Quark flavour physics

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IOP-HEPP, Bristol
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Science & Technology Facilities Council

Searching for new physics in heavy flavour

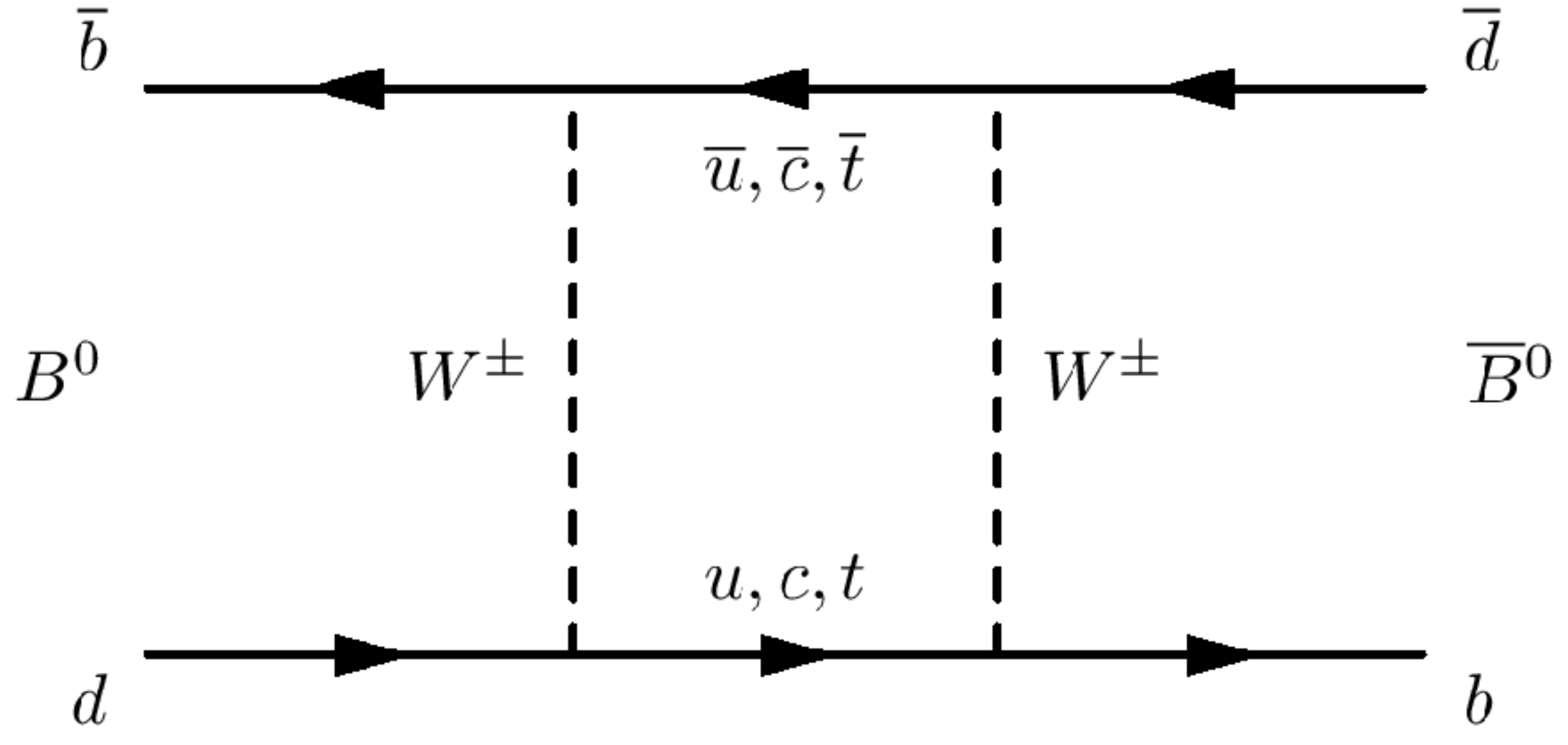
Heavy-quark hadrons provide excellent way to search for **new sources of CPV** and **very rare decays**. Both allow to probe high energy scales beyond the energy frontier.

→ Historical precedent, e.g., B^0 meson mixing @ ARGUS led to first indications about top quark mass > 50 GeV

[PLB 192 (1987) 245]
[PLB 186 (1987) 247]

Generic flavour structures ruled out by many orders of magnitude.

Complementarity between flavour and high-pT searches can help us understand what NP is (or is not…)



[T. Gershon, CERN courier last week]

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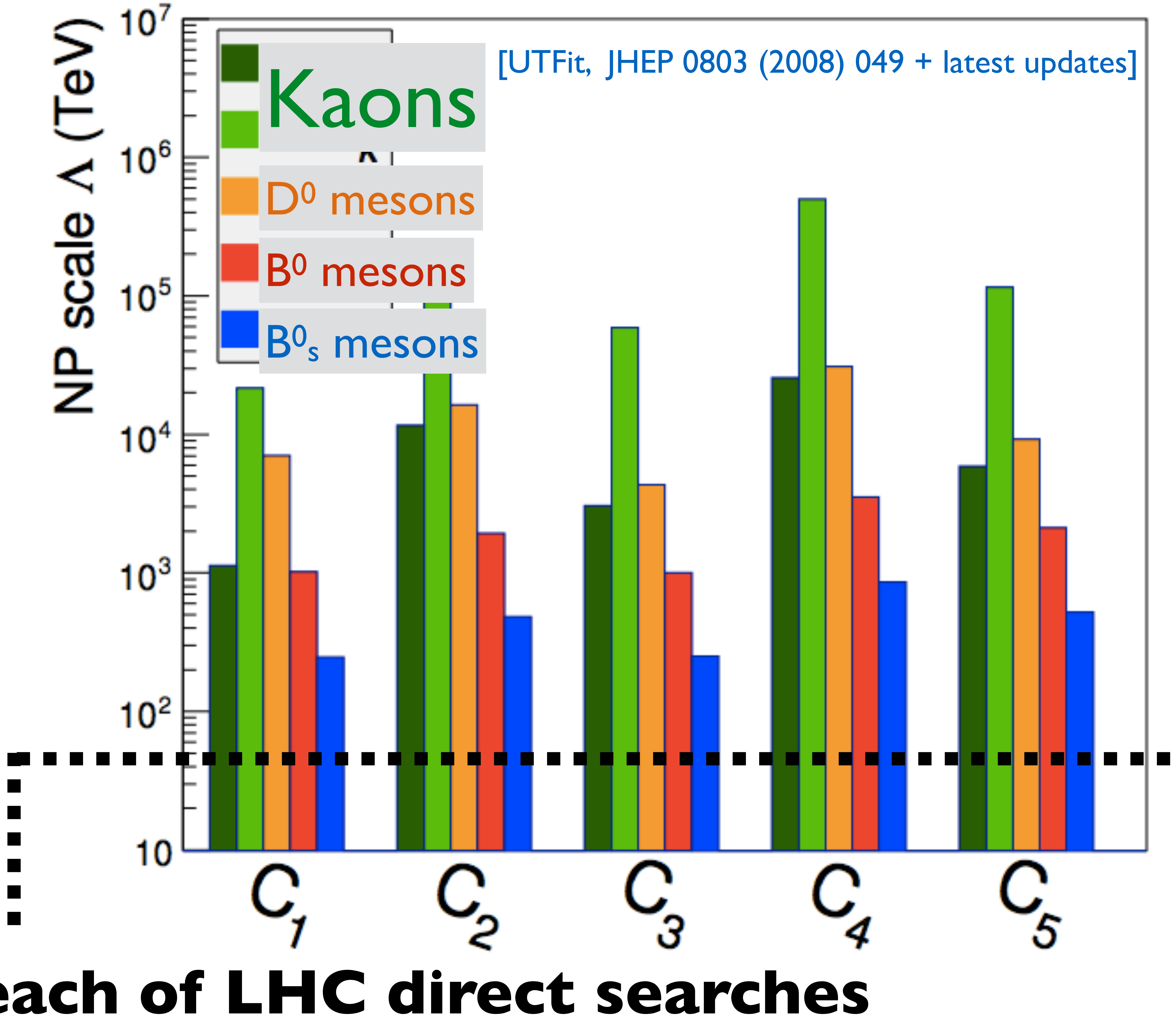


+ excellent chance to study QCD production + spectroscopy

[T. Gershon, CERN courier last week]

LHCb-UK

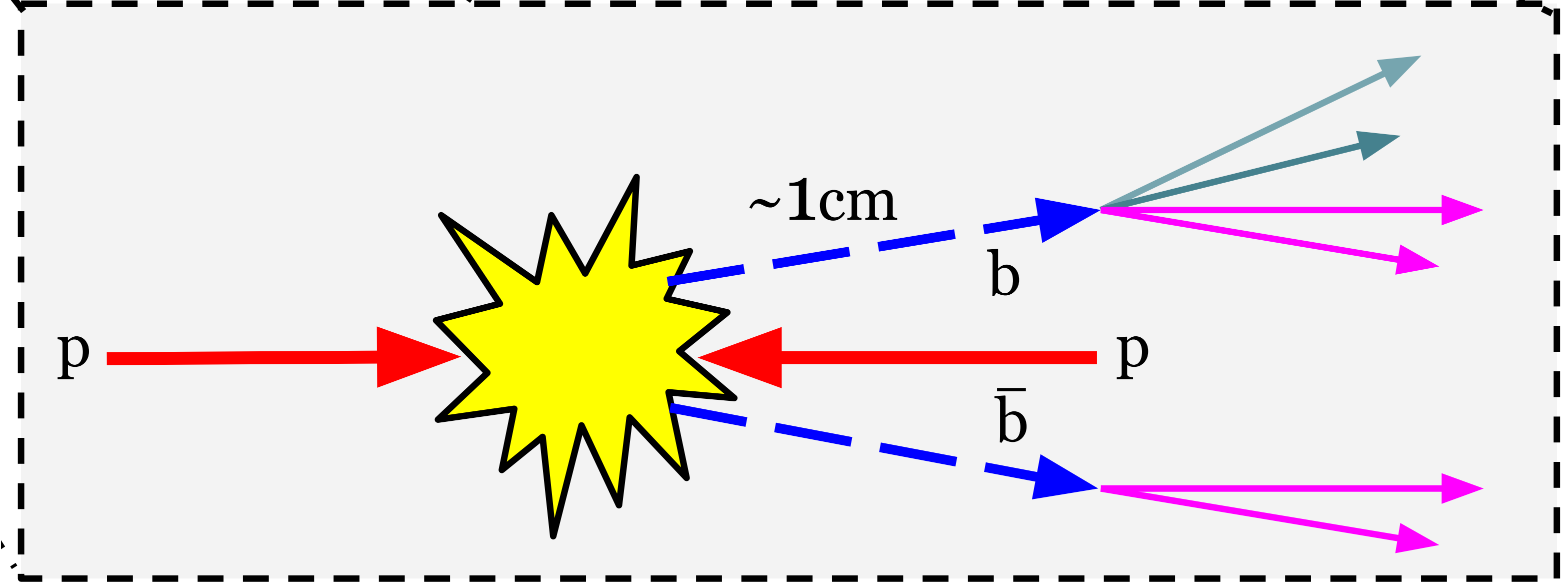
- deputy spokesperson + collaboration chair
- RICH/VELO project leaders
- 30% of physics WG coordinators
- 11 institutes; ~20% of collaboration

NA62-UK

- physics coordination
- CEDAR/KTAG project leaders
- HLT, reco + physics WG coordination
- 5 institutes; ~11% of collaboration

+ ATLAS B physics WG coordinator

The LHCb experiment

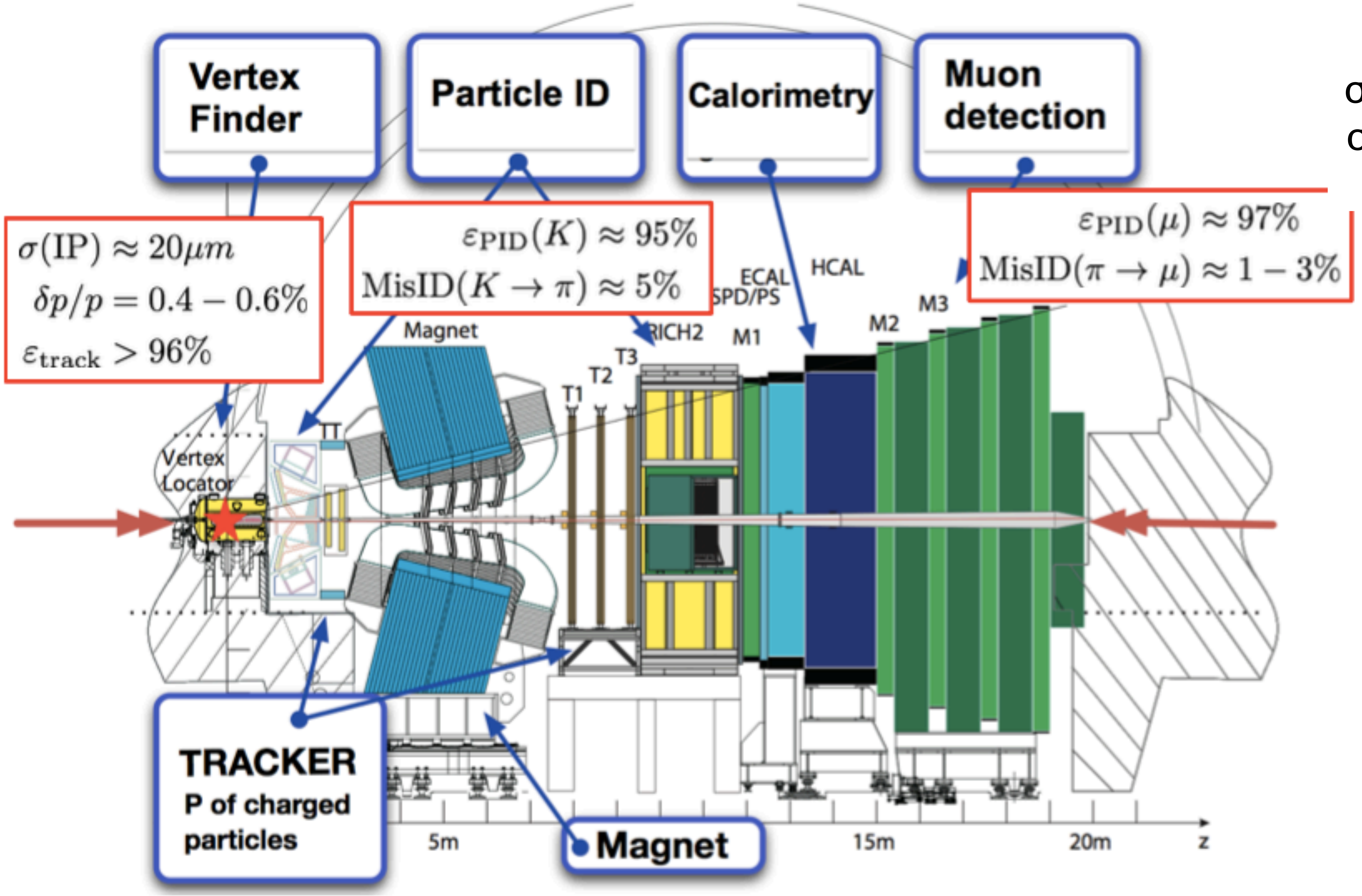


$\sigma(pp \to b\bar{b}X)^{7\,\mathrm{TeV}} = 72.0 \pm 0.3 \pm 6.8\ \mu b$

$\sigma(pp \to b\bar{b}X)^{13\,\mathrm{TeV}} = 154.3 \pm 1.5 \pm 14.3\ \mu b$

$\sigma(pp \to D^0X)^{13\,\mathrm{TeV}} = 2072 \pm 2 \pm 124\ \mu b$

[PRL 118 (2017) 052002]
[JHEP 05 (2017) 074]

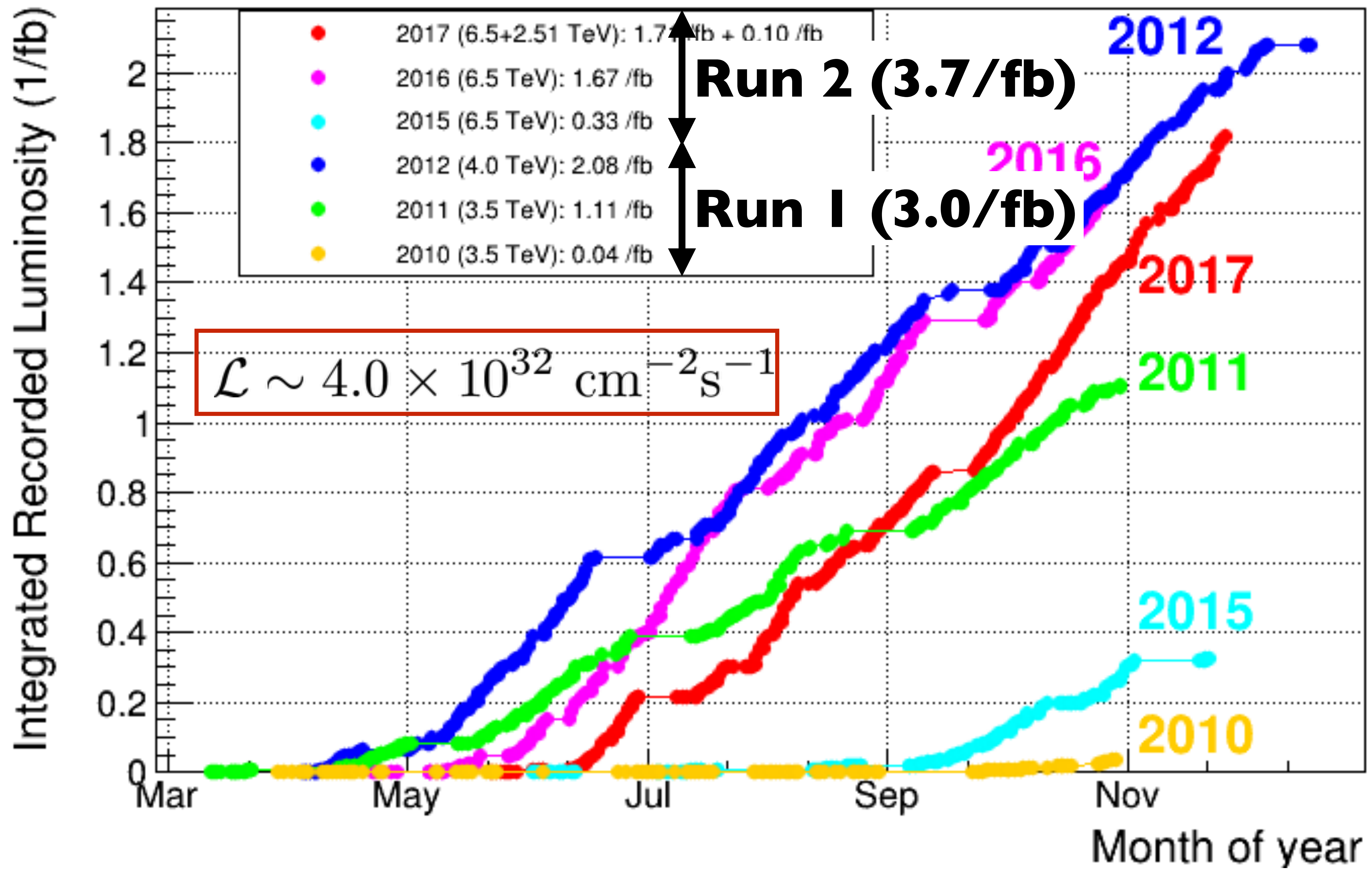


See talk from M. Gersabeck for details of charm CPV/mixing with these huge data samples

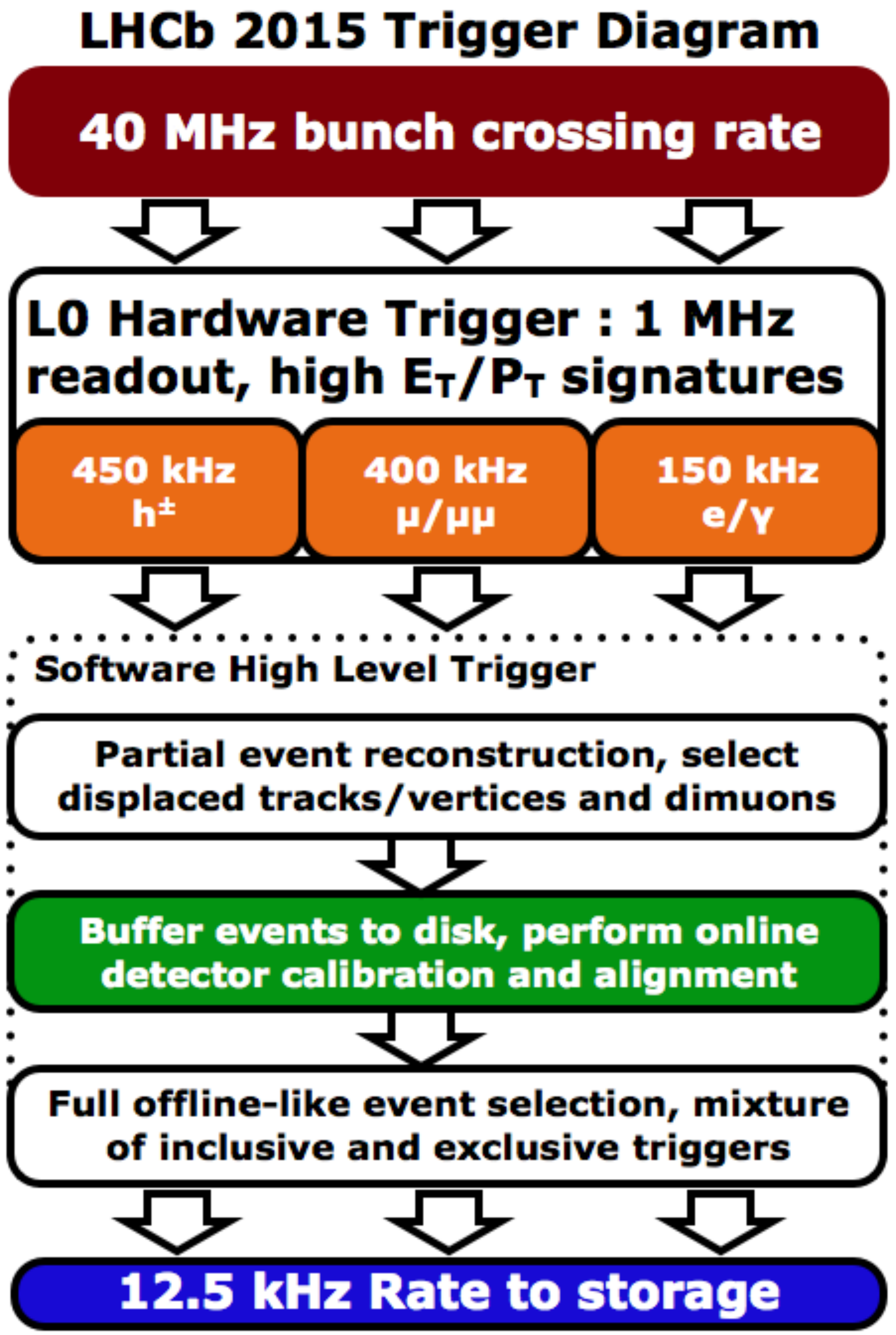
~800 authors and > 400 papers

http://lhcbproject.web.cern.ch/lhcbproject/Publications/LHCbProjectPublic/Summary_all.html

LHCb data sample



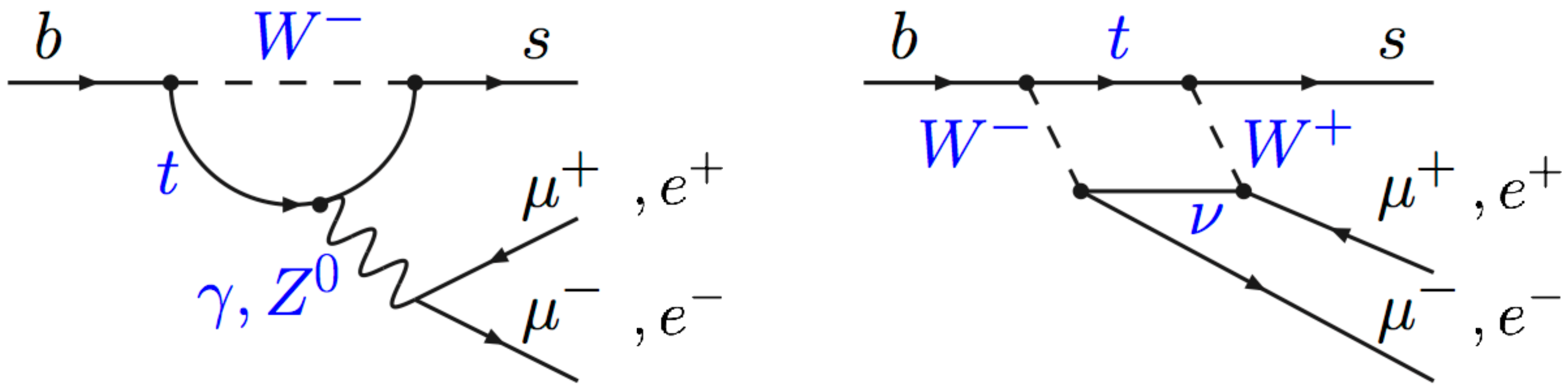
Most results here from Run 1 only



Make use of real-time alignment and calibration to allow analysis straight from the trigger

Major step towards realising upgrade trigger strategy [J. Phys. Conf. Ser. 664 (2015) 082010]

Rare decays (BR $\lesssim 10^{-7}$)

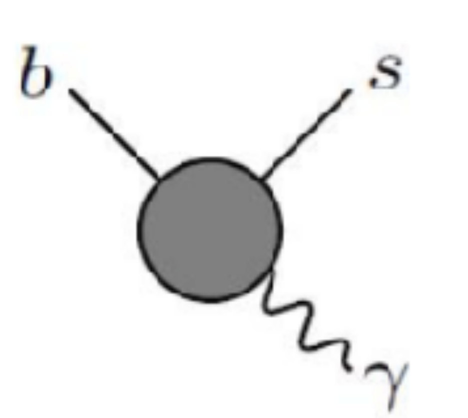


Test lepton-flavour universality by comparing muon and electron modes

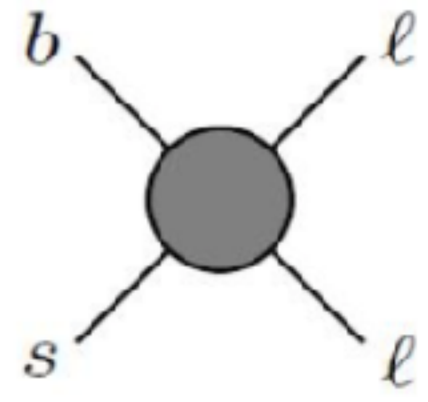
Effective Hamiltonian for b → s transitions

zero in the SM

$$H_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i [\underbrace{C_i(\mu) O_i(\mu)}_{\text{left-handed part}} + \underbrace{C'_i(\mu) O'_i(\mu)}_{\text{right-handed part}}]$$

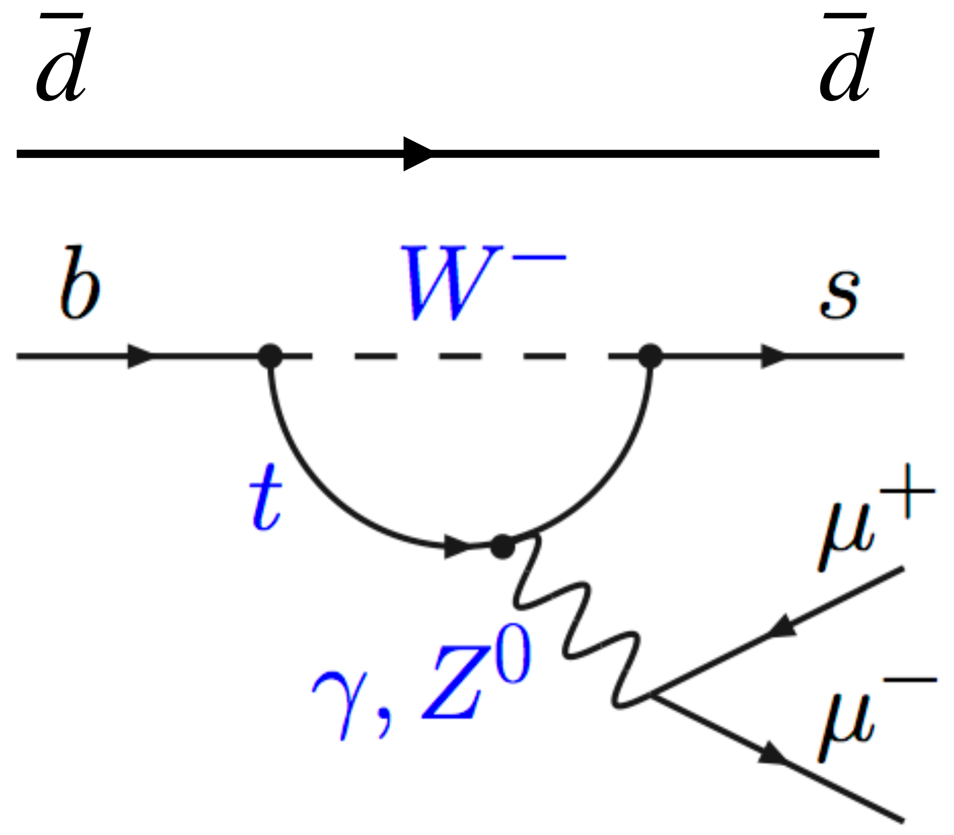


i=7 photon penguin

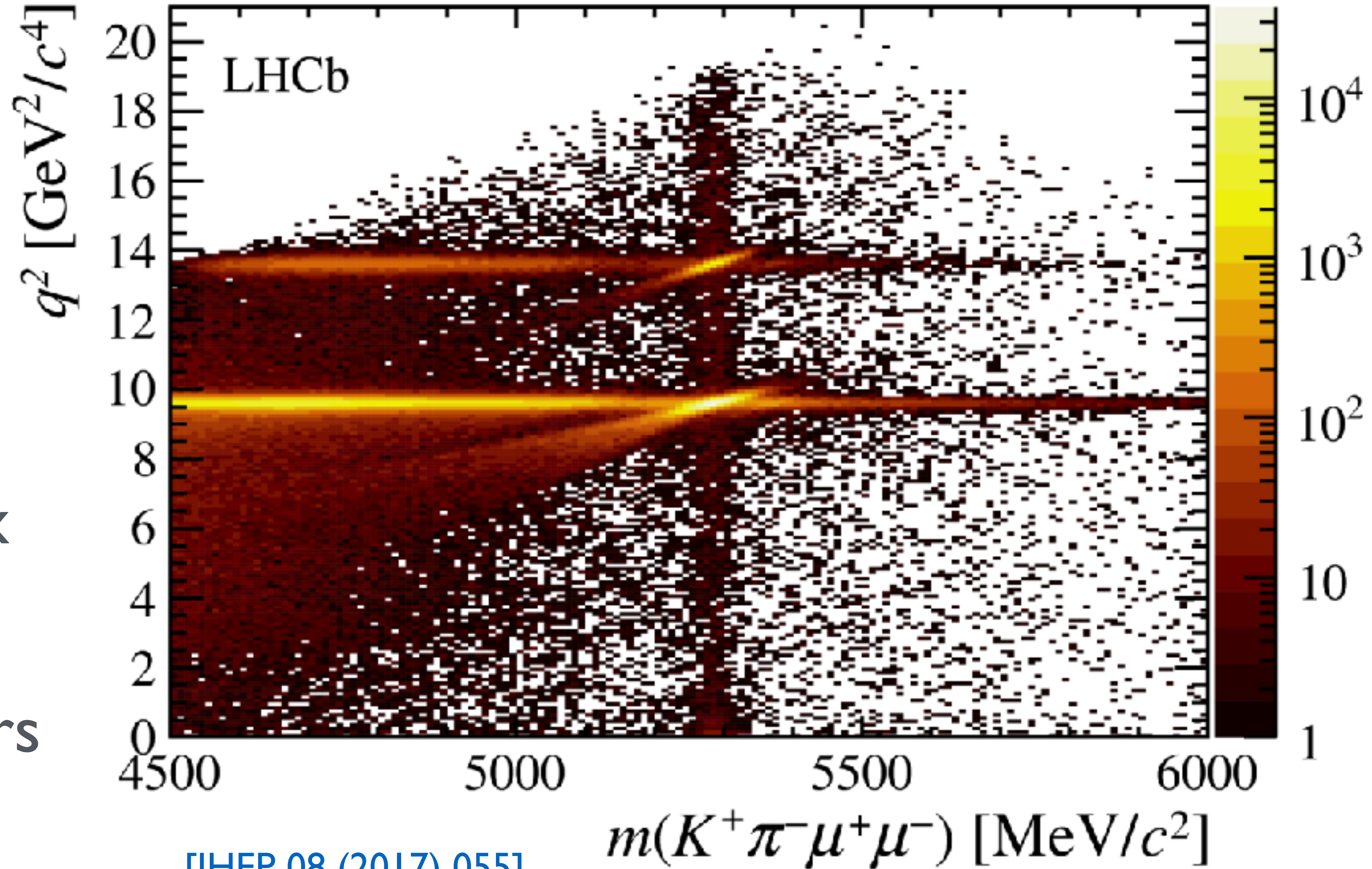


i=9, 10, P, S

i = 1,2	Tree
i = 3 − 6,8	Gluon penguin
i = 7	Photon penguin
i = 9,10	Electroweak penguin
i = S	Higgs (scalar) penguin
i = P	Pseudoscalar penguin



$q^2 = m(\mu\mu)^2$



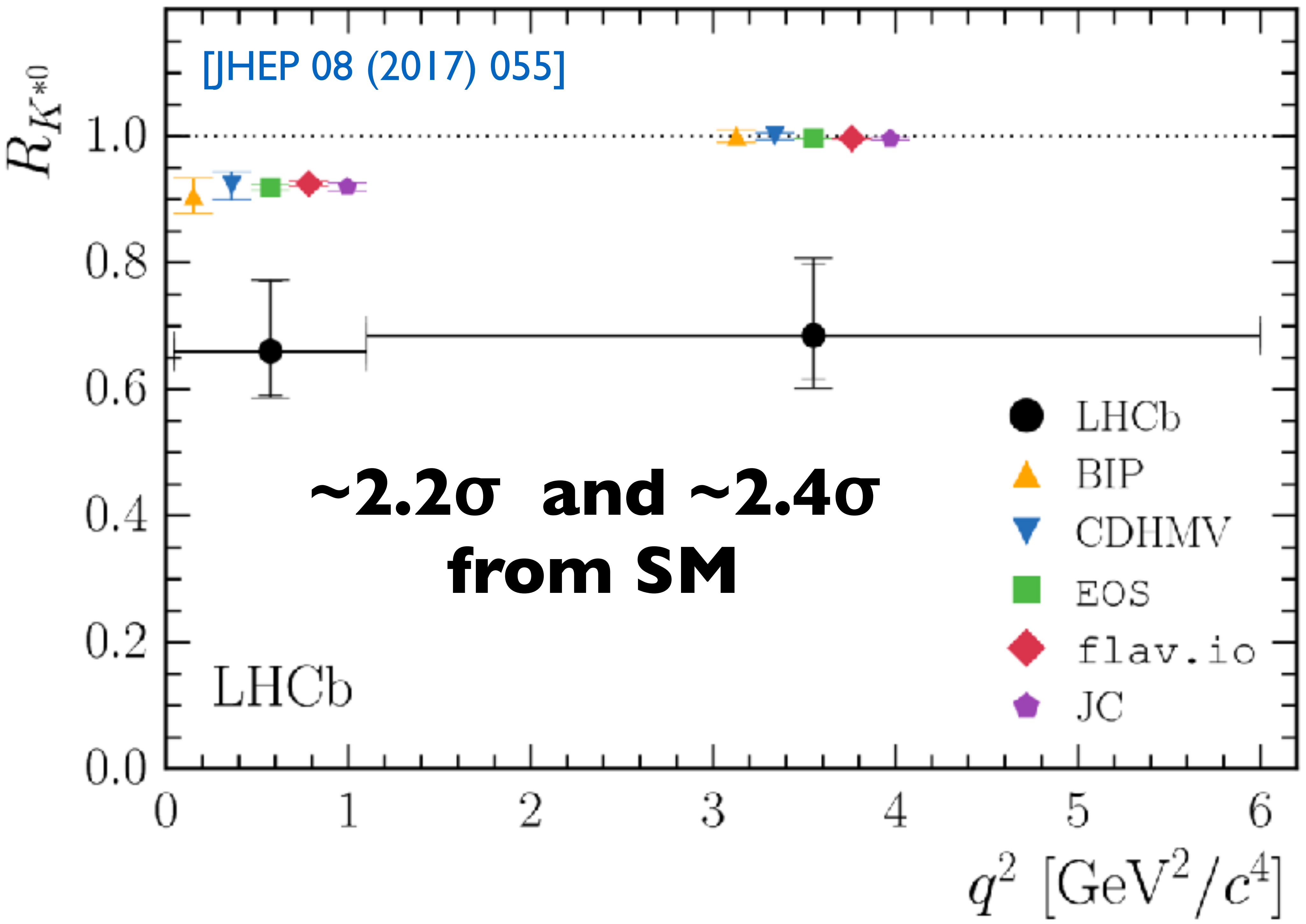
[JHEP 08 (2017) 055]

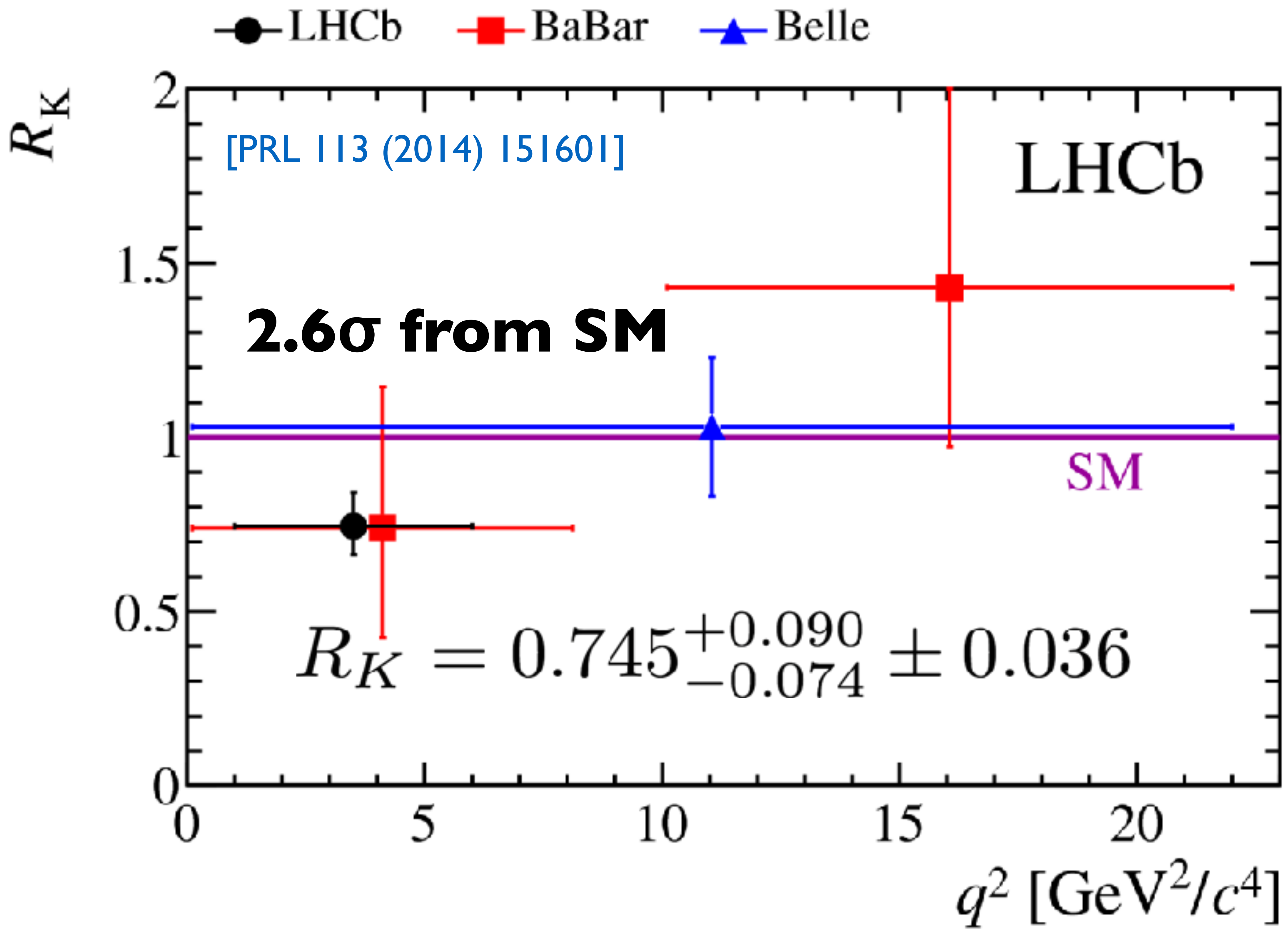
***C_i* Wilson coefficients**: short-distance physics (perturbative) couplings, μ = energy scale

