Experimental Charm Physics

Dr Marco Gersabeck
The University of Manchester

The 2018 Weihai High-Energy Physics School,
Weihai, 21-23 August 2018

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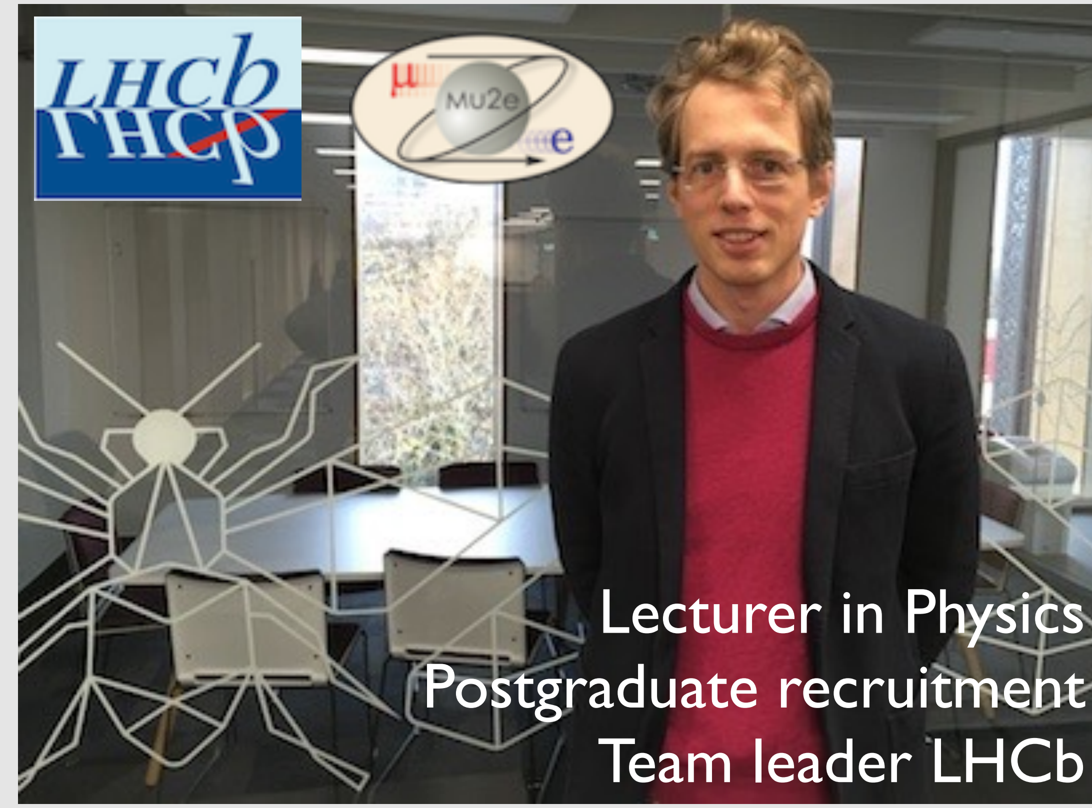
Your lecturer



Research Associate on the LHCb experiment

Job Reference : S&E-12555
Location : Oxford Road, Manchester
Closing Date : 17/09/2018

ShanghaiRanking's Global Ranking of Academic Subjects 2018 - Physics 2018

Field: Natural Sciences **Subject:** Physics

ACADEMIC RANKING OF WORLD UNIVERSITIES SINCE 2003

World Rank	Institution*			
9	The University of Manchester		305.5	67

Scope

- Experimental charm physics
  - ➡ Mostly CP violation, other symmetries, and rare decays
  - ➡ I’m on LHCb, so some bias is likely
  - ➡ Experiments are based on theory, so we’ll also cover the basics there
    - Leaving the specifics to the dedicated lectures

Further reading

- Books
  - ➡ *Sozzi: Discrete Symmetries and CP violation
  - ➡ Kleinknecht: Uncovering CP violation
  - ➡ Giorgi et al.: CP violation: from Quark to Leptons
  - ➡ Bigi and Sanda: CP violation
  - ➡ Branco Lavoura: CP violation
- Publication
  - ➡ *Gersabeck: Introduction to charm physics

*Main sources for this course

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Outcomes

- By the end you should expect
  - ➡ To be able to connect charm mixing and CP violation observables to the corresponding theory parameters
  - ➡ To have an up-to-date overview of the relevant measurements, including selected analysis methods and systematic uncertainties
  - ➡ To have an overview of current and future experiments

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Outline

1. Introduction and charm mixing theory
2. Experiments, indirect CP violation, and time-dependent two-body measurements
3. Time-dependent multi-body measurements and super-weak constraint
4. Direct CP violation theory and two-body measurements
5. CP violation in multi-body decays, techniques and results, and other decays
6. Rare decays, other symmetries, and future directions

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Lecture 1

- Charm introduction
- Neutral mesons — Mixing

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Charm's first time

The very beginning

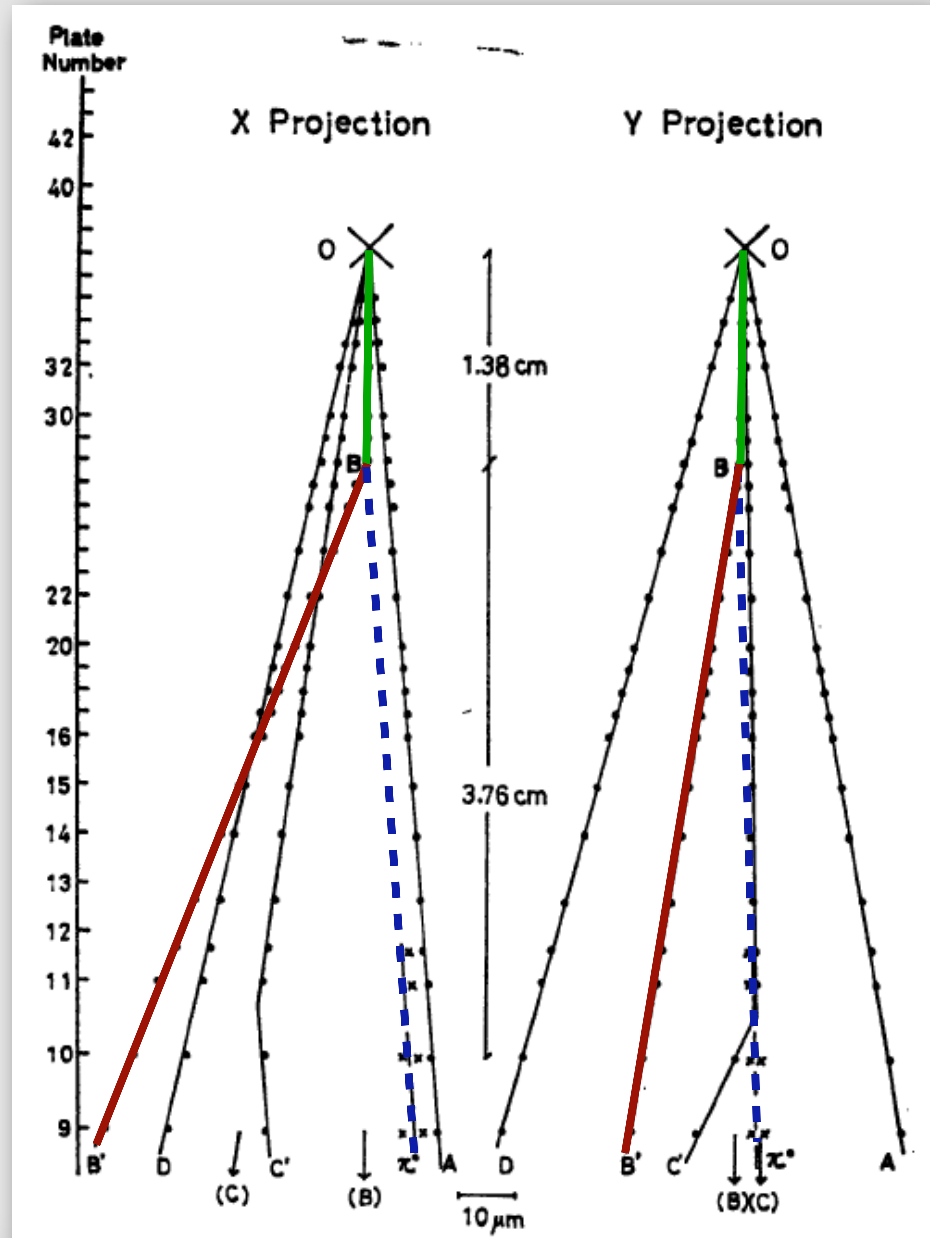
Prog. Theor. Phys. Vol. 46 (1971), No. 5

A Possible Decay in Flight of a New Type Particle

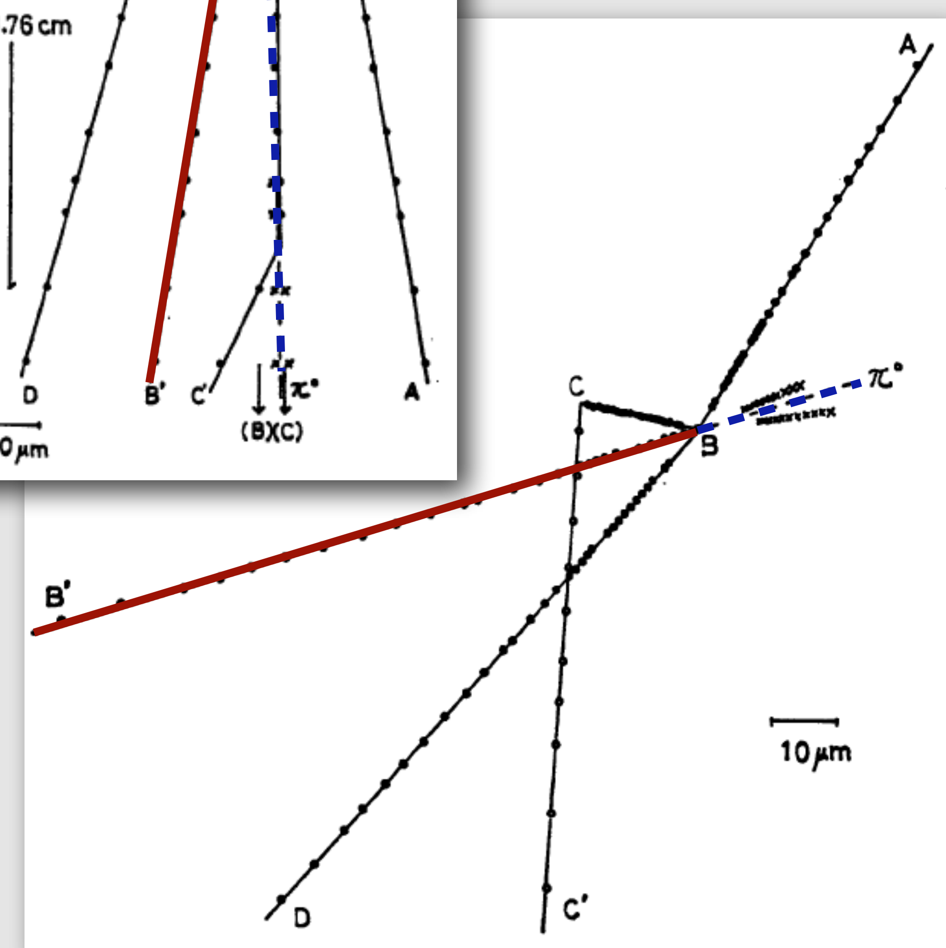
Kiyoshi NIU, Eiko MIKUMO and Yasuko MAEDA*

Institute for Nuclear Study
University of Tokyo
**Yokohama National University*

August 9, 1971



- Cosmic showers
- Observed in emulsion chambers
- 500 hours aboard a cargo plane



Assumed decay mode	M_x GeV	T_x sec
$X \to \pi^0 + \pi^\pm$	1.78	2.2×10^{-14}
$X \to \pi^0 + p$	2.95	3.6×10^{-14}

The Nobel beginning

VOLUME 33, NUMBER 23 PHYSICAL REVIEW LETTERS 2 DECEMBER 1974

Experimental Observation of a Heavy Particle J†

J. J. Aubert, U. Becker, P. J. Biggs, J. Burger, M. Chen, G. Everhart, P. Goldhagen, J. Leong, T. McCorriston, T. G. Rhoades, M. Rohde, Samuel C. C. Ting, and Sau Lan Wu
Laboratory for Nuclear Science and Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

and

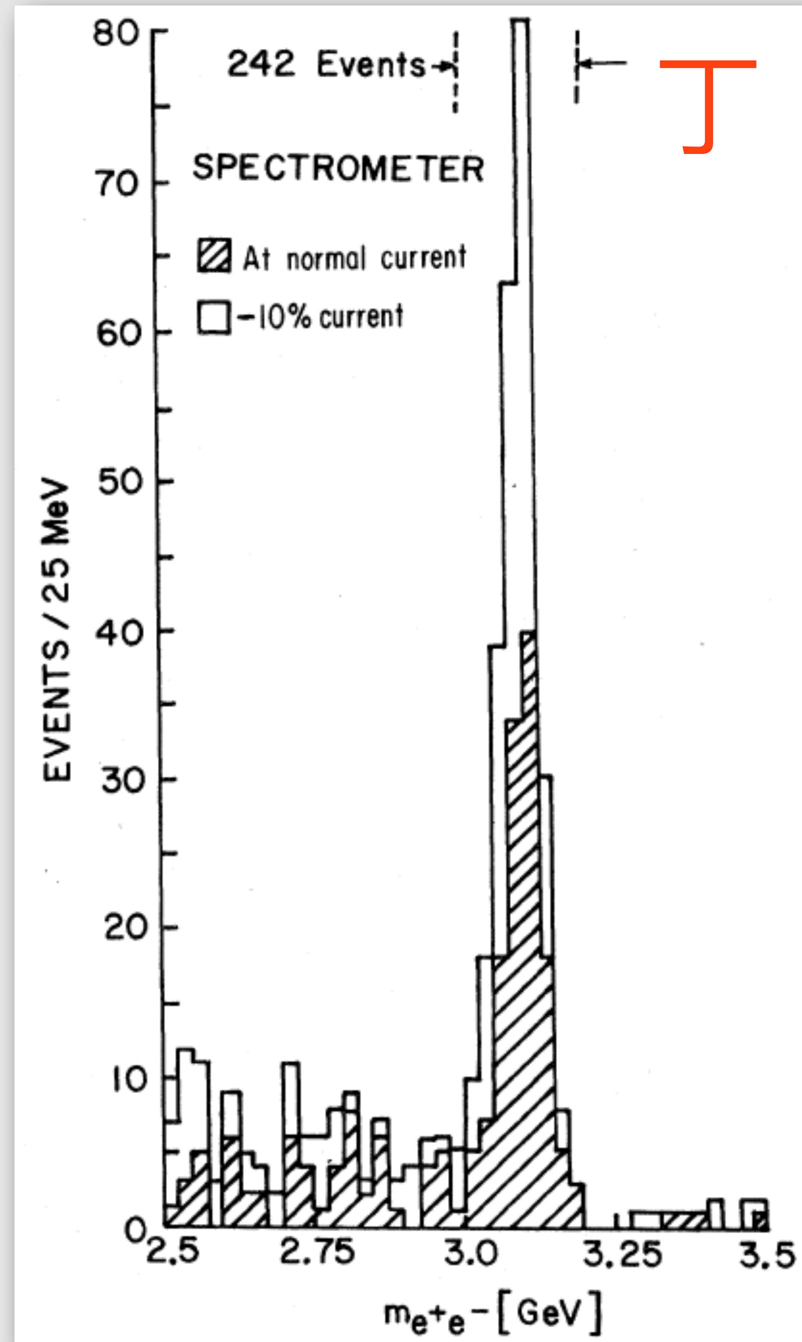
Y. Y. Lee
Brookhaven National Laboratory, Upton, New York 11973
(Received 12 November 1974)

