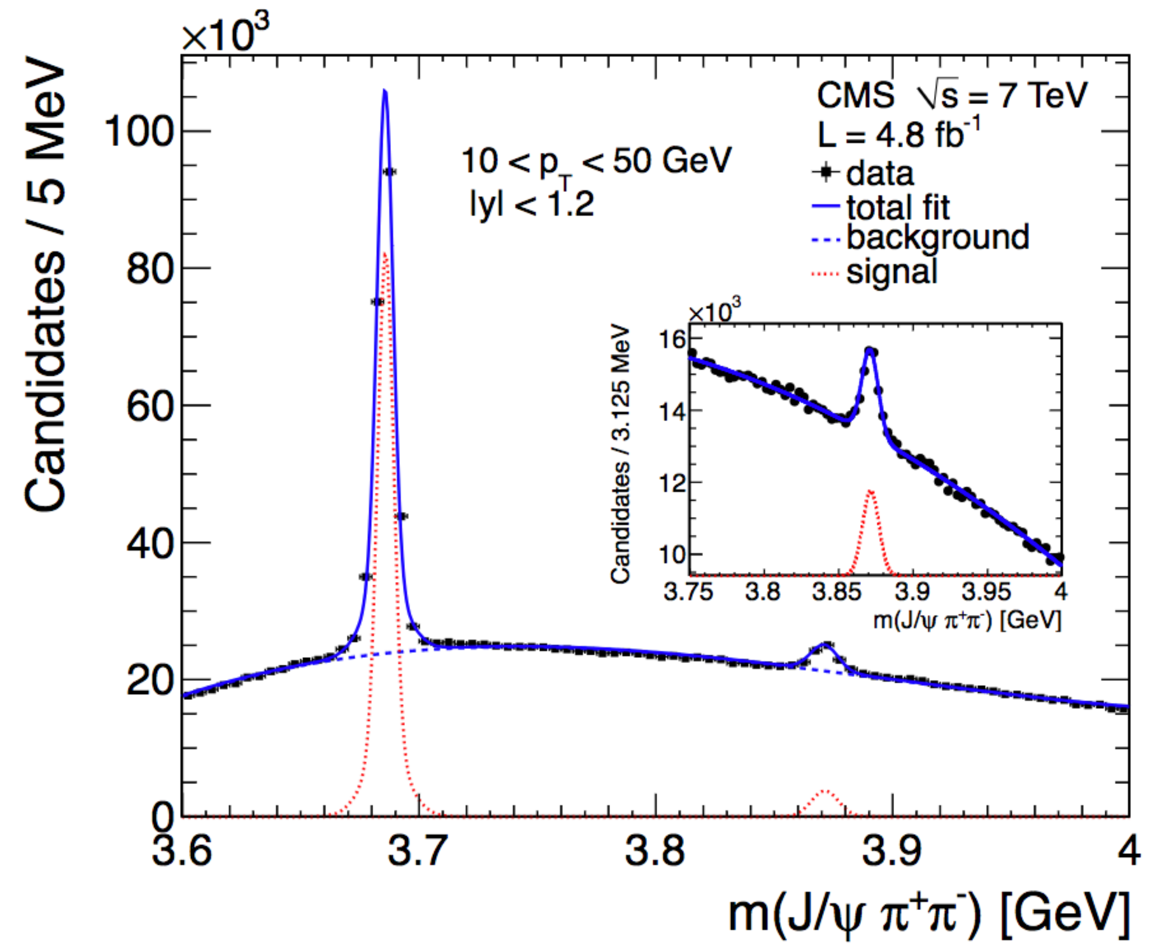


PbPb

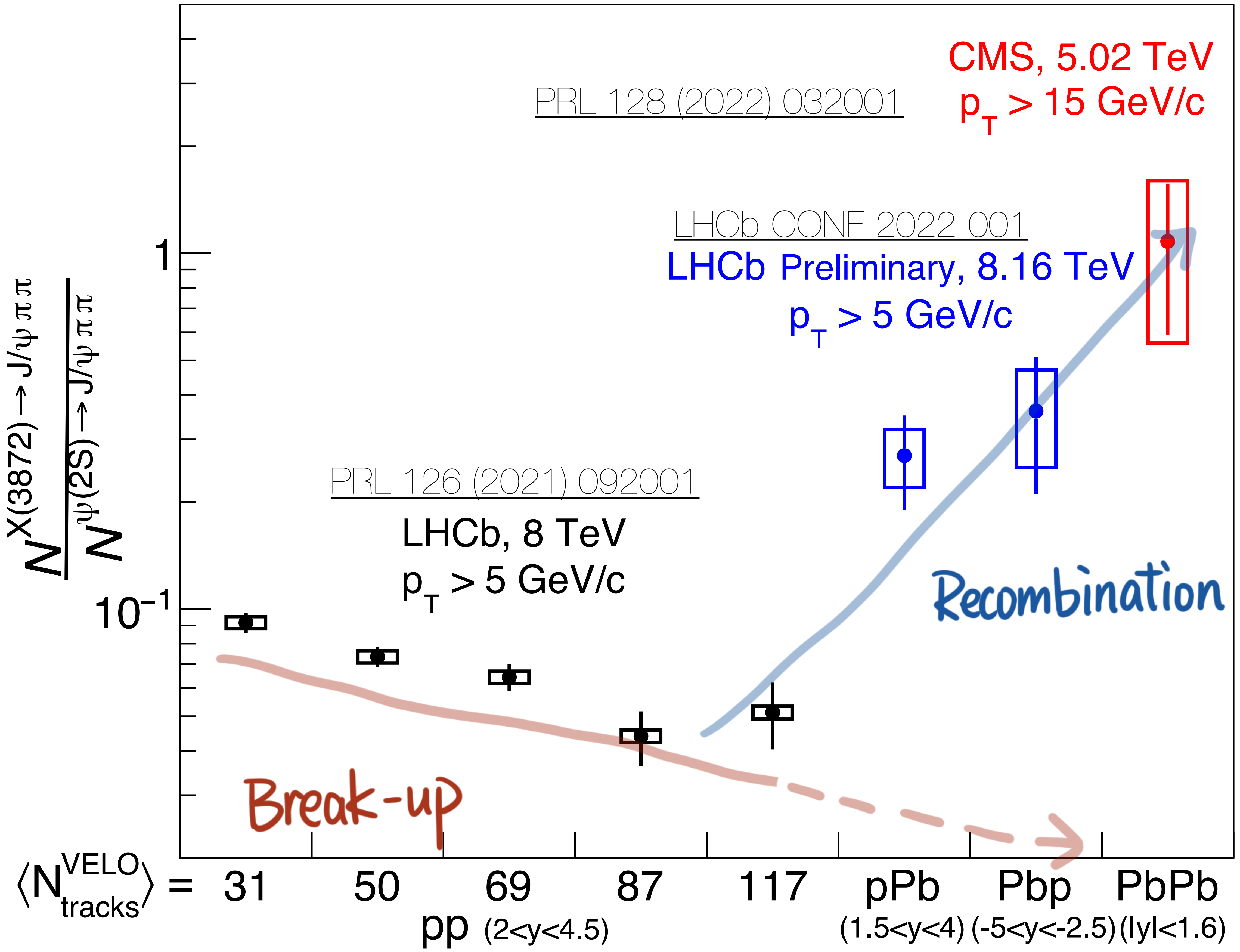
HIN-19-005

pp

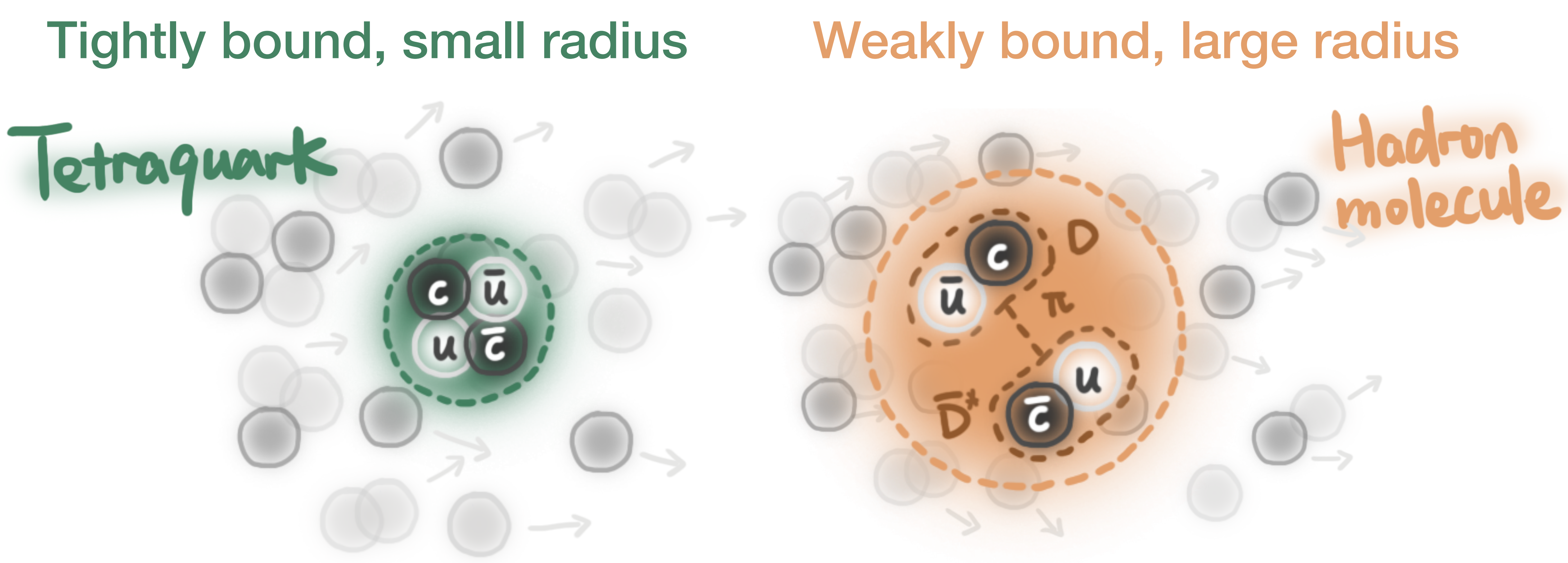
BPH-11-011



A new window into the X(3872) structure



- **Dissociated** by interactions with comovers
- Enhanced production via **coalescence**
- Its response in color dense environment indicates its inner structure



20-year debate of X(3872) nature

Summary

- CMS continues to accumulate increasingly sensitive datasets
  - — exploring standard & novel trigger & data-taking paradigms
- rare (and forbidden) decays are highly sensitive processes
- production studies further probing eg MPI and hadronization
- investigation of exotic hadron structures being furthered
- both open- and hidden- (and exotic) flavour employed as novel probes of the QCD hot medium
- ongoing Run3 shall facilitate more **precise** measurements, **clarification** of ongoing puzzles, plus new **observations**

Stay tuned. *Thank you for listening!*