***O_i* operators**: long-distance (non-perturbative) matrix elements, e.g. from lattice QCD

New physics can modify coeffs and/or add new operators

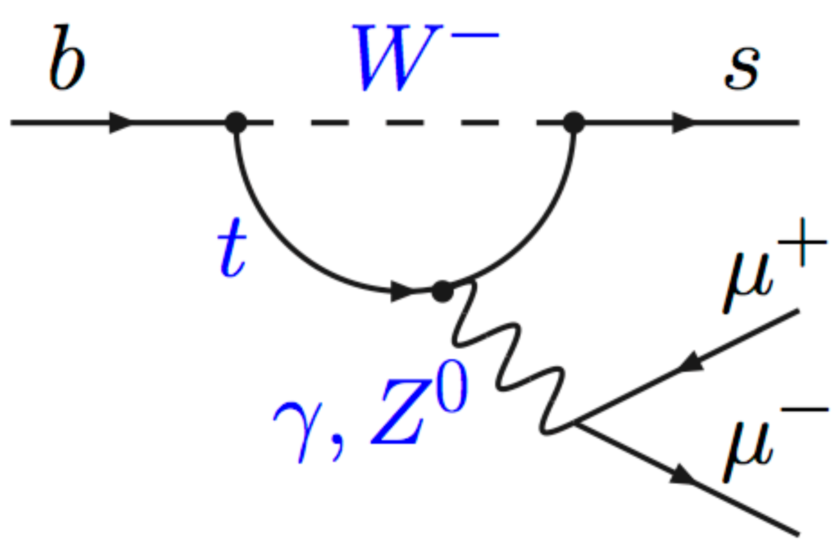
Testing lepton-flavour universality





Likewise R_K

$$R_{K^{*0}} = \frac{\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi\,(\to \mu^+\mu^-))} \Bigg/ \frac{\mathcal{B}(B^0 \to K^{*0}e^+e^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi\,(\to e^+e^-))}$$

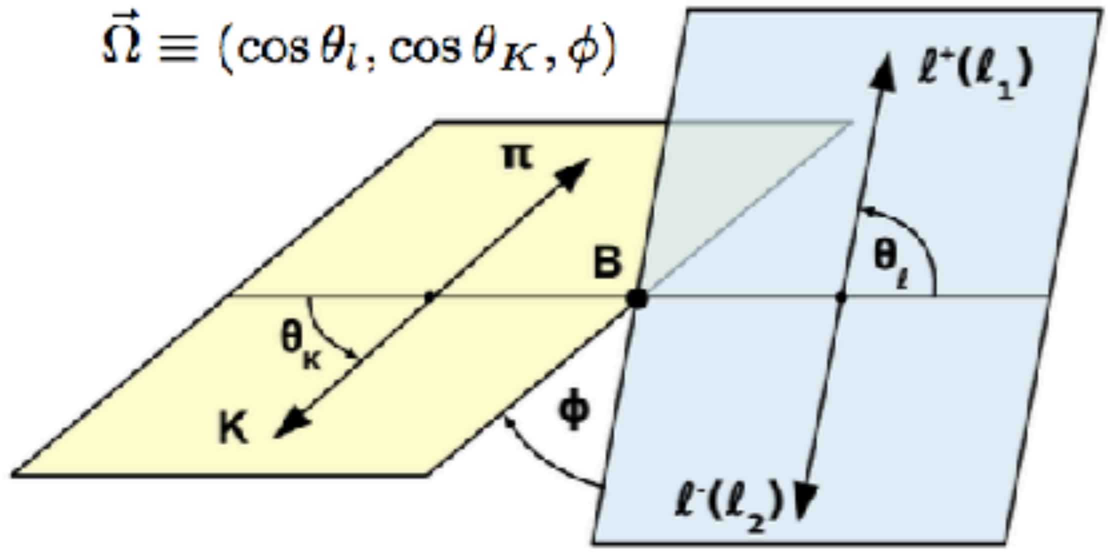


O(1%) uncertainty on SM predictions

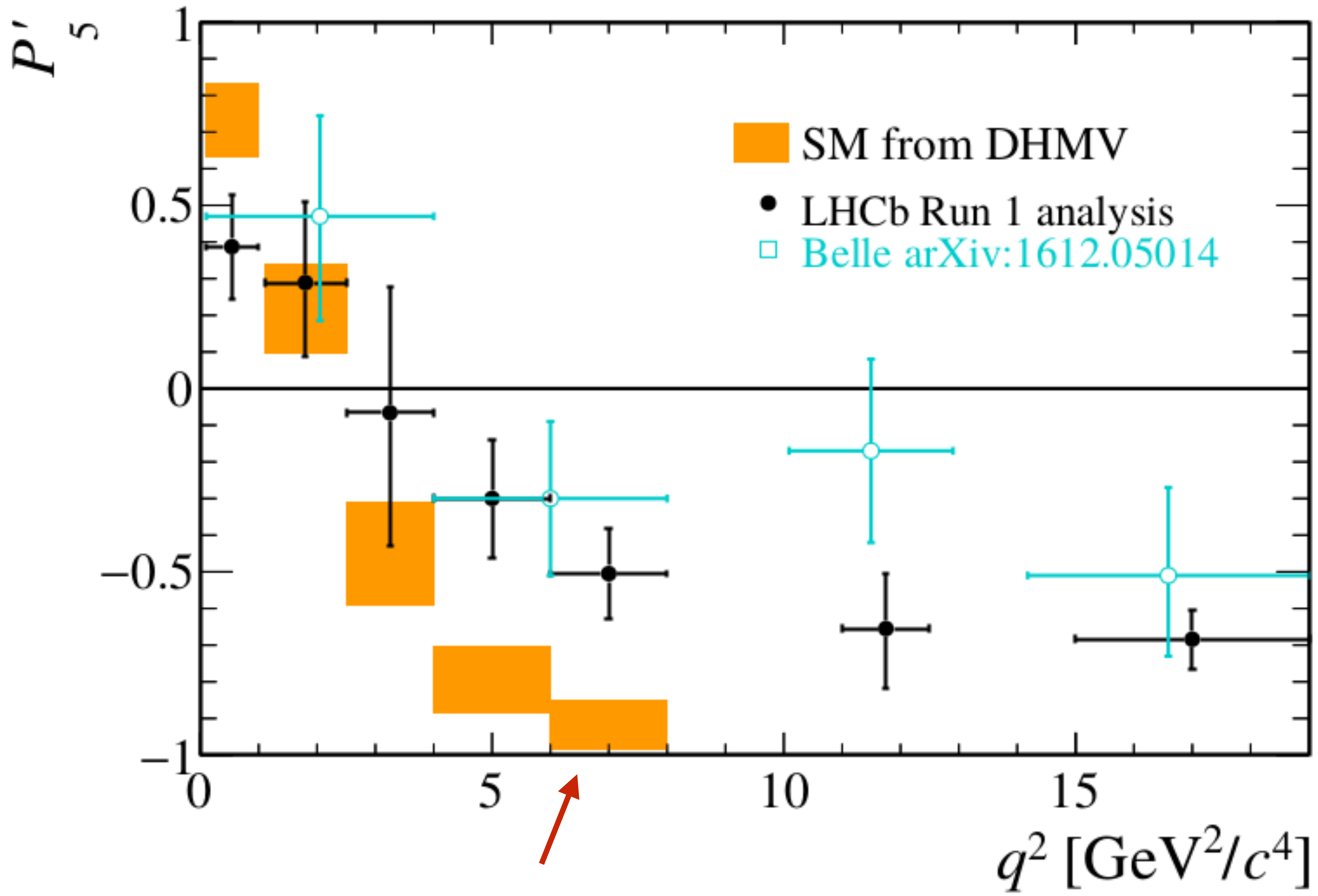
- ▲ BIP [Bordone et al., EPJC 76 (2016)]
- ▼ CDHMV [arXiv:1510.04239, 1605.03156, 1701.08672]
- ■ EOS [arXiv:1610.08761, https://eos.github.io]
- ◆ flav.io [arXiv:1503.05534, 1703.09189, flav-io/flavio]
- ⬟ JC [arXiv:1412.3183]

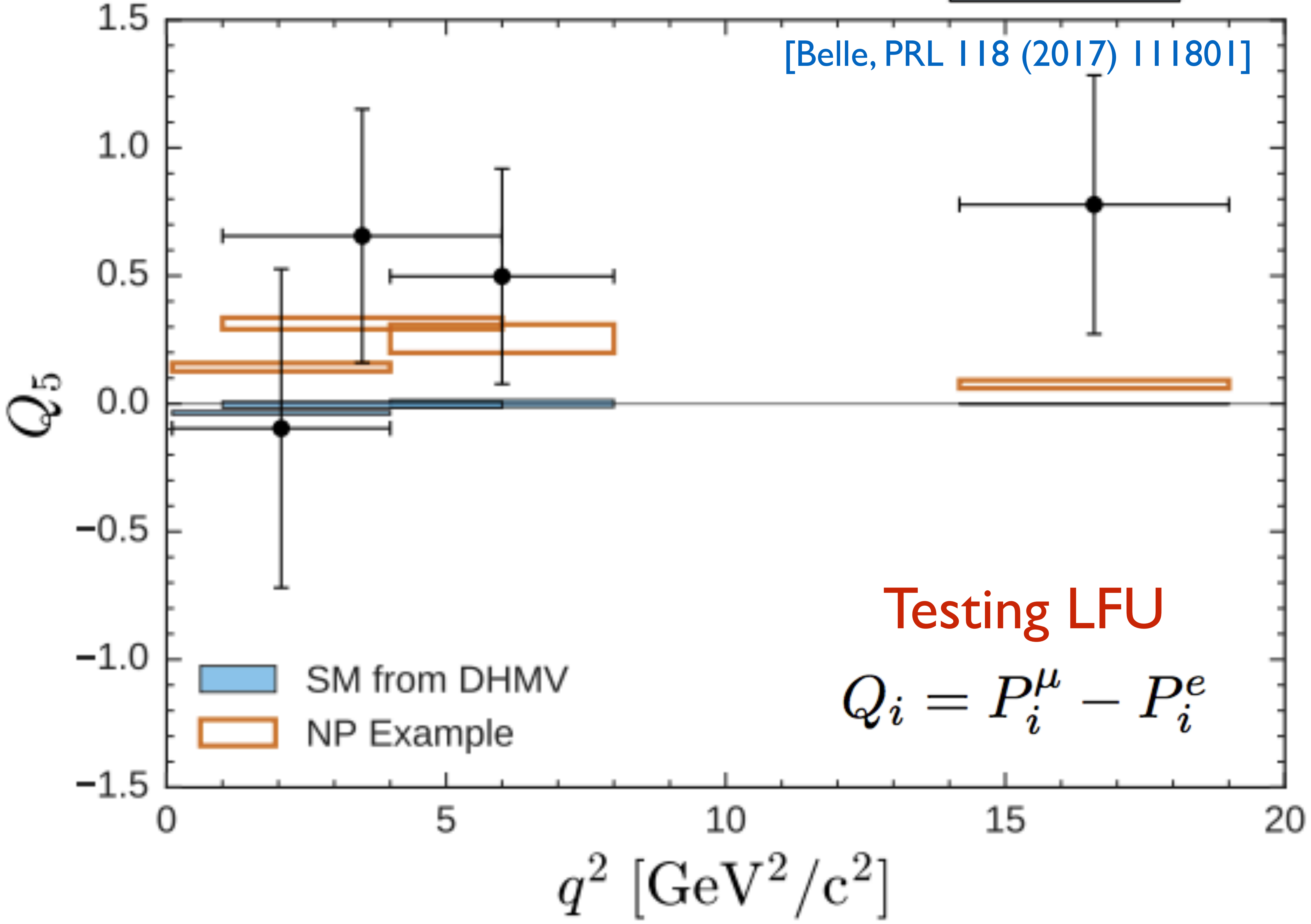
See talks: Chatzikonstantinidis, Glew and A. Lenz (next!)

Angular analysis of $B^0 \to K^*\ell^+\ell^-$



[JHEP 02 (2016) 104, ATLAS-CONF-2017-023, arXiv:1710.02846, PRL 118 (2017) 111801]





Or is this QCD?

[Lyon and Zwicky, arXiv:1406.0566] [Altmannshofer and Straub arXiv:1503.06199] [Ciuchini et al., arXiv:1512.07157] [LHCb, EPJC (2017) 77]

Q_i != 0 would be indication of new physics

Will hear more about these observables in the future

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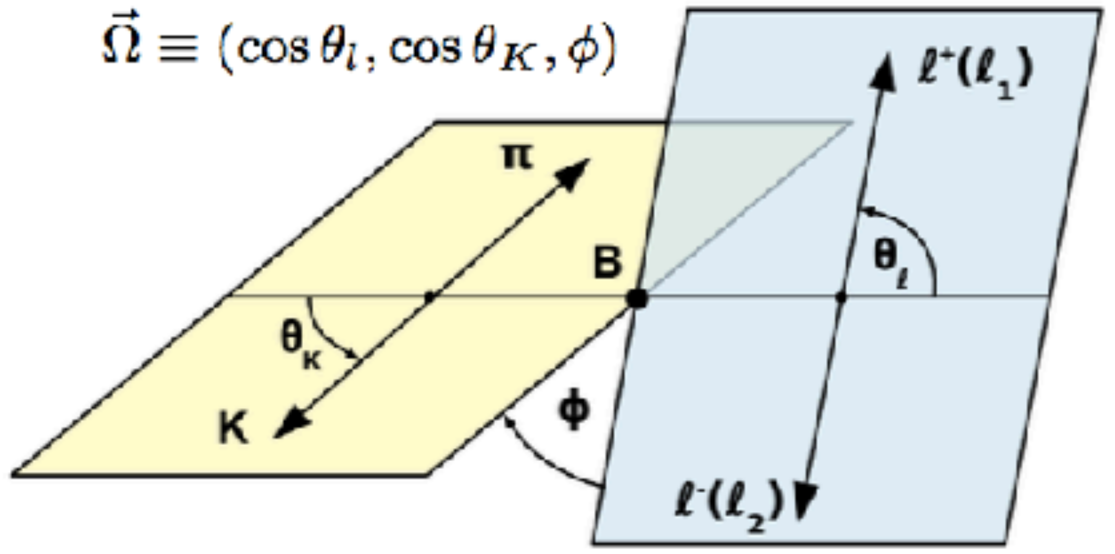

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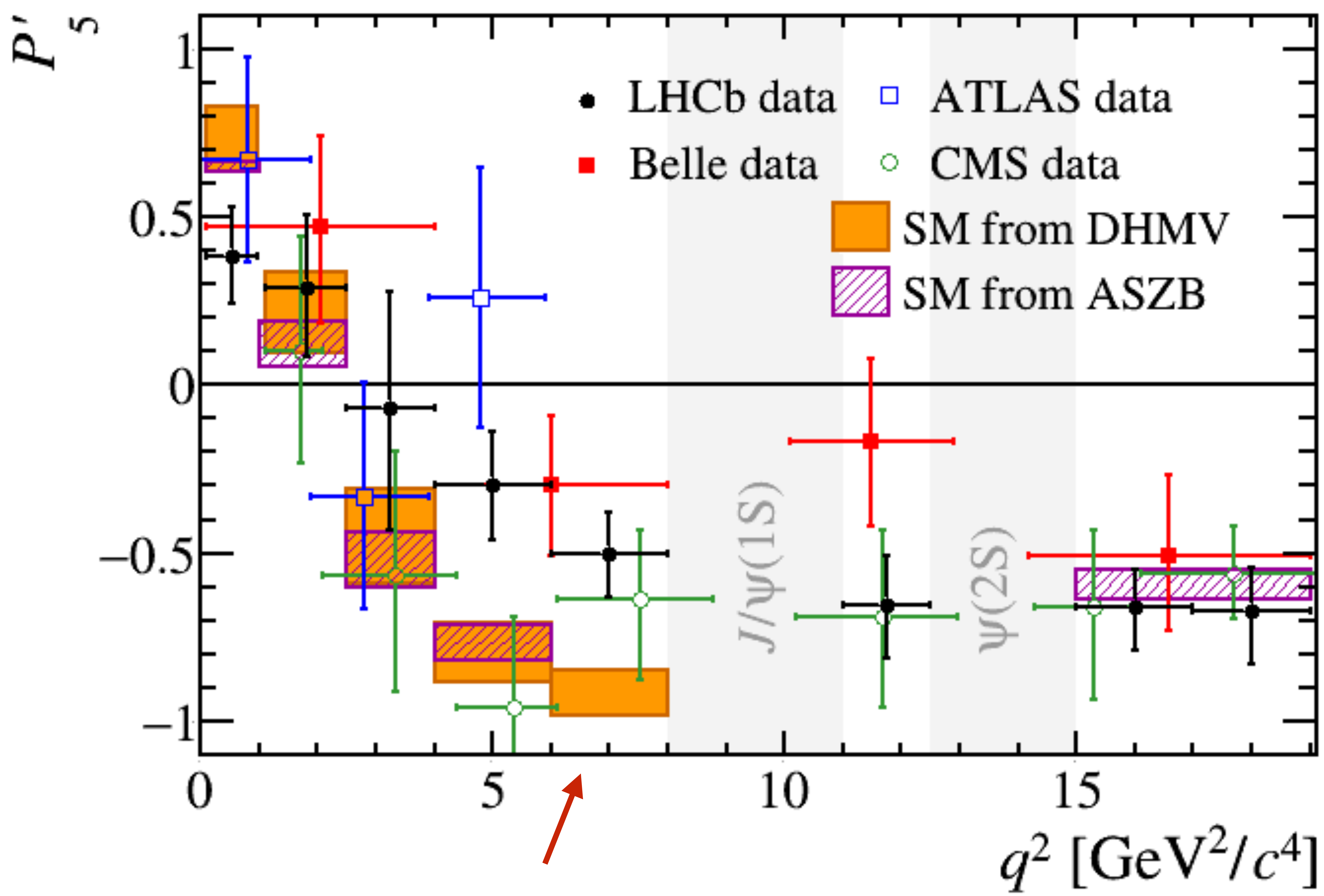

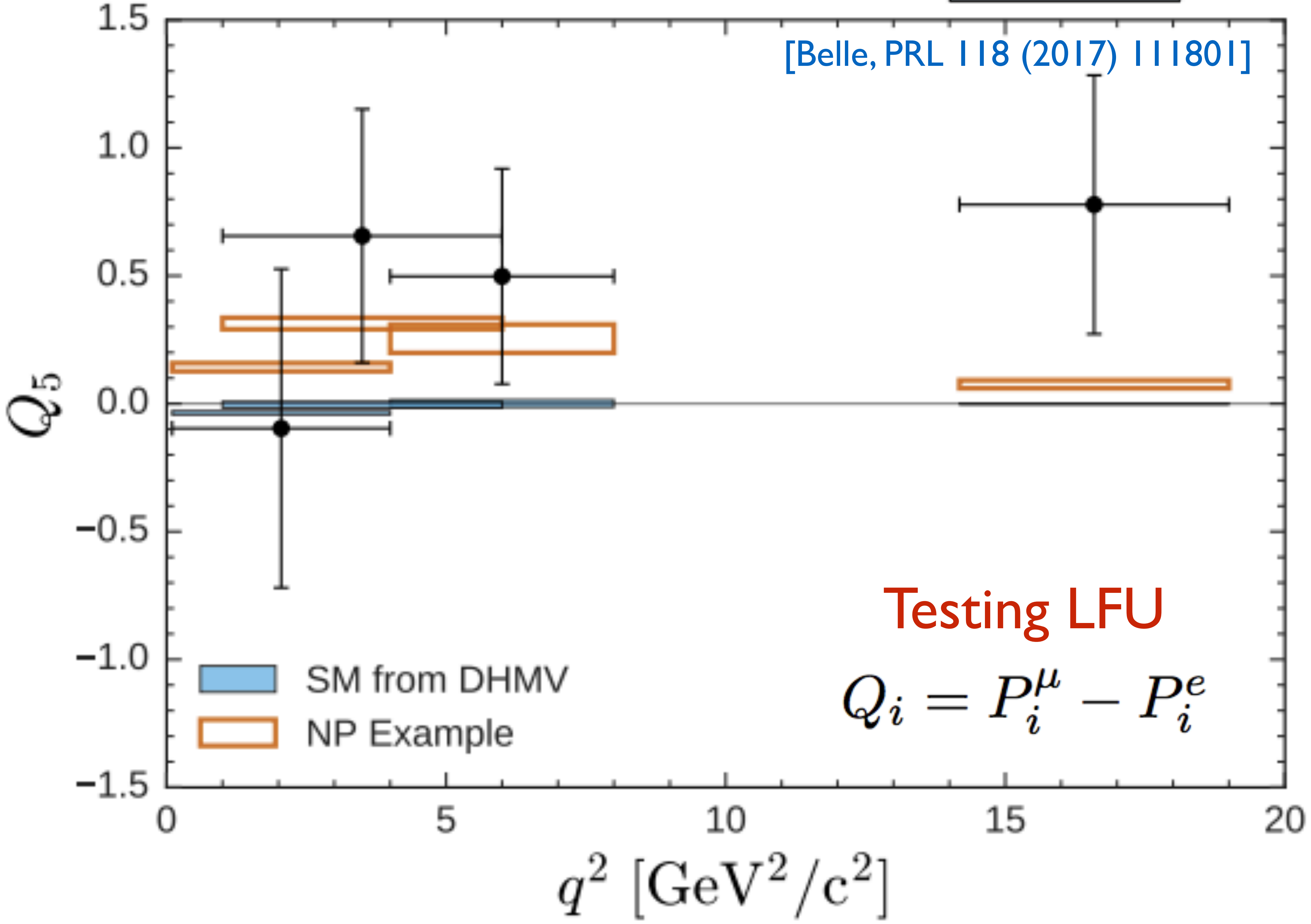

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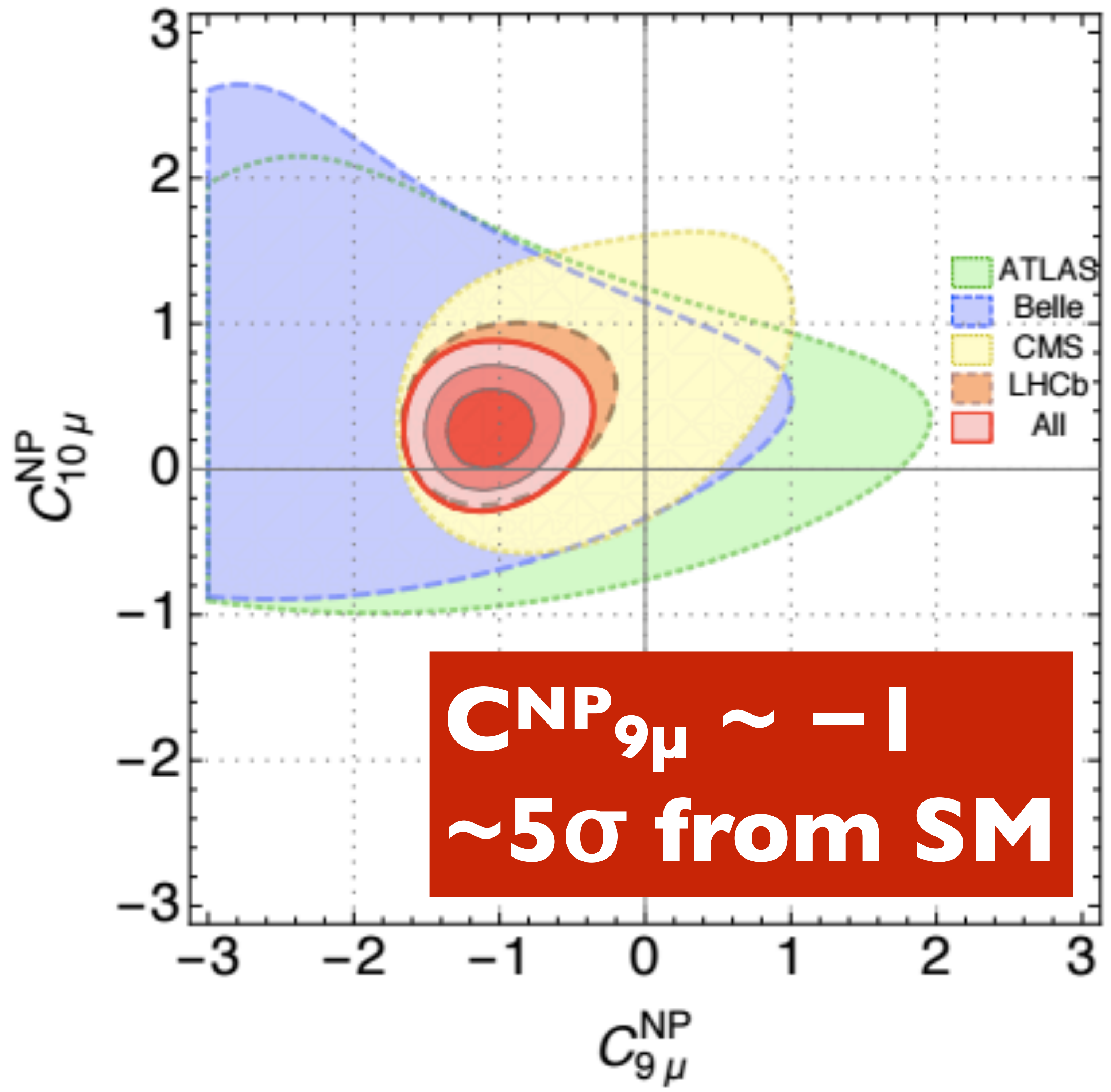
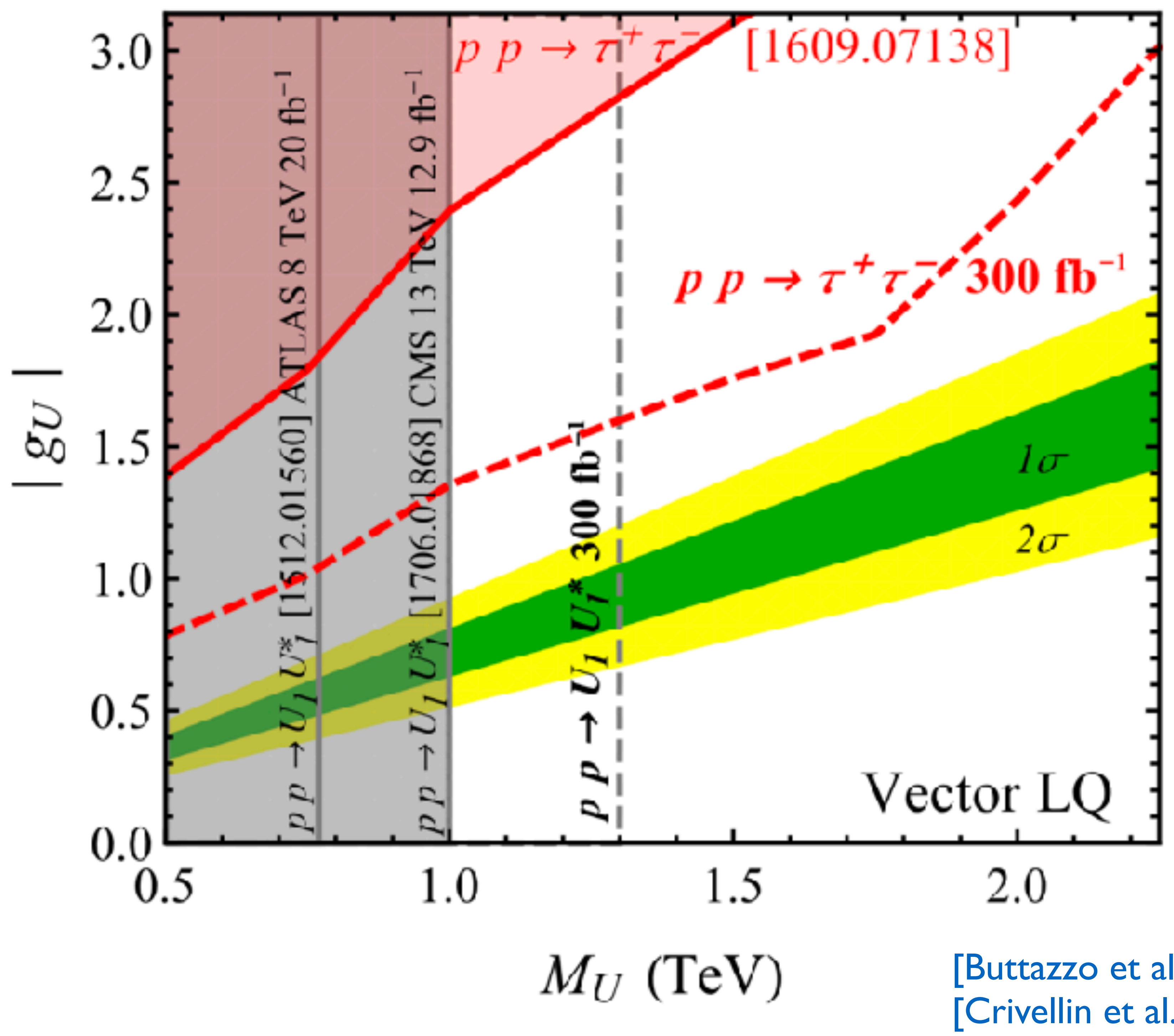
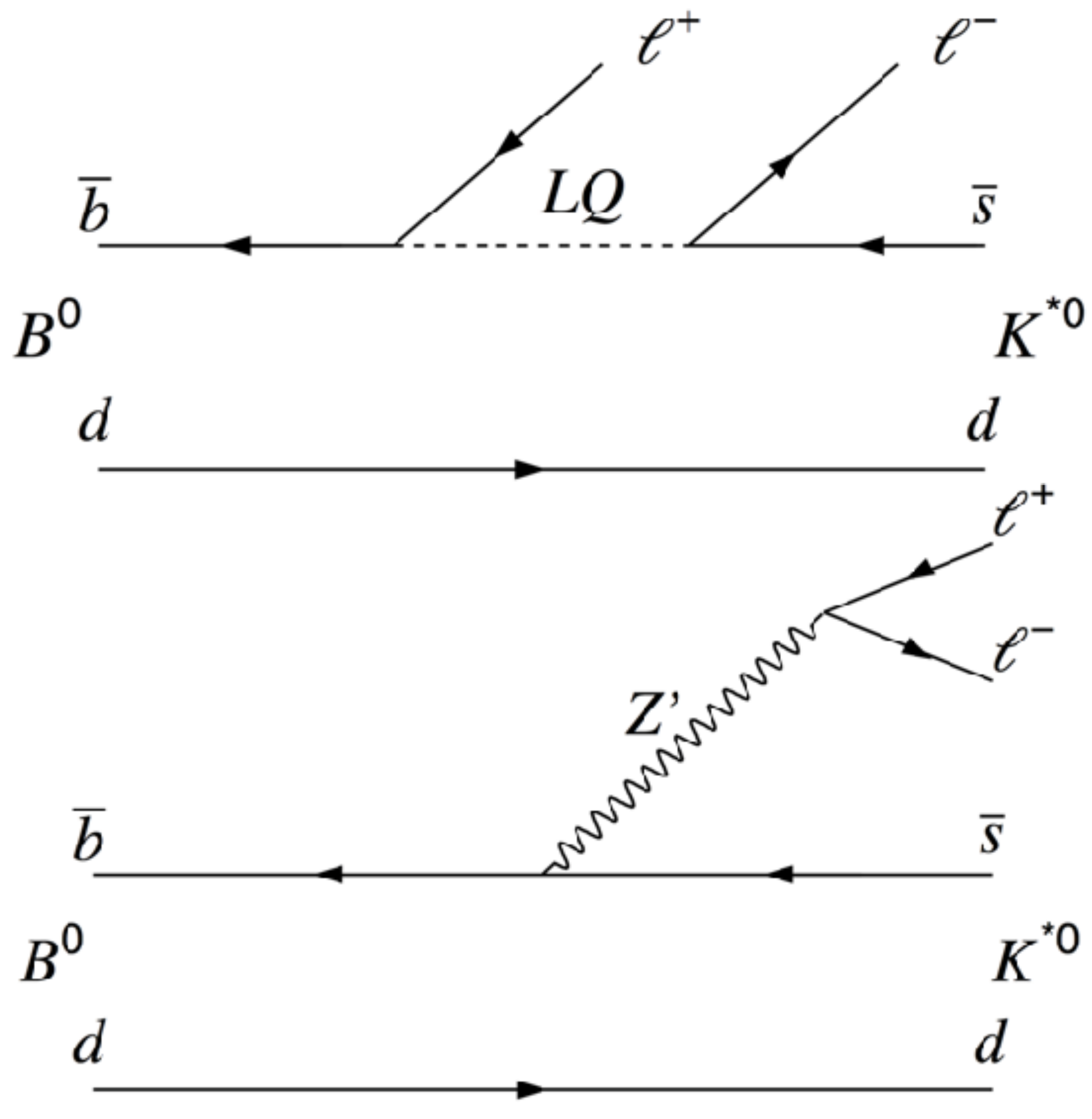
Consistent picture forming?