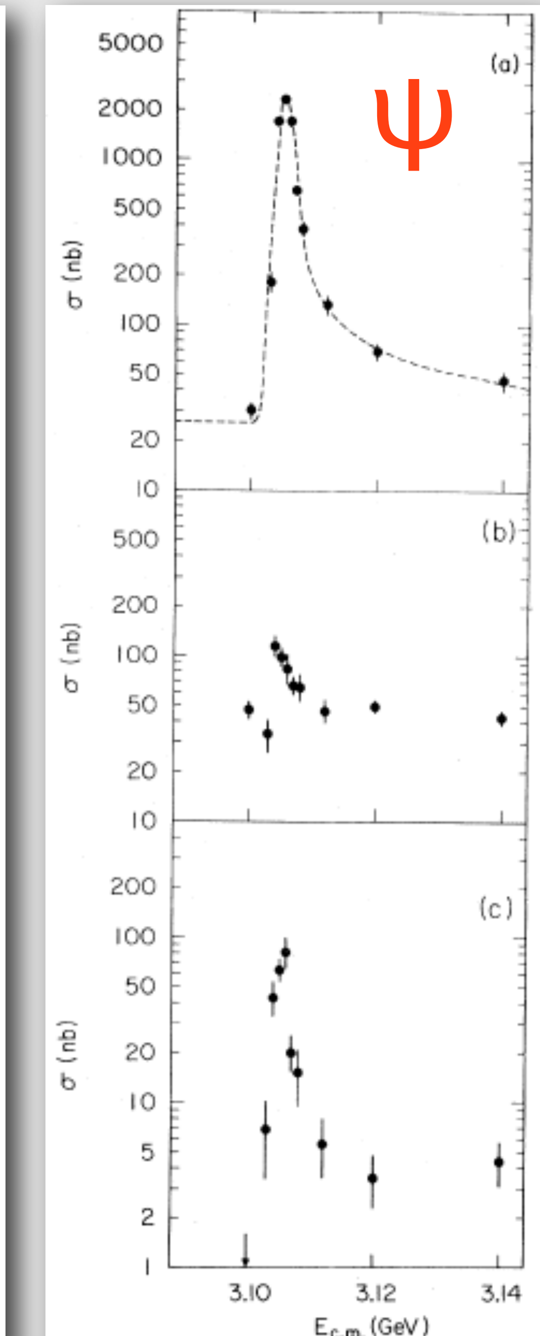
Discovery of a Narrow Resonance in e^+e^- Annihilation*

J.-E. Augustin,† A. M. Boyarski, M. Breidenbach, F. Bulos, J. T. Dakin, G. J. Feldman, G. E. Fischer, D. Fryberger, G. Hanson, B. Jean-Marie,† R. R. Larsen, V. Lüth, H. L. Lynch, D. Lyon, C. C. Morehouse, J. M. Paterson, M. L. Perl, B. Richter, P. Rapidis, R. F. Schwitters, W. M. Tanenbaum, and F. Vannucci‡
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

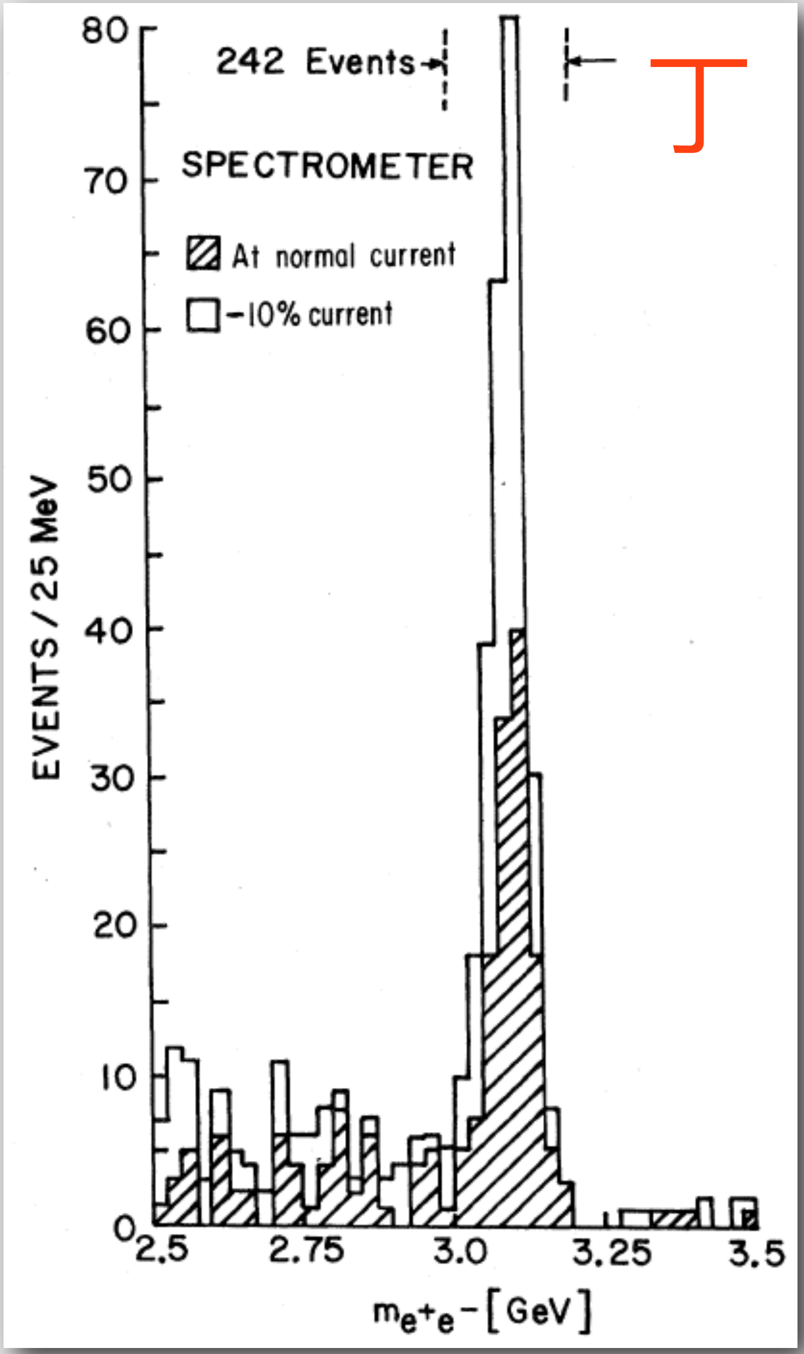
and

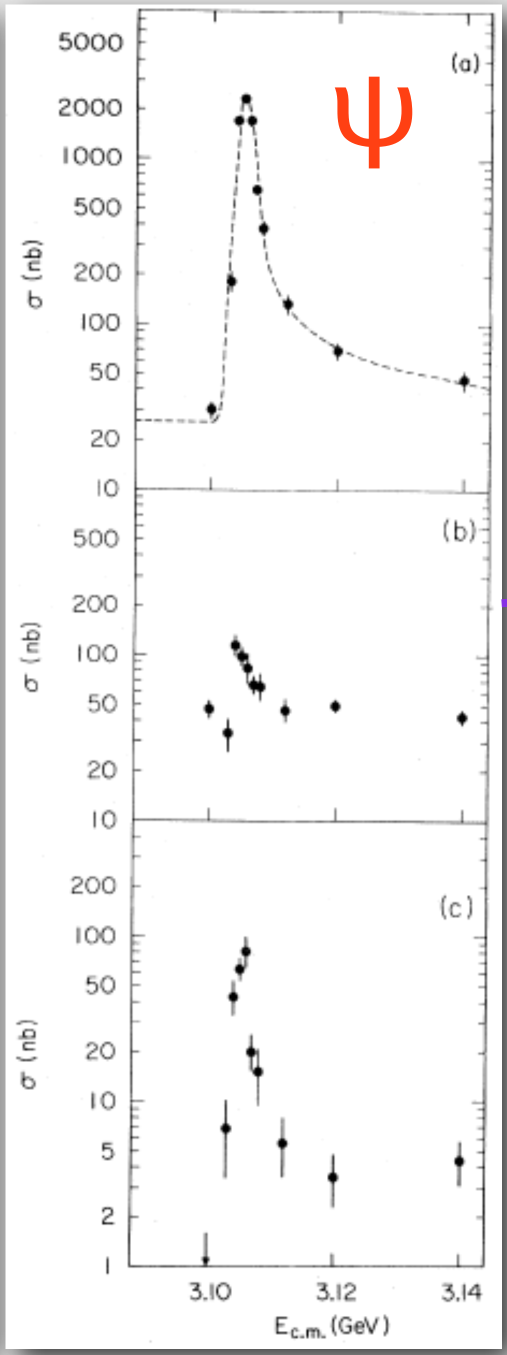
G. S. Abrams, D. Briggs, W. Chinowsky, C. E. Friedberg, G. Goldhaber, R. J. Hollebeek, J. A. Kadyk, B. Lulu, F. Pierre,§ G. H. Trilling, J. S. Whitaker, J. Wiss, and J. E. Zipse
Lawrence Berkeley Laboratory and Department of Physics, University of California, Berkeley, California 94720
(Received 13 November 1974)