[Capdevilla et al., arXiv:1704.05340]



[Buttazzo et al., JHEP11 (2017) 044]





[Buttazzo et al., JHEP 1608 (2016) 035], [Bauer et al., PRL 116 (2016) 141802], [Crivellin et al., PRL 114 (2015) 151801], [Altmannshofer et al., PRD 89 (2014) 095033] [Diptomoy et al., PRD 89 (2014) 071501], [Descotes-Genon et al., PRD 88 (2013) 074002]…

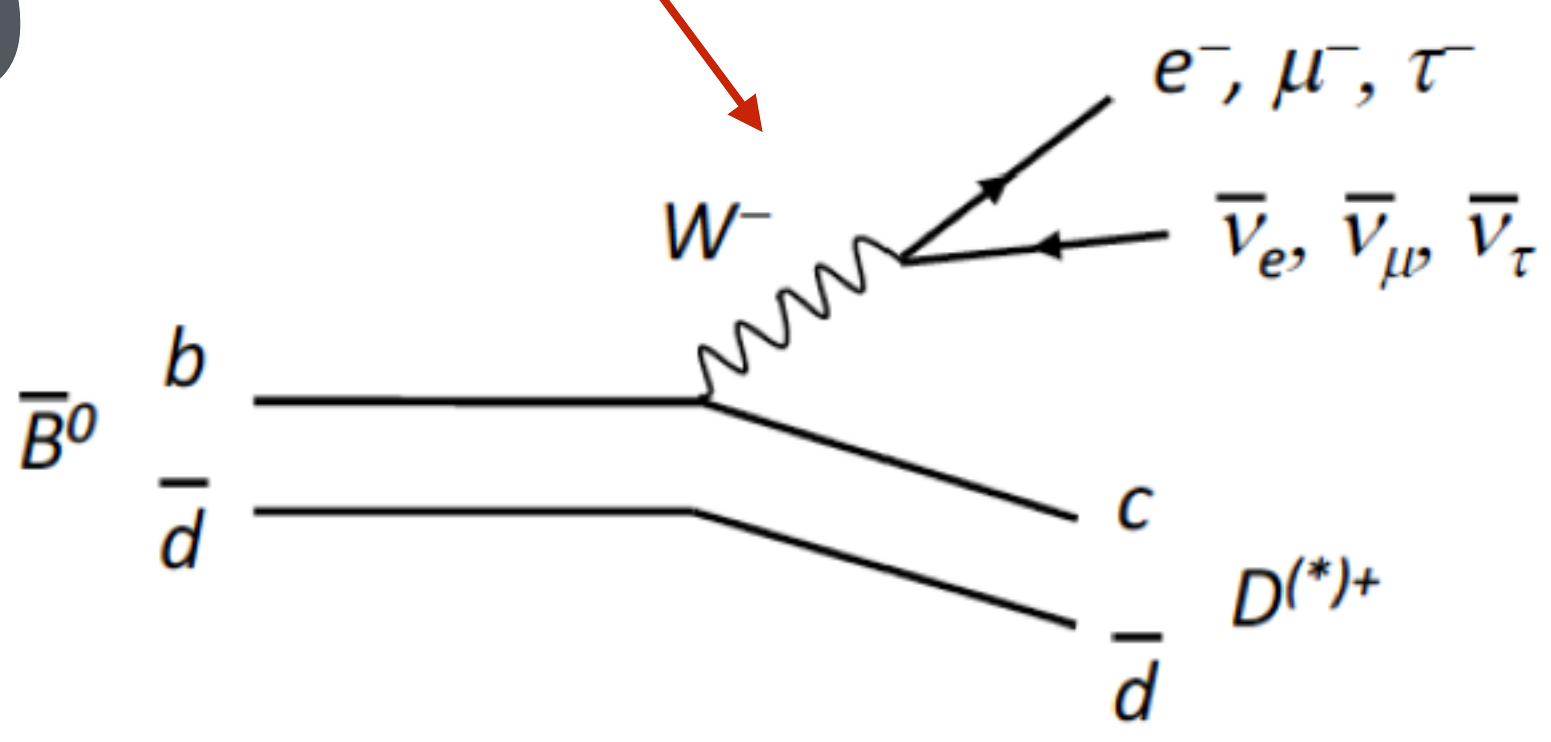
Fit $\mathcal{H}_{eff}$ to ~170 LFUV, P5', BRs… observables → NP in **$C^{NP}_{9\mu}$ only** (OR $C^{NP}_{9\mu} = -C^{NP}_{10\mu}$ OR $C^{NP}_{9\mu} = -C^{NP\prime}_{9\mu}$)

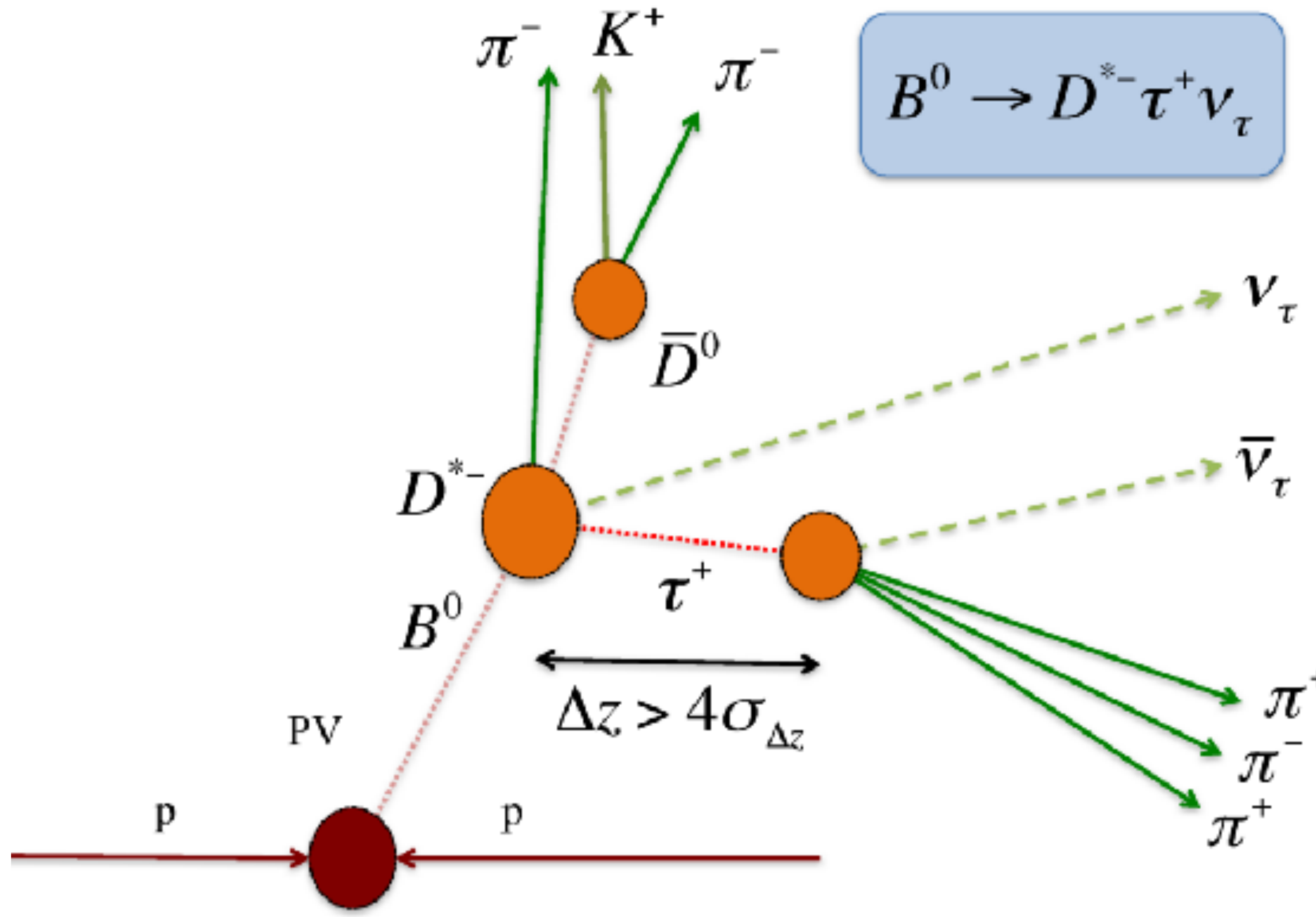
Limits from direct searches providing complementary information to b meson decays, but may be able to escape bounds with more elaborate models or fine tuning [Crivellin et al., arXiv:1703.09226]

x2 data from LHCb now being analysed…

LFUV in b → cℓυ transitions

could have a LQ here…





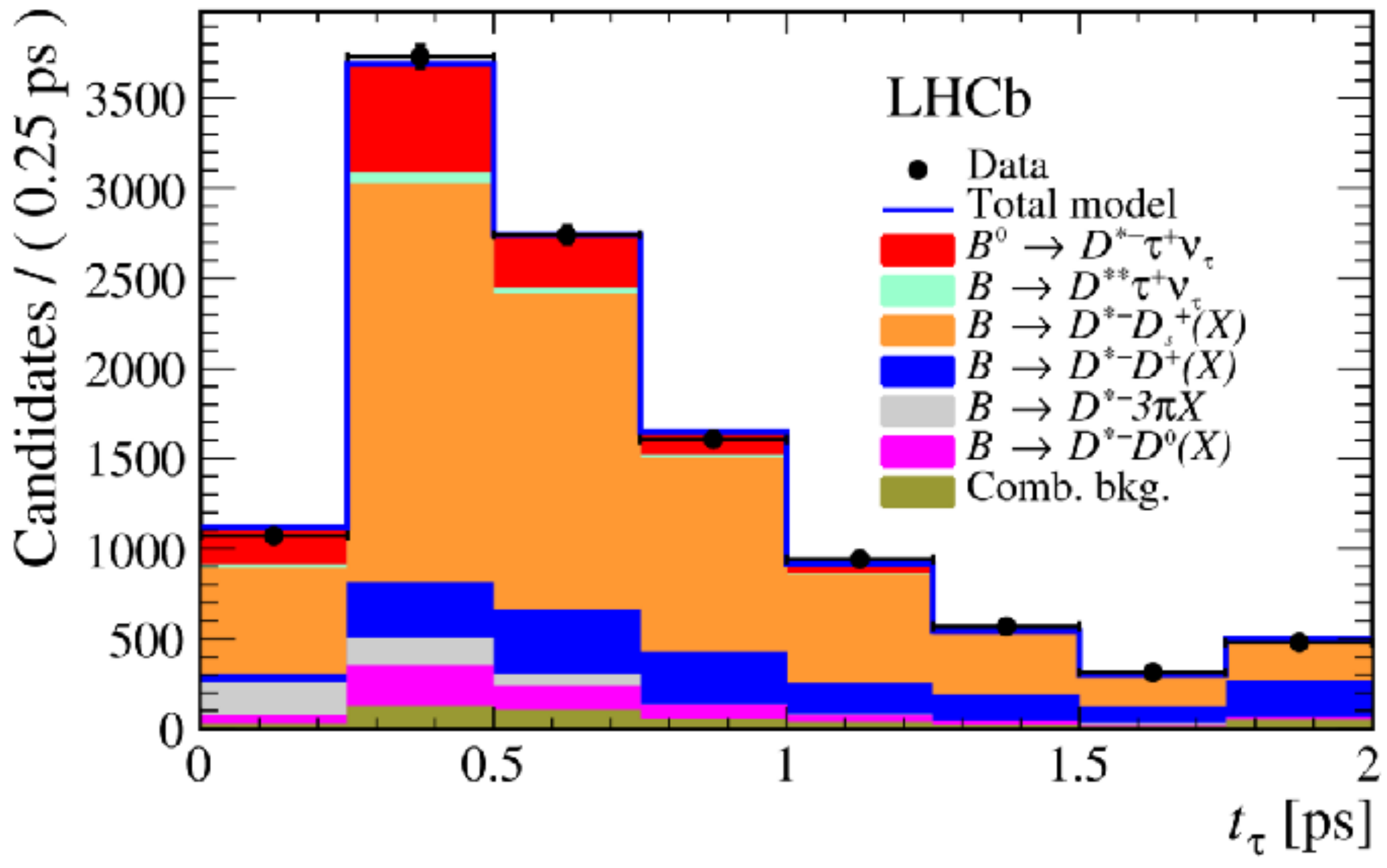
$$R(D^{(*)}) \equiv \frac{\mathcal{B}(\overline{B}^0 \to D^{(*)+}\tau^-\overline{\nu}_\tau)}{\mathcal{B}(\overline{B}^0 \to D^{(*)+}\mu^-\overline{\nu}_\mu)}$$

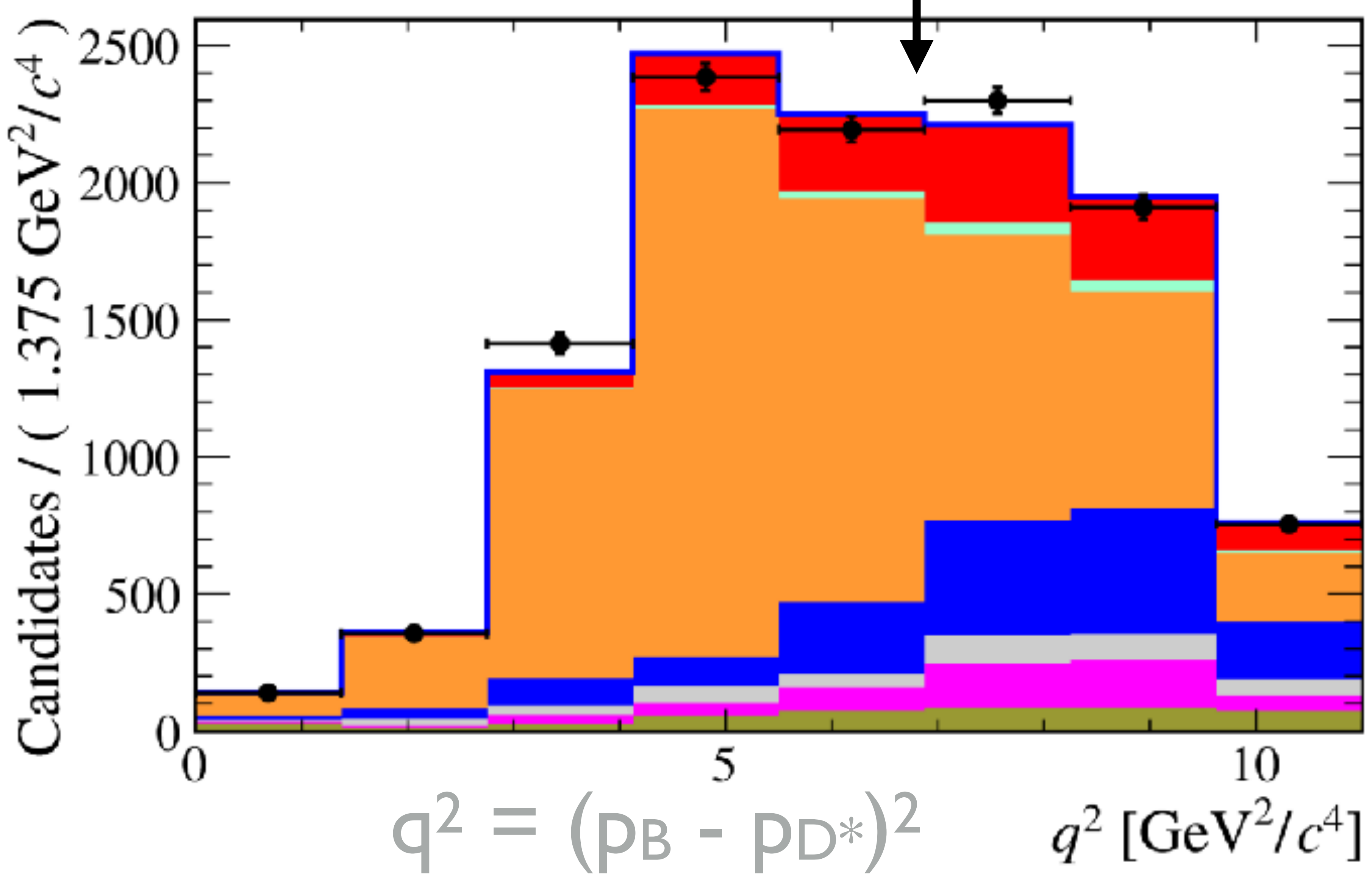
$\mathcal{R}(D^*)^{\text{muonic}} = 0.336 \pm 0.027 \pm 0.030$ [PRL 115 (2015) 111803]

$\mathcal{R}(D^*)^{\text{hadronic}} = 0.286 \pm 0.019 \pm 0.025 \pm 0.021$ [arXiv:1708.08856] [arXiv:1711.02505]

Systematically limited due to size of simulation samples for bkg templates

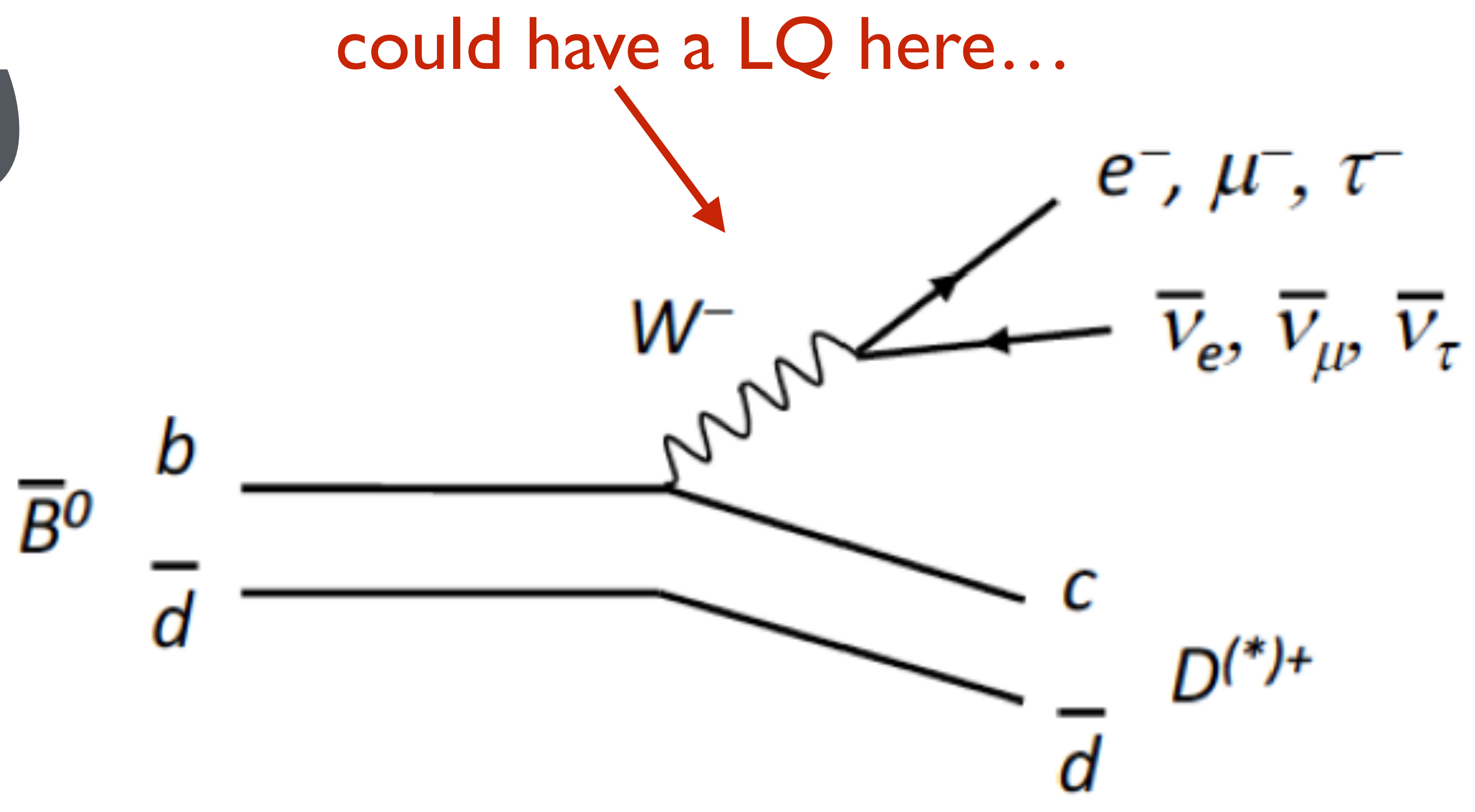
- Missing neutrino(s) → no narrow peak to fit
- Background from partially reconstructed decays

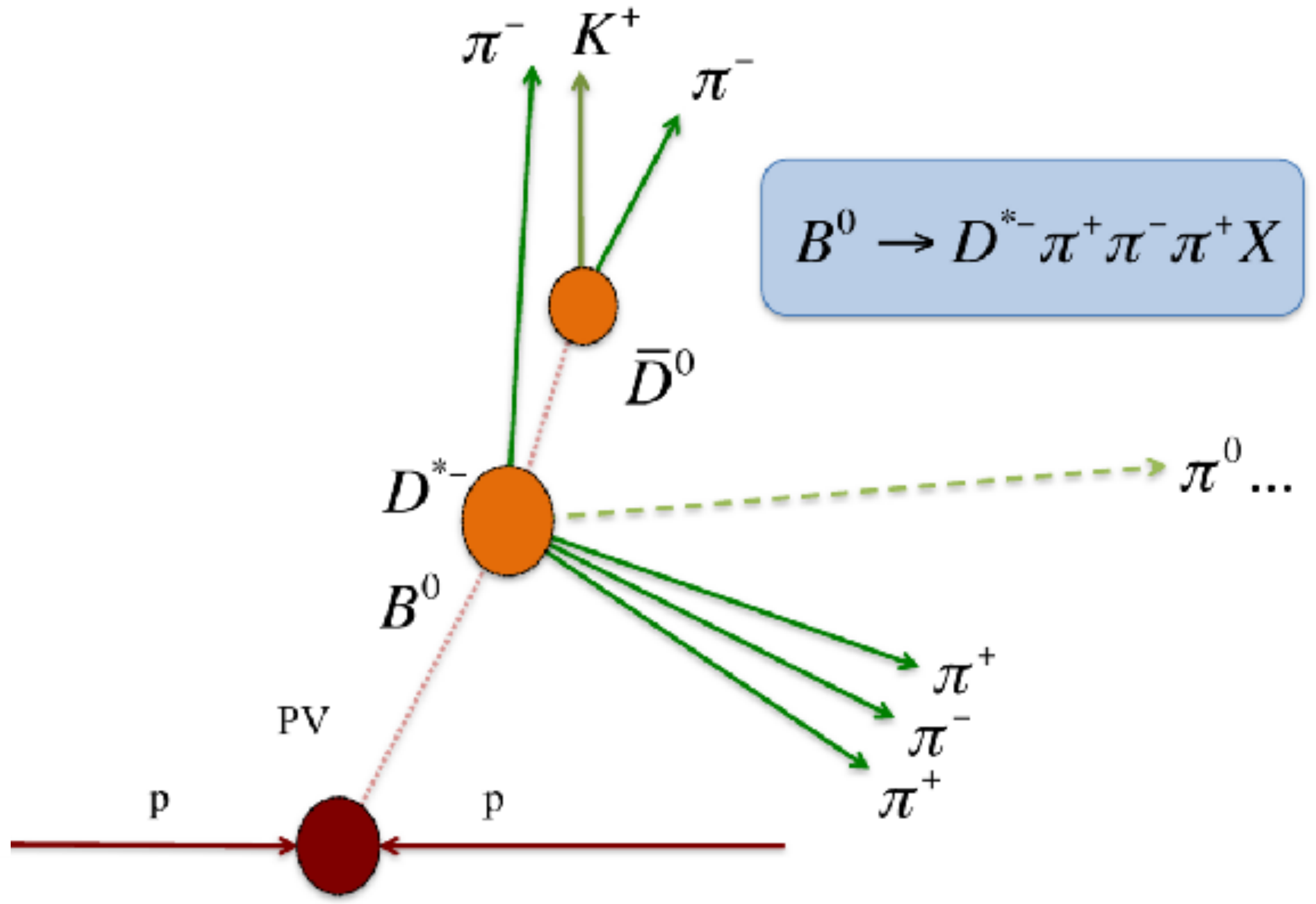




$q^2 = (p_B - p_{D^*})^2$

LFUV in $b \to c \ell \upsilon$ transitions





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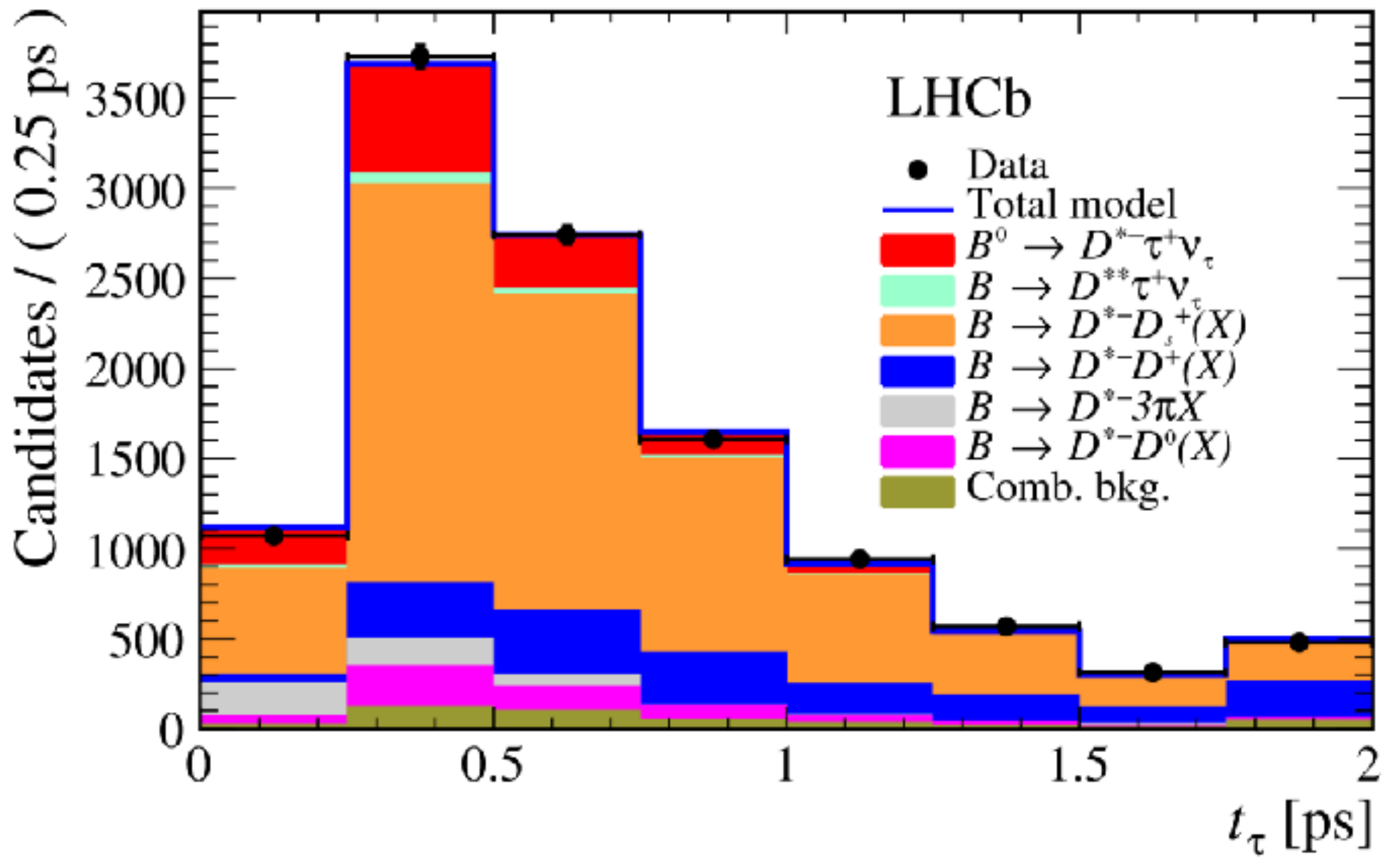

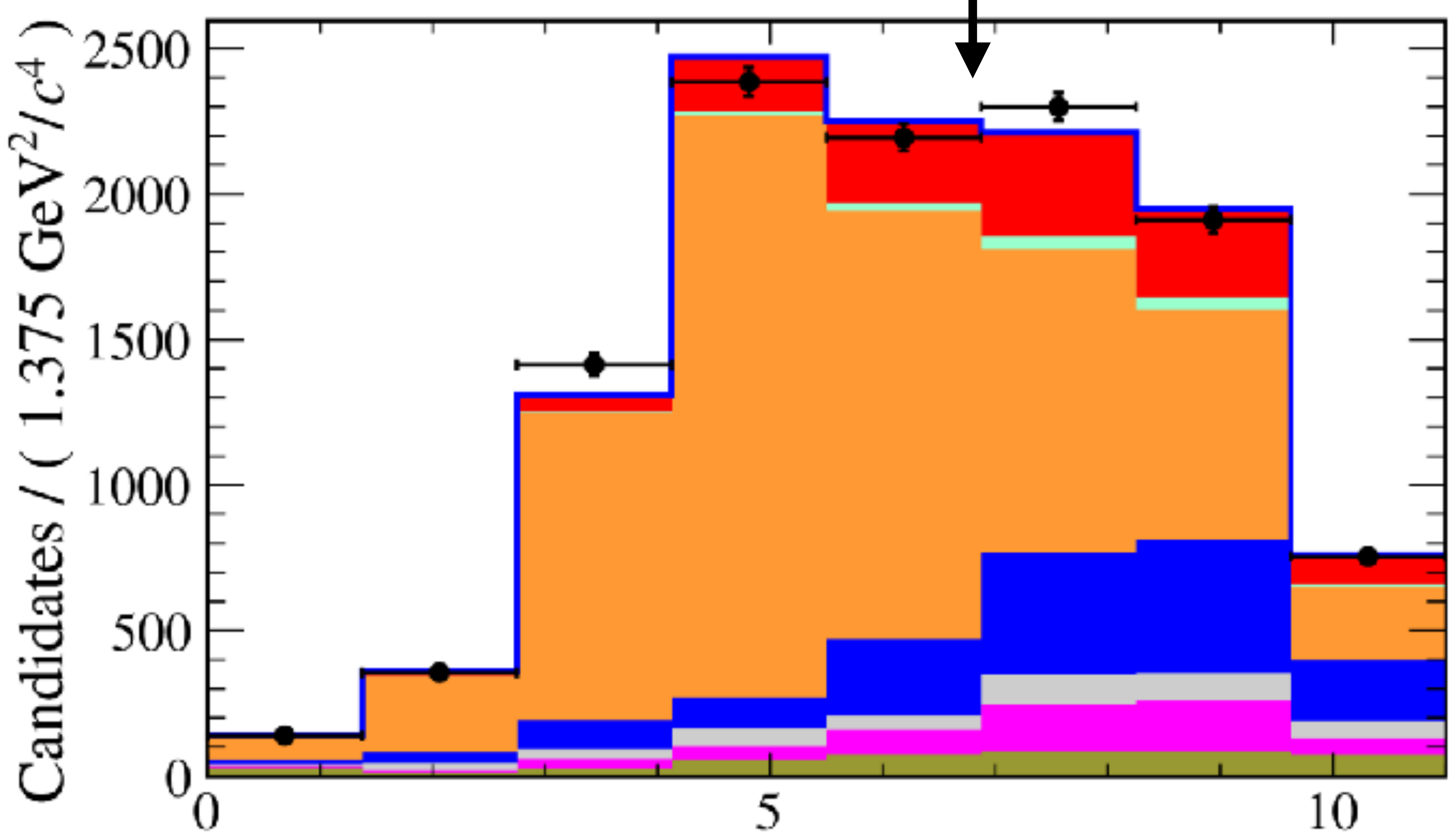

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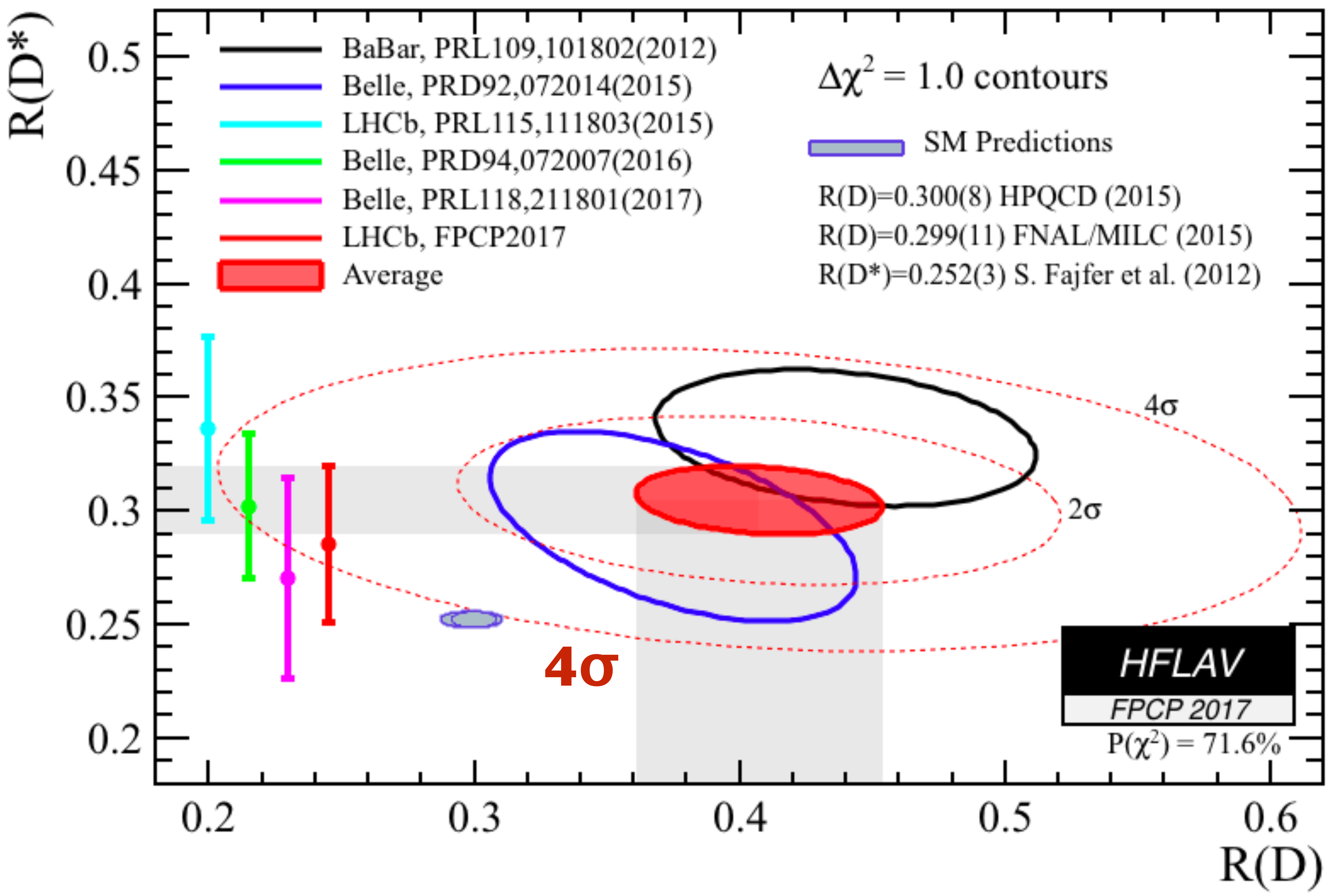
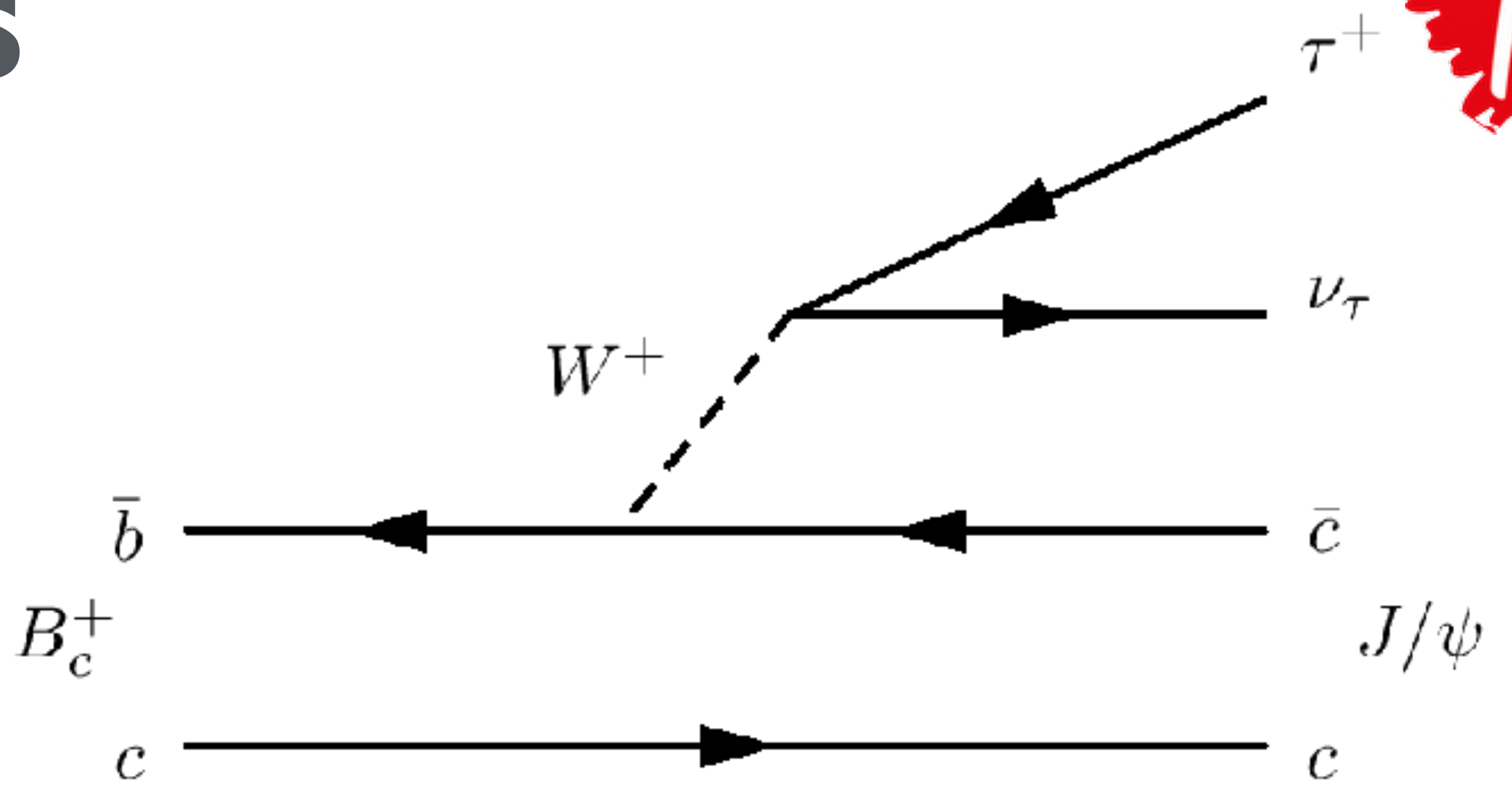


All measurements above SM: R(D*) - 3.4σ, R(D) - 2.3σ

Updates to the SM prediction for R(D*) slightly reduce the tension [arXiv:1703.05330, 1707.09509, 1707.09977]

~3% effect from QED, in simulation? [arXiv:1803.05881]



[arXiv:1711:05623]

First evidence (3σ) for $B_c \to J/\psi\tau\upsilon$

$\mathcal{R}(J/\psi) = 0.71 \pm 0.17 \pm 0.18$ → 2σ above SM prediction [PLB 452 (1999) 129][arXiv:0211021] [PRD 73 (2006) 054024][PRD 74 (2006) 074008]

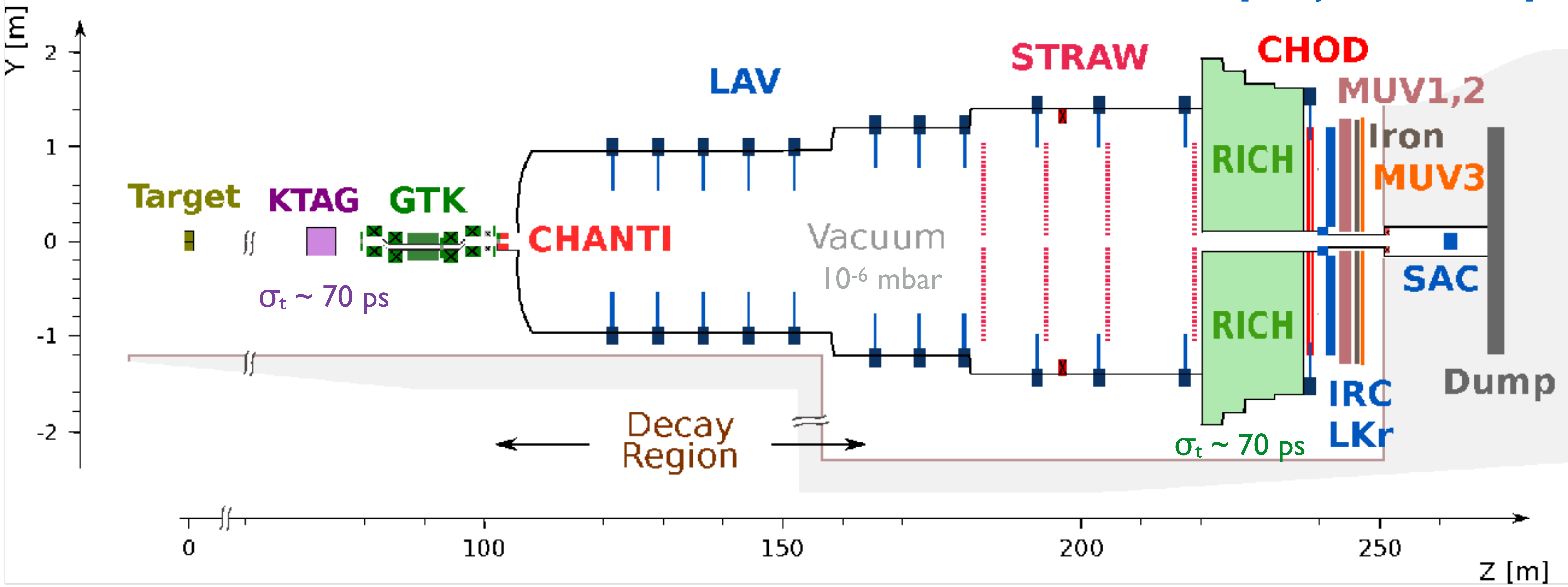
Short B_c lifetime (~0.5 ps) separates signal from other b-hadrons (~1.5 ps)

Next steps: measure $R(\Lambda_c^{(*)})$, $R(D_s^{(*)})$…

See talk: M Tilley

Rare kaon decays

[2017 JINST 12 P05025]



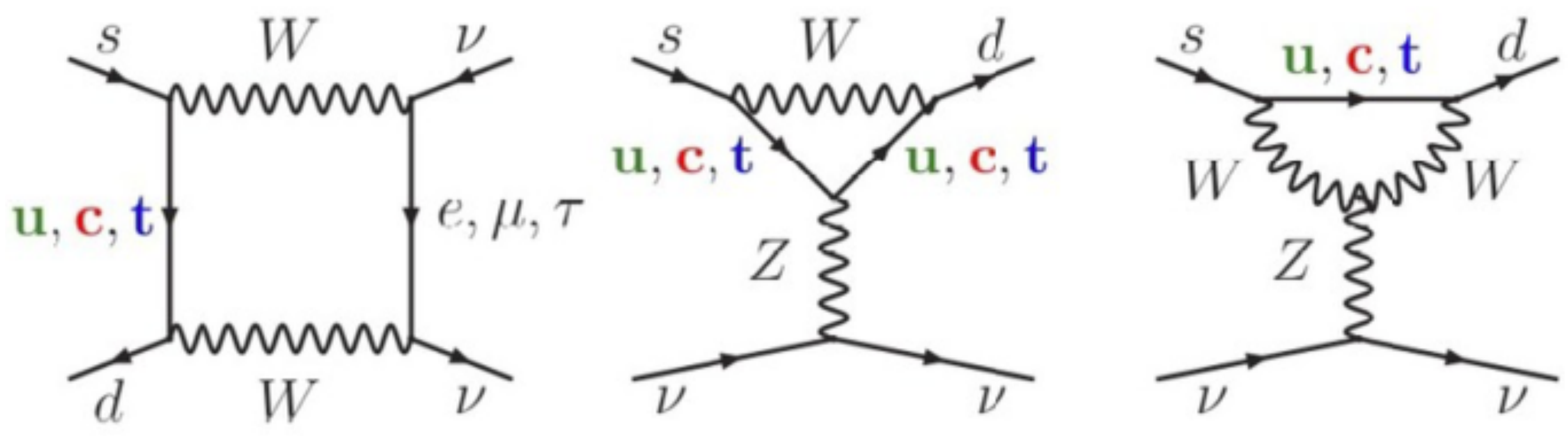
Search for $K^+ \rightarrow \pi^+ \upsilon\bar{\upsilon}$, rare/forbidden decays and exotic processes