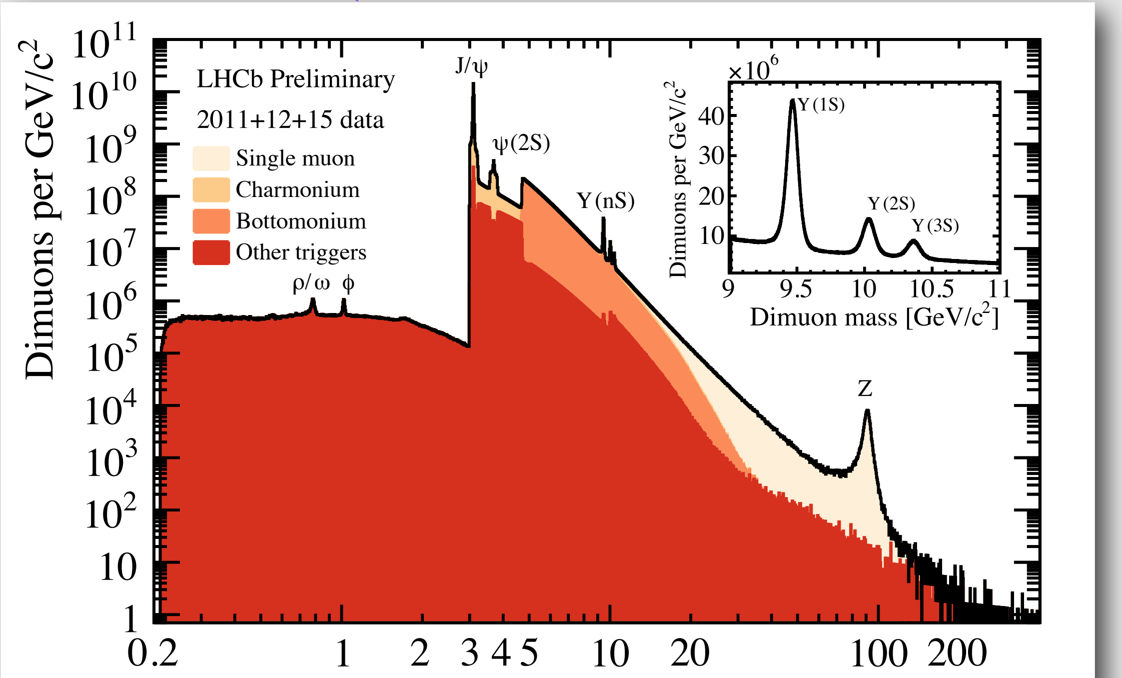
Charmonium





+42 years

+8 orders of magnitude



LHCb-CONF-2016-005

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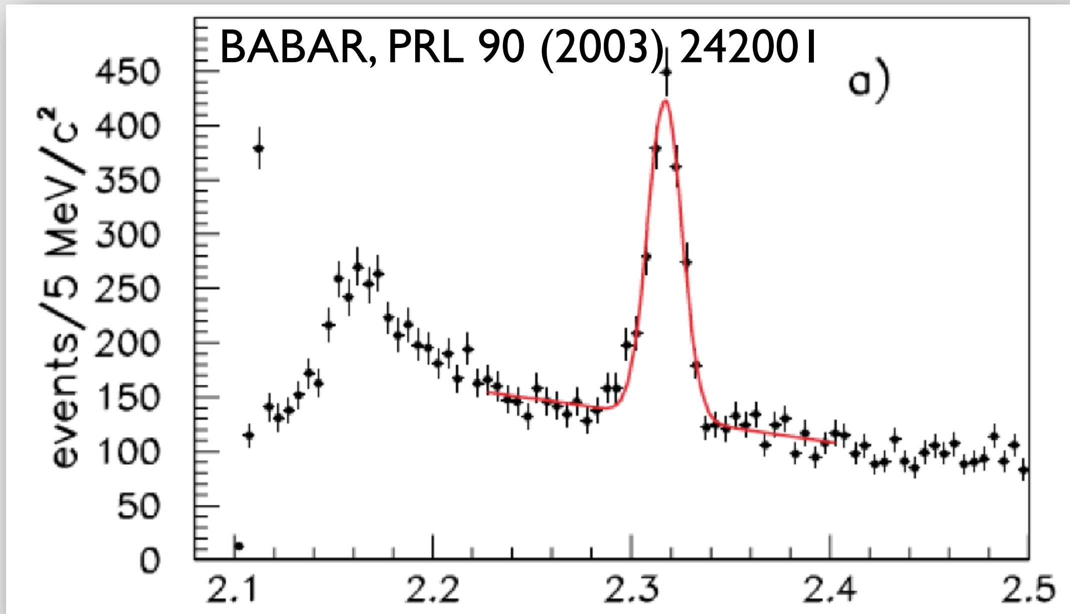
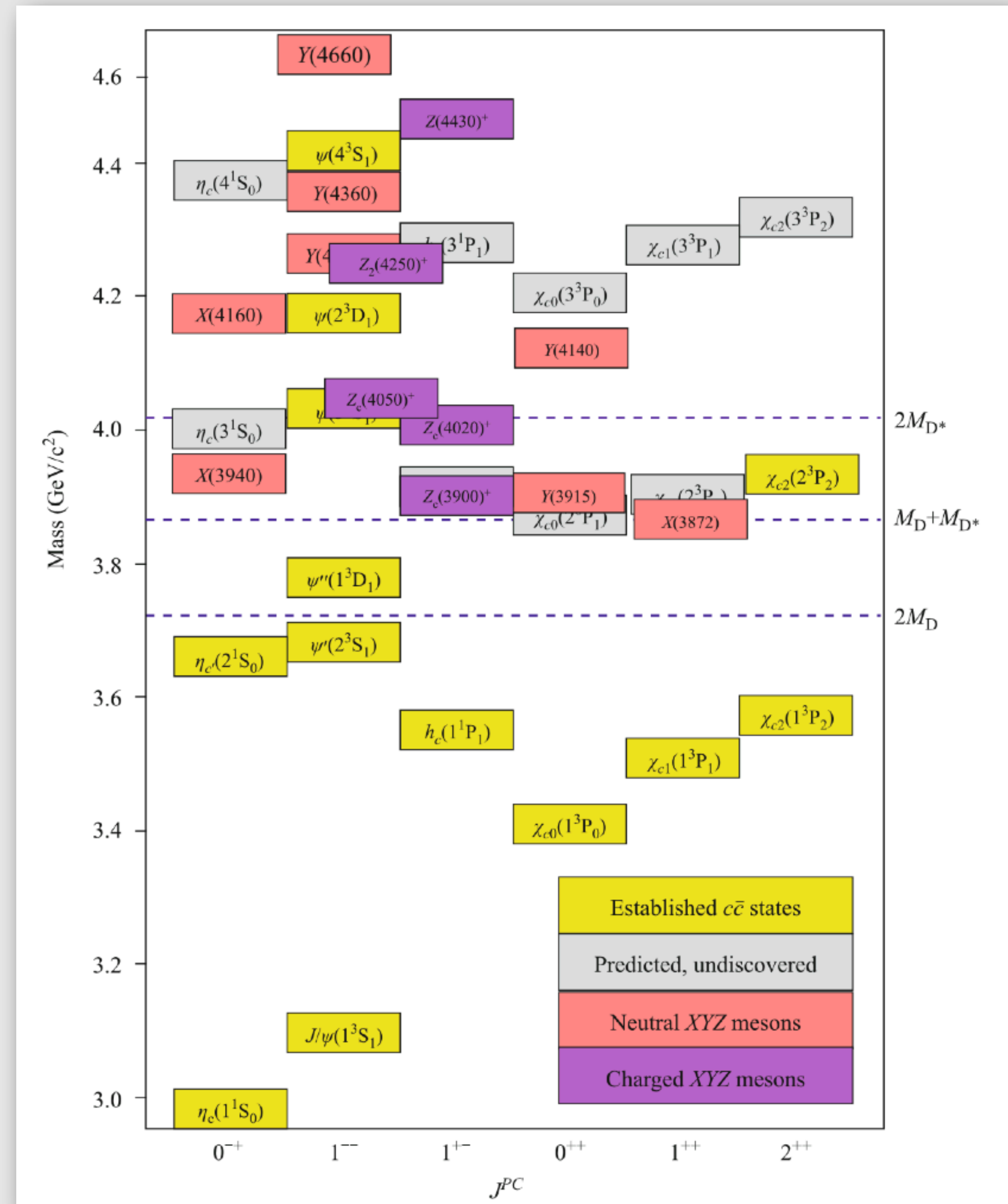
Charm's second time

Spectroscopy





S. Olsen, Front. Phys. 10 (2015) 101401

- Strange peaks started appearing in 2003/04
- Matching with quark model predictions still difficult
  - ➡ Many gaps in possible states
  - ➡ Some observed states may be exotics
- Different production mechanisms
  - ➡ Prompt vs B decays

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Could

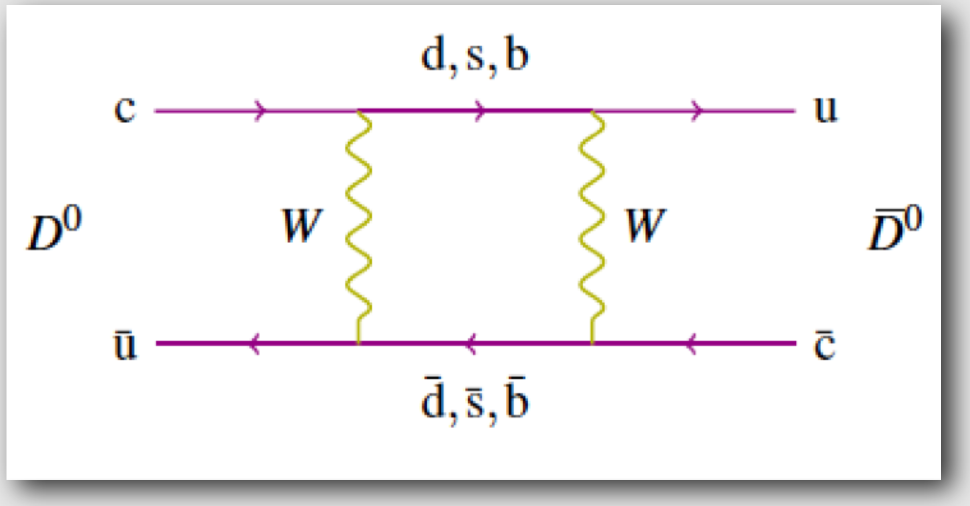
Charm's third time

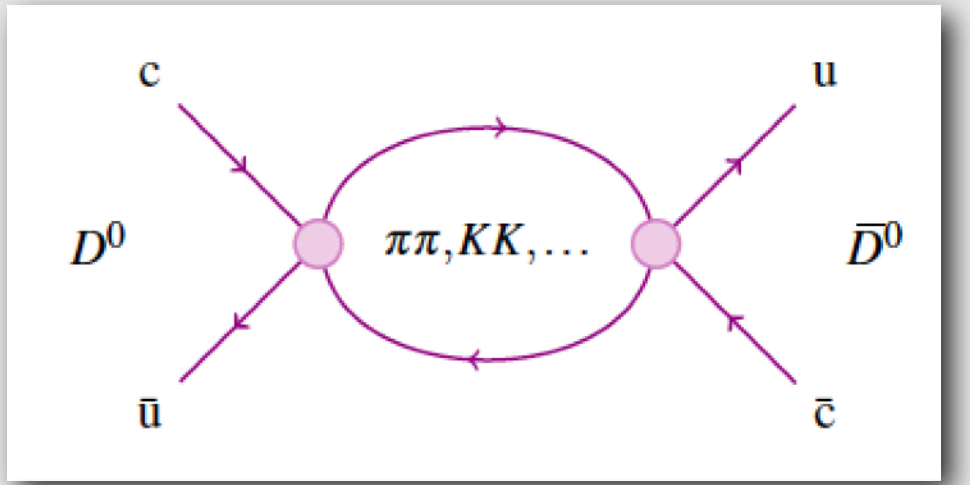
the real charm?

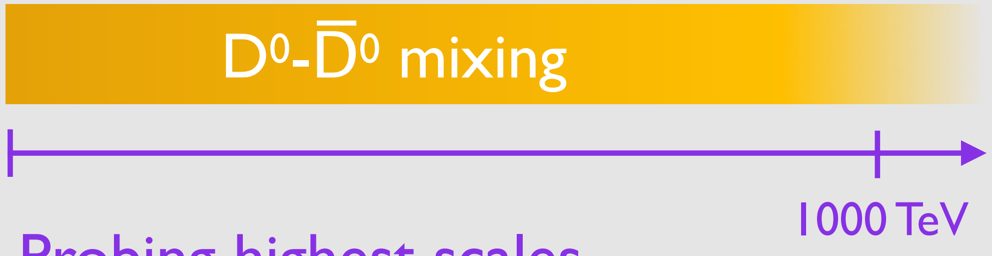
Ikaros Bigi, arXiv:0902.3048 [hep-ph]

Charm: hardly a CKM triangle

- Mixing
  - ➡ Discovered 2007
  - ➡ Huge cancellations
  - ➡ Theoretically difficult
- CP violation
  - ➡ Predictions even smaller
- Only up-type quark to form mixing neutral mesons
  - ➡ Unique physics access
- Need highest precision
- Huge LHCb dataset
  - ➡ Blessing and a curse







Probing highest scales

→ Isidori, Nir, Perez, ARNPS 60 (2010) 355

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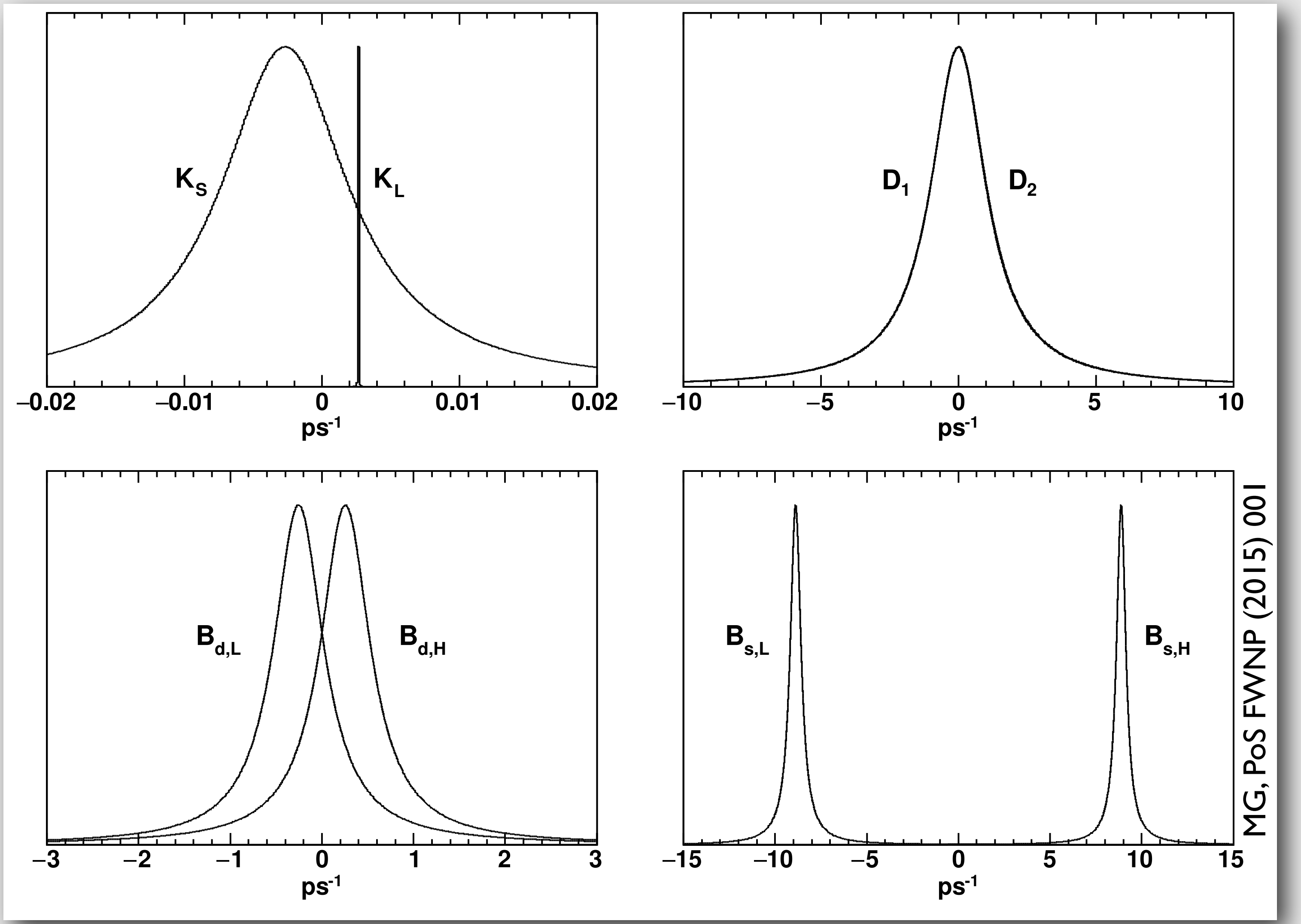
Let’s have a closer look

Mixing recap

$$|M_{1,2}\rangle = p|M^0\rangle \pm q|\overline{M}^0\rangle$$

Physical states

Flavour eigenstates



Mixing recap

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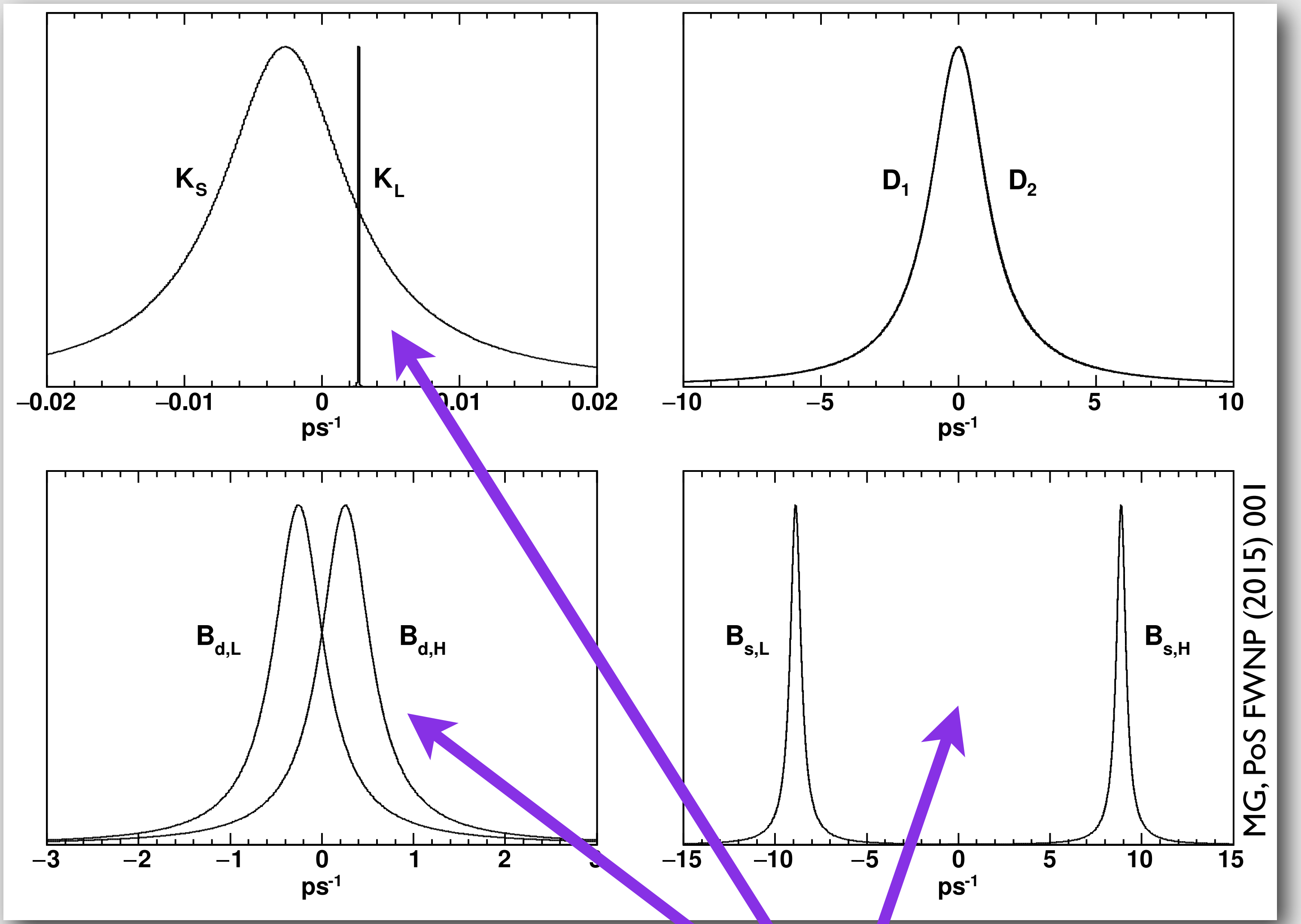
Physical states — Flavour eigenstates



Mass difference

→ Oscillation

$$\Delta m \equiv m_2 - m_1$$

$$P(M^0 \to \overline{M}^0, t) = \frac{1}{2}\left|\frac{q}{p}\right|^2 e^{-\Gamma t}(\cosh(y\Gamma t) - \cos(x\Gamma t))$$

$$x \equiv \Delta m/\Gamma$$

Mixing recap

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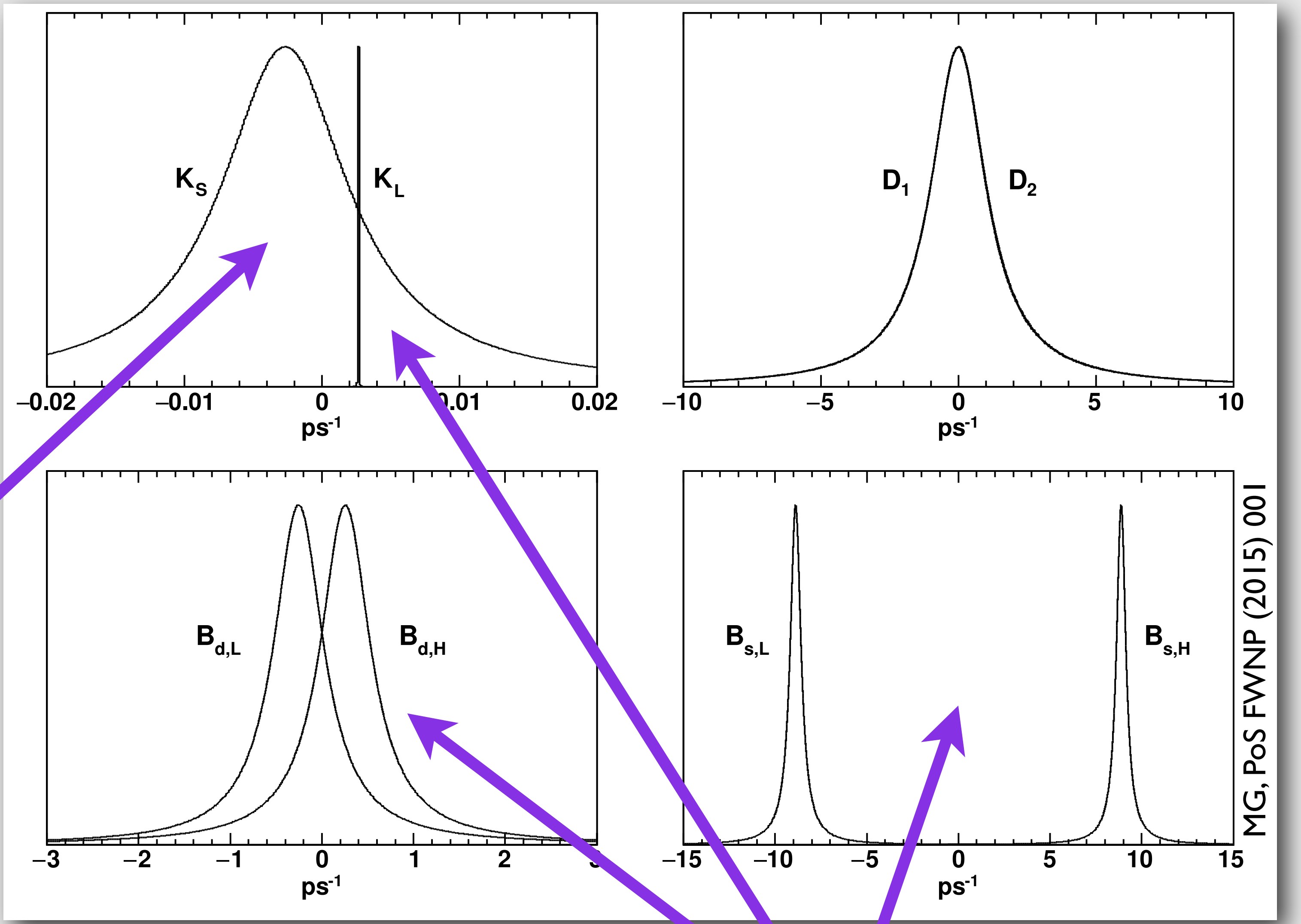
Physical states

Flavour eigenstates



Width difference

→ Lifetime difference

$$\Delta\Gamma \equiv \Gamma_2 - \Gamma_1$$

$$y \equiv \Delta\Gamma/(2\Gamma)$$

$$P(M^0 \to \overline{M}^0, t) = \frac{1}{2}\left|\frac{q}{p}\right|^2 e^{-\Gamma t}(\cosh(y\Gamma t) - \cos(x\Gamma t))$$

Mass difference

→ Oscillation

$$\Delta m \equiv m_2 - m_1$$

$$x \equiv \Delta m/\Gamma$$

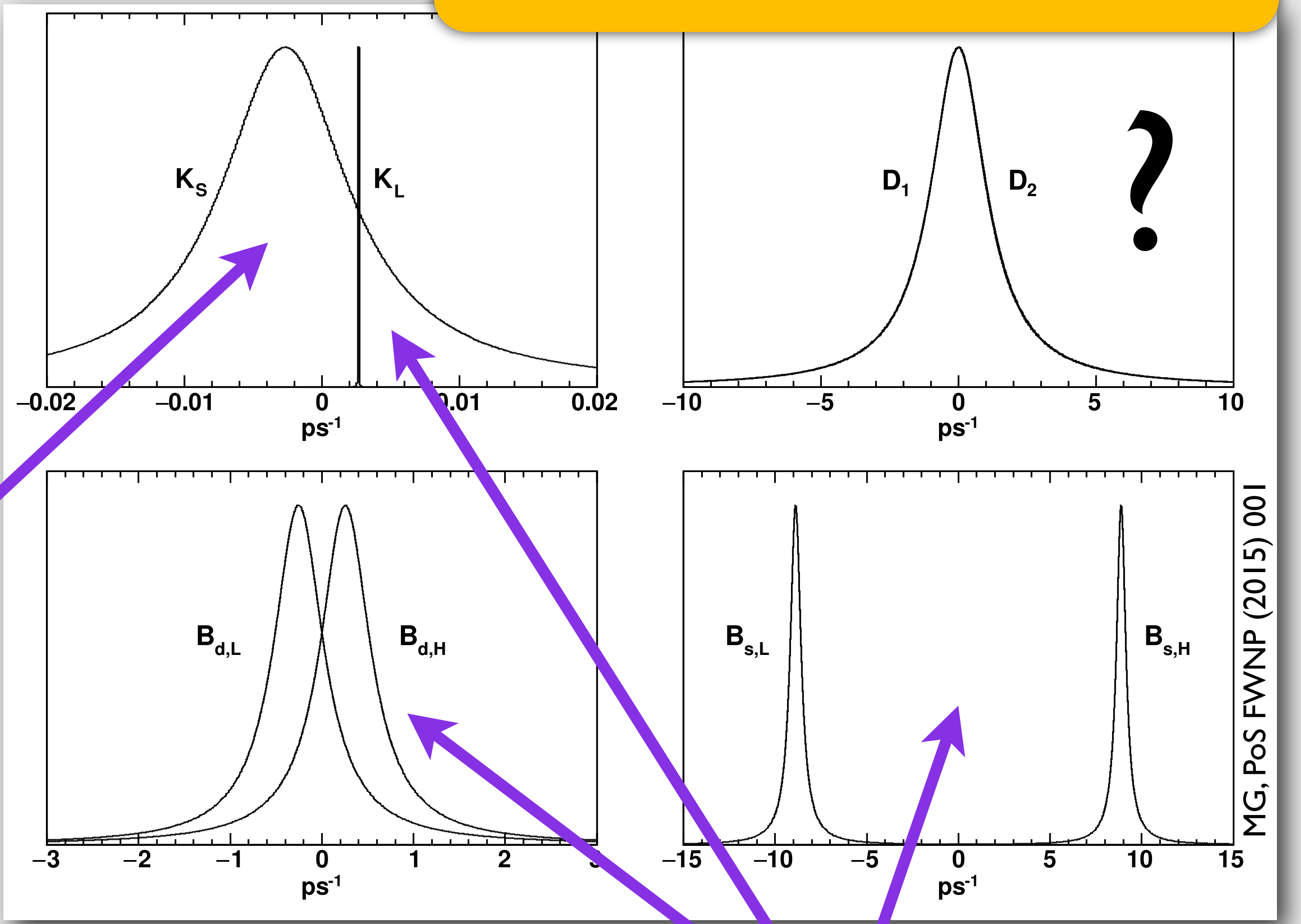
Mixing recap

Charm mixing:
Need ~1000 lifetimes
to see a full oscillation!

$$|M_{1,2}\rangle = p|M^0\rangle \pm q|\overline{M}^0\rangle$$

Physical states

Flavour eigenstates



Width difference
→ Lifetime difference

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Mass difference
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Lecture 2