[PLB 778 (2018) 137]

searching for $K_L \rightarrow \pi^0 \upsilon\bar{\upsilon}$, currently taking data

See talks in Monday parallels

Search for $K^+ \to \pi^+\nu\bar{\nu}$



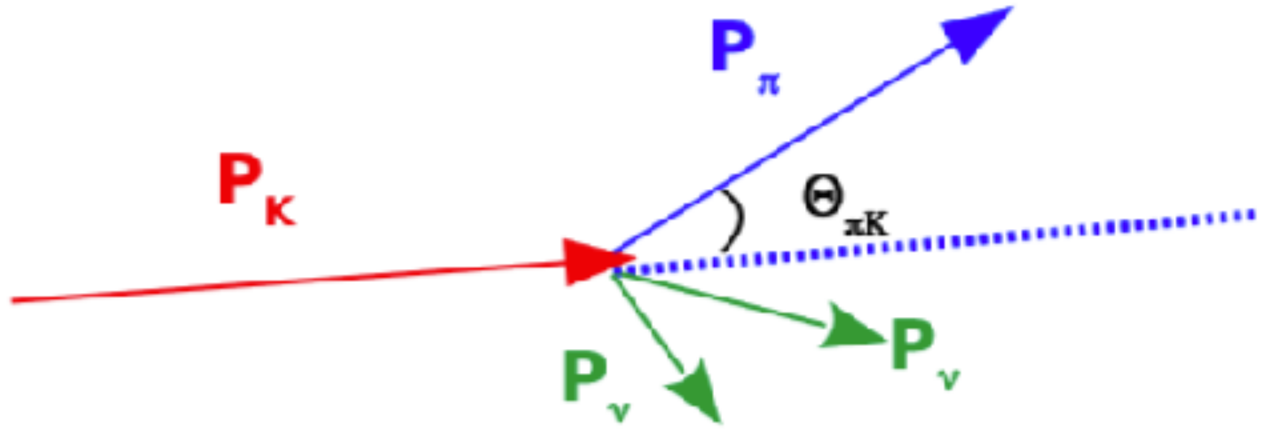
Theoretically clean s → d FCNC process (dominated by short distance)
[Brod et al., PRD 83, 034030 (2011)]
[Buras et al., JHEP 11 (2015) 033]

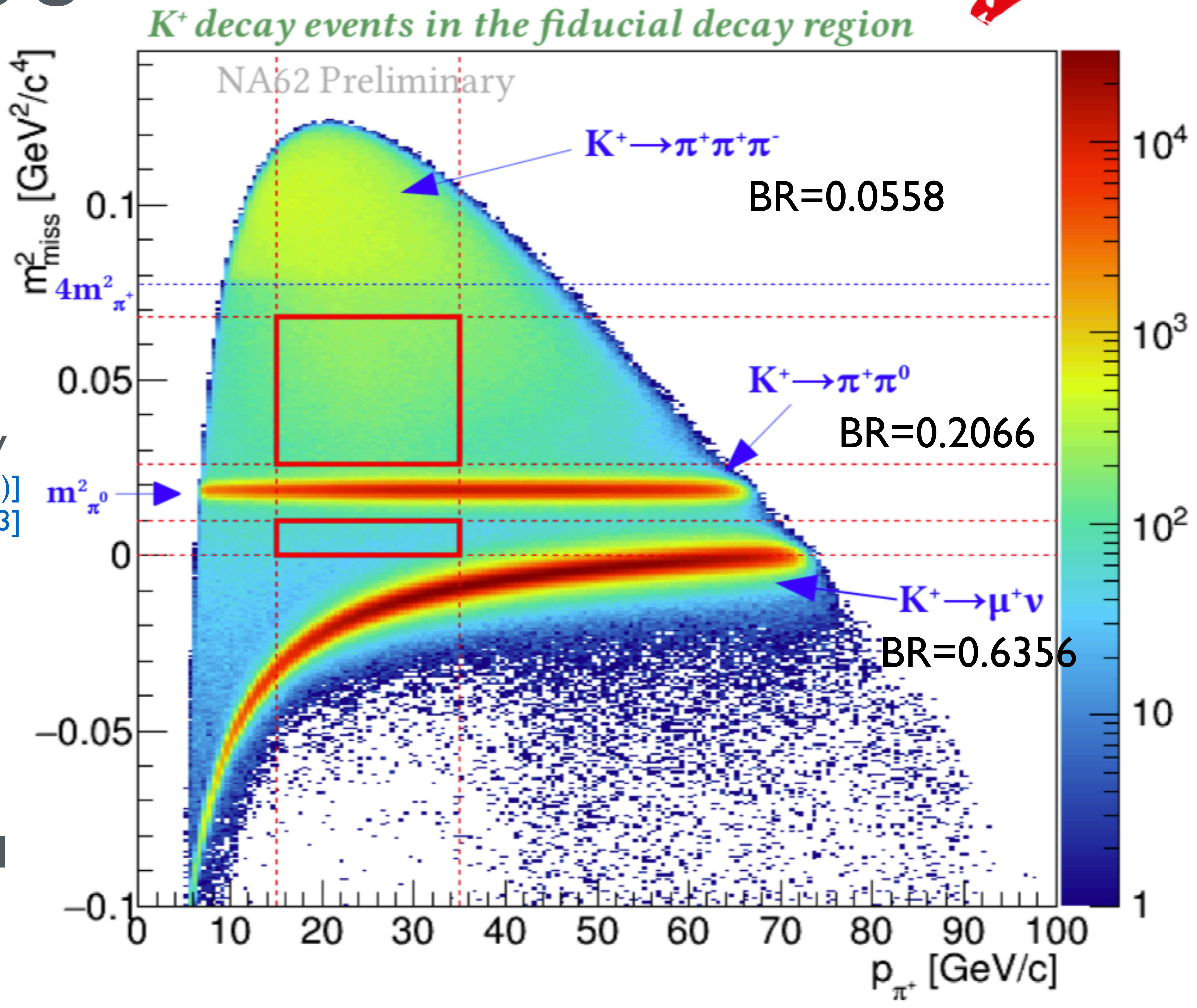
$BR(K^+ \to \pi^+\nu\bar{\nu})^{SM} = (8.4 \pm 1.0)\times10^{-11}$

Sensitive probe of BSM models (SUSY, Z'…)
[Buras et al., JHEP 11 (2015) 166]

Detector timing (σ_t ~100 ps) and background suppression are key ($\sigma(m^2_{miss})$ ~ 10^{-3} GeV²)

Decay in flight technique



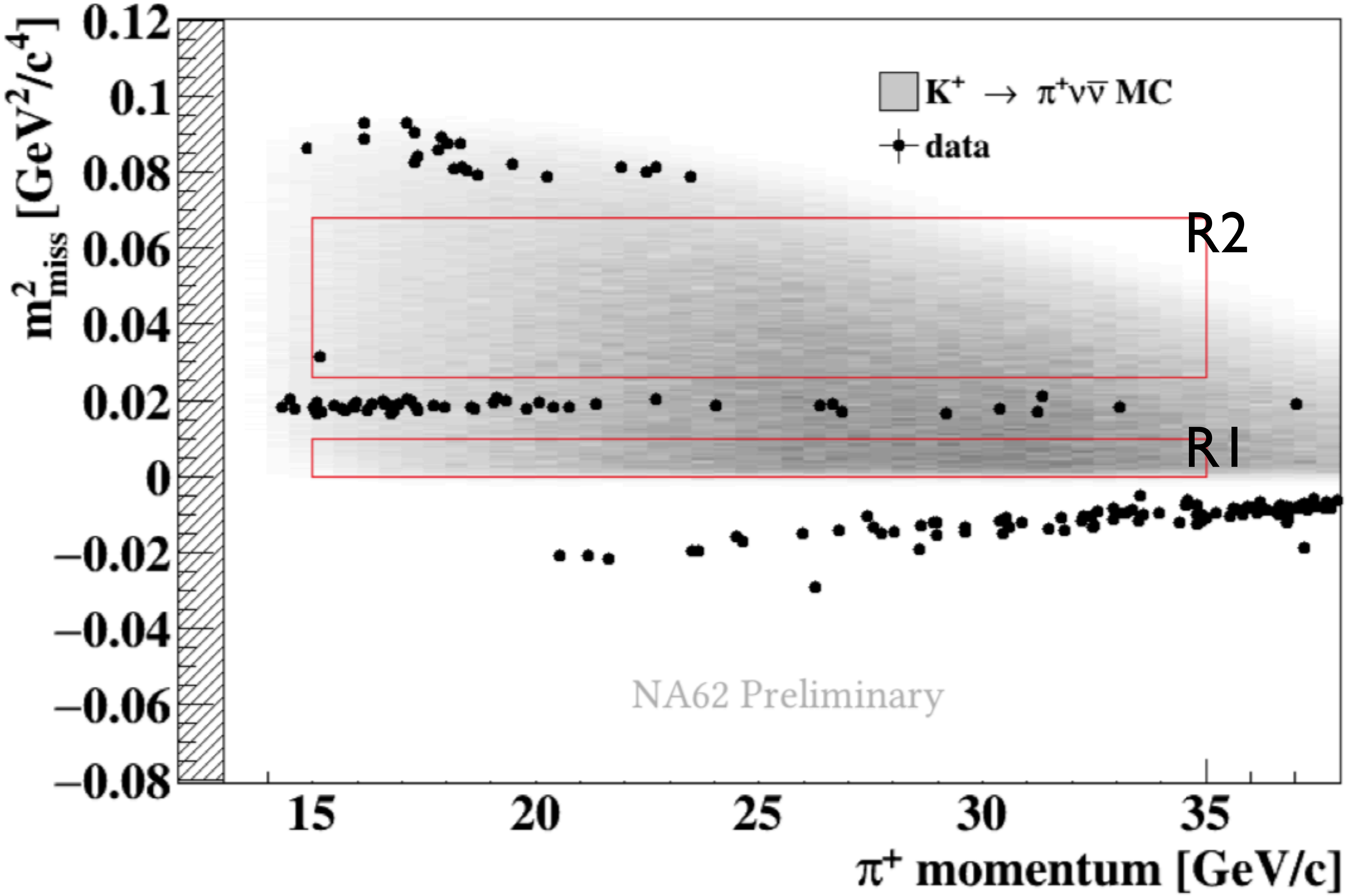


$m^2_{miss} = (p_K - p_\pi)^2$

NA62 results

NEW

https://indico.in2p3.fr/event/16579/contributions/60808/attachments/47182/59257/Moriond_rmarchev.pdf



One event observed

Process	Expected events in R1 + R2
$K^+ \to \pi^+\nu\bar{\nu}$ (SM)	$0.267 \pm 0.001_{stat} \pm 0.029_{syst} \pm 0.032_{ext}$
$K^+ \to \pi^+\pi^0(\gamma)$ IB	$0.064 \pm 0.007_{stat} \pm 0.006_{syst}$
$K^+ \to \mu^+\nu_\mu(\gamma)$ IB	$0.020 \pm 0.003_{stat} \pm 0.003_{syst}$
$K^+ \to \pi^+\pi^-e^+\nu_e$	$0.018^{+0.024}_{-0.017}\vert_{stat} \pm 0.009_{syst}$
$K^+ \to \pi^+\pi^-\pi^+$	$0.002 \pm 0.001_{stat} \pm 0.002_{syst}$
Upstream background	$0.050^{+0.090}_{-0.030}$
Total background	$0.15 \pm 0.09_{stat} \pm 0.01_{syst}$

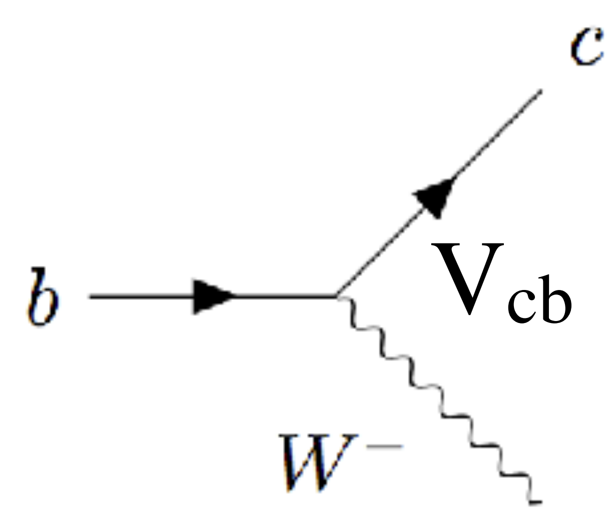
BR($K^+ \to \pi^+\nu\bar{\nu}$) < 140 x$10^{-11}$ @ 95% CL.
Consistent with SM and E949@BNL
[PRL 101 (2008) 191802]

Data from 2017 now being analysed → x20 increase!

2018 data-taking being prepared → 20 SM events expected

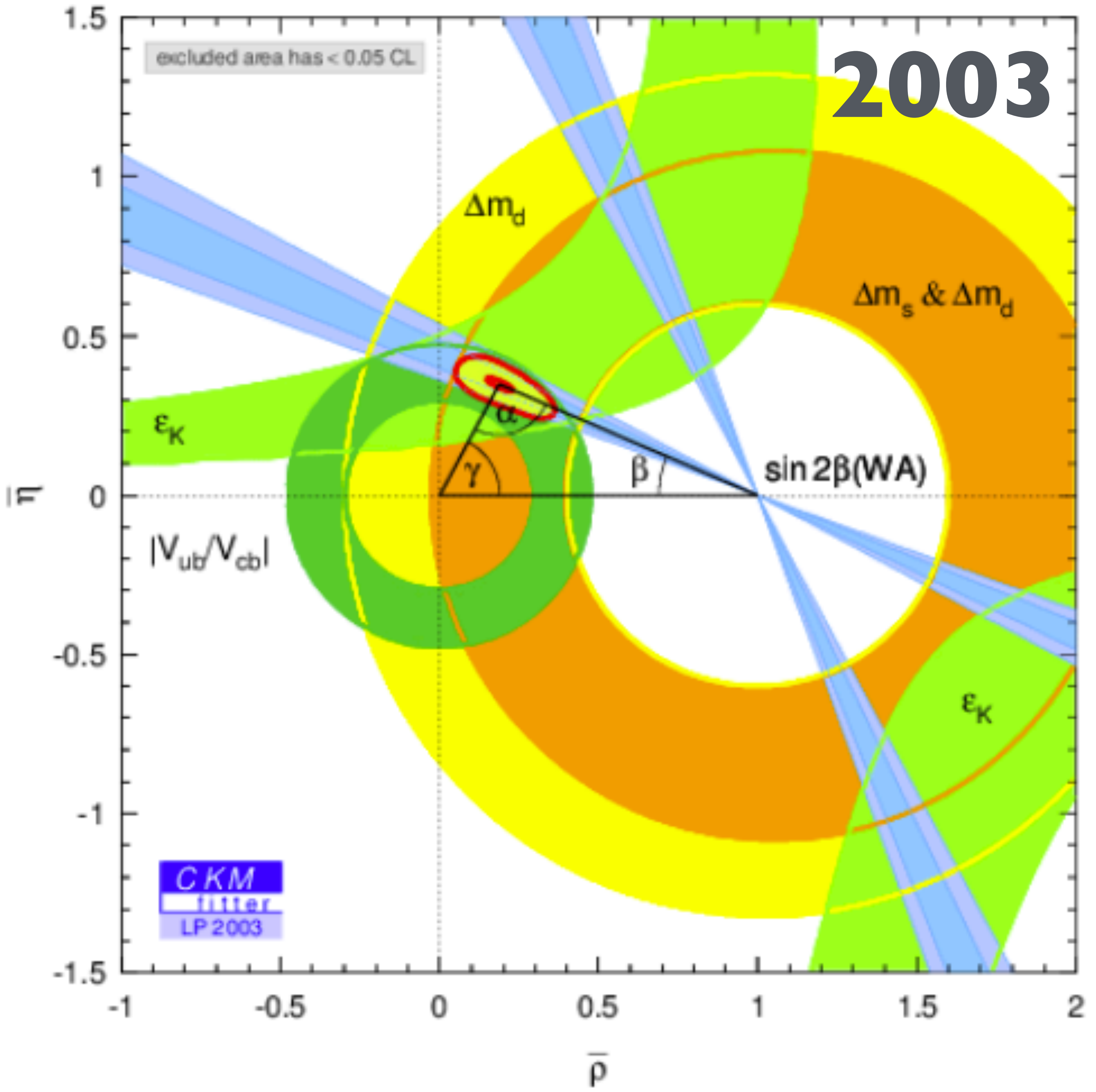
See talk: A Romano

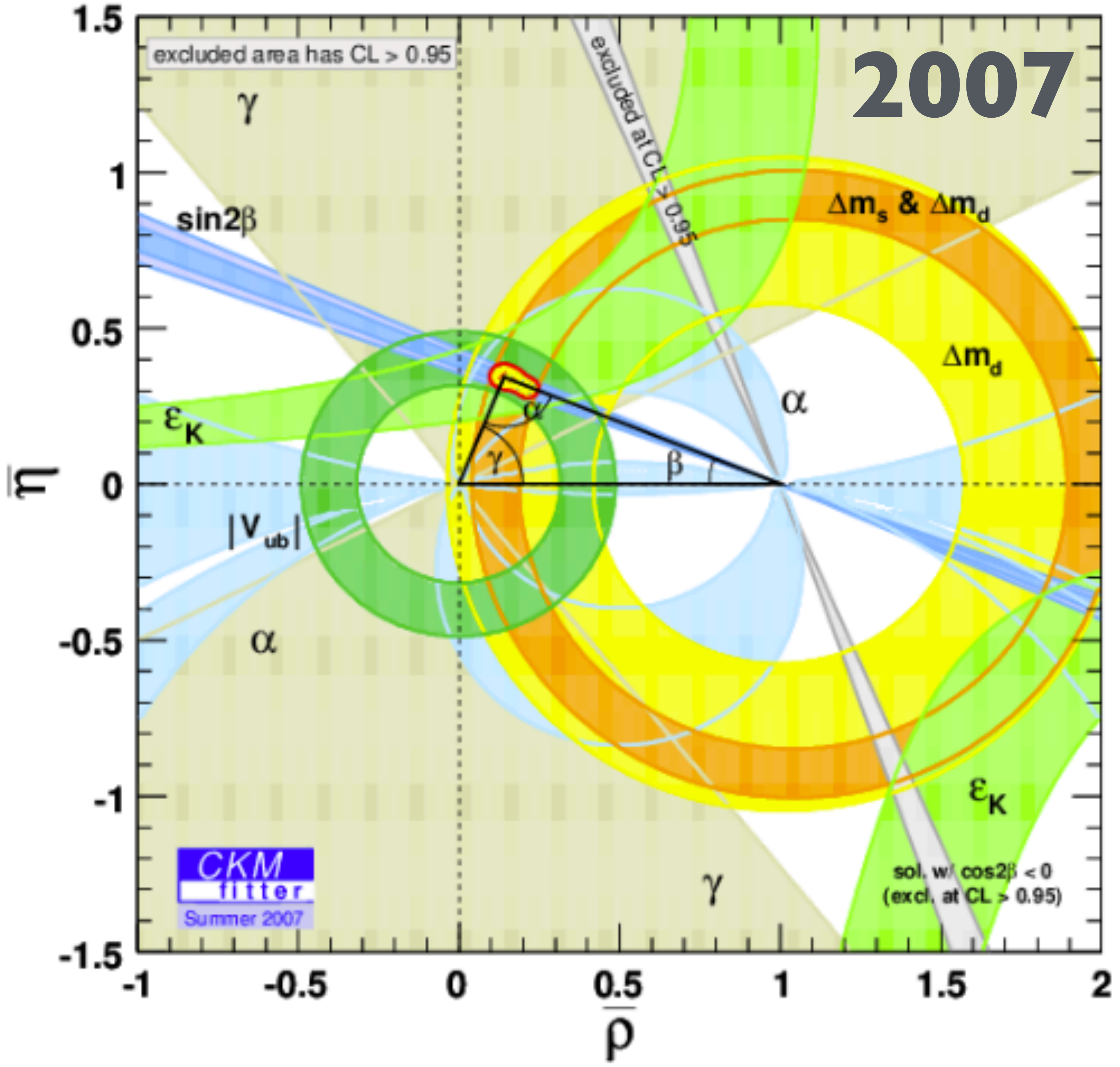
The CKM mechanism

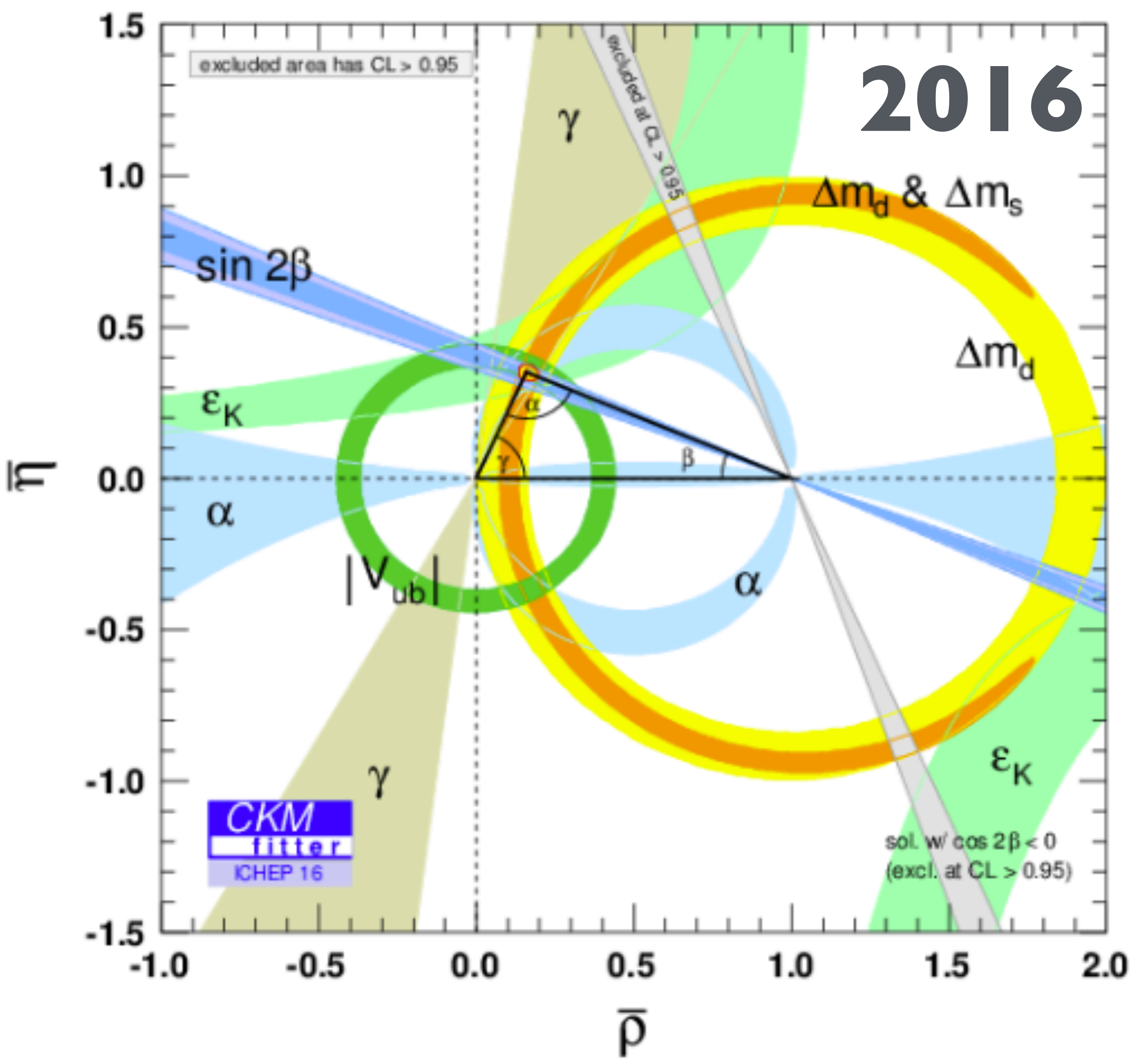


$$V_{\rm CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \cong \begin{pmatrix} 0.97 & 0.23 & 0.0037 \cdot e^{-i\gamma} \\ -0.23 & 0.97 & 0.042 \\ 0.0087 \cdot e^{-i\beta} & -0.041 & 0.9991 \end{pmatrix}$$

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$





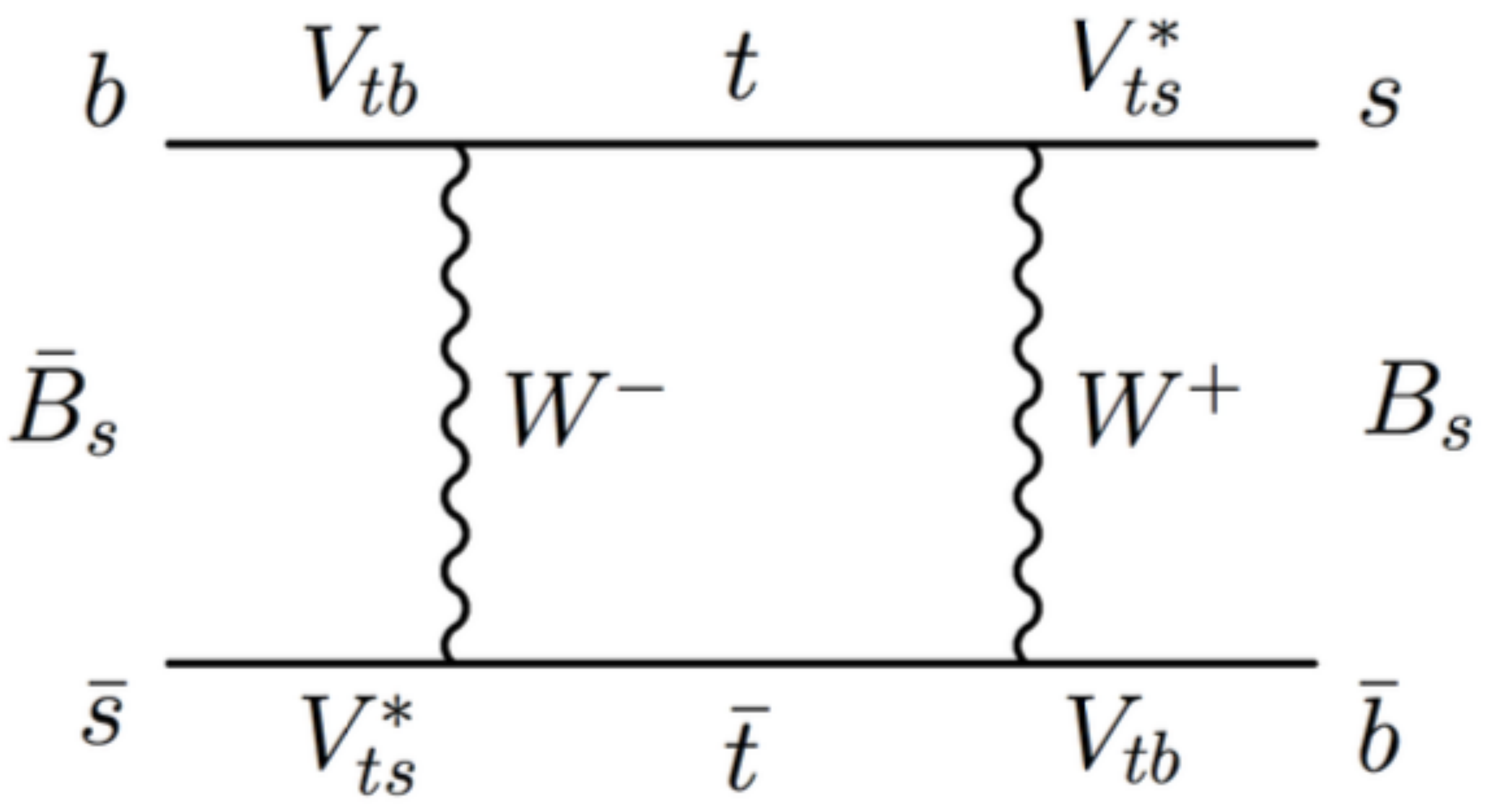


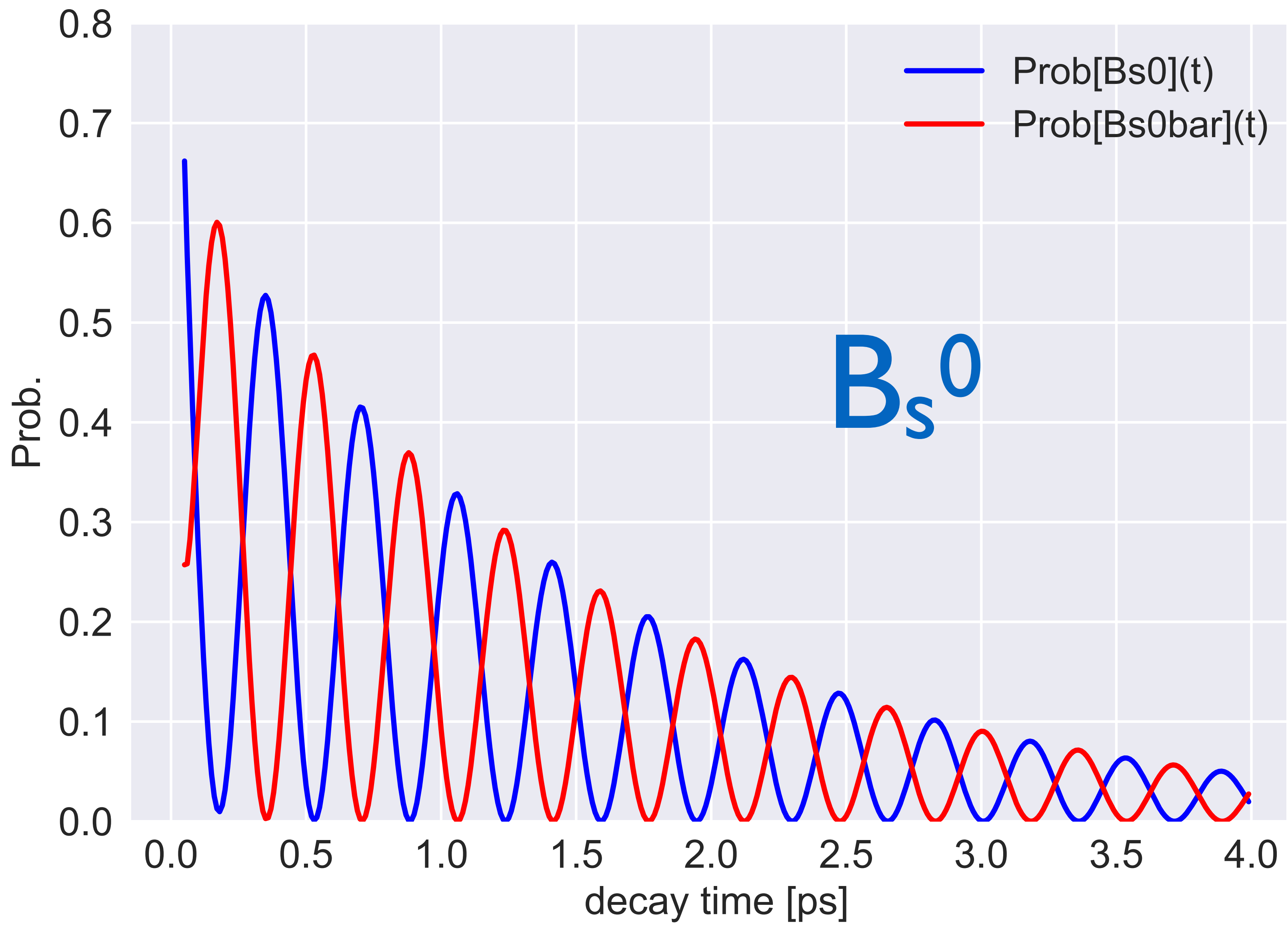
Huge programme of experimental, theoretical and Lattice QCD calculations e.g., [Fermilab-MILC, PRD 93 (2016) 113016]

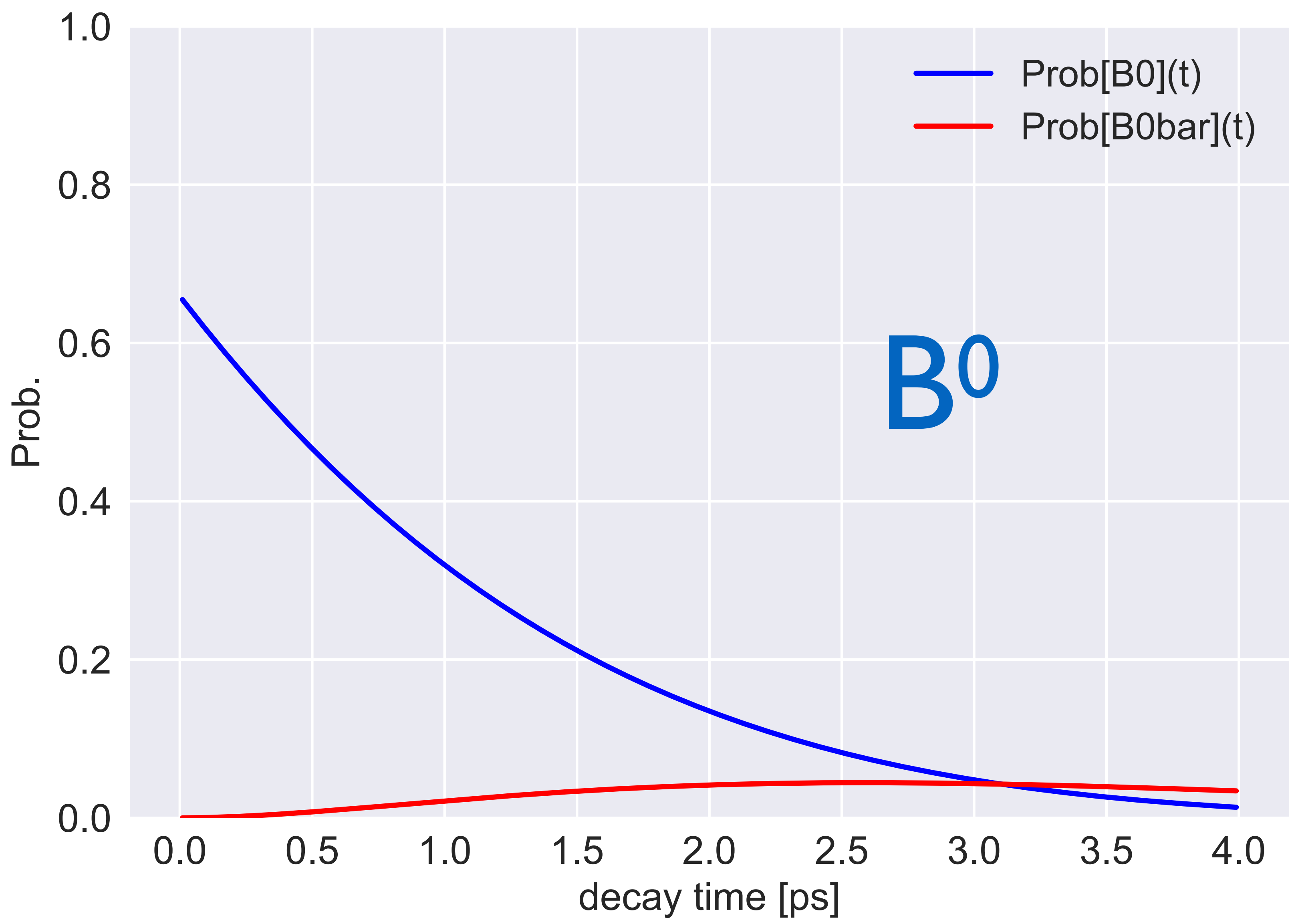
Measurement consistency tests the SM and provide model-independent constraints on New Physics

SM working well, but still room for 10-20% NP contributions → More precision!