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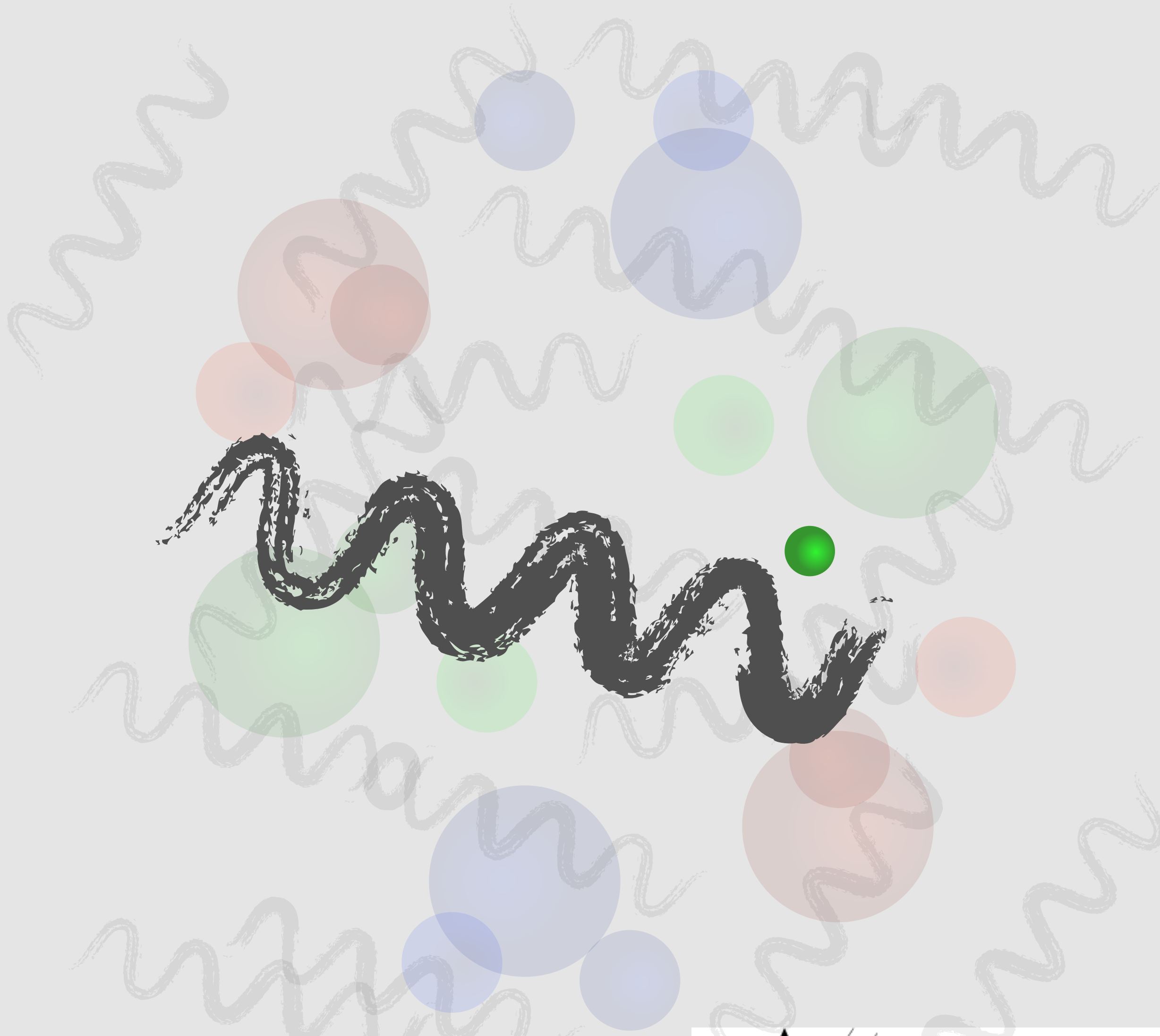
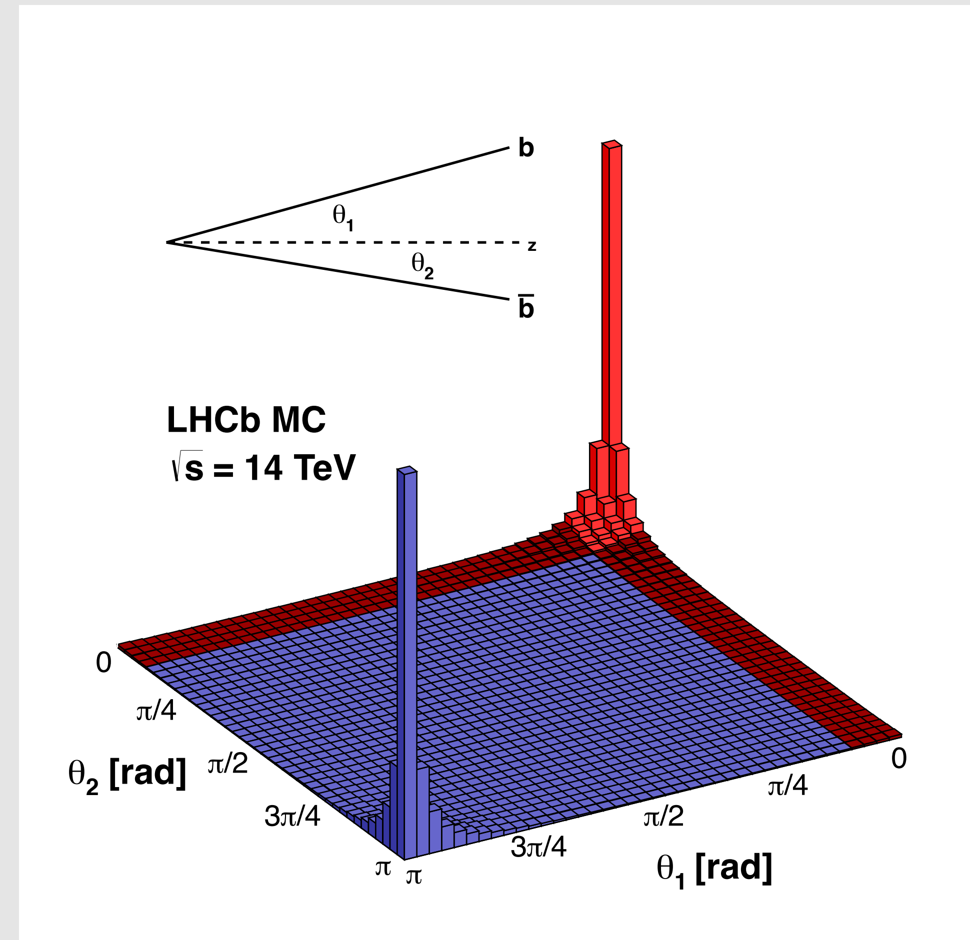
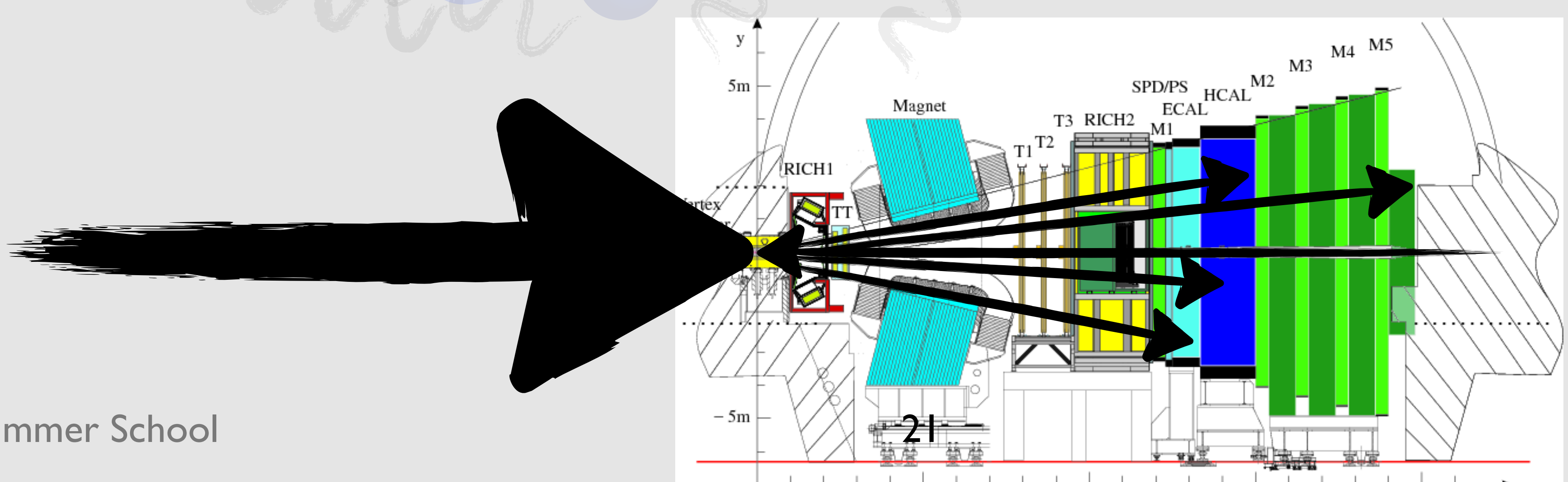
Lecture 2

- Experiments overview and charm production
- Flavour-tagging in charm
- Mixing and indirect CP violation measurements
  - ➡ Two-body

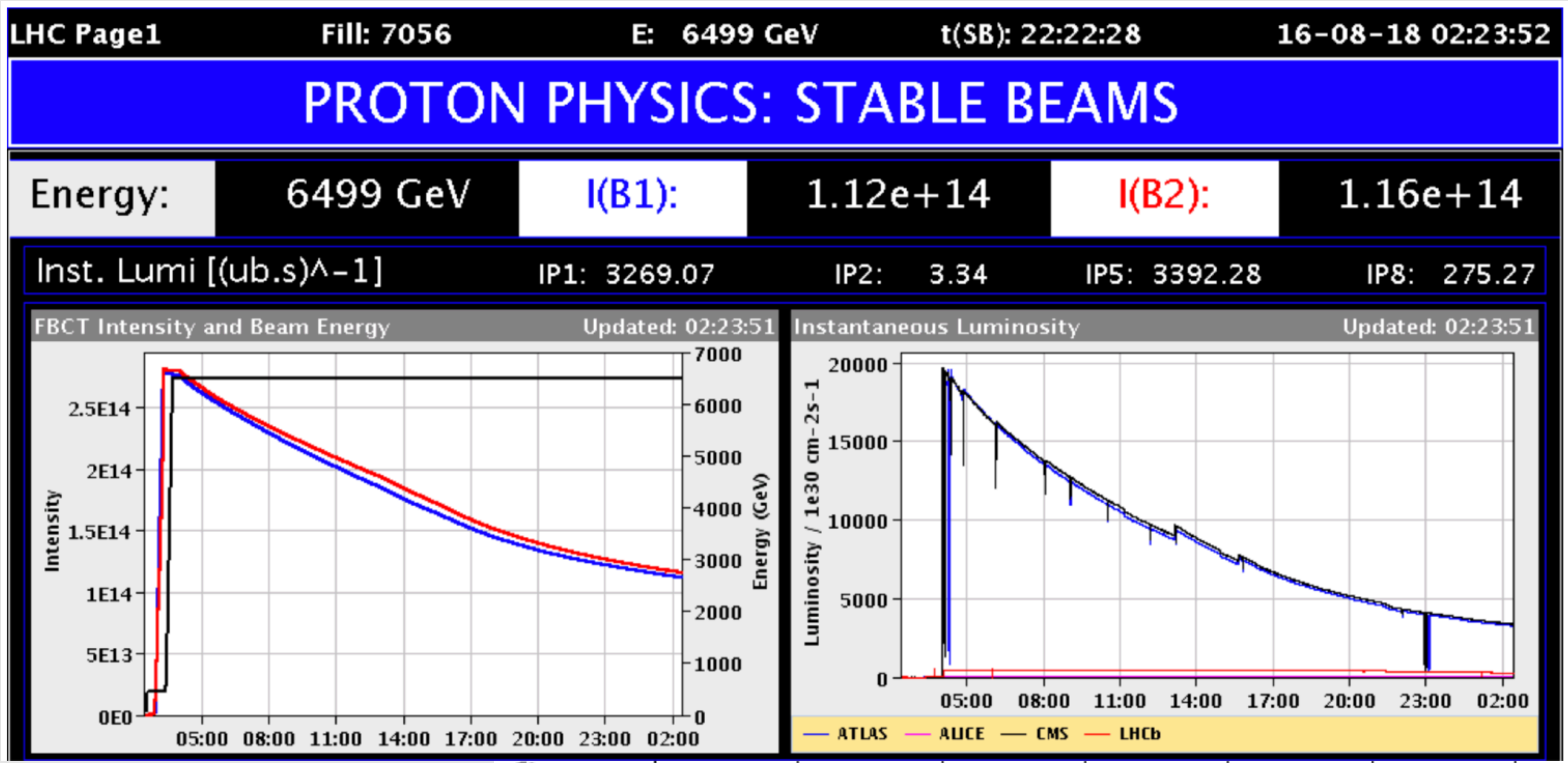
Asymmetric collisions

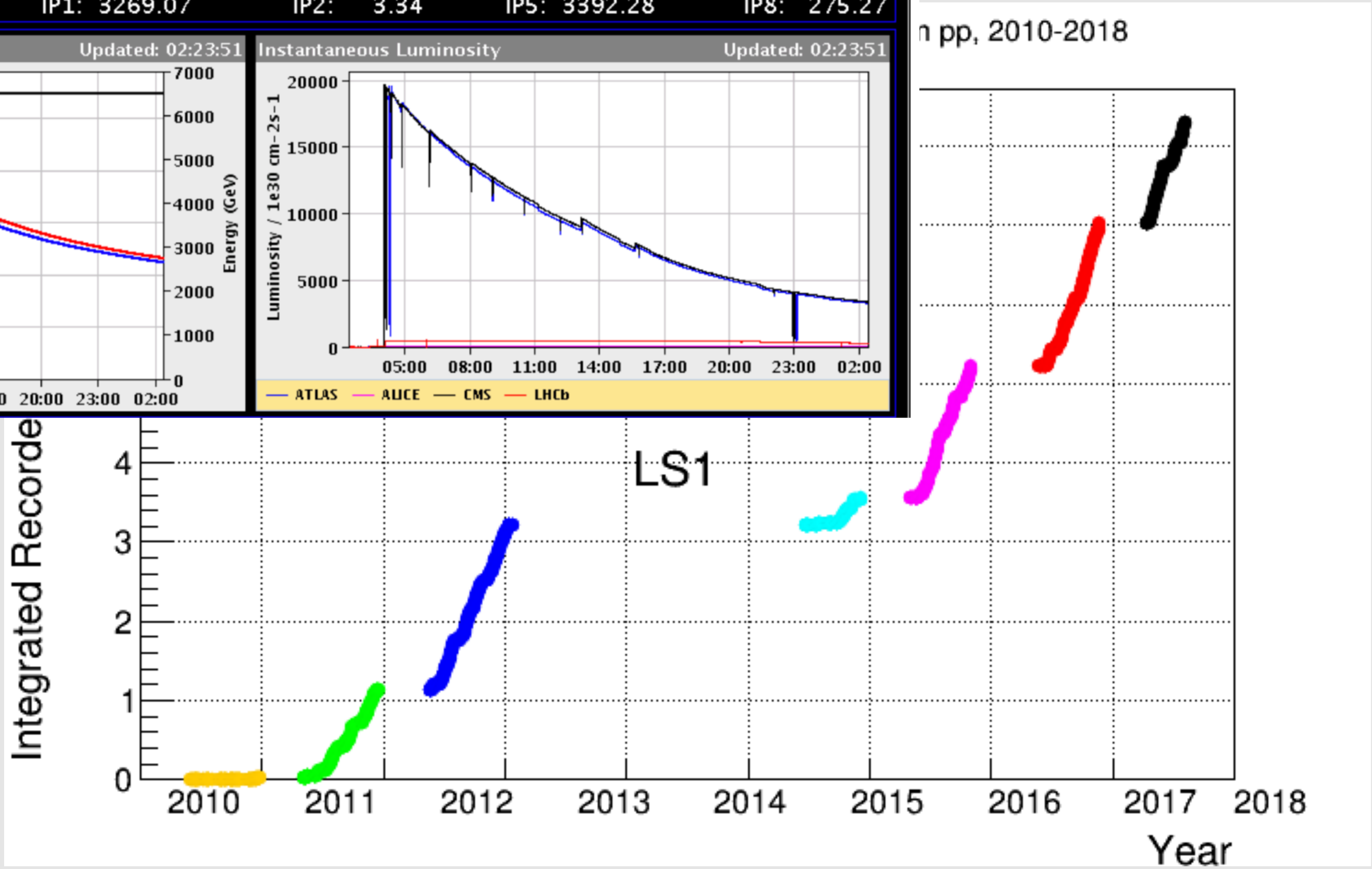




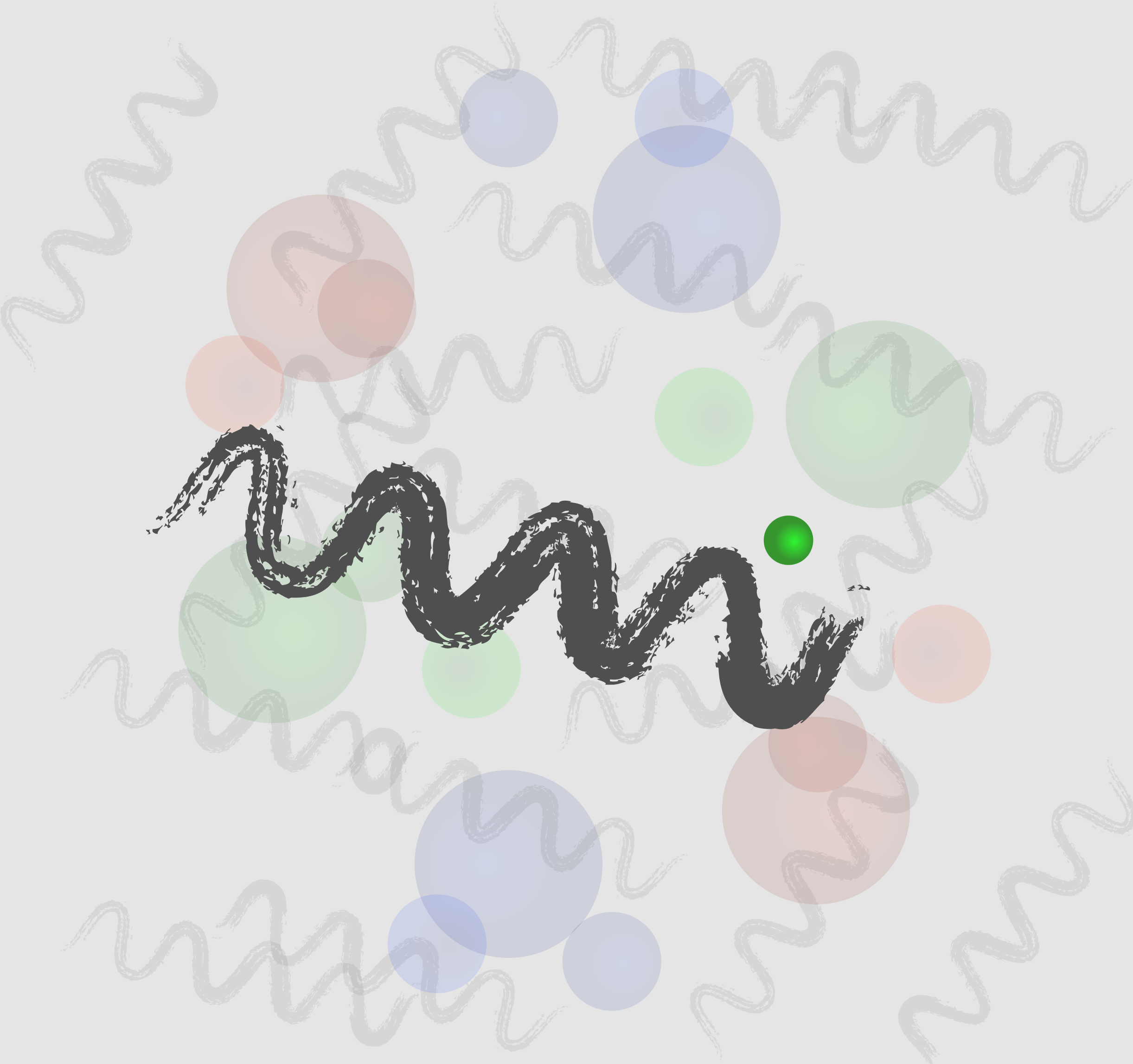


Constant luminosity



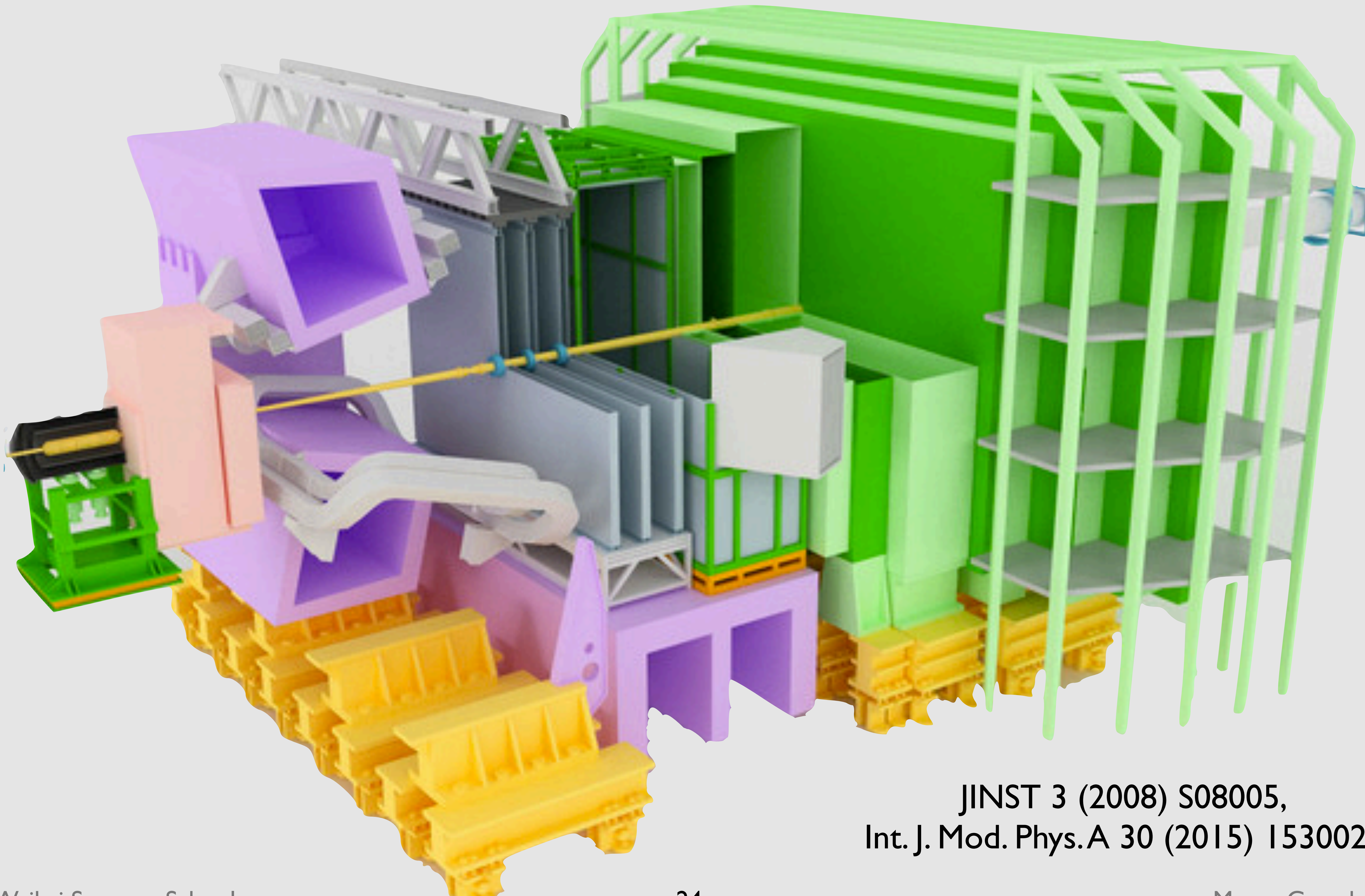


Matter dominance



- pp collisions
- Matter-antimatter asymmetric
- Causes production asymmetries
  - ➡ Not present at Tevatron or B-factories

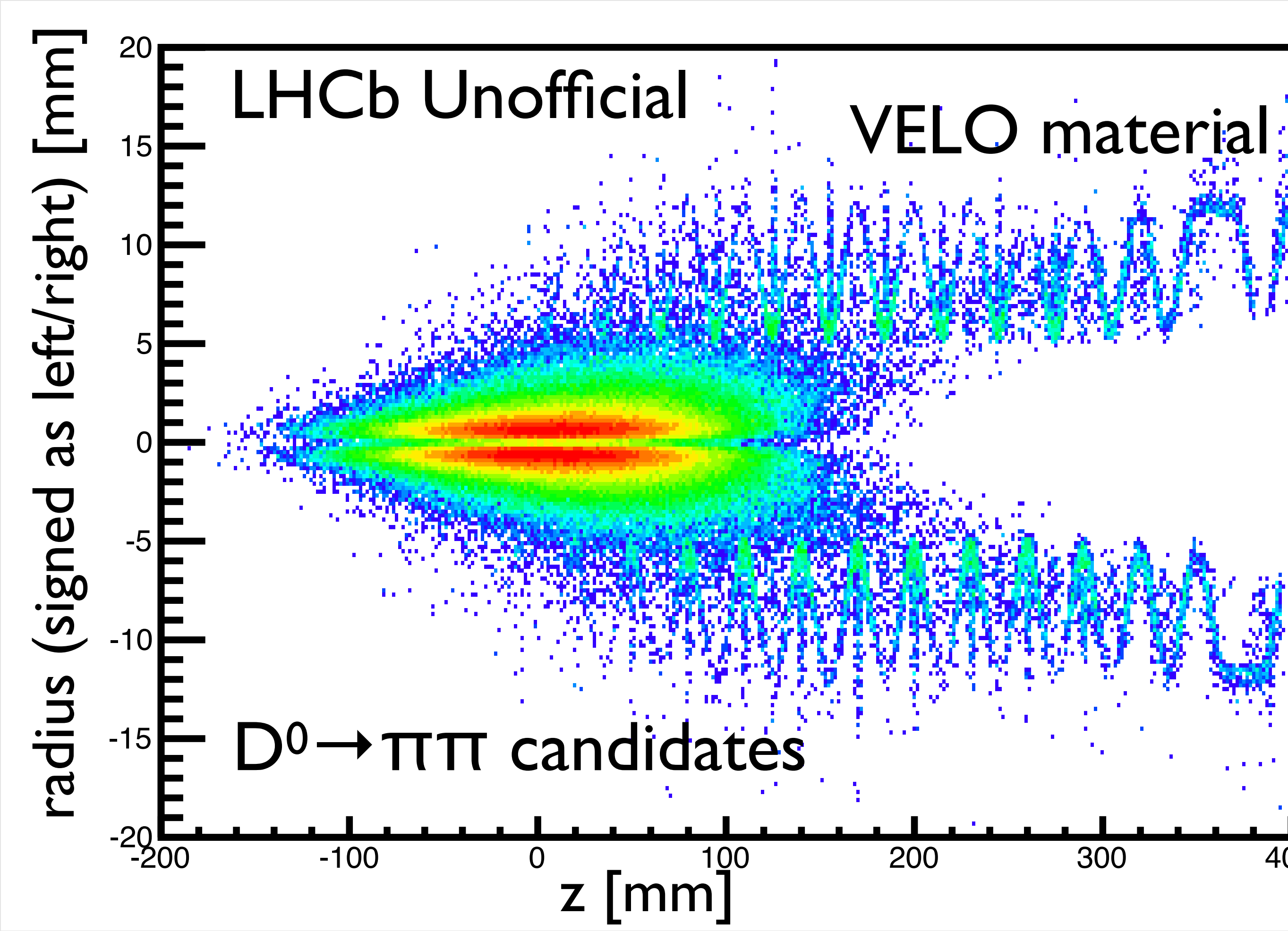
Enter LHCb



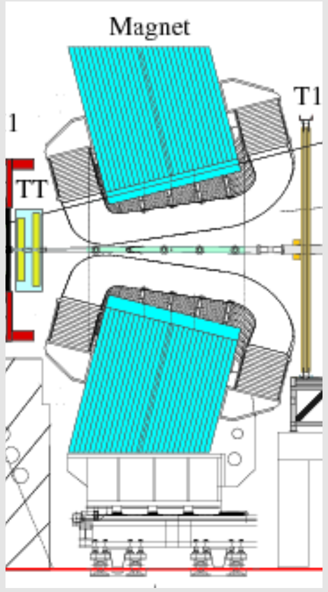
JINST 3 (2008) S08005,
Int. J. Mod. Phys. A 30 (2015) 1530022