Neutral meson oscillations







$$|B^0_{\mathrm{L,H}}\rangle = p|B^0\rangle \pm q|\overline{B}^0\rangle$$

$$\mathrm{Prob}(B^0 \to \overline{B}^0) = \frac{\Gamma e^{-\Gamma t}}{2}[\cosh(\Delta\Gamma/2t) - \cos(\Delta m t)]|q/p|^2$$

+ similar equations for other mixing probabilities

$\Delta m \equiv (m_H - m_L)$	Mixing frequency
$\Gamma \equiv (\Gamma_L + \Gamma_H)/2$	Average width
$\Delta\Gamma \equiv \Gamma_L - \Gamma_H$	Width difference

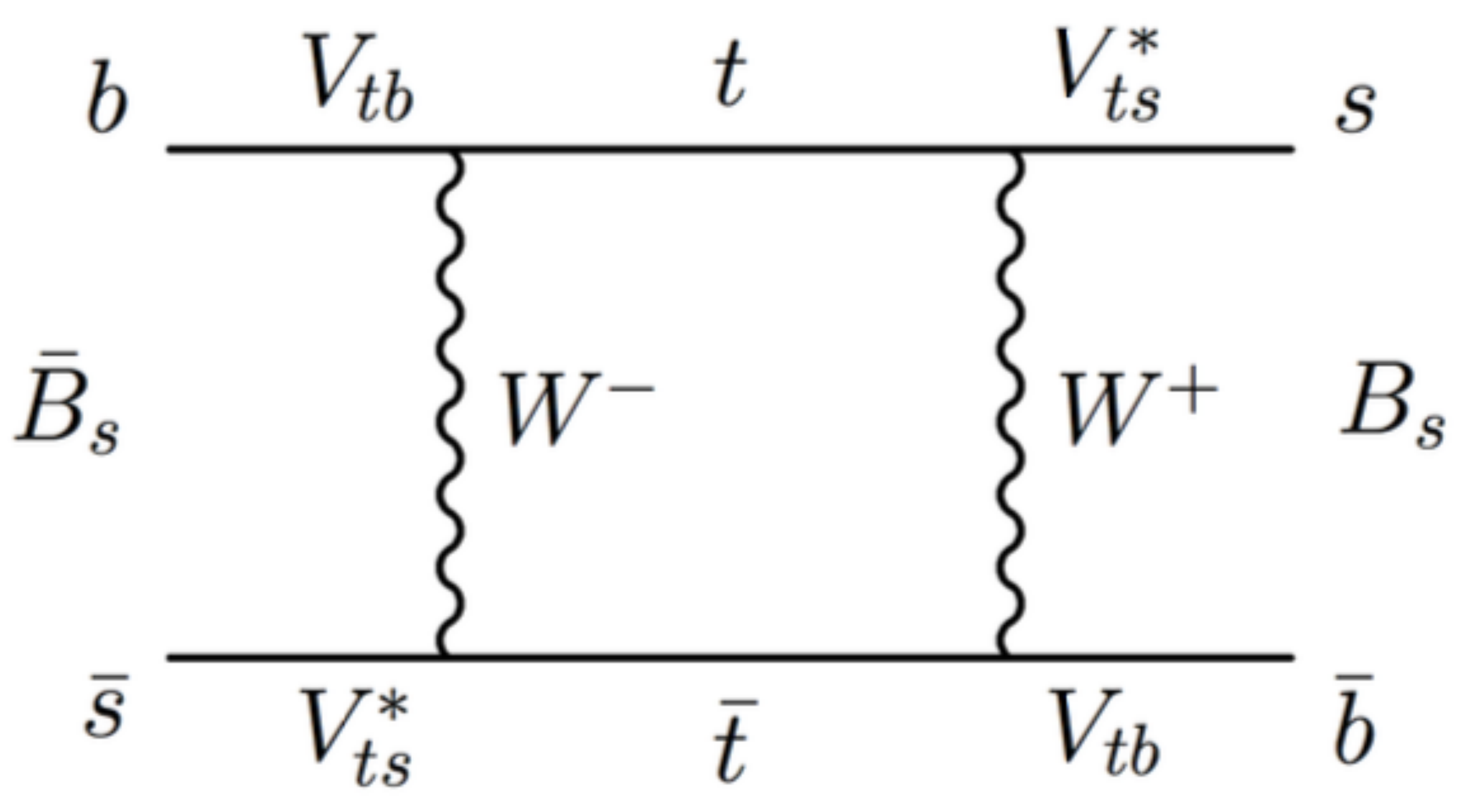
New physics particles could enter the loop

Same description for **charm system**, but mixing frequency much **smaller** due to no top quarks in the loop

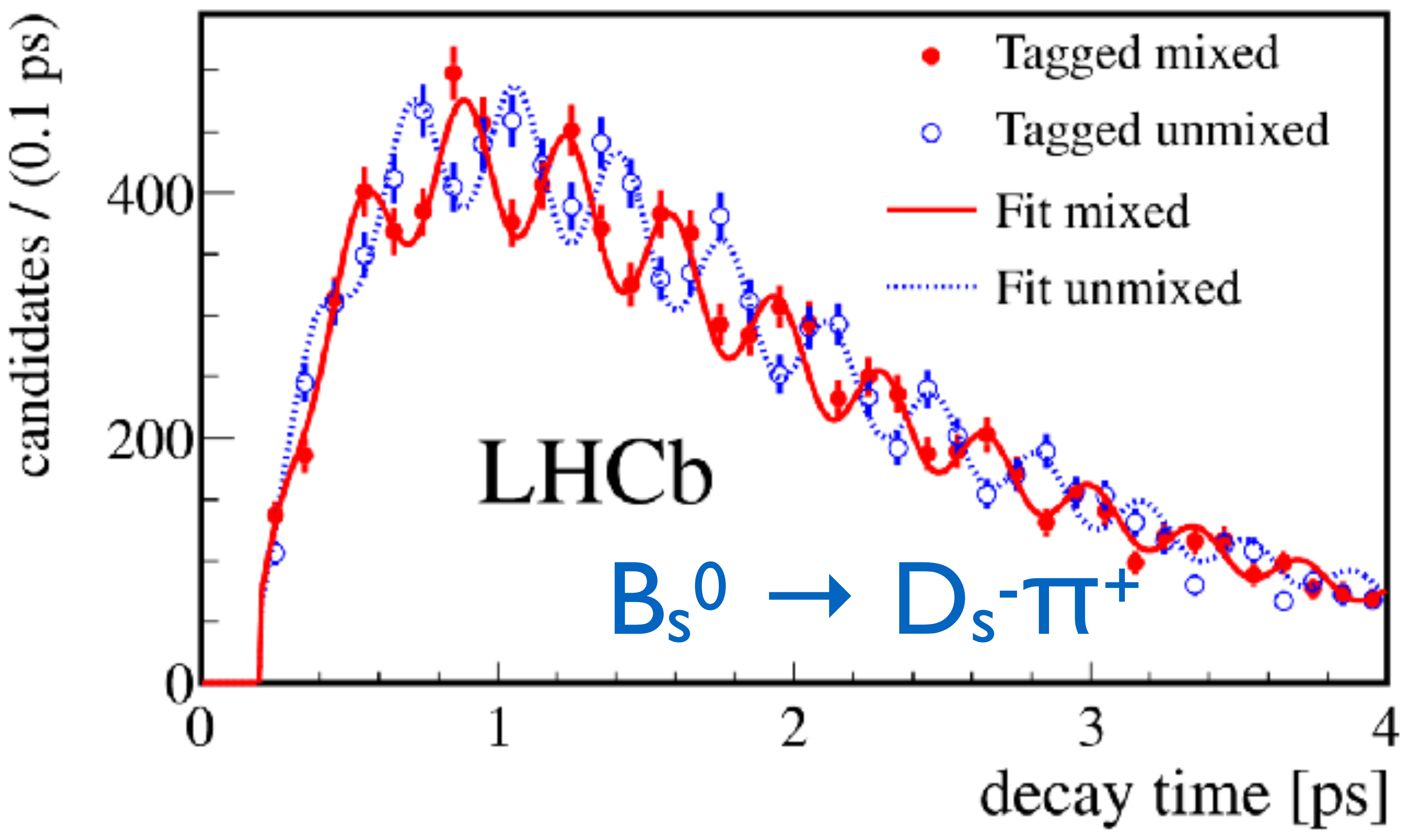
[HFLAV]

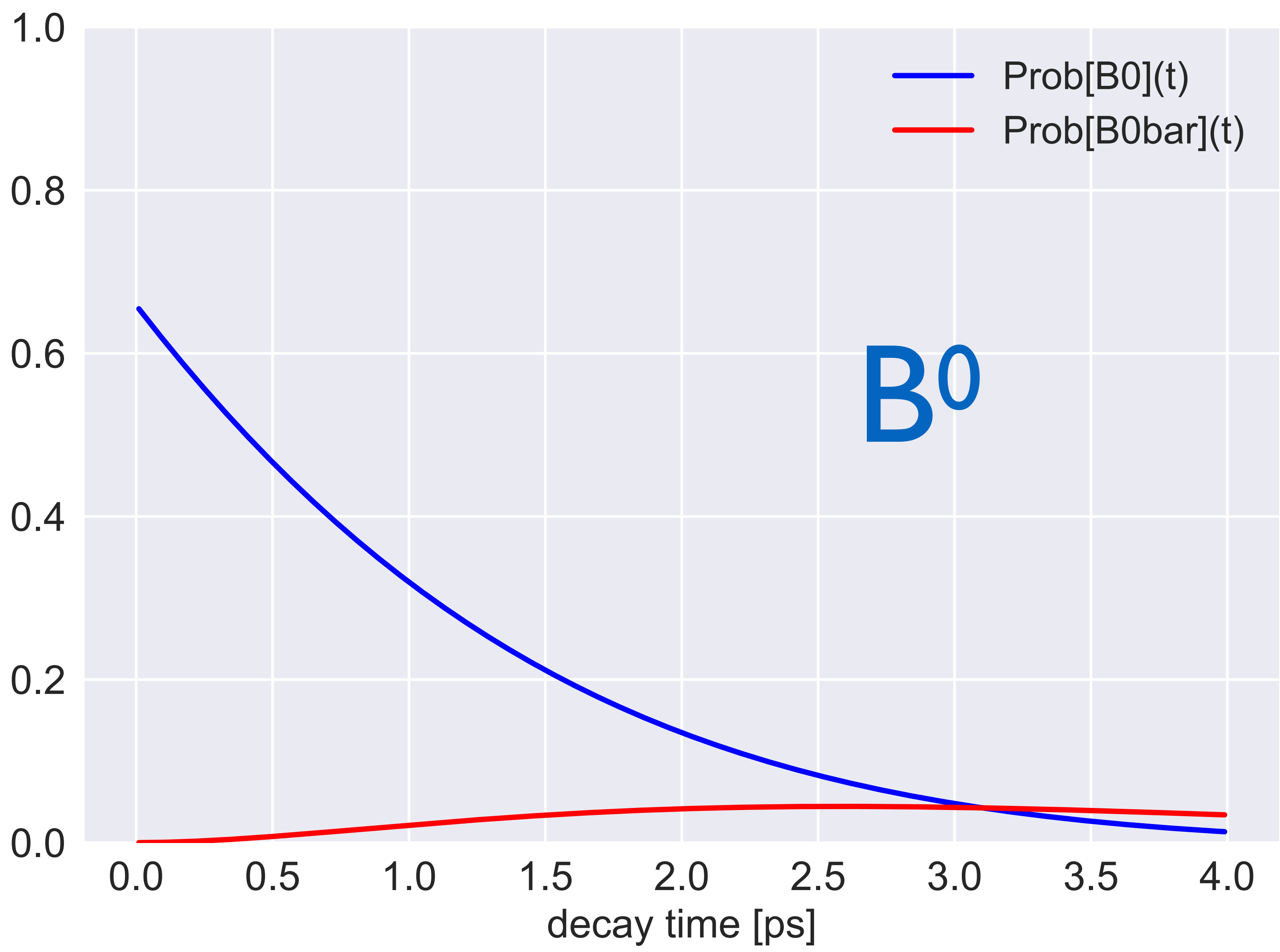
Δm_s = 17.757 ± 0.021/ps is 1.8σ below SM prediction… [Luzio et al., arXiv:1712.06572] [See talk from A. Lenz]

Neutral meson oscillations



[NJP 15 (2013) 053021]





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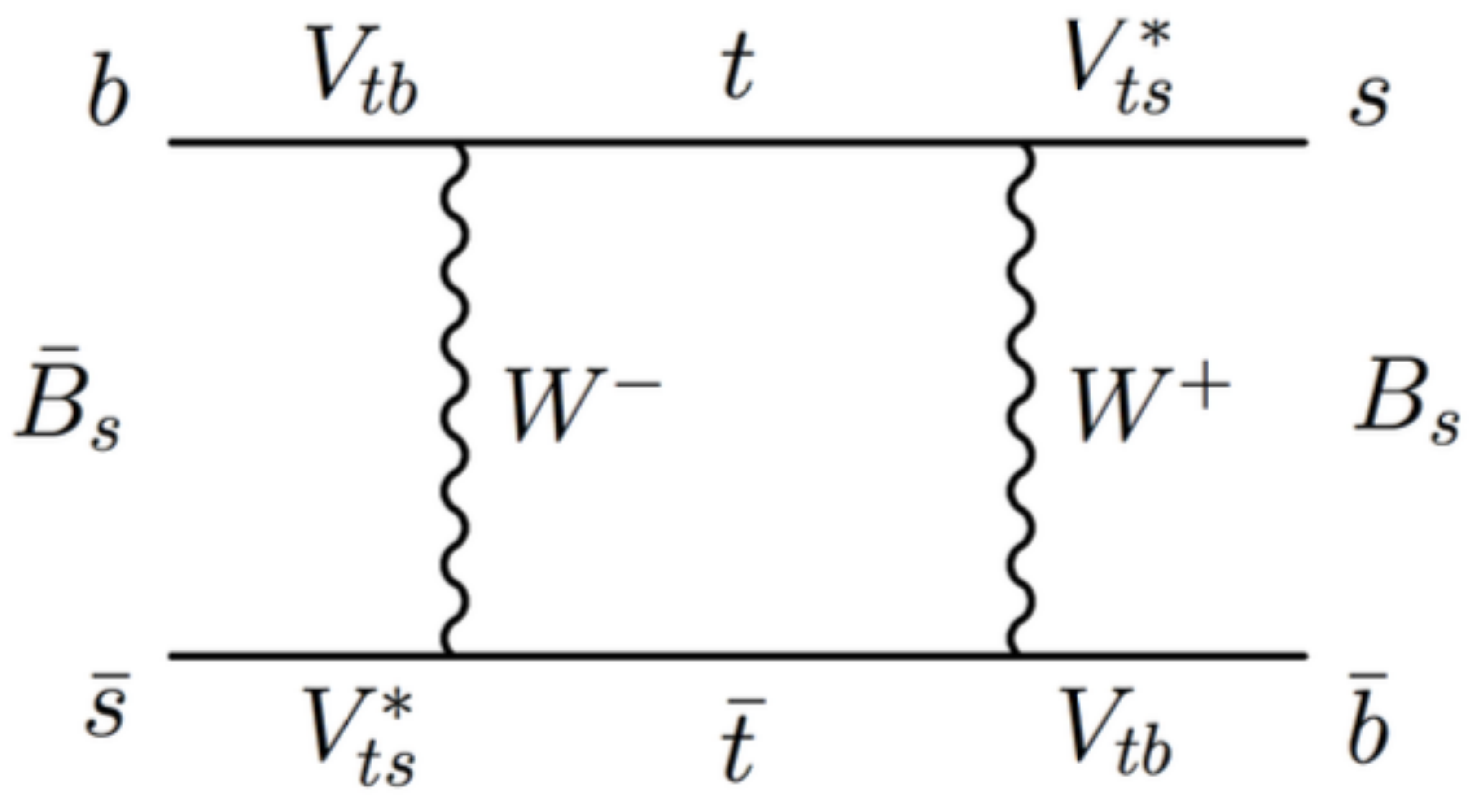
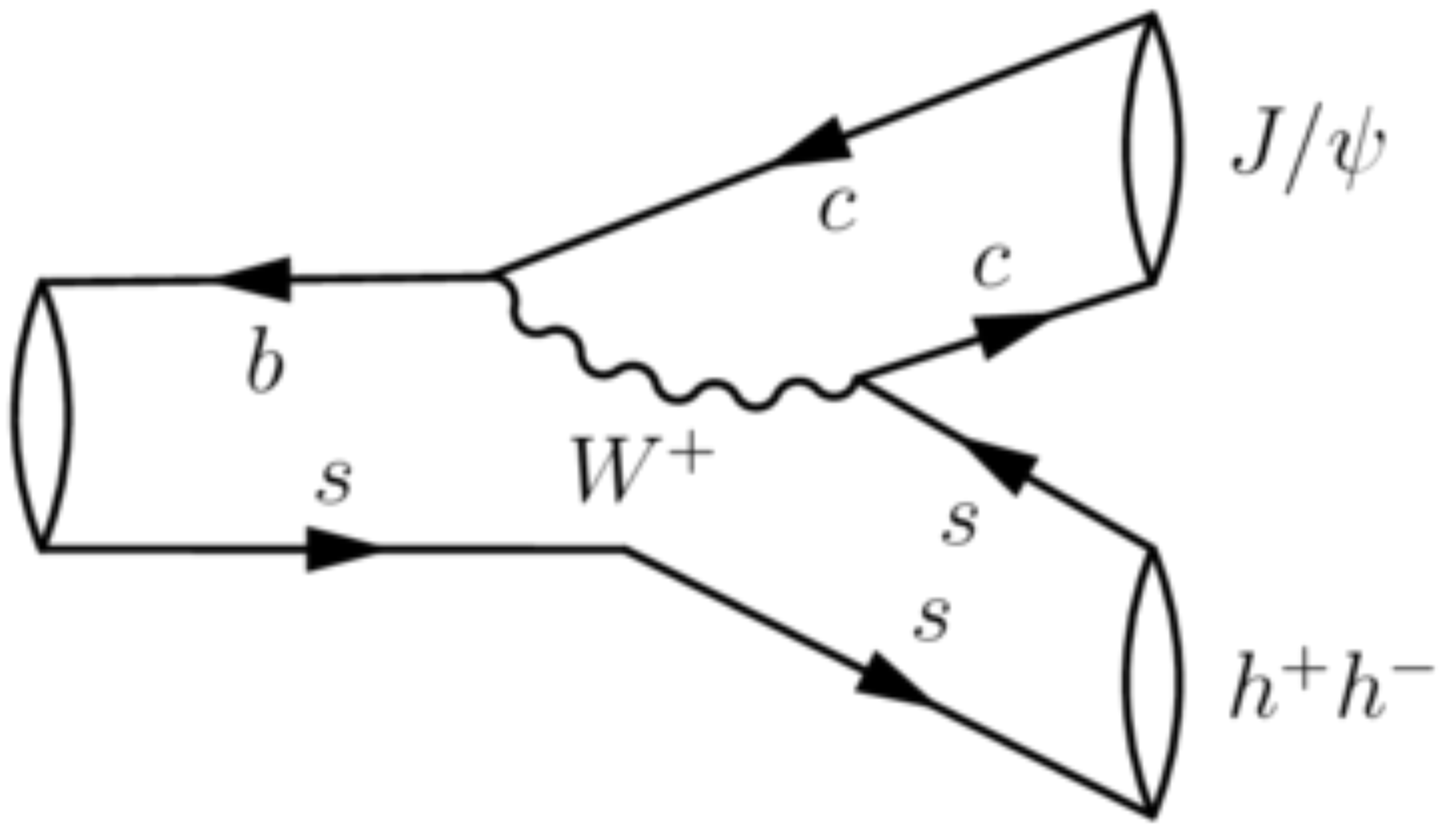
[Luzio et al., arXiv:1712.06572]
[See talk from A. Lenz]

CPV in B^0_s mixing + decay



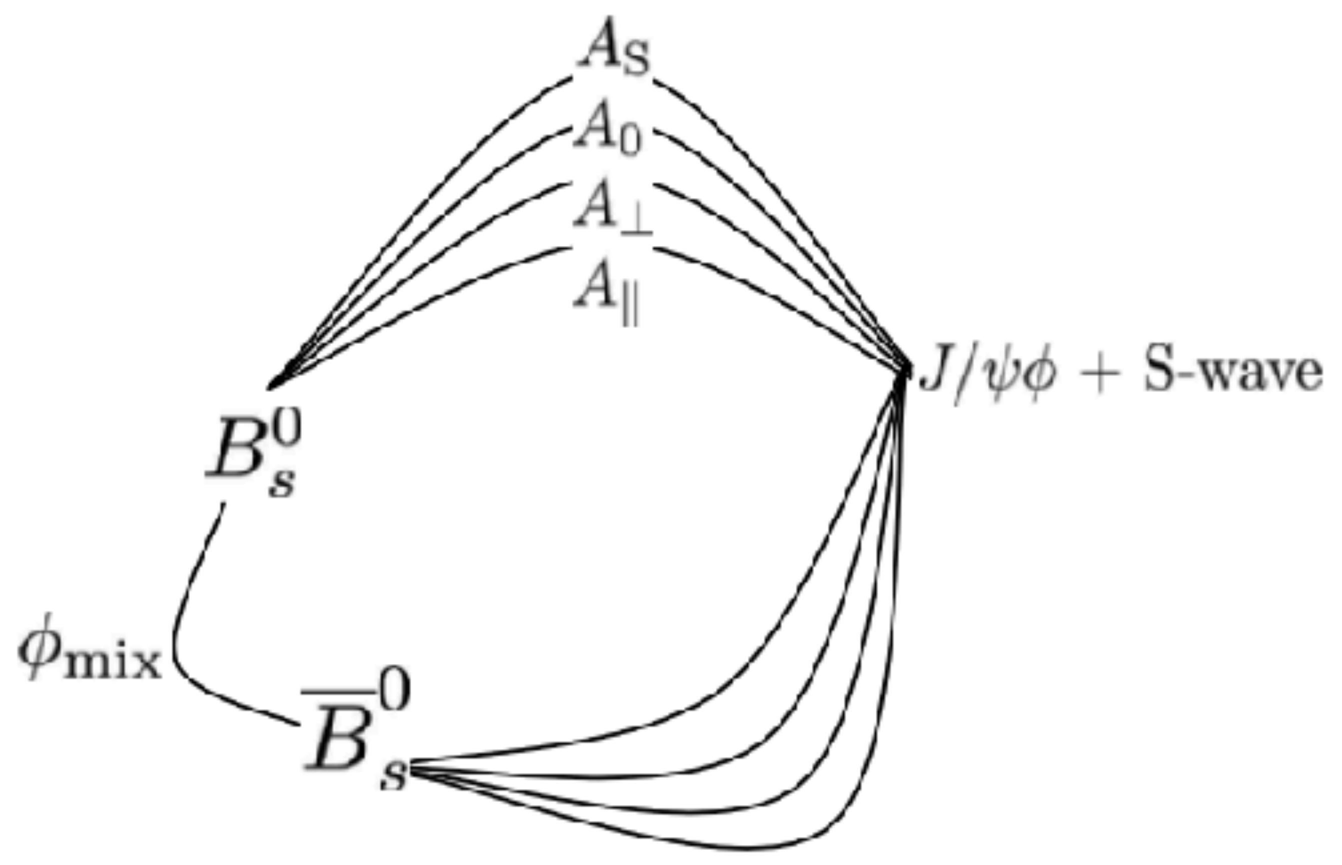


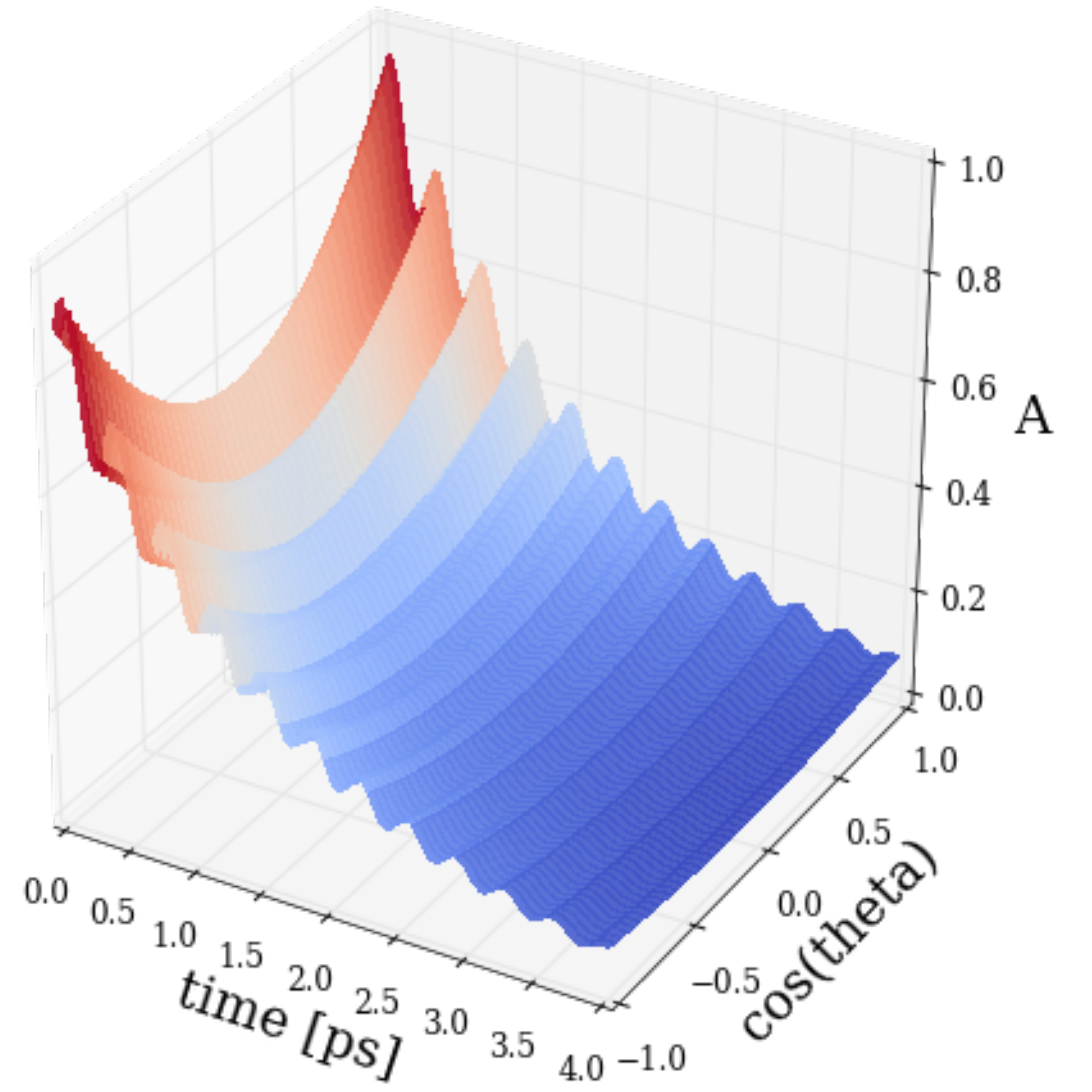
$B^0_s \rightarrow J/\psi\varphi$ is the **golden mode** for measuring ϕ_s

Dominated by b → ccs tree diagram

$$\phi_s \stackrel{\mathrm{SM}}{=} -2\arg\left(-\frac{V_{cb}V_{cs}^*}{V_{tb}V_{ts}^*}\right) \equiv -2\beta_s$$

ϕ_s^{SM} = -36.5 ± 1.3 mrad [CKMFitter]





2 vector particles in final state so use angular analysis to separate CP-odd/even components

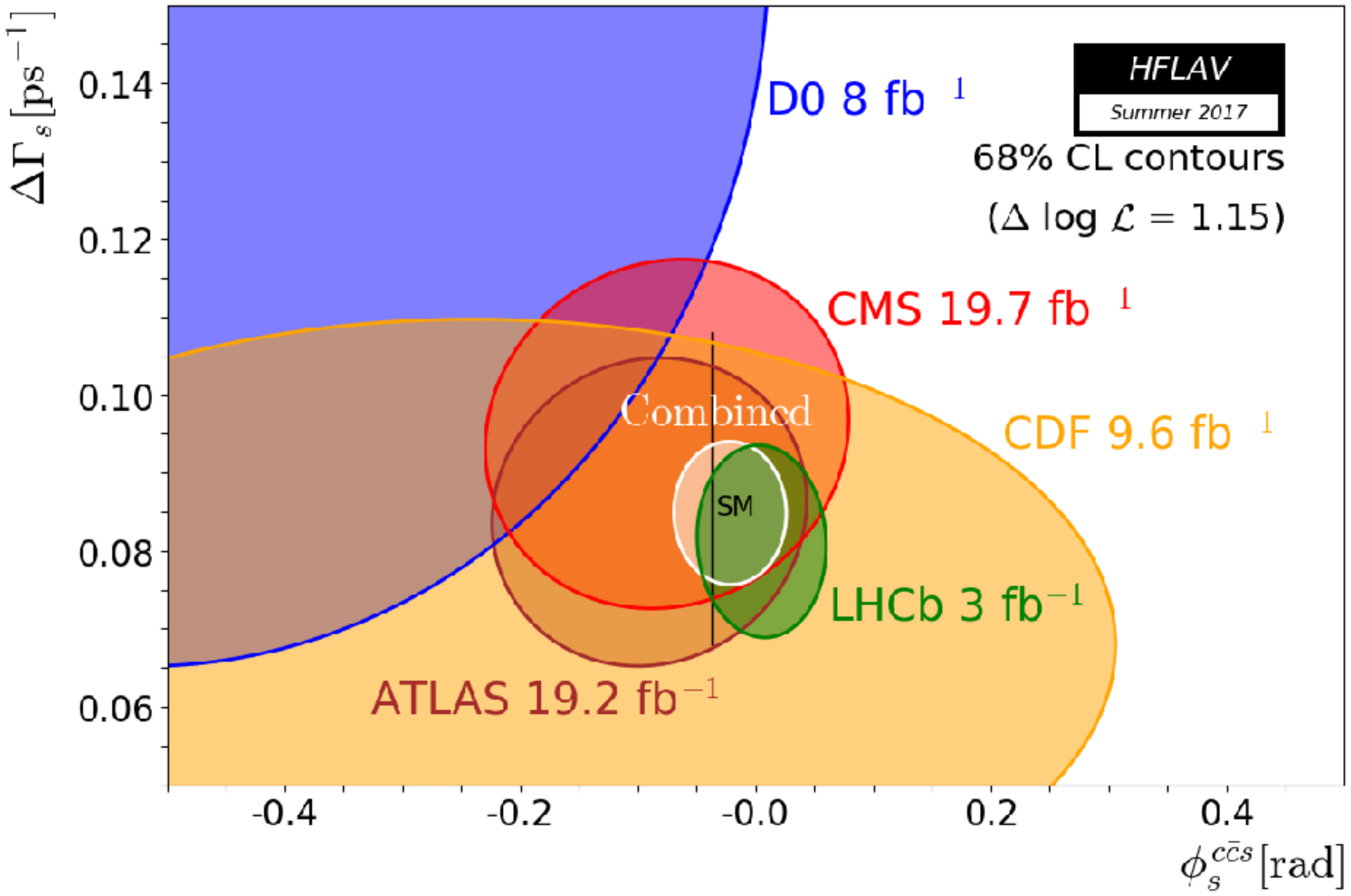
$$\mathrm{CP}|J/\psi\phi\rangle_\ell = (-1)^\ell|J/\psi\phi\rangle_\ell$$

See talk: K. Gizdov

ϕ_s-$\Delta\Gamma_s$ global combination

$\varphi_s = -0.021 \pm 0.031$ rad

$\Delta\Gamma_s = +0.090 \pm 0.005$ /ps



LHCb:

- $J/\psi\phi$ [PRL114, 041801 (2015)]
- $J/\psi K^+K^-$ [arXiv:1704.08217 (2017)]
- $J/\psi\pi^+\pi^-$ [Phys. Lett. B736, (2014) 186]
- $\psi(2S)\phi$ [Phys. Lett. B762 (2016) 253-262]
- $D_s^+D_s^-$ [PRL113, 211801 (2014)]

CMS:

- $J/\psi\phi$ [Phys. Lett. B 757 (2016) 97]

ATLAS:

- $J/\psi\phi$ [JHEP 08 (2016) 147]

New physics is not large, so we need **increased precision**

Important to control size of the penguin diagram contributions

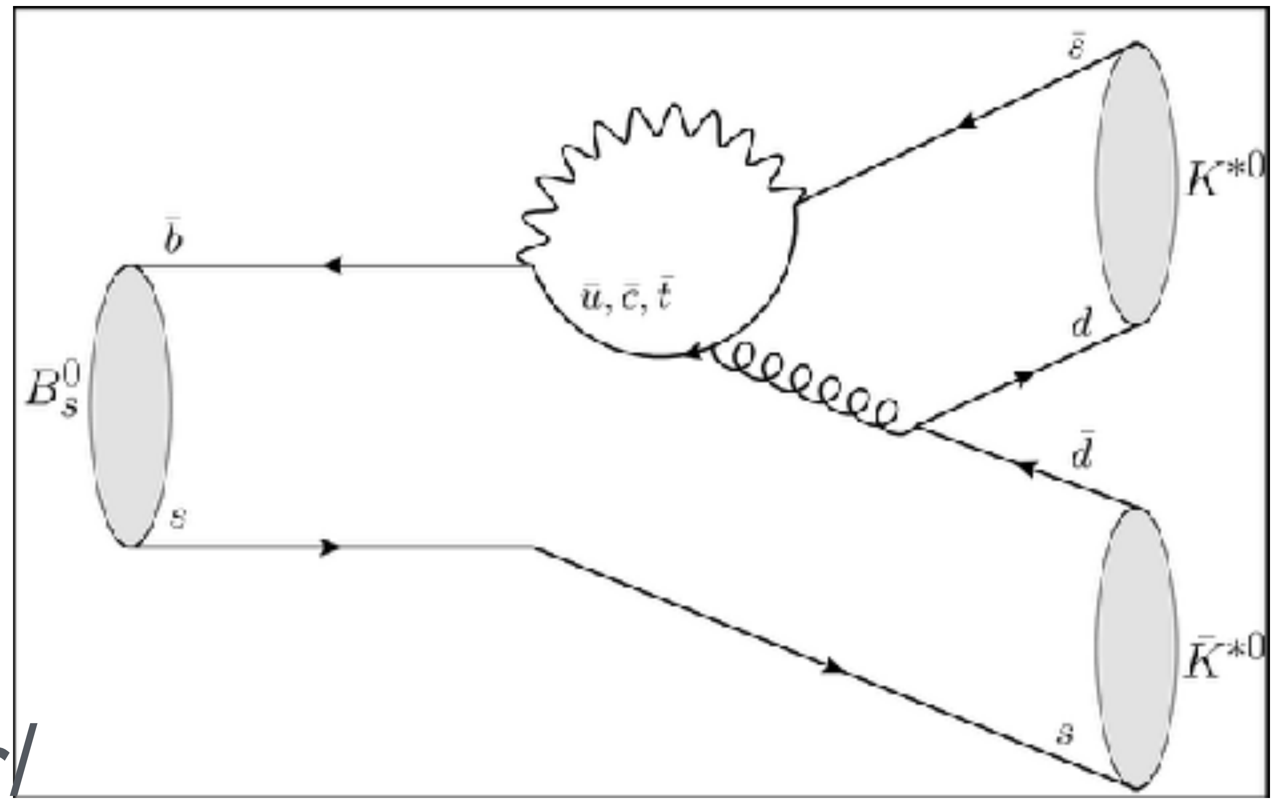
[Faller et al., PRD 79 (2009) 014030]
[Jung, PRD 86 (2012) 053008]
[De Bruyn, Fleischer, JHEP 03 (2015) 145]
[Frings et al., PRL 115 (2015) 061802]
[LHCb, PLB 742 (2015) 38]

ϕ_s from loop-dominated B_s^0 decays NEW

Measure CPV phase in $B_s^0 \to K^+\pi^-K^-\pi^+$ and $B_s^0 \to \varphi\varphi \to KKKK$. Compare to $B^0_s \to J/\psi\varphi$

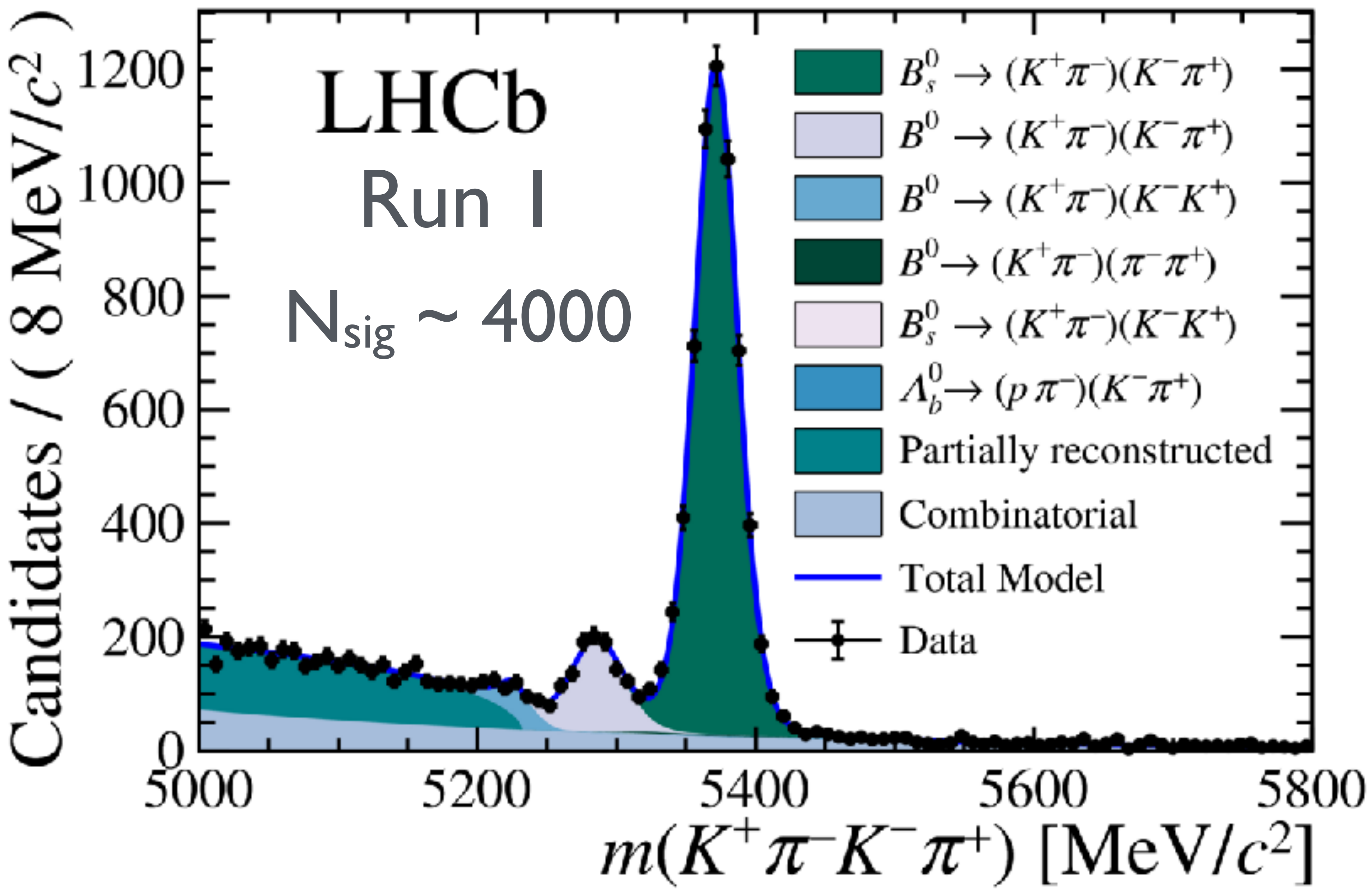
Use excellent hadron-PID for bkg suppression

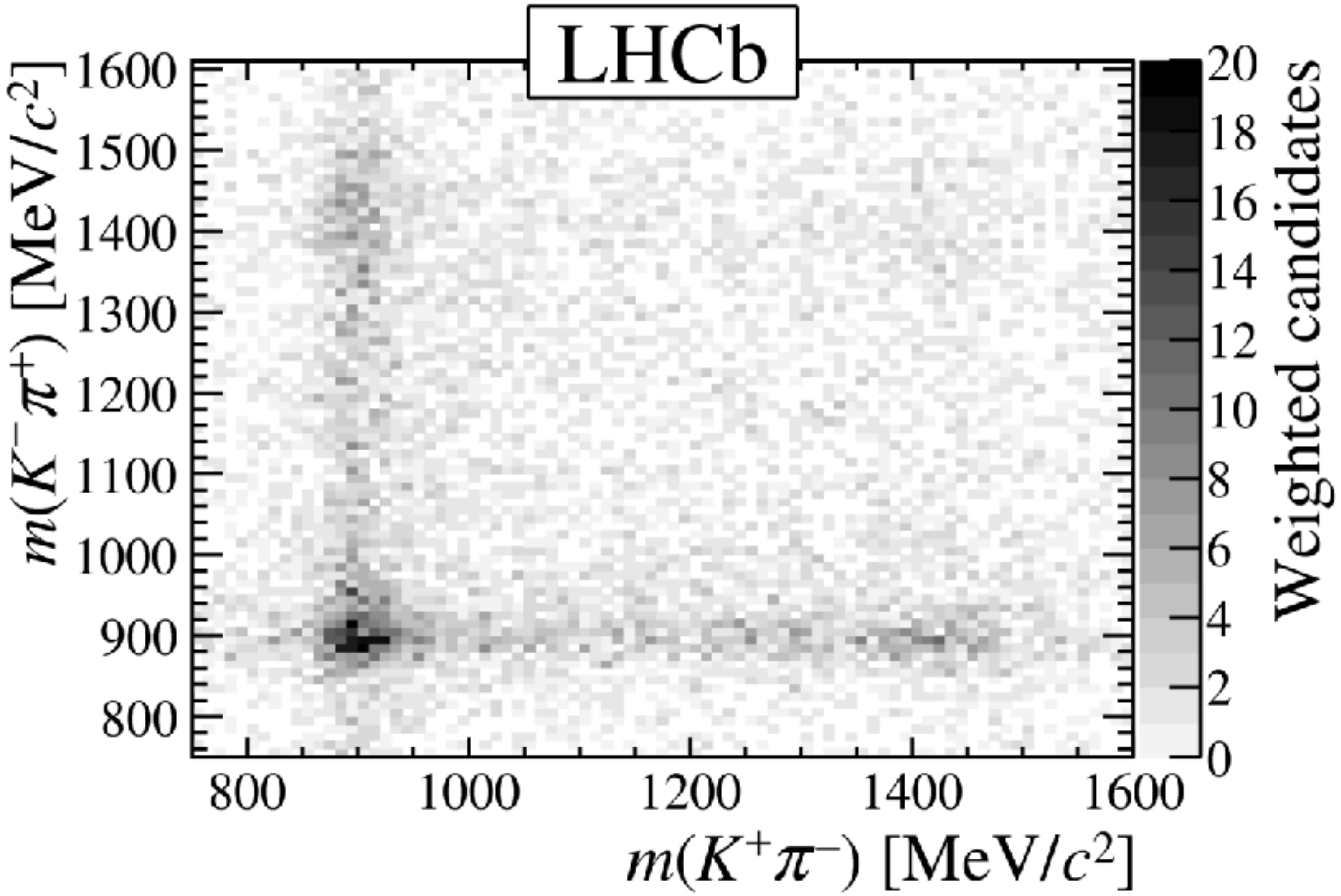
Very rich structure of interfering scalar/vector/tensor $K\pi$ resonances in $B_s^0 \to K^+\pi^-K^-\pi^+$



$$\phi_s^{d\bar{d}} = -0.10 \pm 0.13 \pm 0.14 \text{ rad}$$
$$\phi_s^{s\bar{s}} = -0.06 \pm 0.13 \pm 0.03 \text{ rad}$$

[arXiv:1712.08683] [LHCb-CONF-2018-001]





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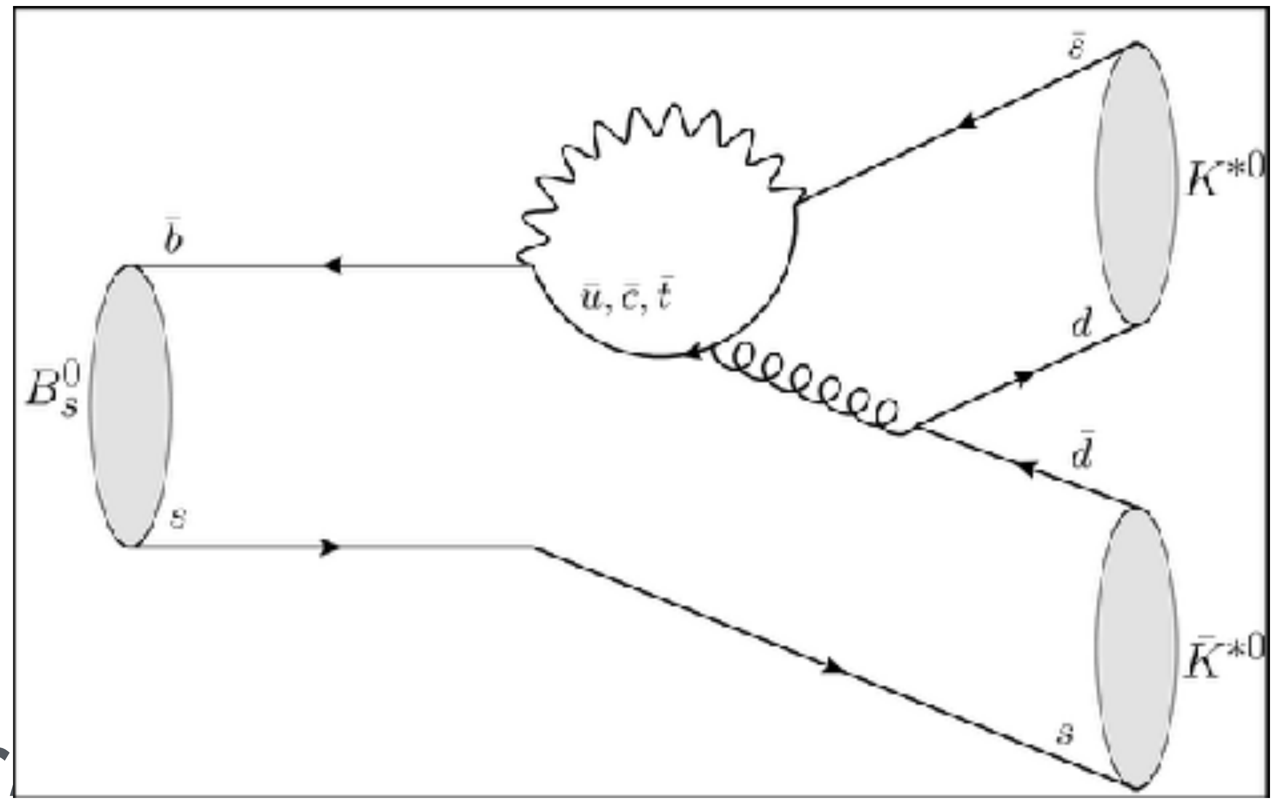

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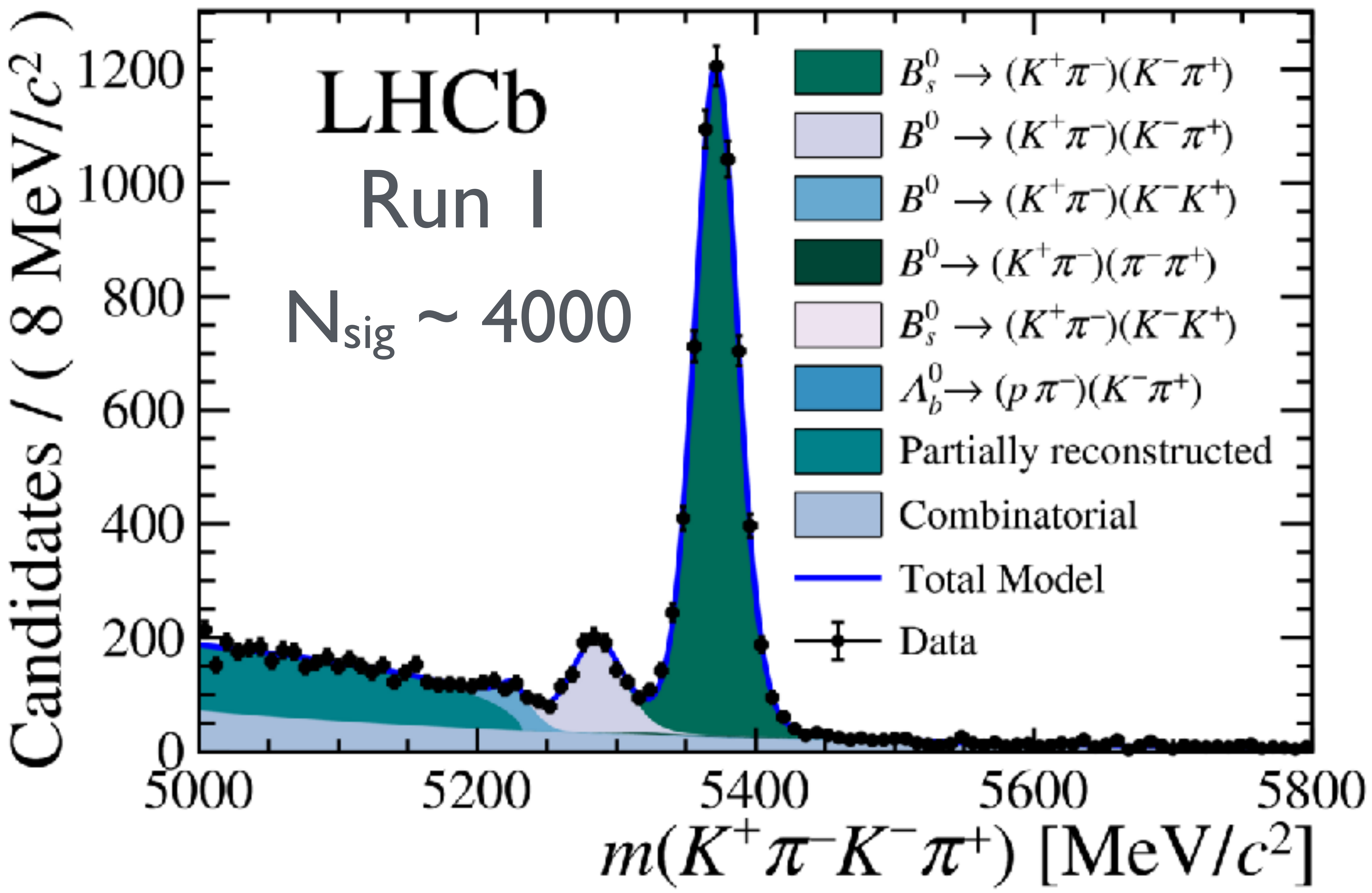
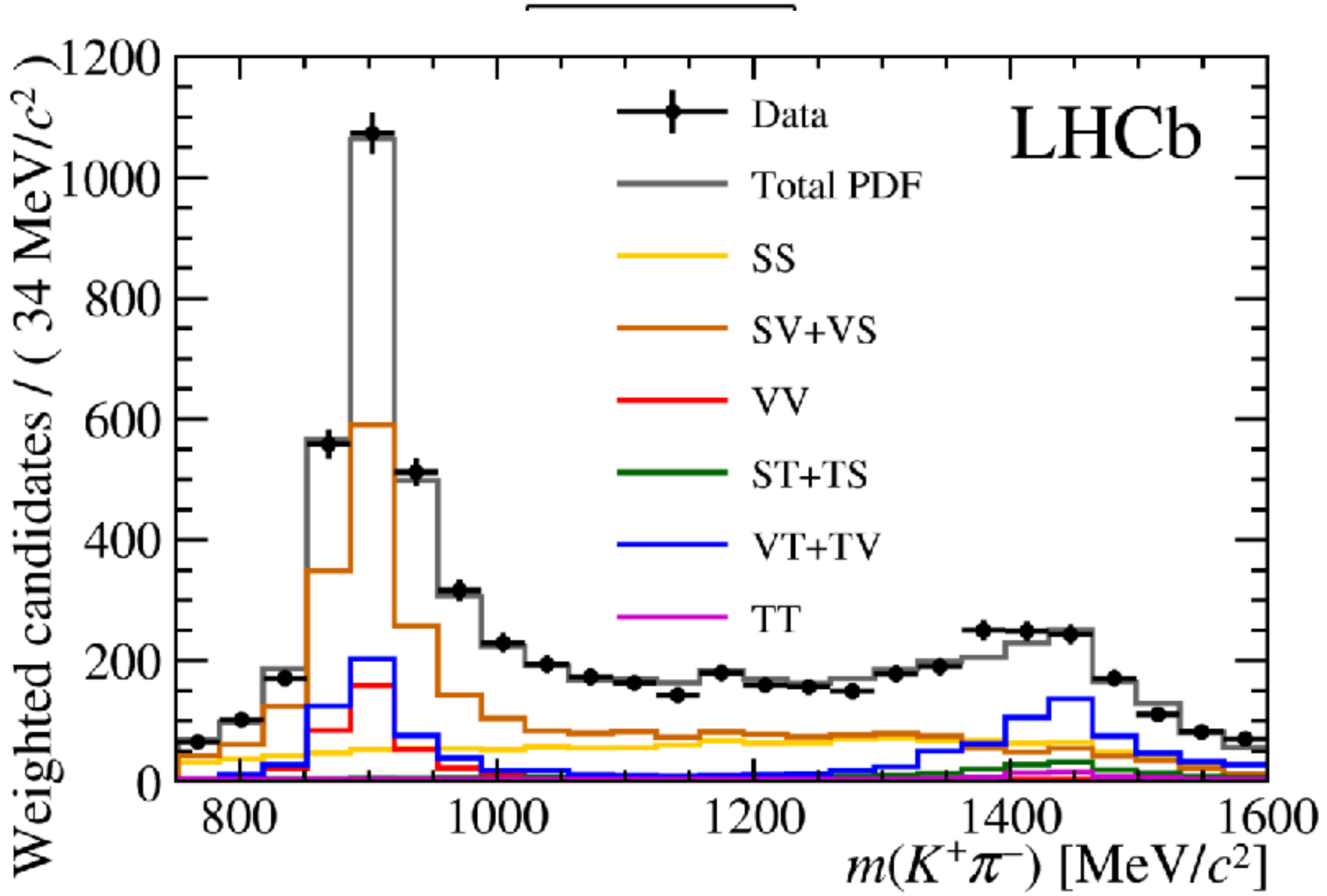
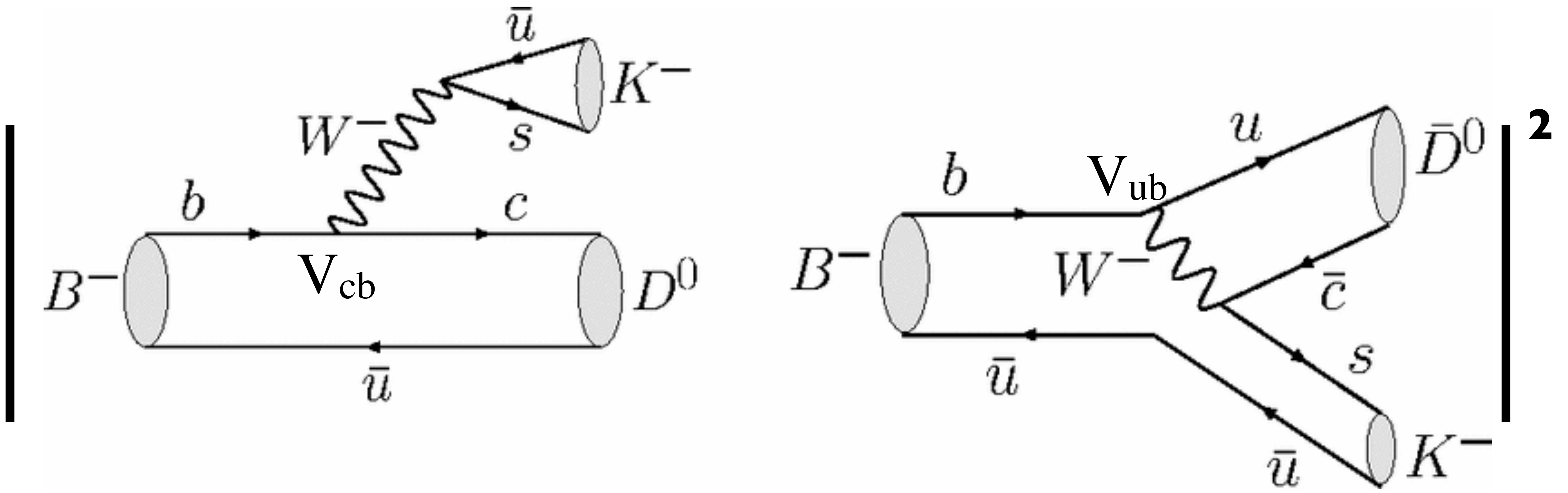




CKM angle γ

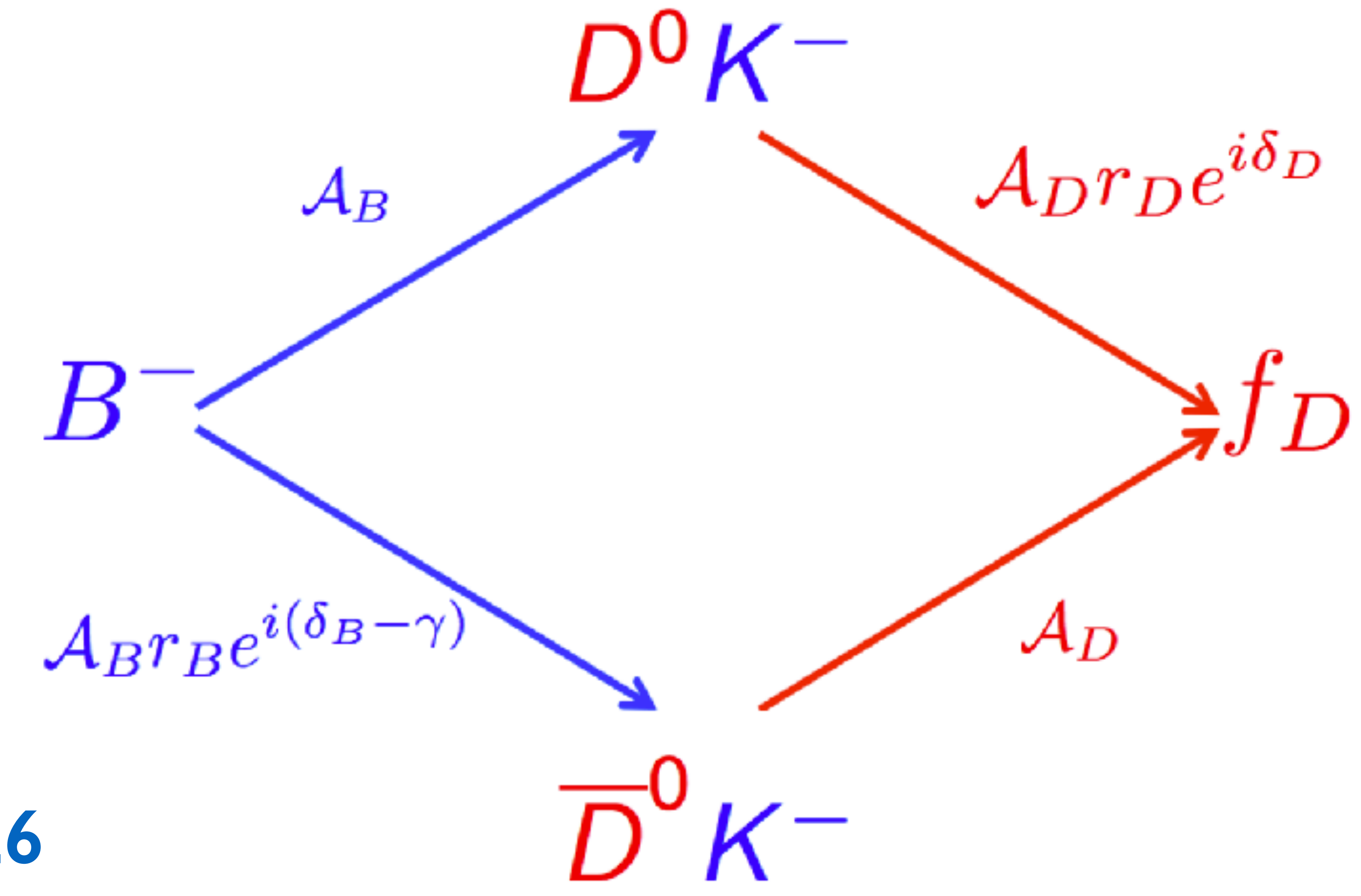
$$\gamma = arg\left[-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right]$$



Only CP-violating parameter that can be measured from tree-level decay $|\delta\gamma| \leq O(10^{-7})$

[Brod, Zupan JHEP 1401 (2014) 051]

Exploit interference between two tree-level amplitudes to same final state



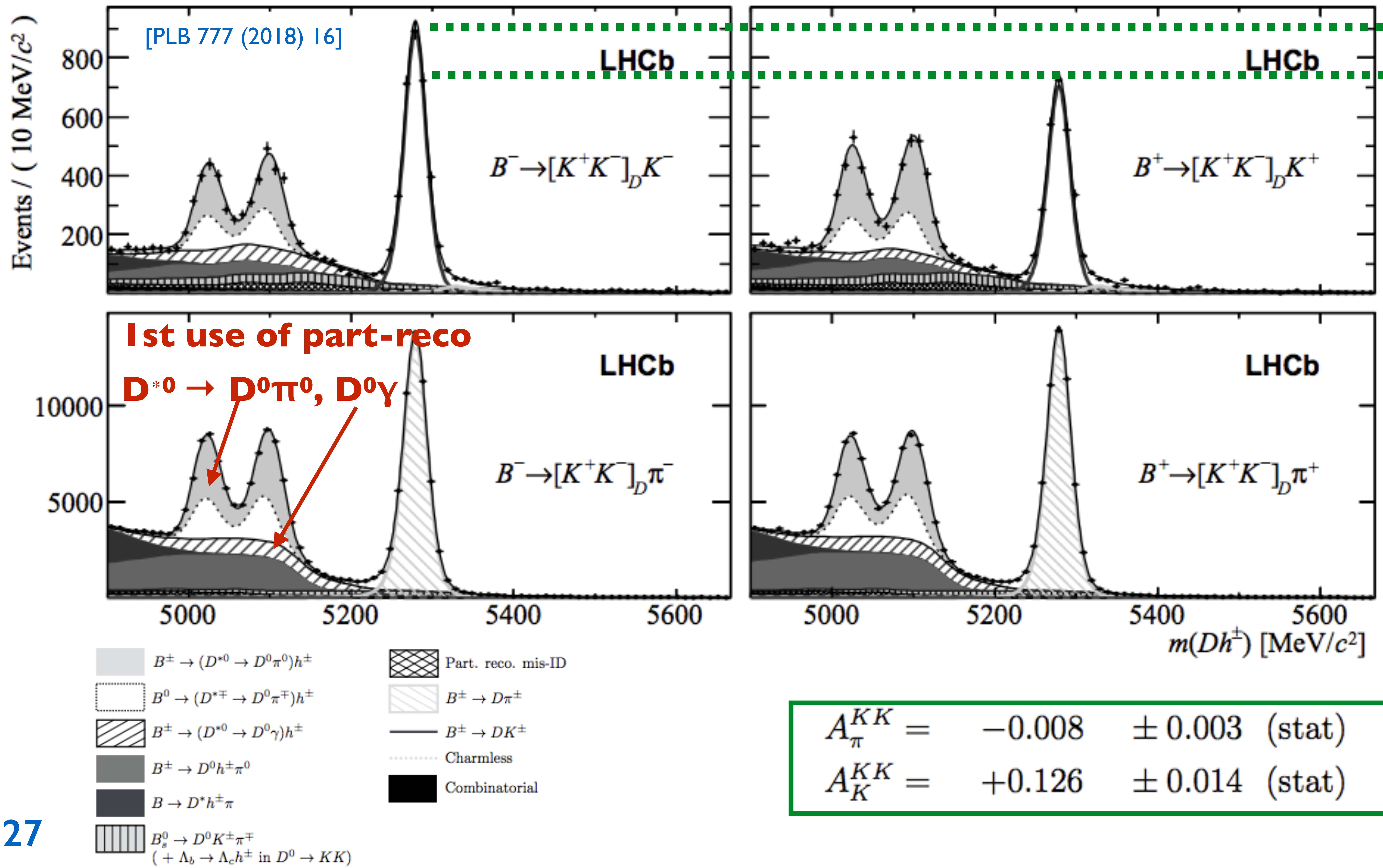
$$A_{CP} = \frac{\Gamma(B \to f) - \Gamma(\overline{B} \to f)}{\Gamma(B \to f) + \Gamma(\overline{B} \to f)} \sim r_B \sin\delta_B \sin\gamma$$

GLW ($f_D = K^+K^-, \pi^+\pi^-$) [PLB 253 (1991) 483, PLB 265 (1991) 172]
ADS ($f_D = K\pi$) [PRL 78 (1997) 3257]
GGSZ ($f_D = K_S\pi^+\pi^-$) [PRD 68 (2003) 054018]

Model-independent ADS+GGSZ approaches uses strong-phase measurements from CLEO, BES-III as input

CKM angle γ

$B^\pm \to D^0K^\pm, D^0\pi^\pm$



CP asymmetry in $B \to D^0K$ peaks related to γ, r^{DK}, δ^{DK} in GLW method

Uses 5 fb^{-1} (run 1+2)

$B^\pm \to [K^\pm pi^\mp]_D \pi^\pm$ control mode to understand small production and detection asymmetries

$$A_\pi^{KK} = -0.008 \pm 0.003\ (\text{stat}) \pm 0.002\ (\text{syst})$$
$$A_K^{KK} = +0.126 \pm 0.014\ (\text{stat}) \pm 0.002\ (\text{syst})$$

γ combination

Use several B → DK measurements (85 observables, 37 parameters)

Many more Run-2 updates and channels expected soon

Expect O(1°) precision after LHCb upgrade

[JHEP 12 (2016) 087]

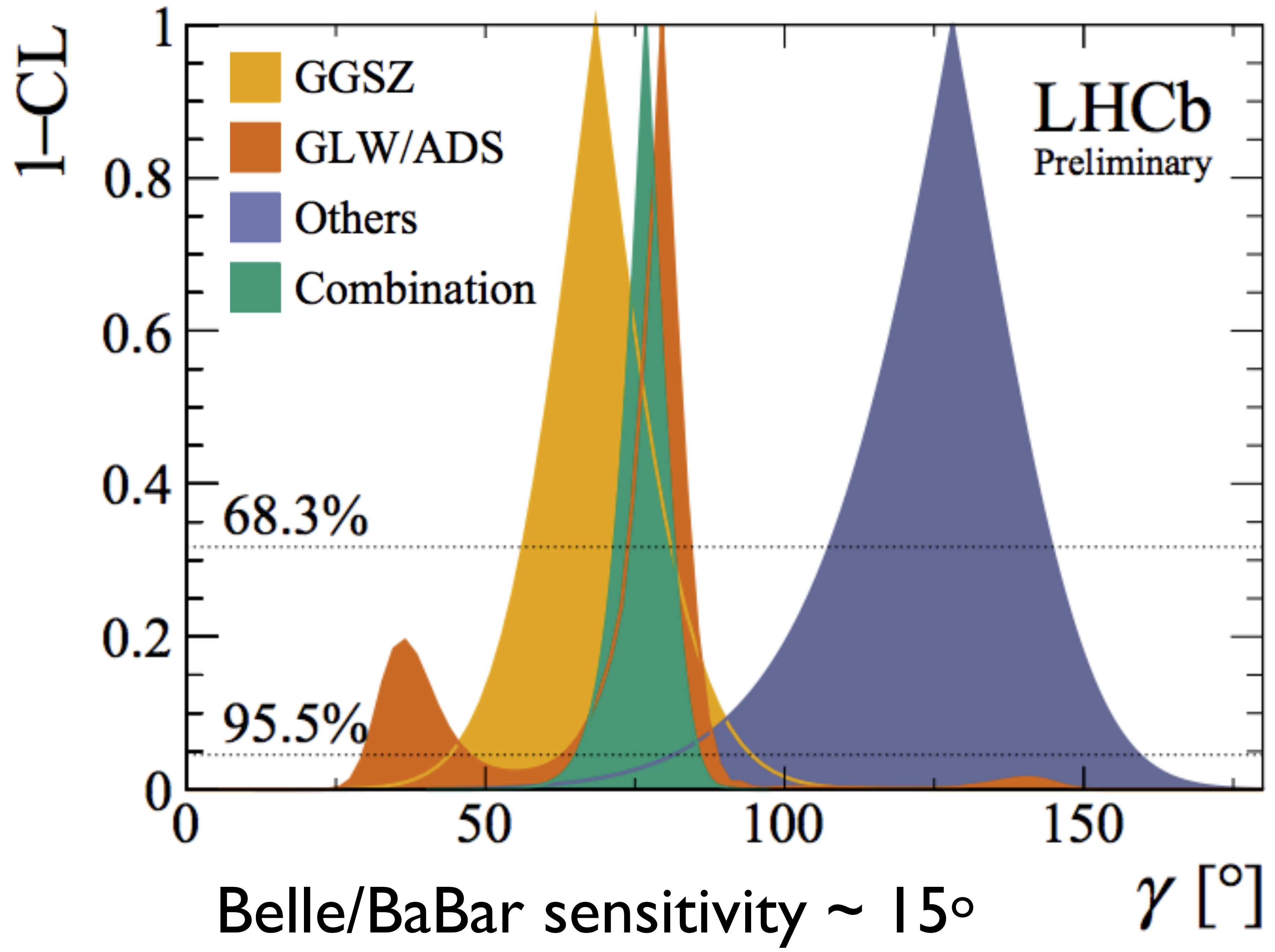
B decay	D decay	Method	Ref.	Status since last combination
$B^+ \to DK^+$	$D \to h^+h^-$	GLW	[16]	Updated to Run 1 + $2\,\mathrm{fb}^{-1}$ Run 2
$B^+ \to DK^+$	$D \to h^+h^-$	ADS	[17]	As before
$B^+ \to DK^+$	$D \to h^+\pi^-\pi^+\pi^-$	GLW/ADS	[17]	As before
$B^+ \to DK^+$	$D \to h^+h^-\pi^0$	GLW/ADS	[18]	As before
$B^+ \to DK^+$	$D \to K^0_S h^+h^-$	GGSZ	[19]	As before
$B^+ \to DK^+$	$D \to K^0_S K^+\pi^-$	GLS	[20]	As before
$B^+ \to D^*K^+$	$D \to h^+h^-$	GLW	[16]	New
$B^+ \to DK^{*+}$	$D \to h^+h^-$	GLW/ADS	[21]	New
$B^+ \to DK^+\pi^+\pi^-$	$D \to h^+h^-$	GLW/ADS	[22]	As before
$B^0 \to DK^{*0}$	$D \to K^+\pi^-$	ADS	[23]	As before
$B^0 \to DK^+\pi^-$	$D \to h^+h^-$	GLW-Dalitz	[24]	As before
$B^0 \to DK^{*0}$	$D \to K^0_S\pi^+\pi^-$	GGSZ	[25]	As before
$B^0_s \to D^{\mp}_s K^{\pm}$	$D^+_s \to h^+h^-\pi^+$	TD	[26]	Updated to $3\,\mathrm{fb}^{-1}$ Run 1

backup (→ $B^+ \to DK^{*+}$)

backup (→ $B^0_s \to D^{\mp}_s K^{\pm}$)

[LHCb-CONF-2017-004] $\gamma = (76.8^{+5.1}_{-5.7})^\circ$

[HFLAV average] $\gamma = (76.2^{+4.7}_{-5.0})^\circ$



Belle/BaBar sensitivity ~ 15°

New CPV measurements sensitive to 2β+γ or -2β_s+γ

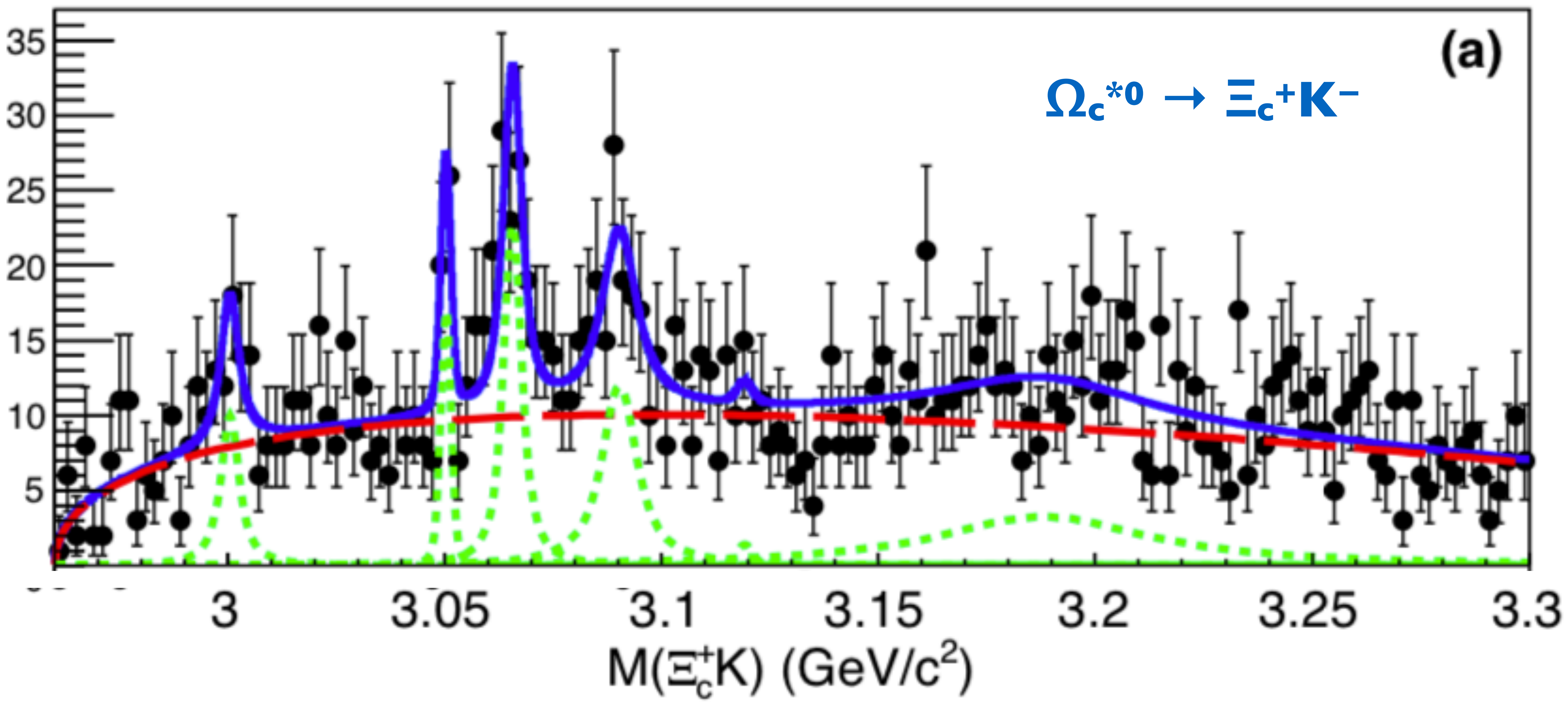
- $B^0 \to D^{\mp}\pi^{\pm}$ [LHCb-PAPER-2018-009]
- $B^0_s \to D^{\mp}_s K^{\pm}$ [JHEP 03 (2018) 059]

NEW

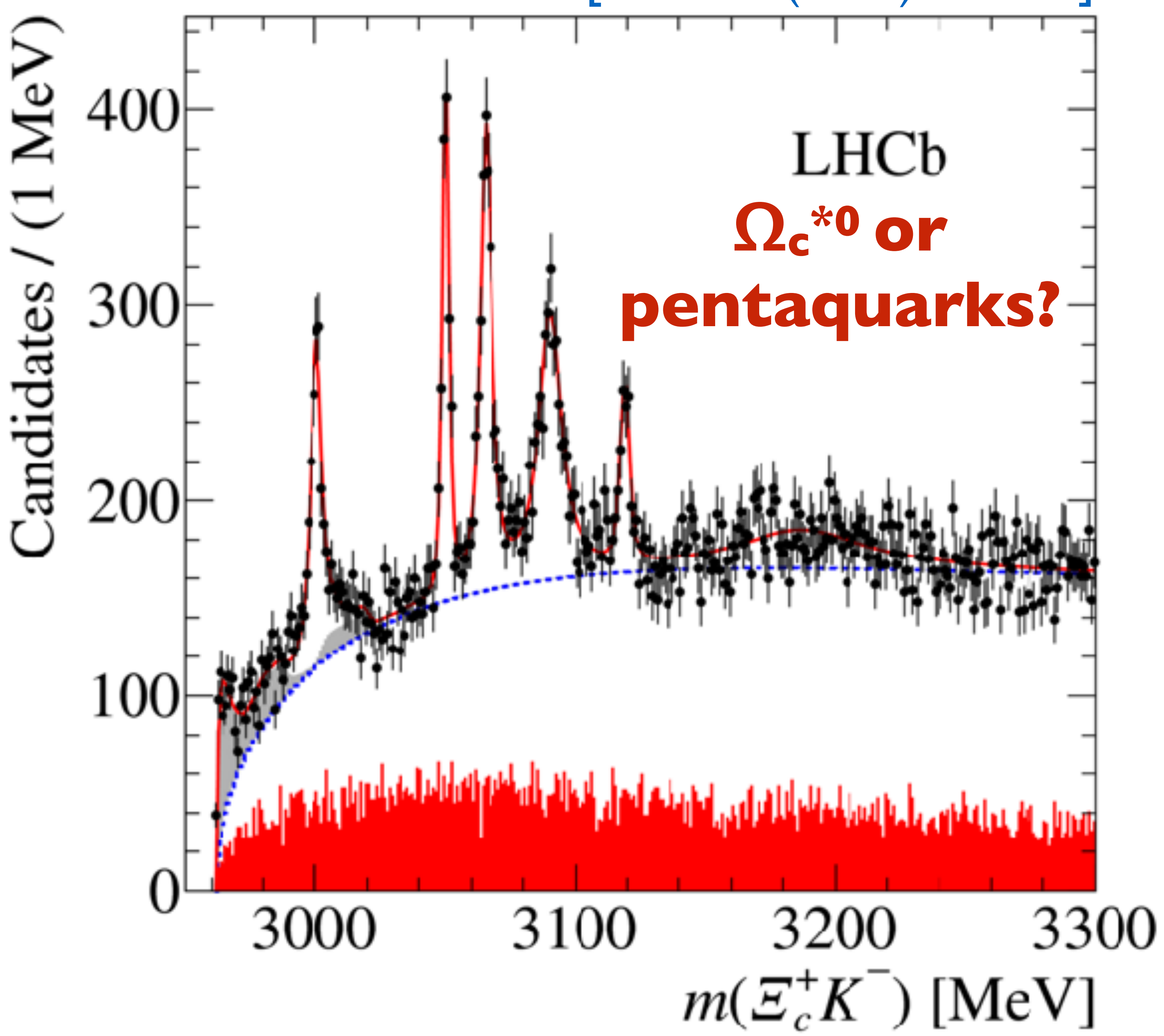
3.8σ evidence for time-dep B_s^0 CPV

Spectroscopy

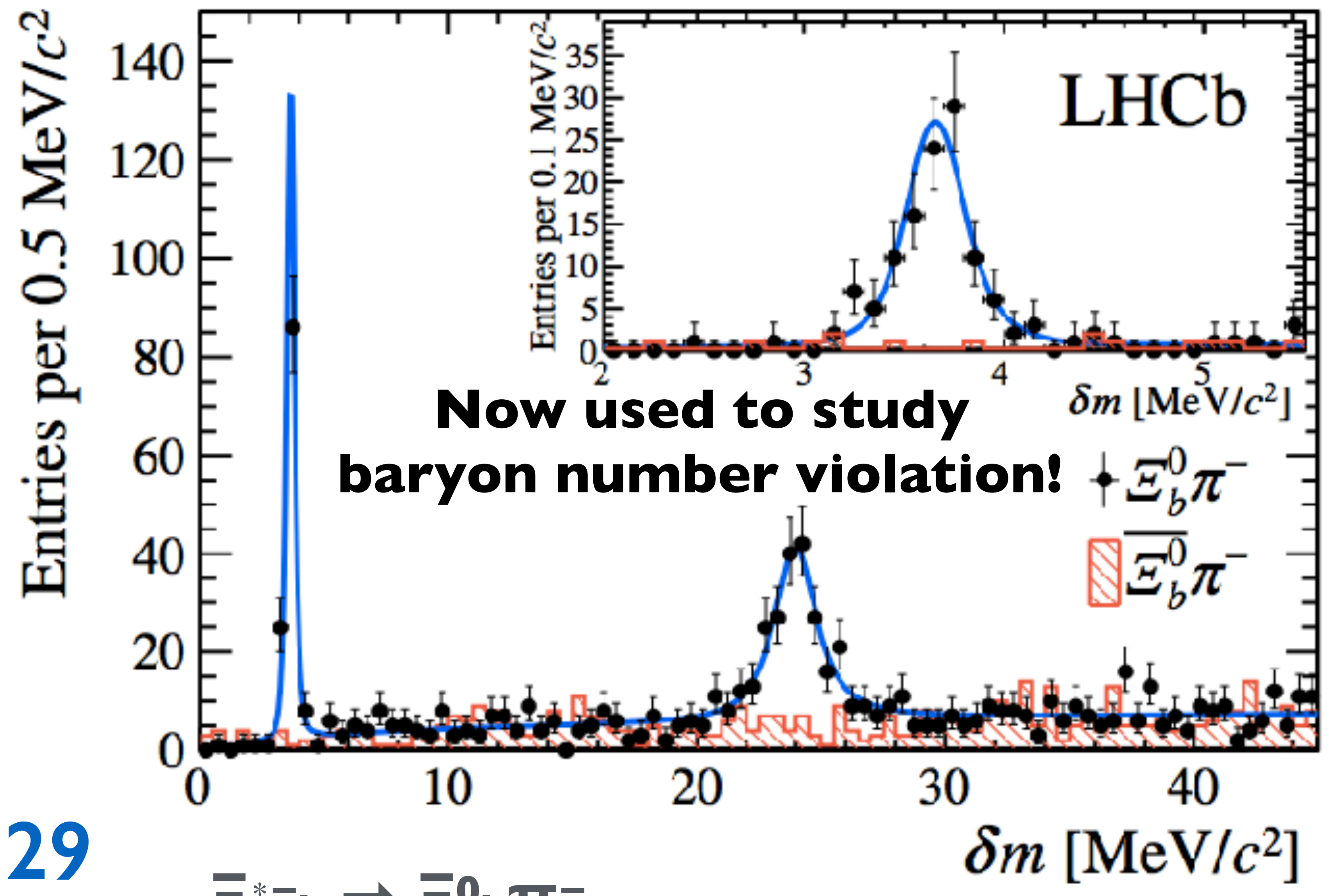
[Belle arXiv:1711.07927]