Boost

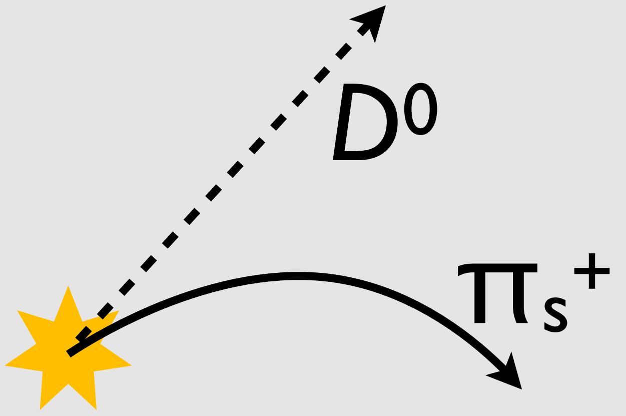
- Average $\beta\gamma$
  - ➡ LHCb: O(10)
  - ➡ BaBar/Belle: ~1
- Heavy flavour particles fly few mm
- First material at 5mm radius
- Decay time resolution ~$0.1\tau_D$



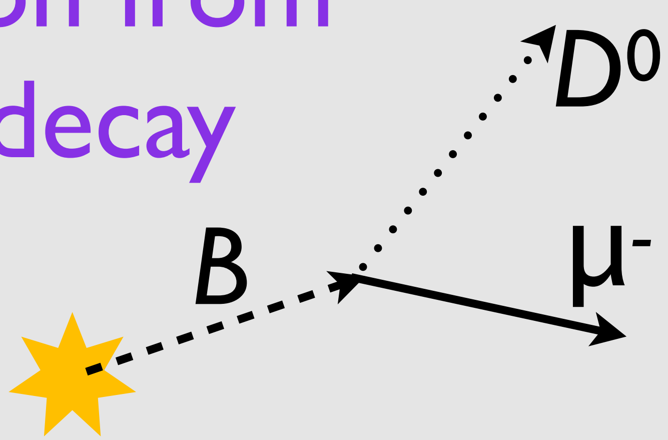
Flavour tagging



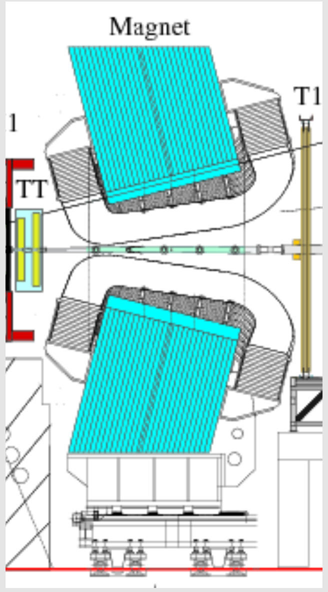
- Can distinguish D^0 from $\overline{D}^0$ in two ways
  - ➡ Charge of soft pion from strong decay $D^{*+} \to D^0 \pi_s^+$



  - ➡ Charge of muon from semi-leptonic decay $B \to D^0 \mu^- X$



Flavour tagging



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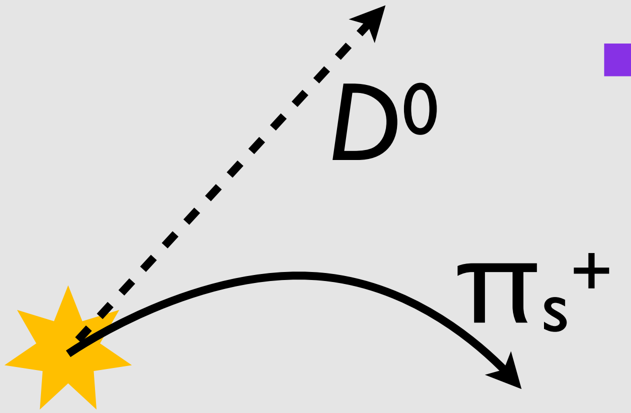

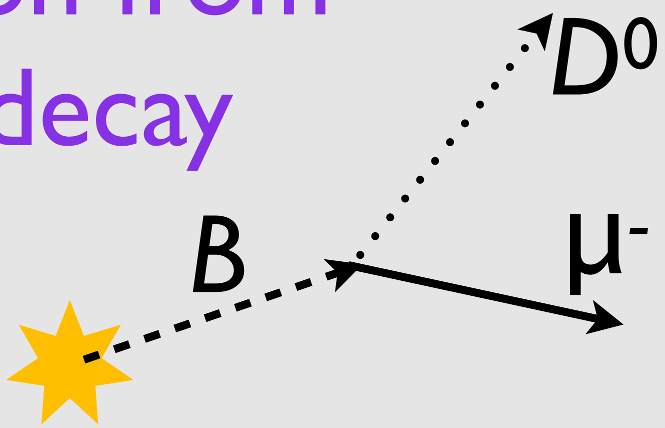

- 4 Tm dipole magnet
  - ➡ Need ~2 GeV/c momentum
  - ➡ σ(p)/p 0.4% - 0.6% @5-100 GeV/c momentum

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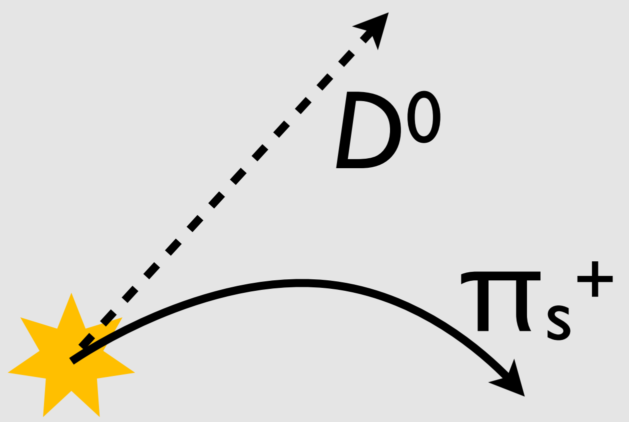
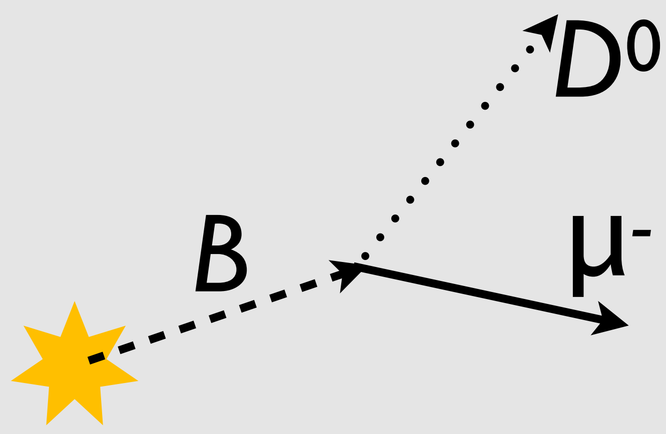
Flavour tagging

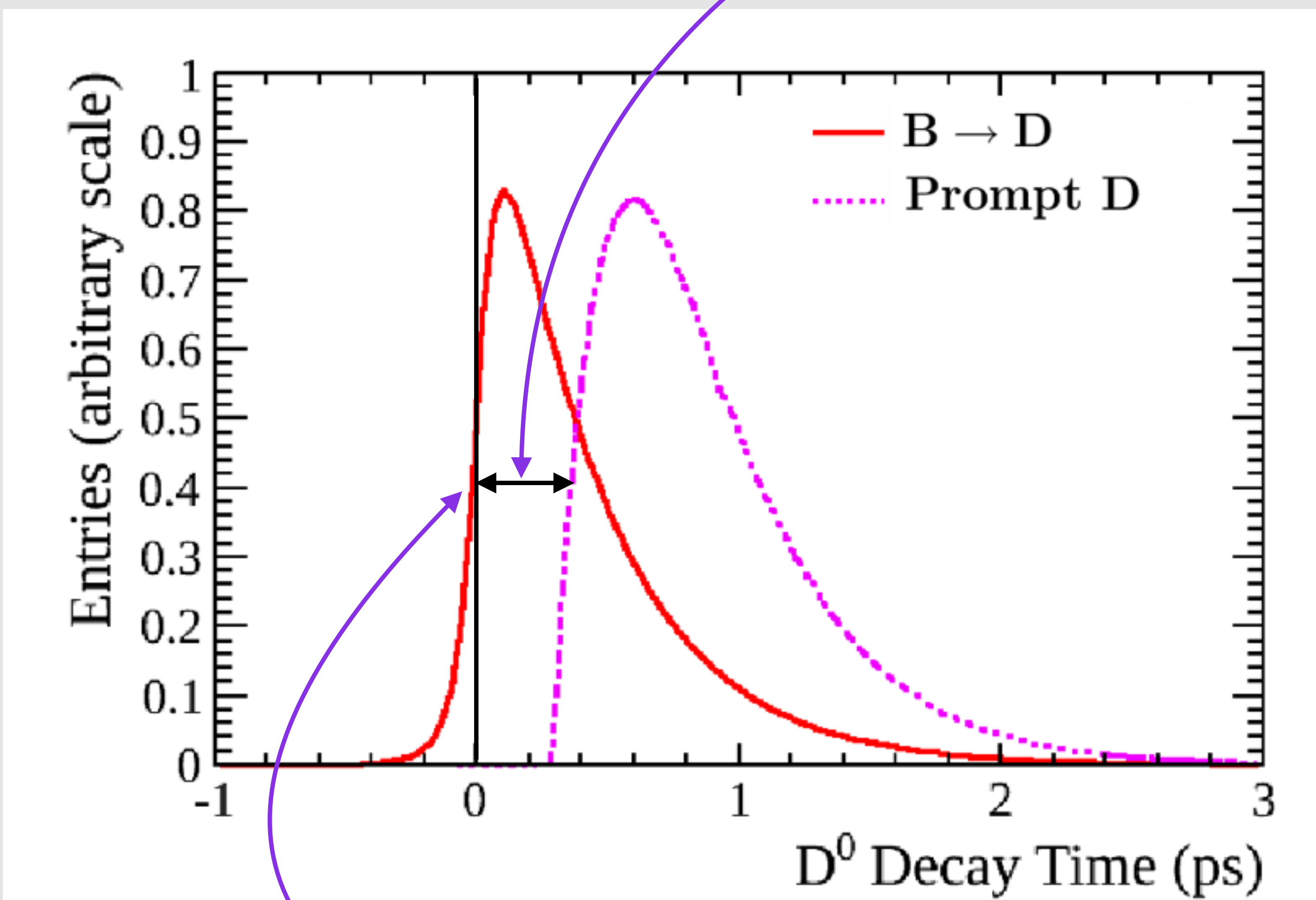
- Prompt D*-tagged
  - ➡ Larger yields
  - ➡ Background from D-from-B
- Muon-tagged
  - ➡ Smaller yields (somewhat)
  - ➡ Larger level of combinatorial background
  - ➡ Independent systematic uncertainties
- Doubly-tagged
  - ➡ The best of both worlds
  - ➡ Smallest samples

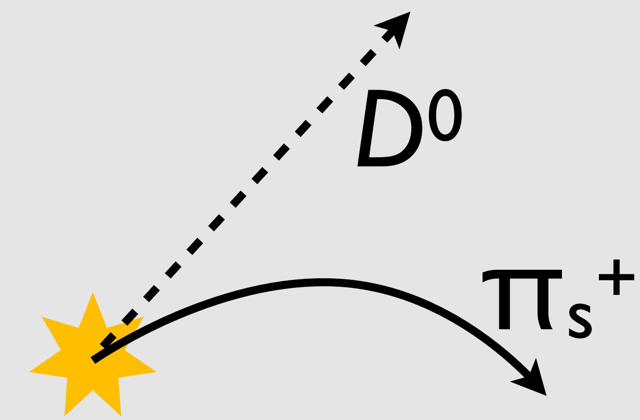


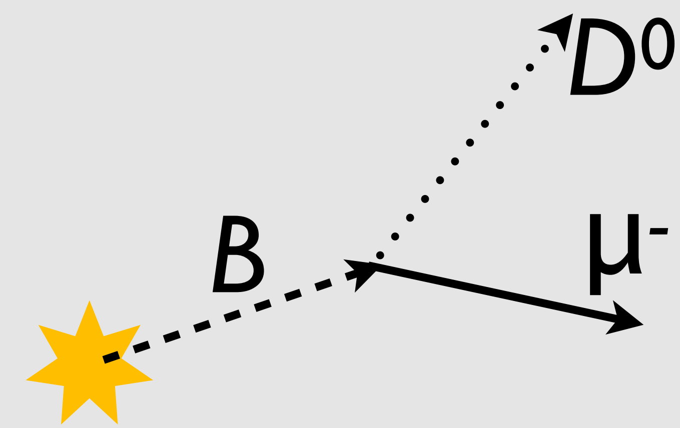


Flavour tagging and decay times

Cannot reconstruct D^0 decays close to **primary** vertex







Can reconstruct D^0 decays close to **displaced B** vertex

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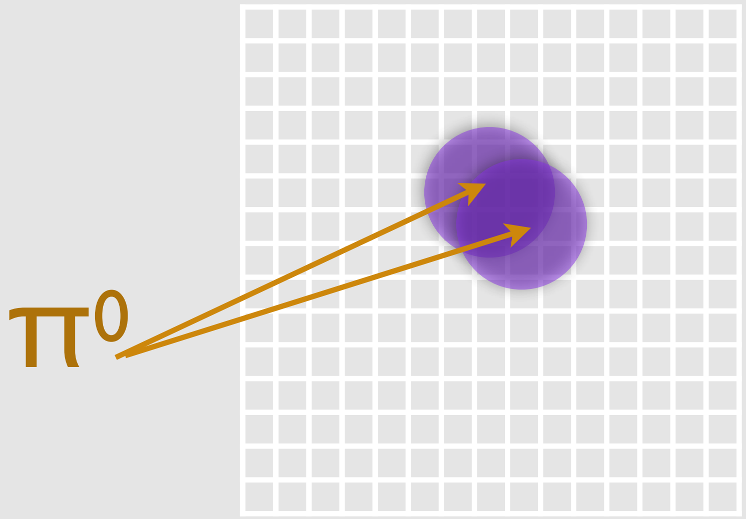
Particle detection