[PRL 118 (2017) 182001]

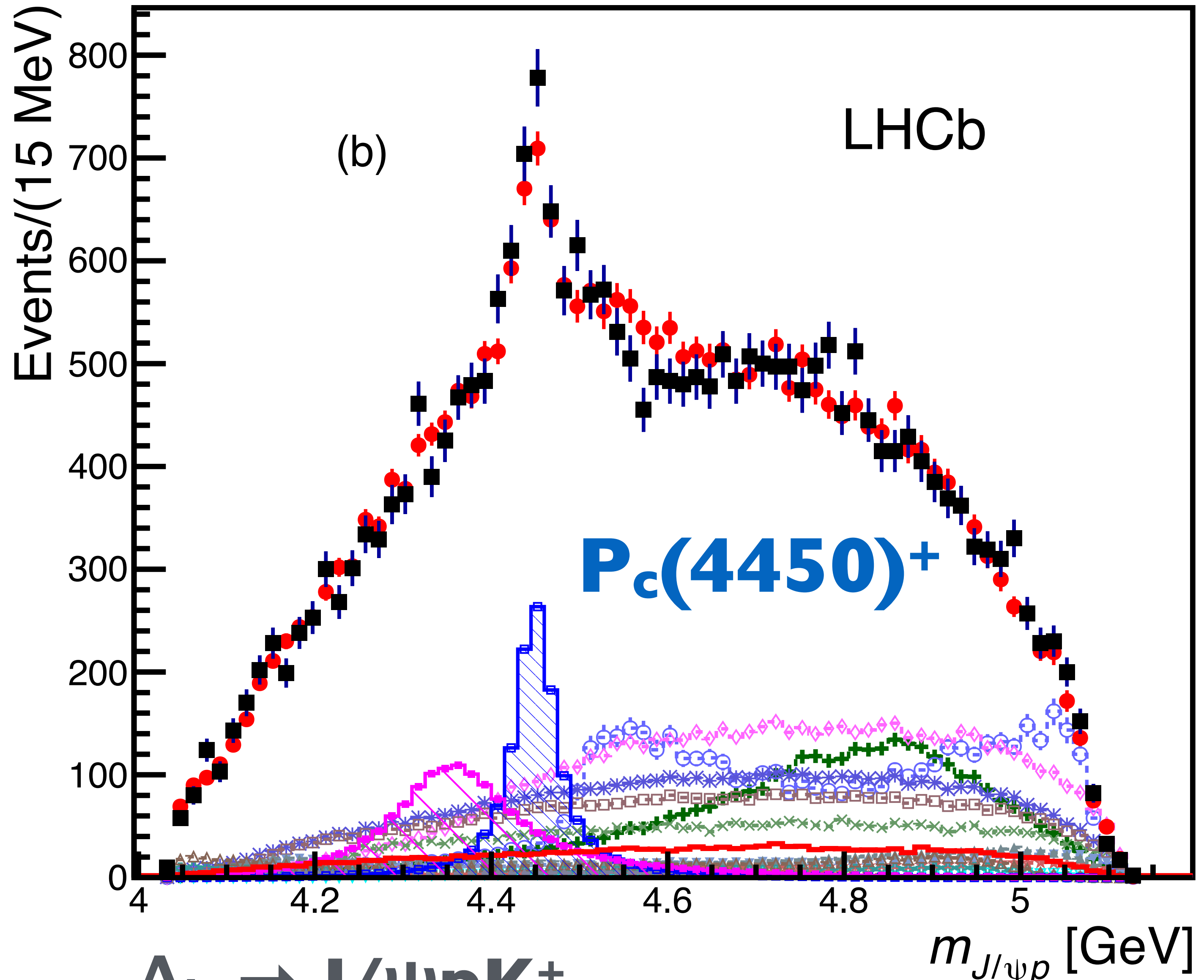


[PRL 119 (2017) 181807]



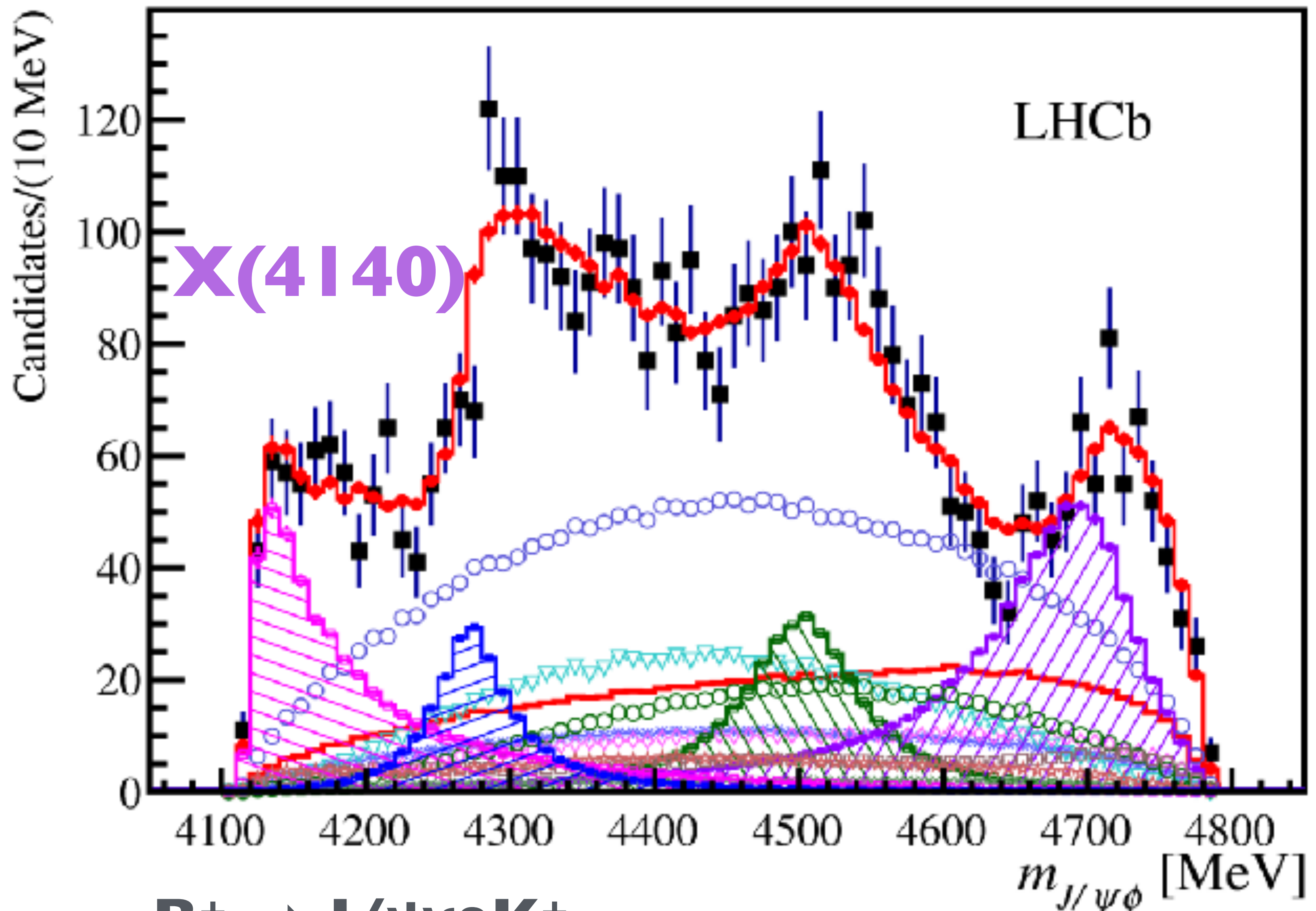
$\Xi^{*-}_b \to \Xi^0_b \pi^-$

[PRL 115 (2015) 072001]



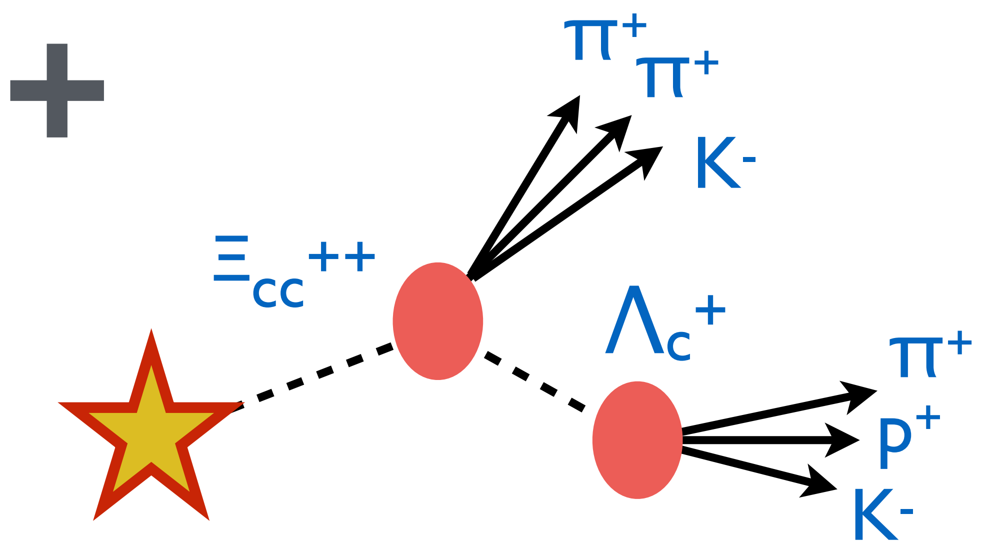
$\Lambda_b \to J/\psi p K^+$

[PRL 118 (2017) 022003]

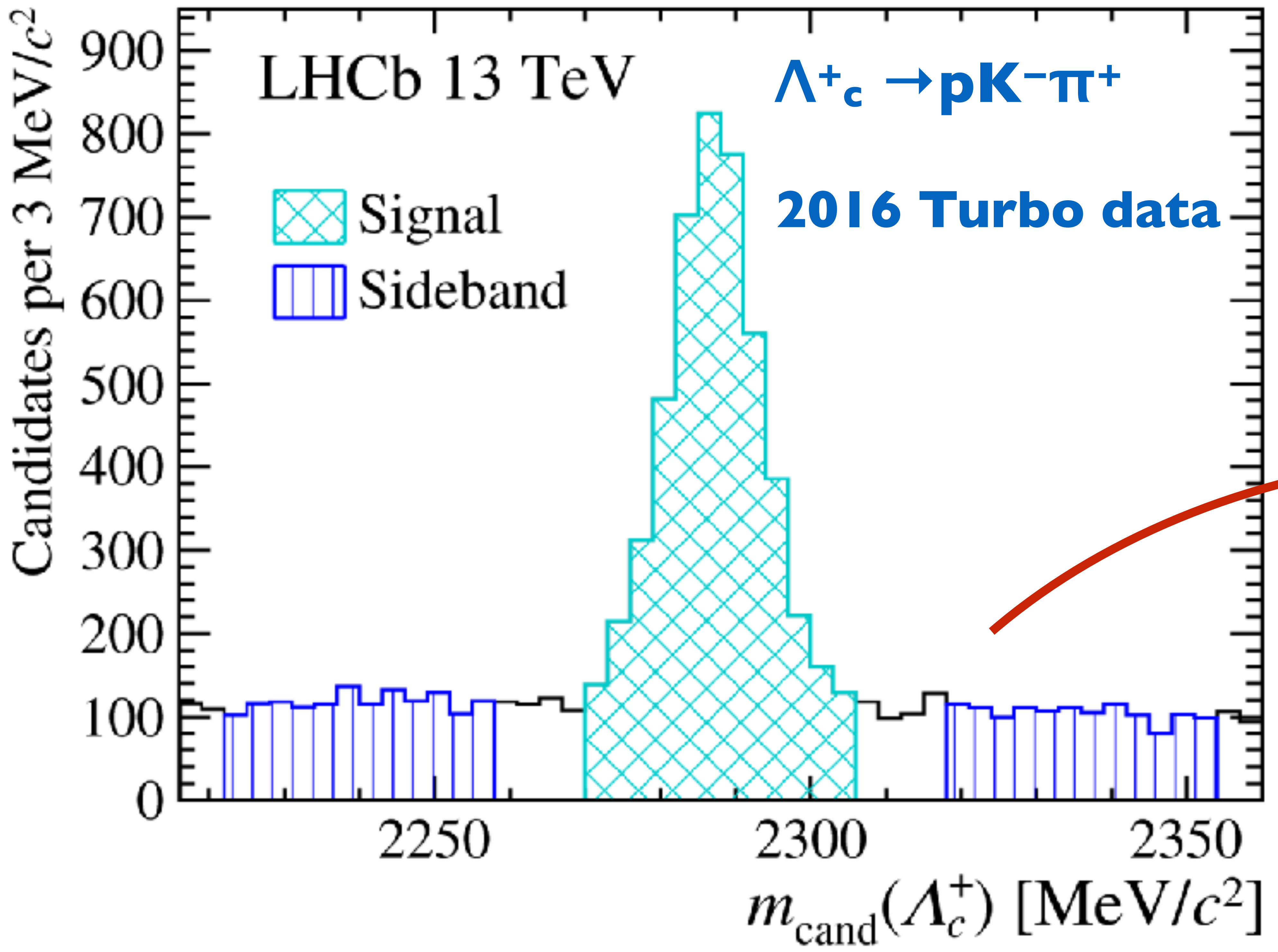


$B^+ \to J/\psi \varphi K^+$

Doubly-charmed baryon, Ξ_{cc}^{++}

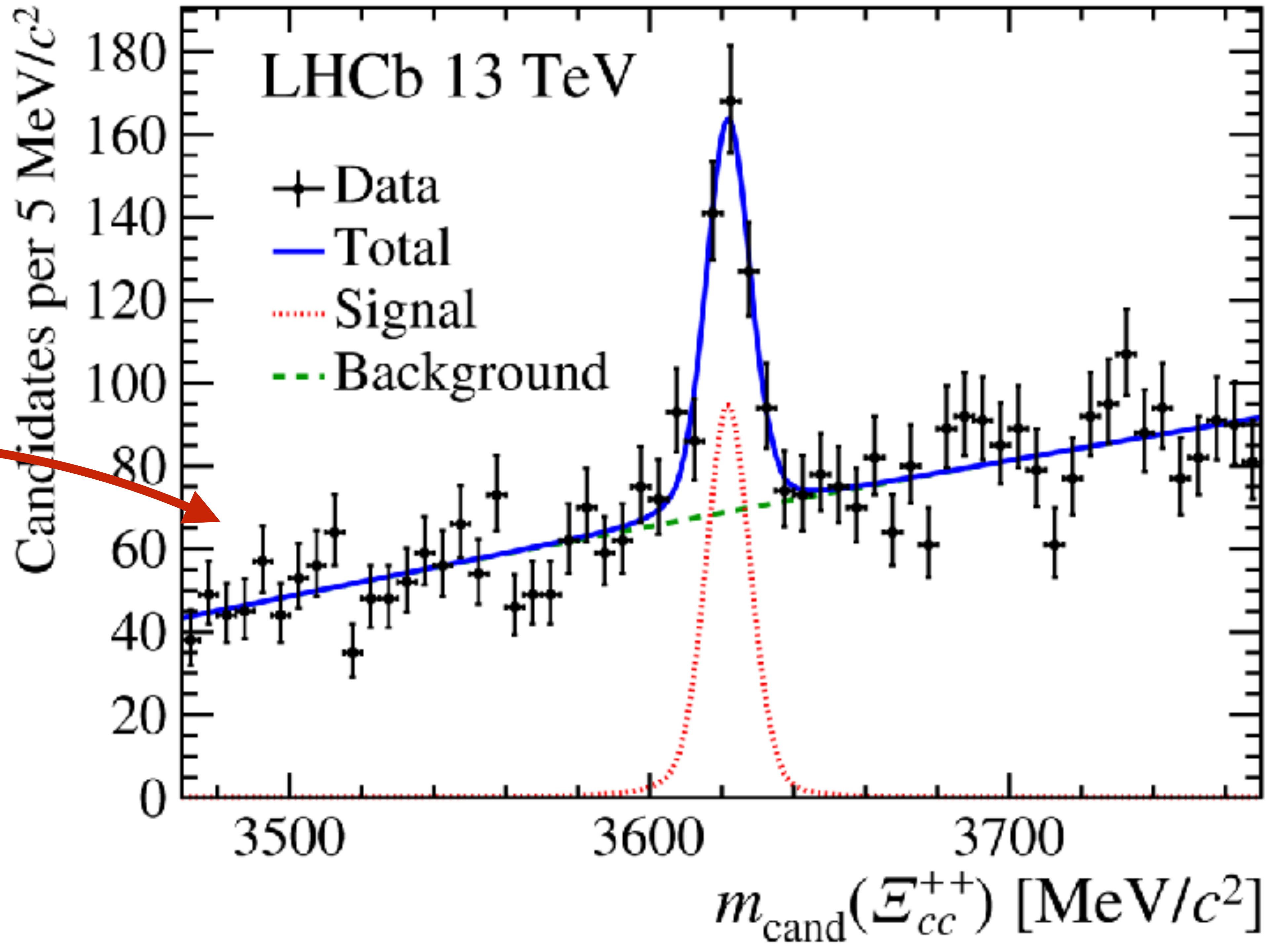


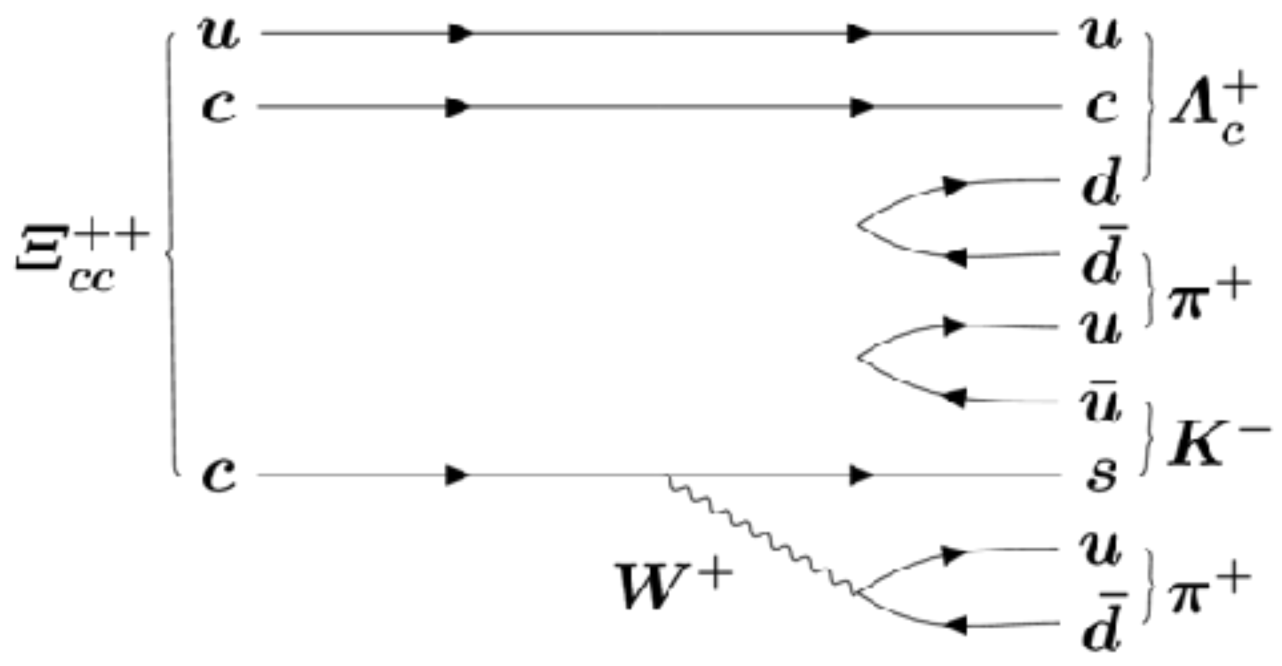
[PRL 119 (2017) 112001]



Add $K^-\pi^+\pi^+$

resolution ~7 MeV





>12σ significant signal observed consistent with a **weakly** decaying state [link] and many theory predictions e.g. Lattice [Alexandrou PRD 96 (2017) 034511]

$m(\Xi_{cc}^{++})$ = 3621.40 ± 0.72 (stat) ± 0.27 (syst) ± 0.14 (Λ_c^+) MeV

See talk: M.Traill

Quark-level analogue of nuclear fusion

The recent discovery of the first doubly charmed baryon…revealed a large binding energy of about 130 MeV between the two charm quarks. Here we report that this strong binding enables a quark-rearrangement, exothermic reaction $\Lambda_c\Lambda_c \to n\Xi_{cc}^{++}$, resulting in an energy release of 12 MeV. This reaction is a quark-level analogue of the deuterium-tritium nuclear fusion reaction…

At present, however, the very short lifetimes of the heavy bottom and charm quarks preclude any practical applications of such reactions.

[Karliner, Rosner Nature 551 (2017) 89]

X(5568)$^{\pm}$ → $B_s\pi^{\pm}$?

~5σ claim for ***bsud*** tetraquark/molecule, but difficult to explain when considering QCD chiral symmetry, heavy quark symmetry and threshold effects

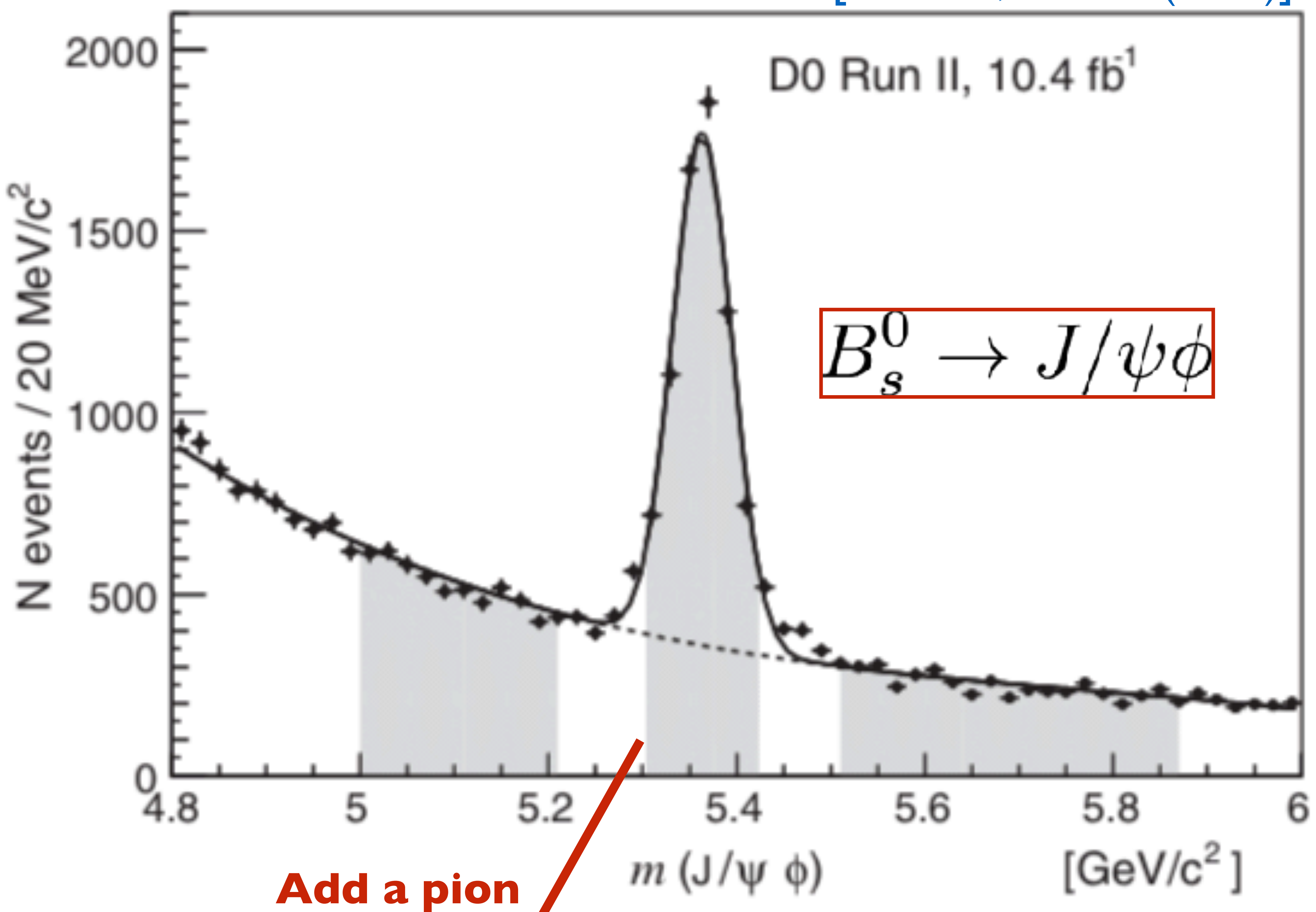
[Liu, Li, arXiv:1603.04366]
[Burns, Swanson, arXiv:1603.04366]
[Guo et al, arXiv:1603.06316]

Large B_s production fraction: ρ_X = (8.6 ± 1.9 ± 1.4)%

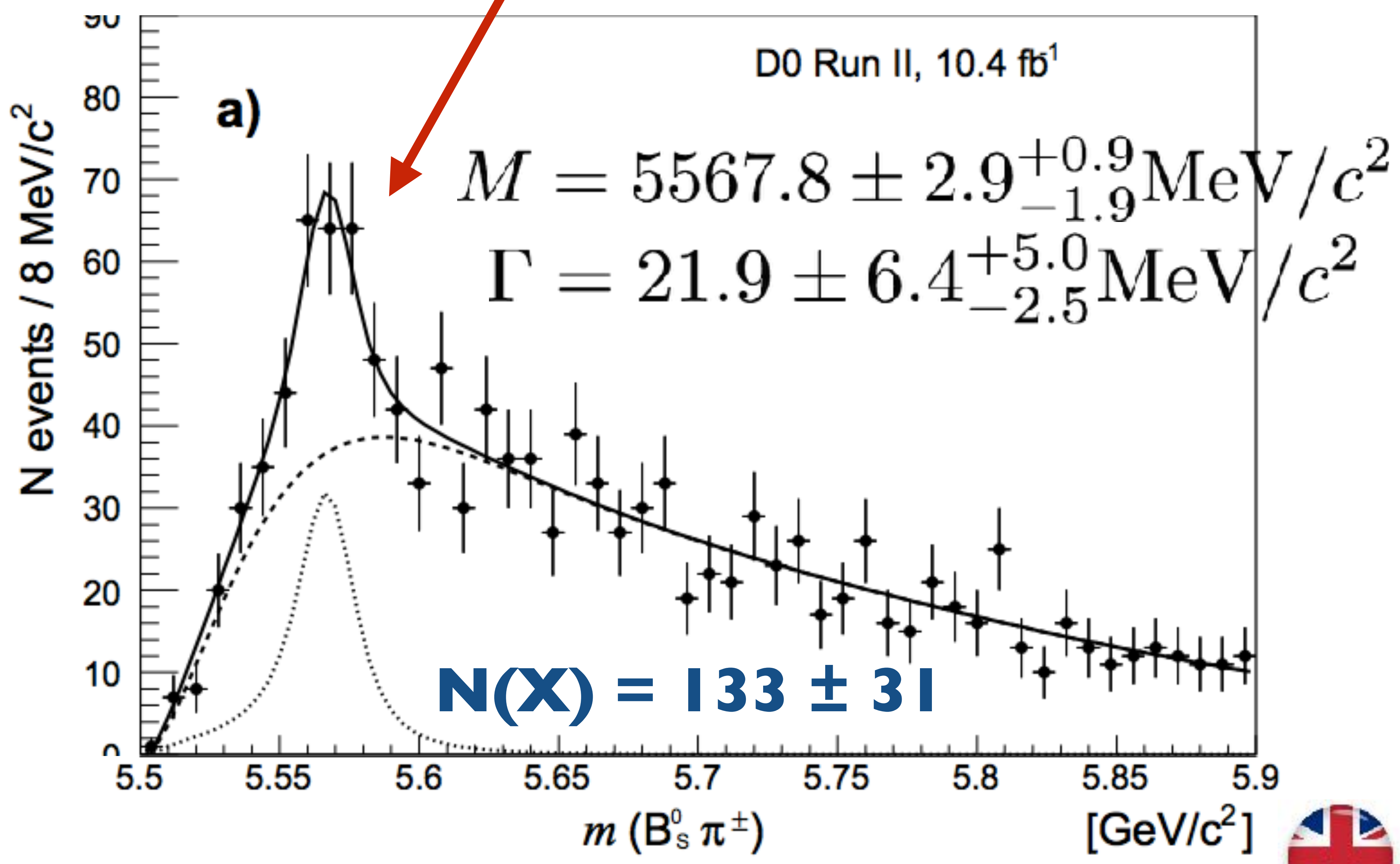
Not due to reflections from kaons/pions

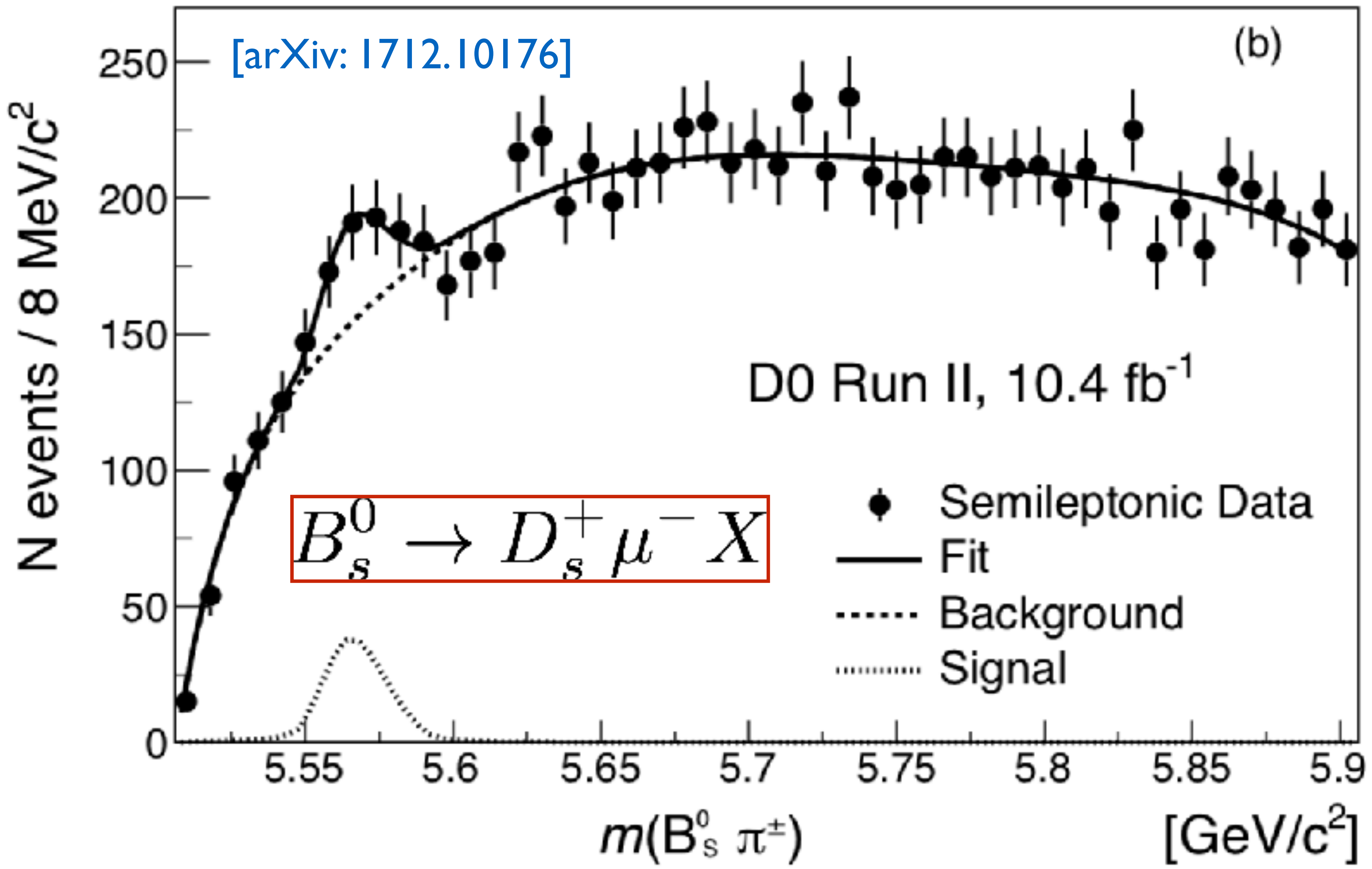
No sign on the lattice [Lang et al., PRD 94 074509 (2016)]

[PRL 117, 022003 (2016)]