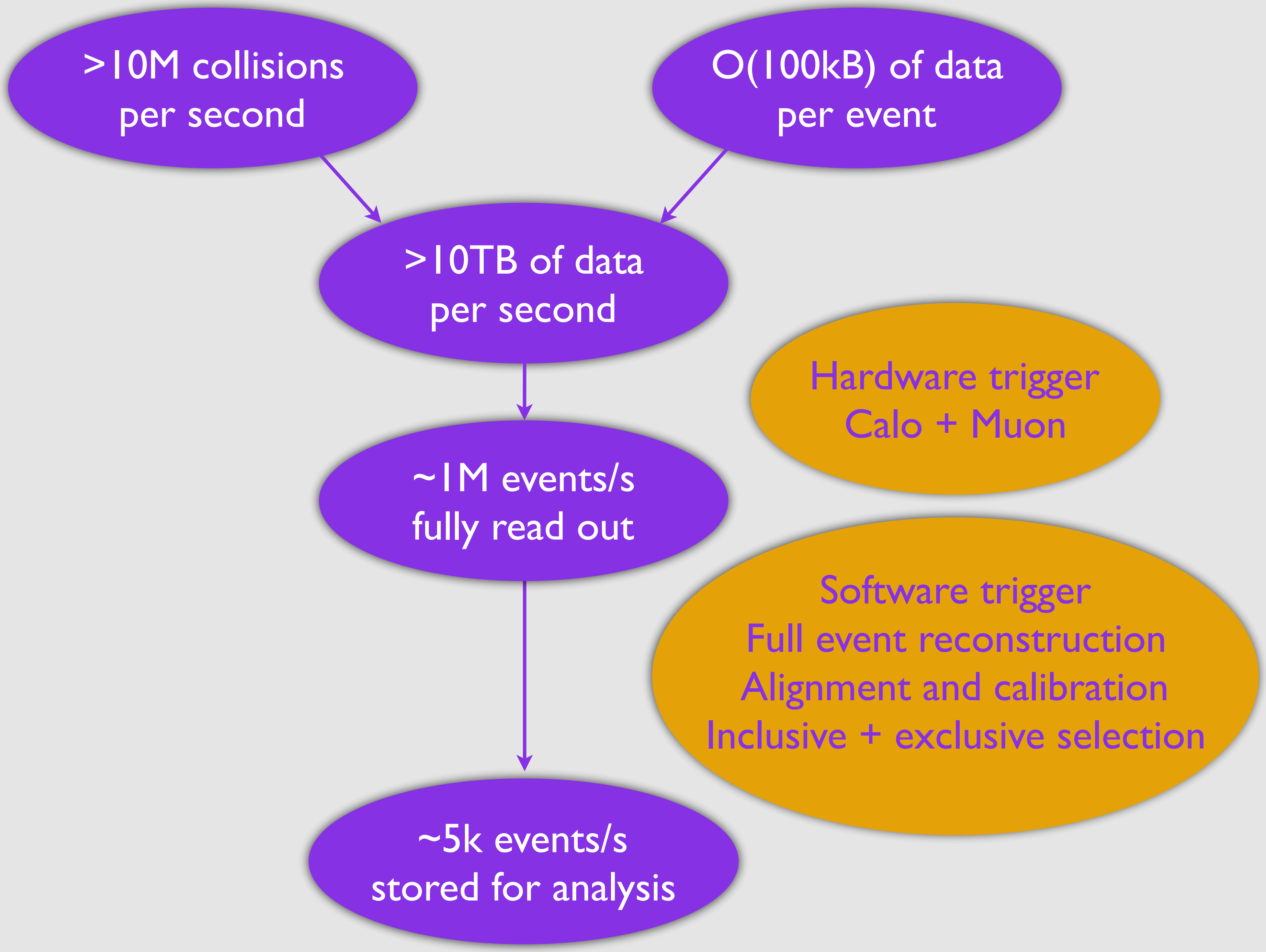
- Excellent charged particle ID
  - ➡ Two ring-imaging Cherenkov detectors
- But even the best detector can challenge you
  - ➡ Detector asymmetries
    - Cancel left-right asymmetries by swapping dipole field
  - ➡ Interaction asymmetries
    - Measure through control modes

Neutral particles

- Need ⩾2 charged particles to define decay vertex
- Additional challenges from neutrals
- K_S and Λ
  - ➡ Long flight distance: Most escape VELO acceptance
- π^0
  - ➡ Coarse granularity: Calorimeter clusters not always separated
- γ
  - ➡ Busy calorimeter: Probability of confusion with electrons or π^0



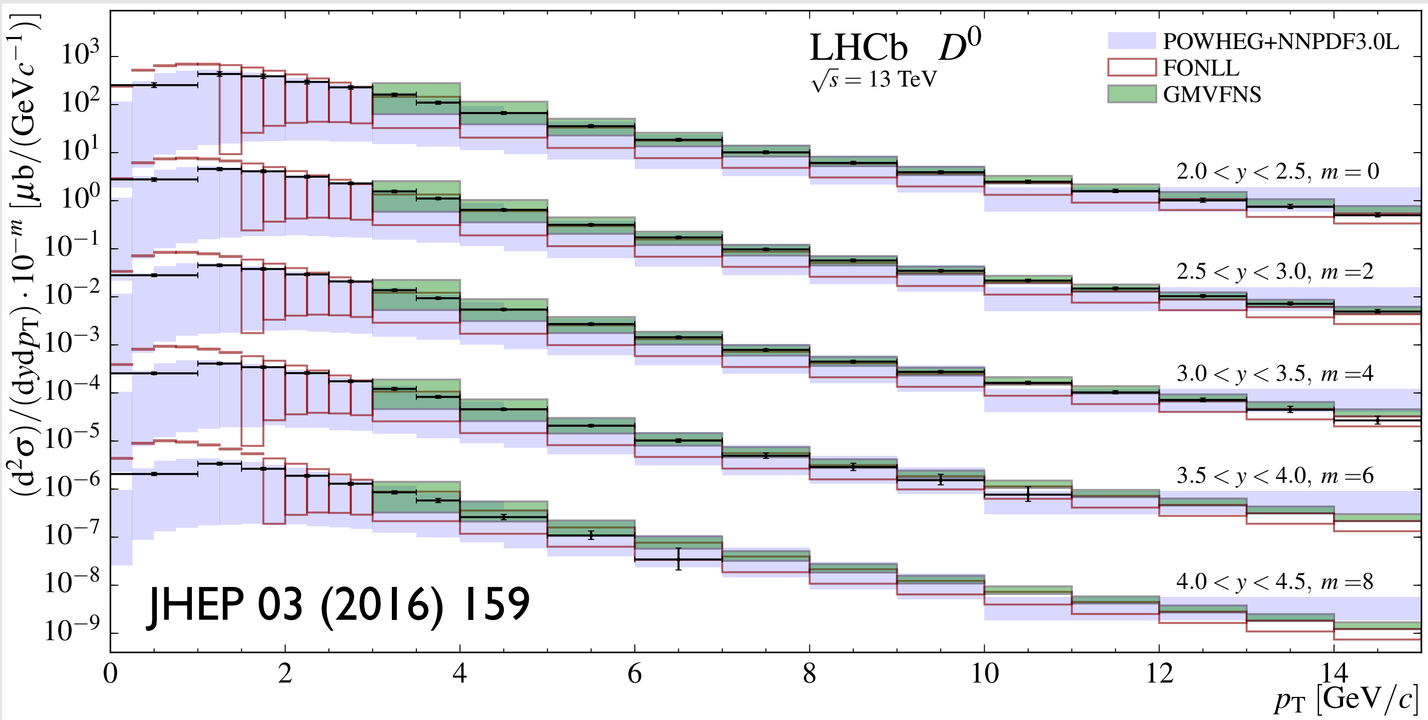
Trigger

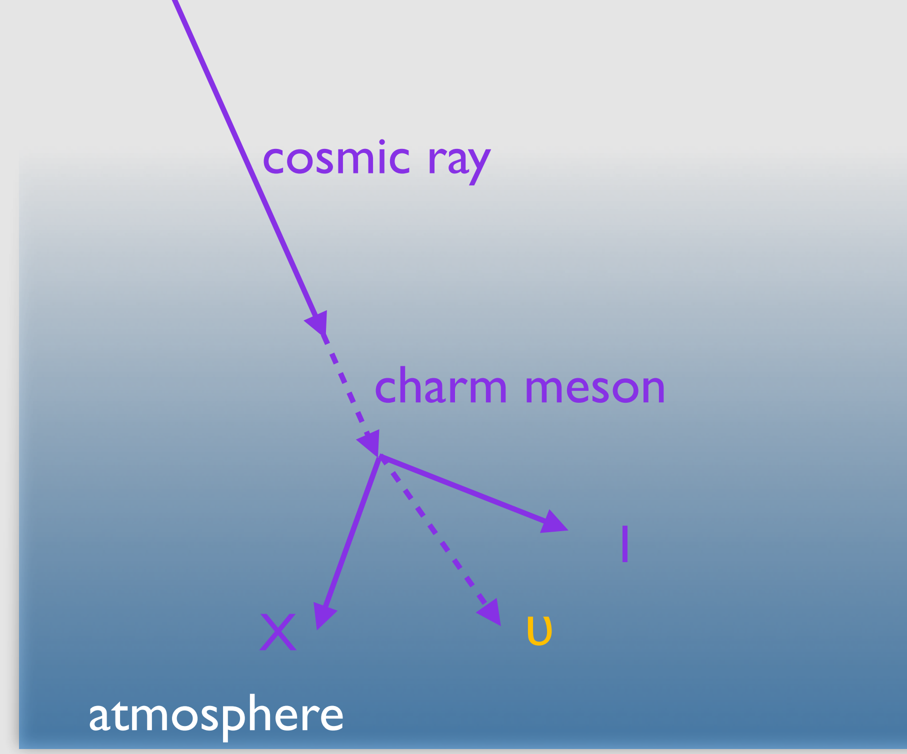


Tough choices:
About 10% of all events before triggering contain charm particles

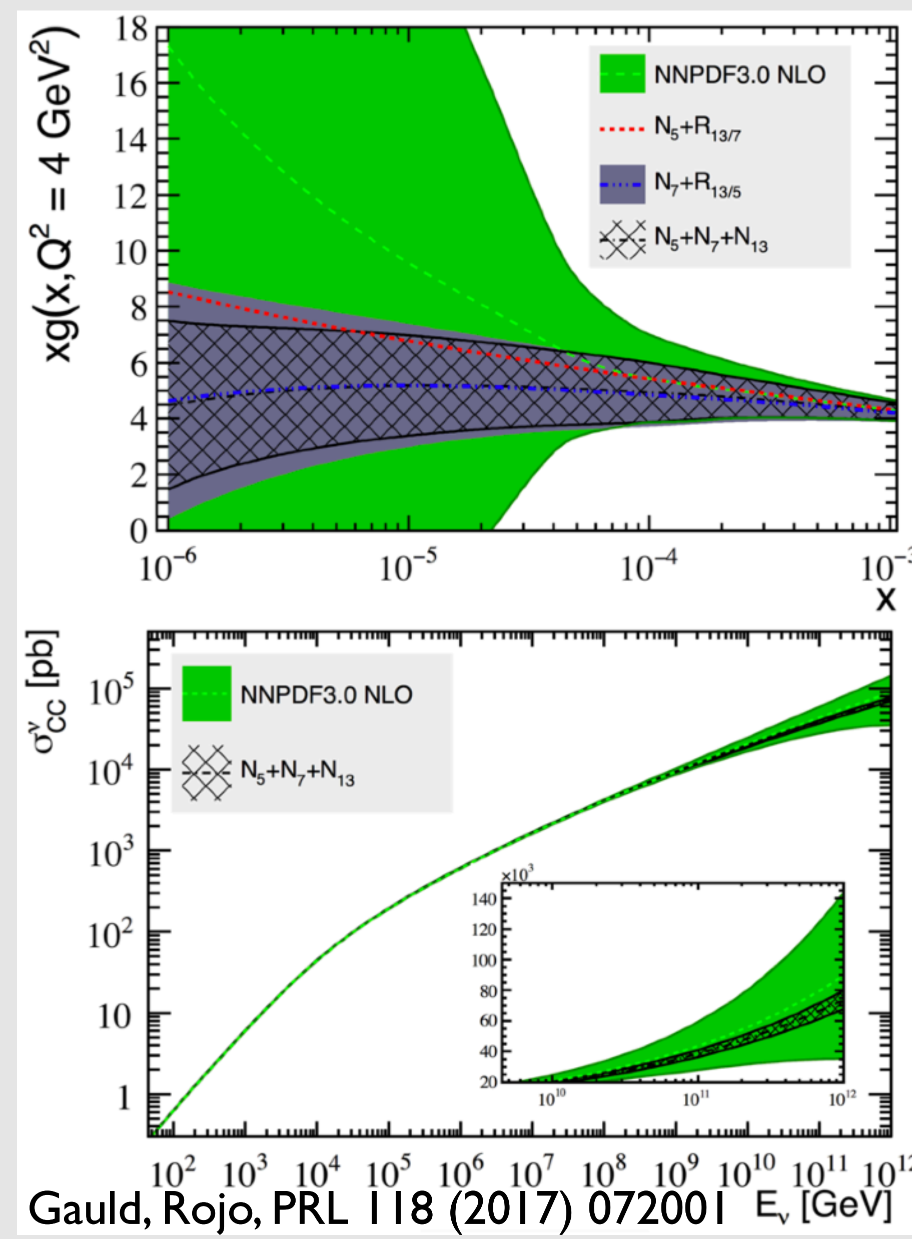
Seemingly plenty:
About 2kHz of charm events written out
→ 10^{10} per year

Production





- Charm production as precision measurements
  - ➡ Constrain PDFs and QCD processes
  - ➡ Puts direct constraints on charm production in atmosphere
    - High-energy neutrino background, e.g. for IceCube
- Production in different collisions crucial in identifying exotica



In numbers

Experiment	$\sqrt{s}$	$\sigma_{acc}(D^0)$	L	$N(D^0)$
BESIII	3.77 GeV	8 nb	3 fb^{-1}	2.4×10^{7}
Belle II	10.6 GeV	1.45 nb	50 ab^{-1}	7.5×10^{10}
LHCb Run 1	7-8 TeV	1.5 mb	3 fb^{-1}	4.5×10^{12}
LHCb Run 2	13 TeV	3 mb	6 fb^{-1}	1.8×10^{13}