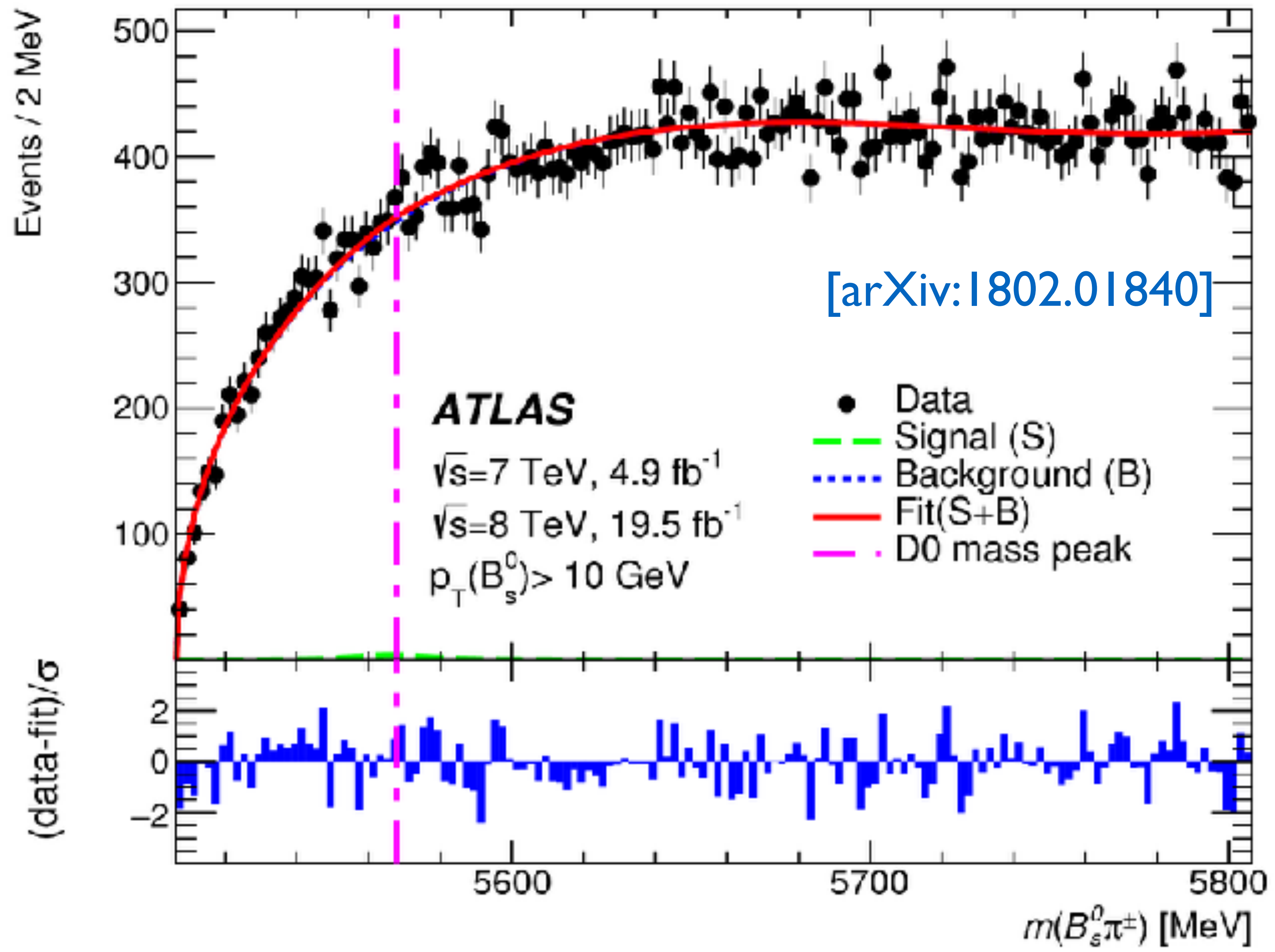
Add a pion

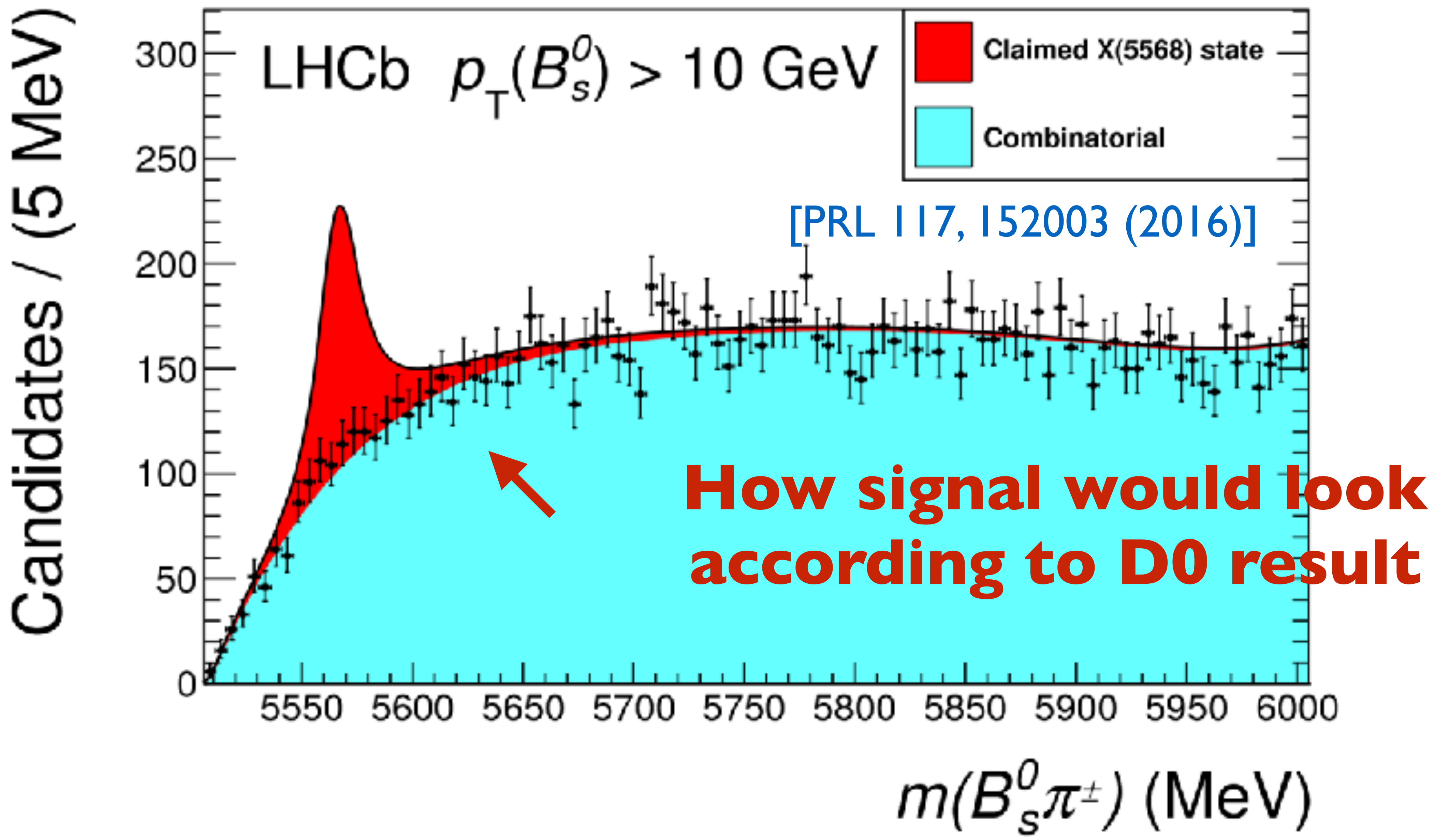


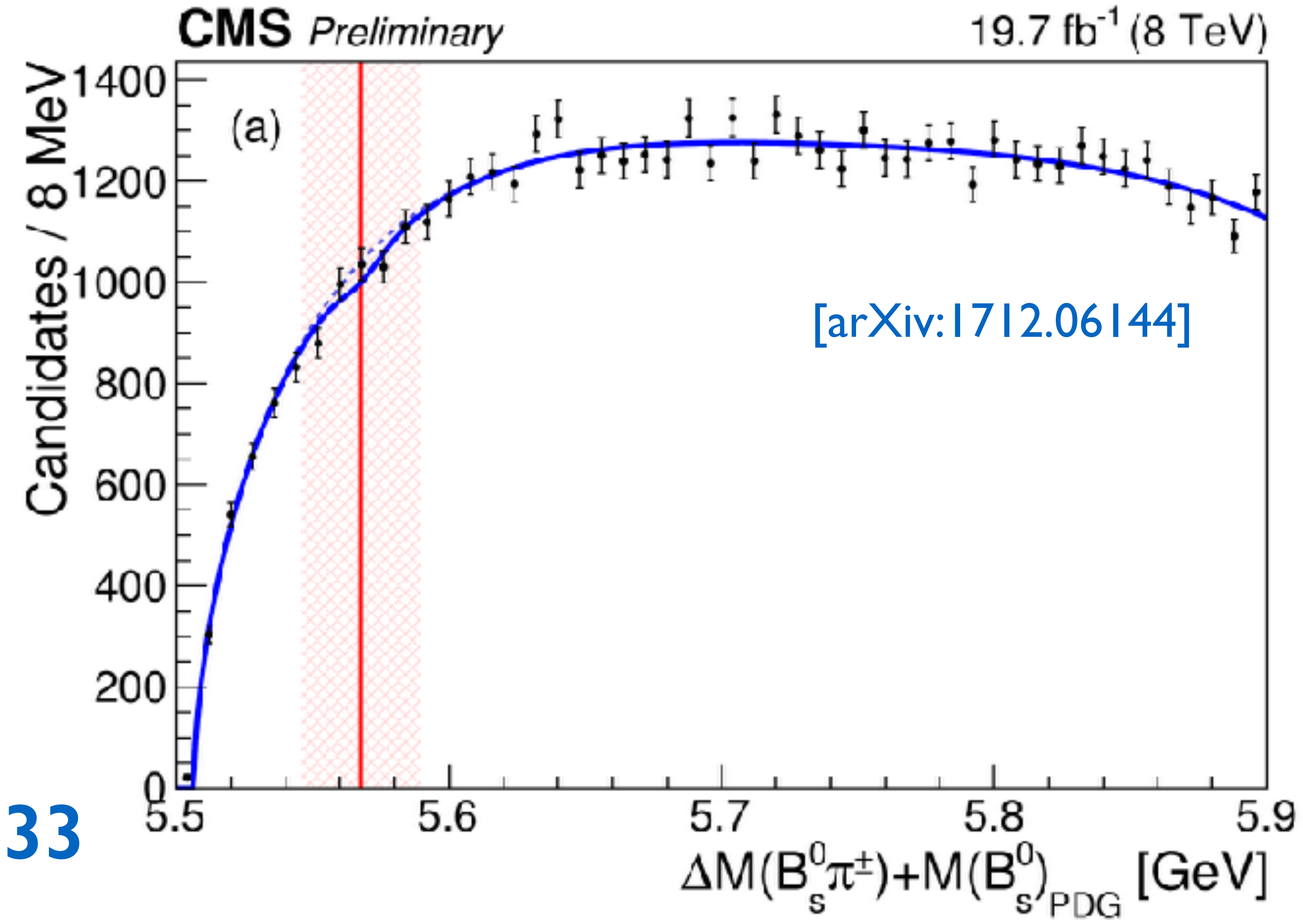


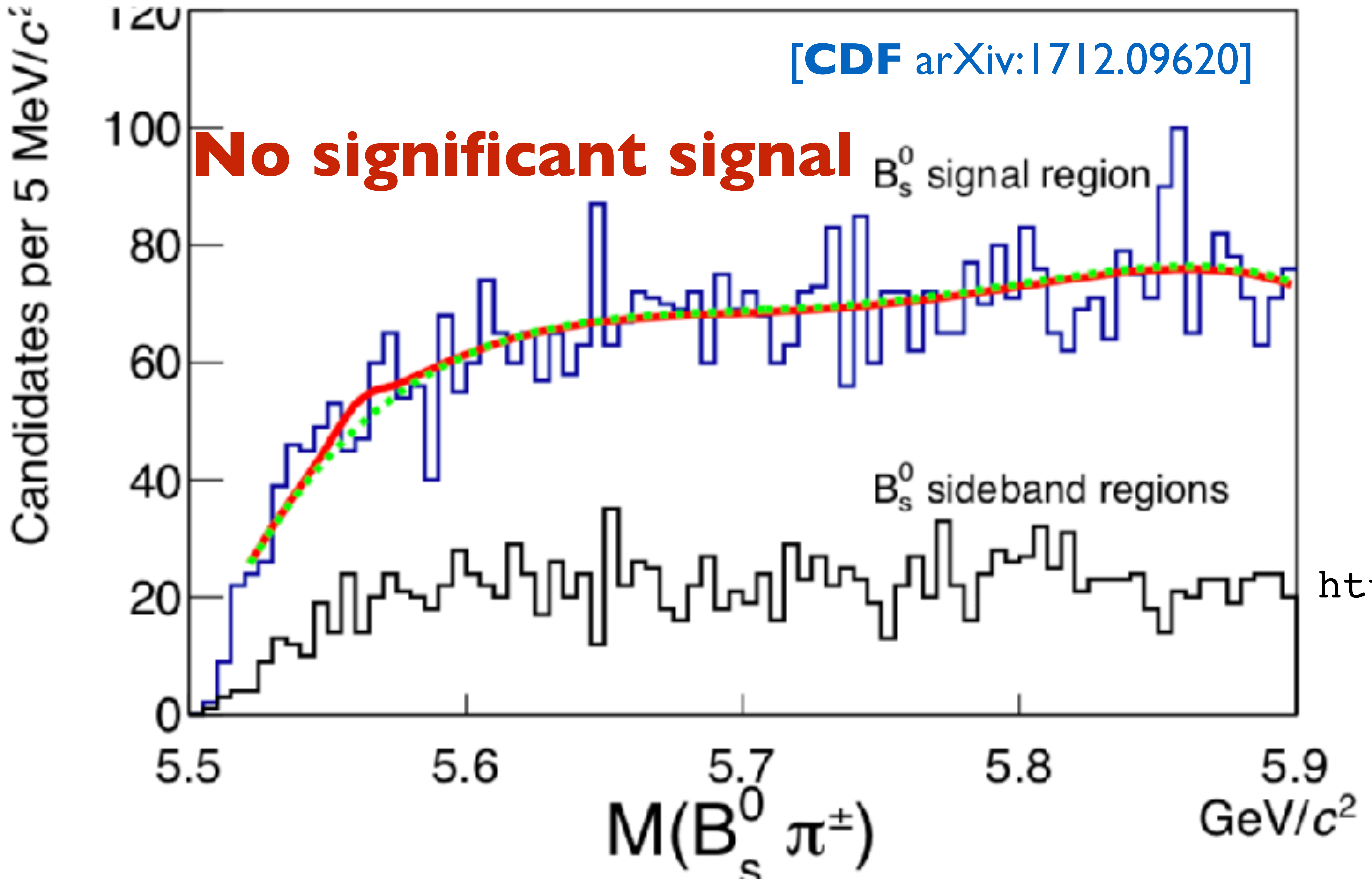
Null searches for X(5568)$^\pm$

$p_T(B_s^0) > 10$ GeV	ρ_X @ 95% CL
CMS	< 0.010
ATLAS	< 0.016
LHCb	< 0.018
CDF	< 0.067









Different kinematics (pT, |η|) for CDF vs D0?

http://moriond.in2p3.fr/QCD/2018/MondayMorning/Hirosky.pdf

The next ~20 years…

LHC phase 2 (HL-LHC) →

We are here (Run 2)

visible int/bunch crossing	~1	~1	~6	~6	~55
inst $\mathcal{L}_{LHCb}$ $cm^{-2}s^{-1}$	4×10^{32}	4×10^{32}	2×10^{33}	2×10^{33}	$1\text{-}2\times10^{34}$
$\int dt\, \mathcal{L}_{LHCb}$	$3\ fb^{-1}$	$9\ fb^{-1}$		$50\ fb^{-1}$	$300\ fb^{-1}$
	2011-2012 Run 1	2015-2018 Run 2	2021-2023 Run 3	2026-2029 Run 4	2031-… Run 5/6

LS2: install LHCb upgrade I

LS3: upgrade I consolidation

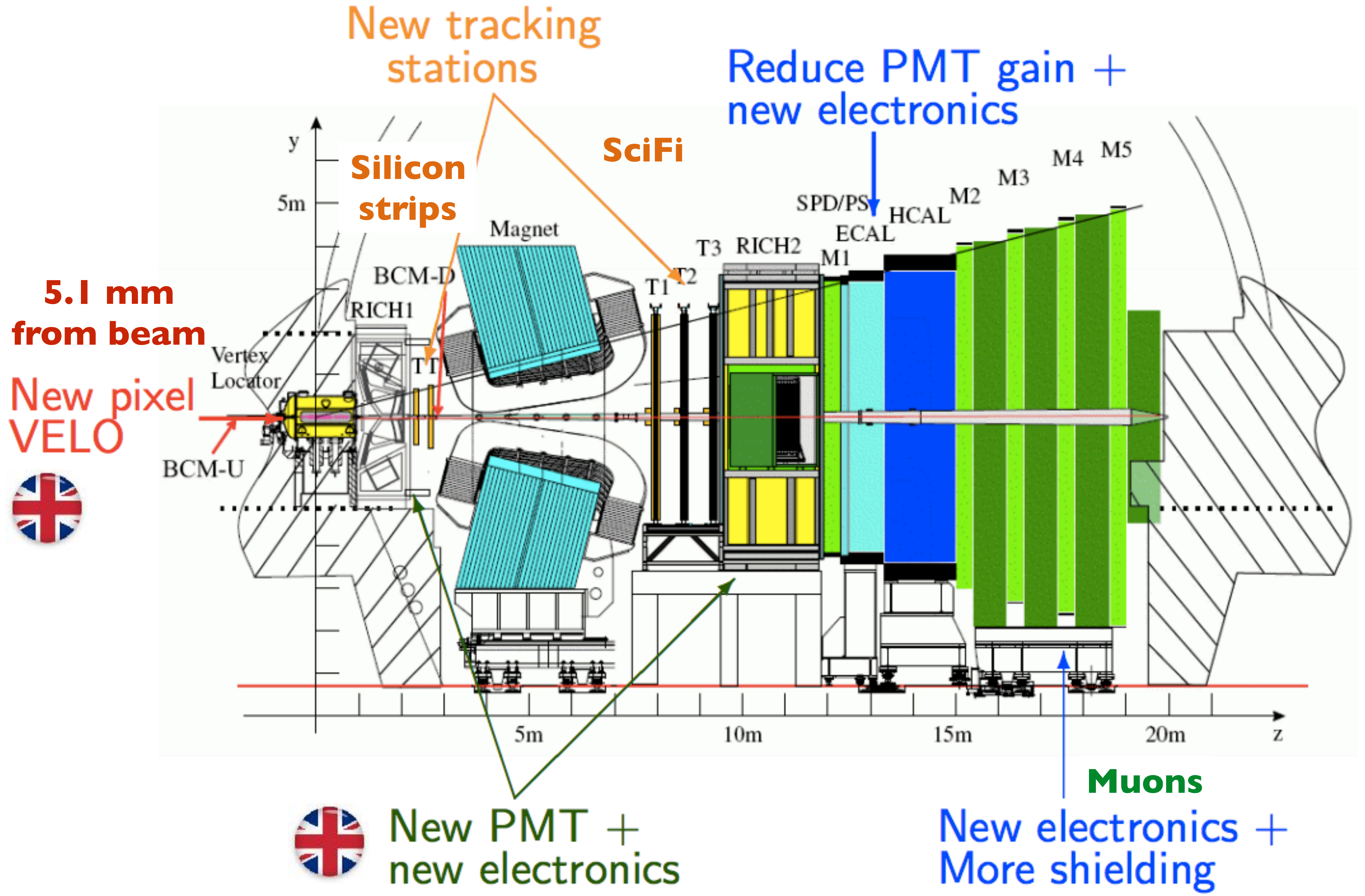
LS4: install LHCb upgrade II

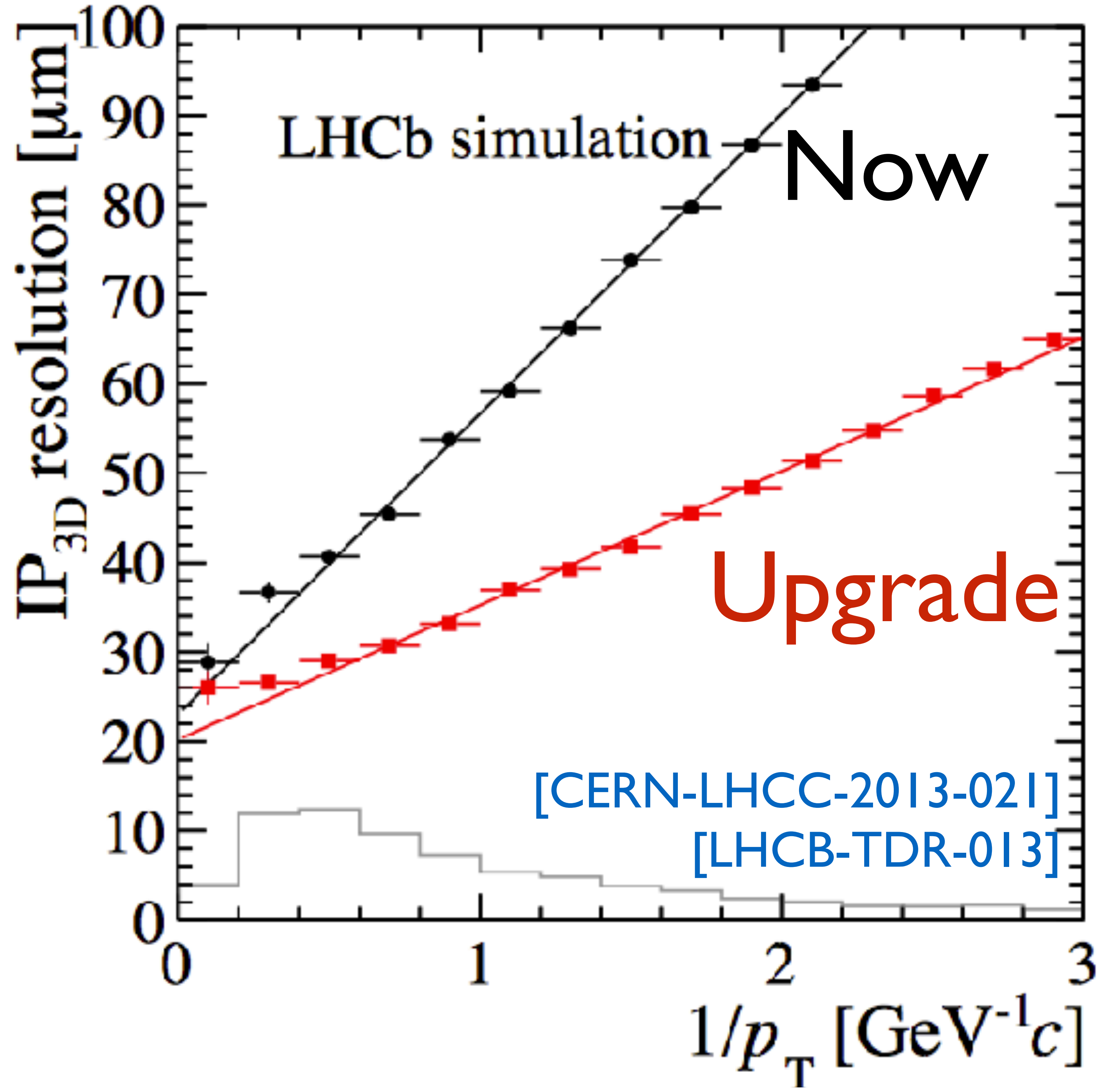
Install ATLAS/CMS phase 2 upgrades in LS3

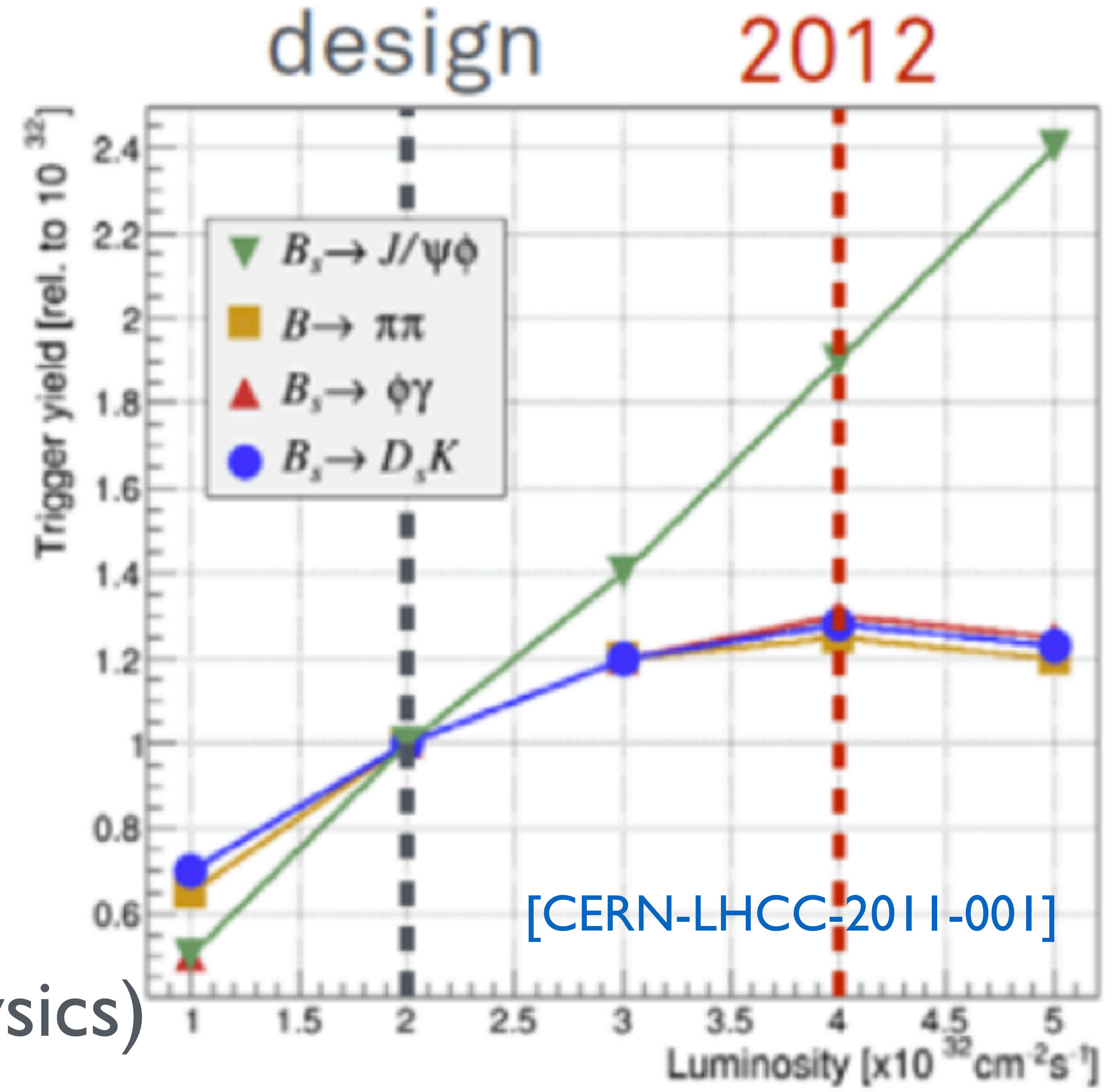
Belle-II and BES-III complete ~2025

"New" experiments to take advantage of the HL-LHC

Status of Upgrade I







40 MHz readout, flexible software-only trigger at ~50 kHz

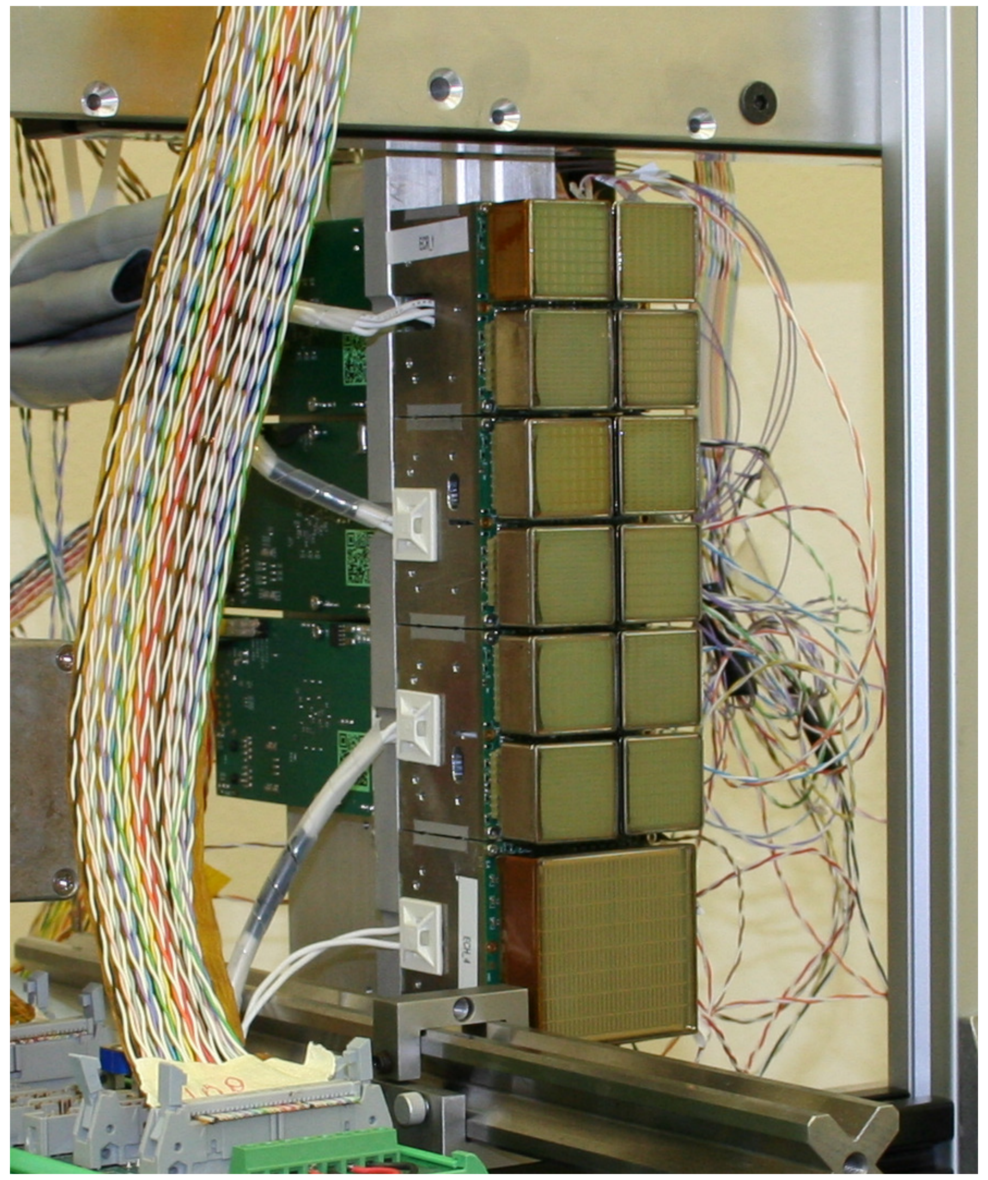
→ Factor 2 increase in efficiency for hadronic B decays (higher for charm, soft physics)

Status of Upgrade I

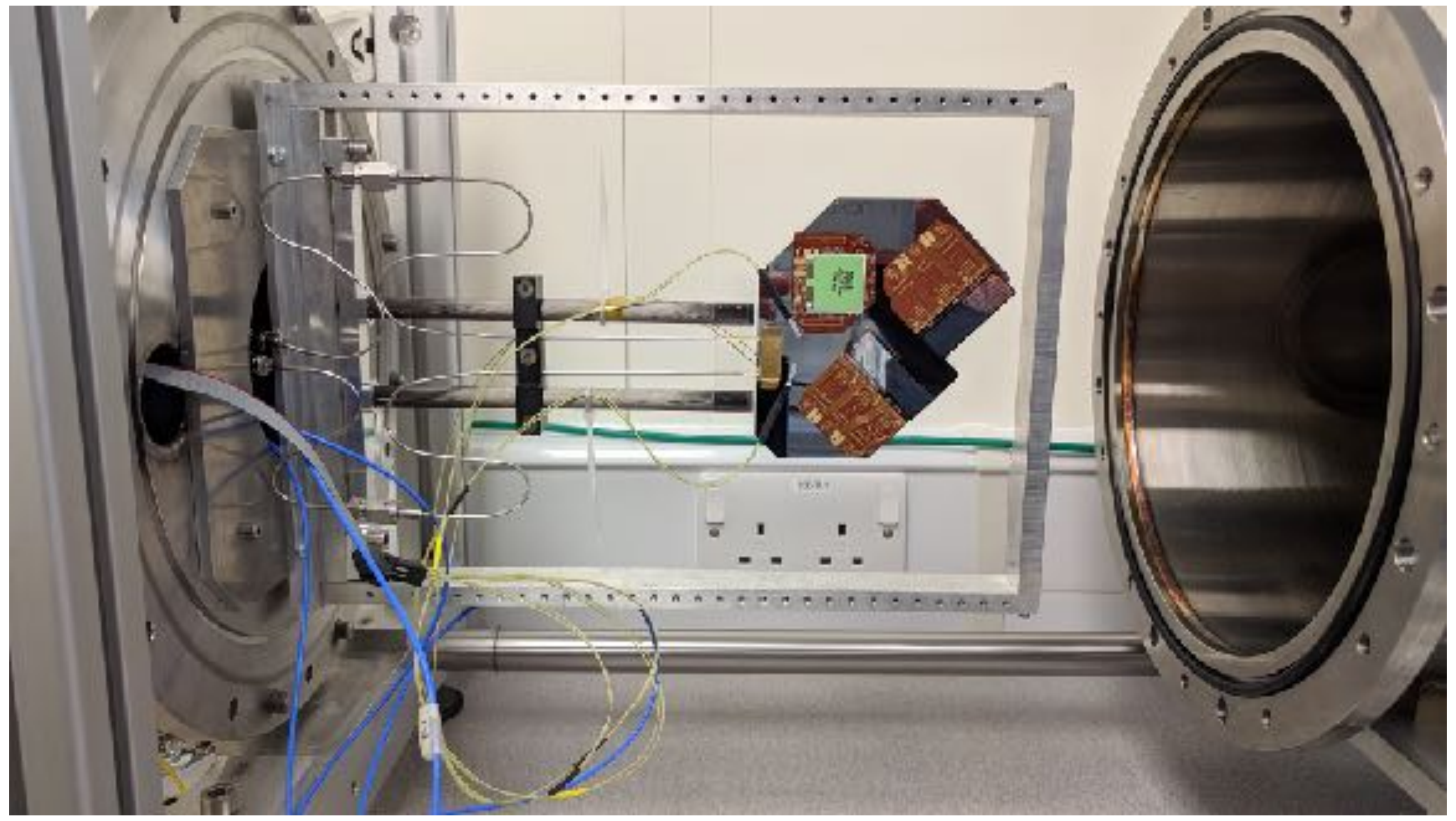
Significantly advanced production/ construction of many sub-systems

40 MHz read-out

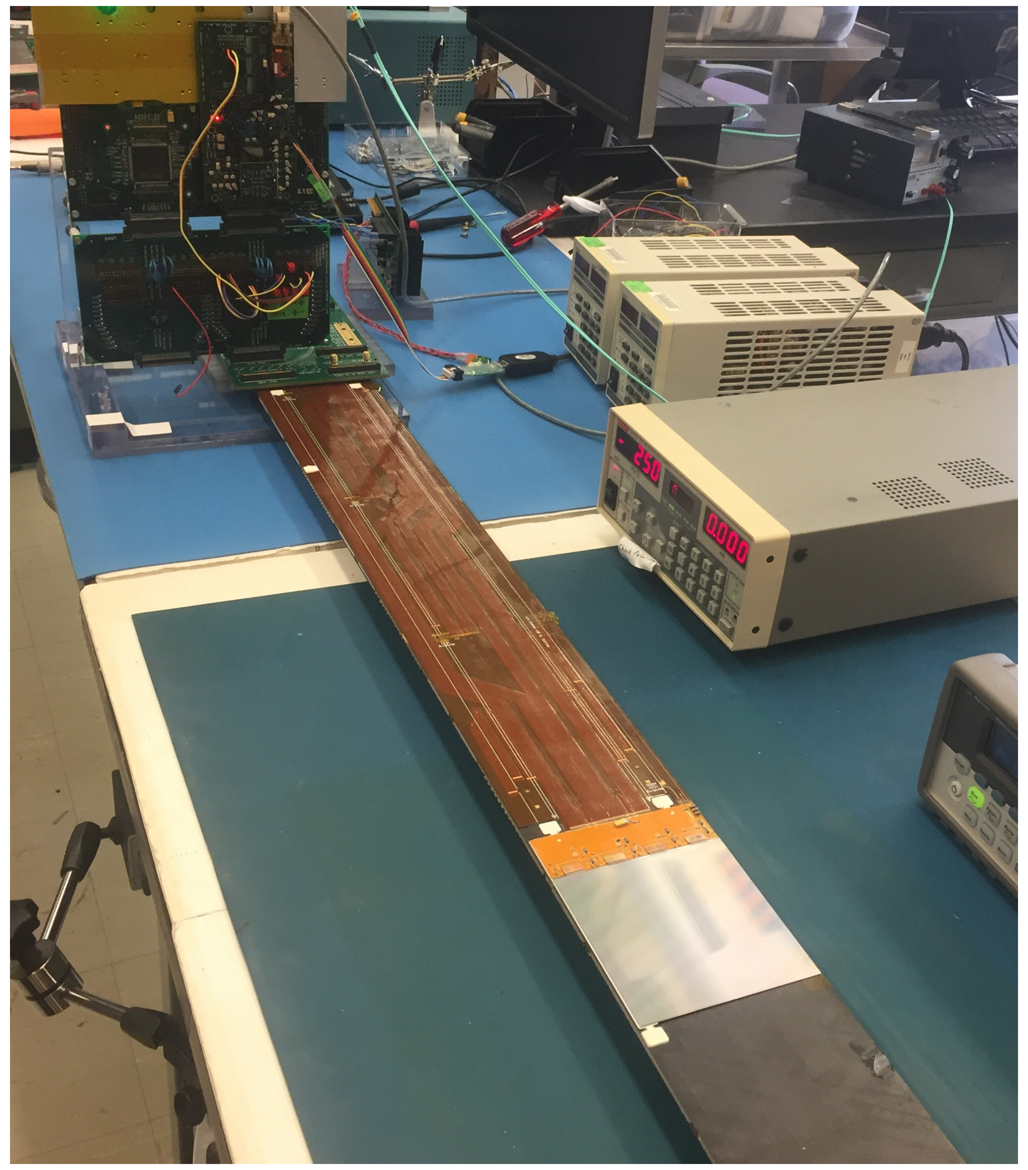
First SciFi modules at LHCb



RICH MAPMTs in test beam



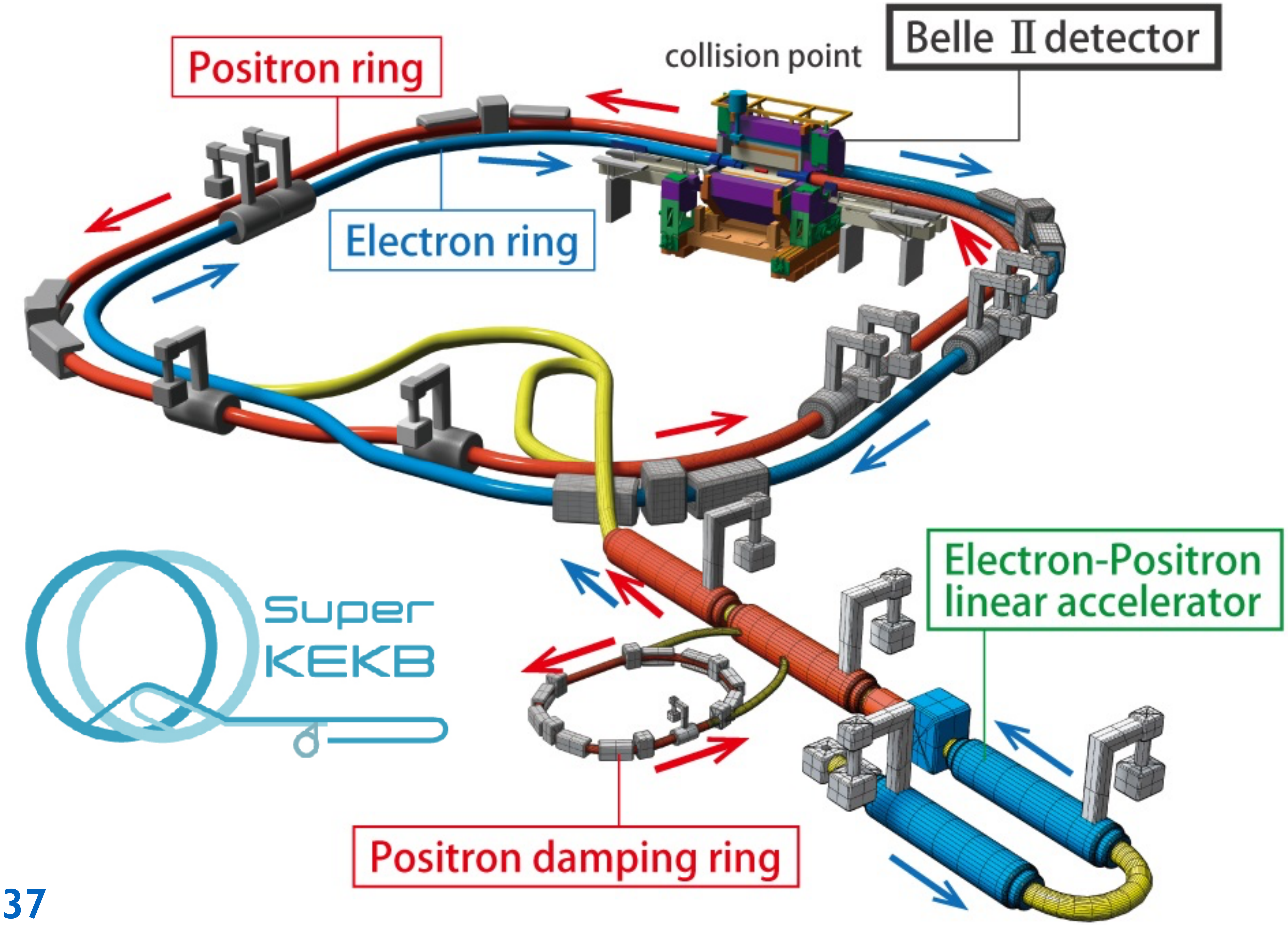
Microchannel VELO module mechanical deflection tests

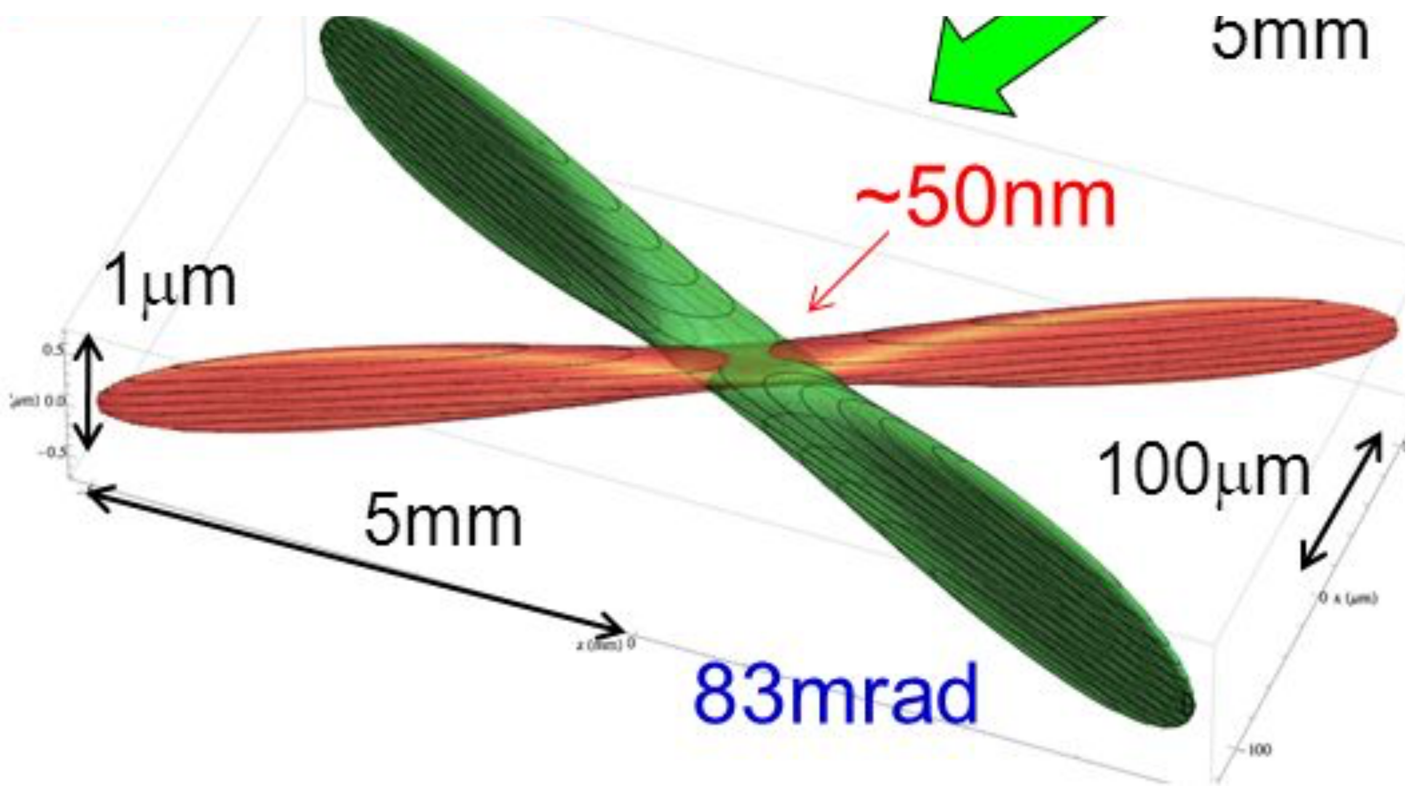


UT sensor with SALT electronics connected to a stave

See talks: Burr, Dutta, Franco Lima

Belle-II @ Super-KEKb





Use nano-beams and 2x beam current for **40x luminosity** ($2.1 \times 10^{34} \rightarrow 8 \times 10^{35}\ cm^{-2}s^{-1}$)

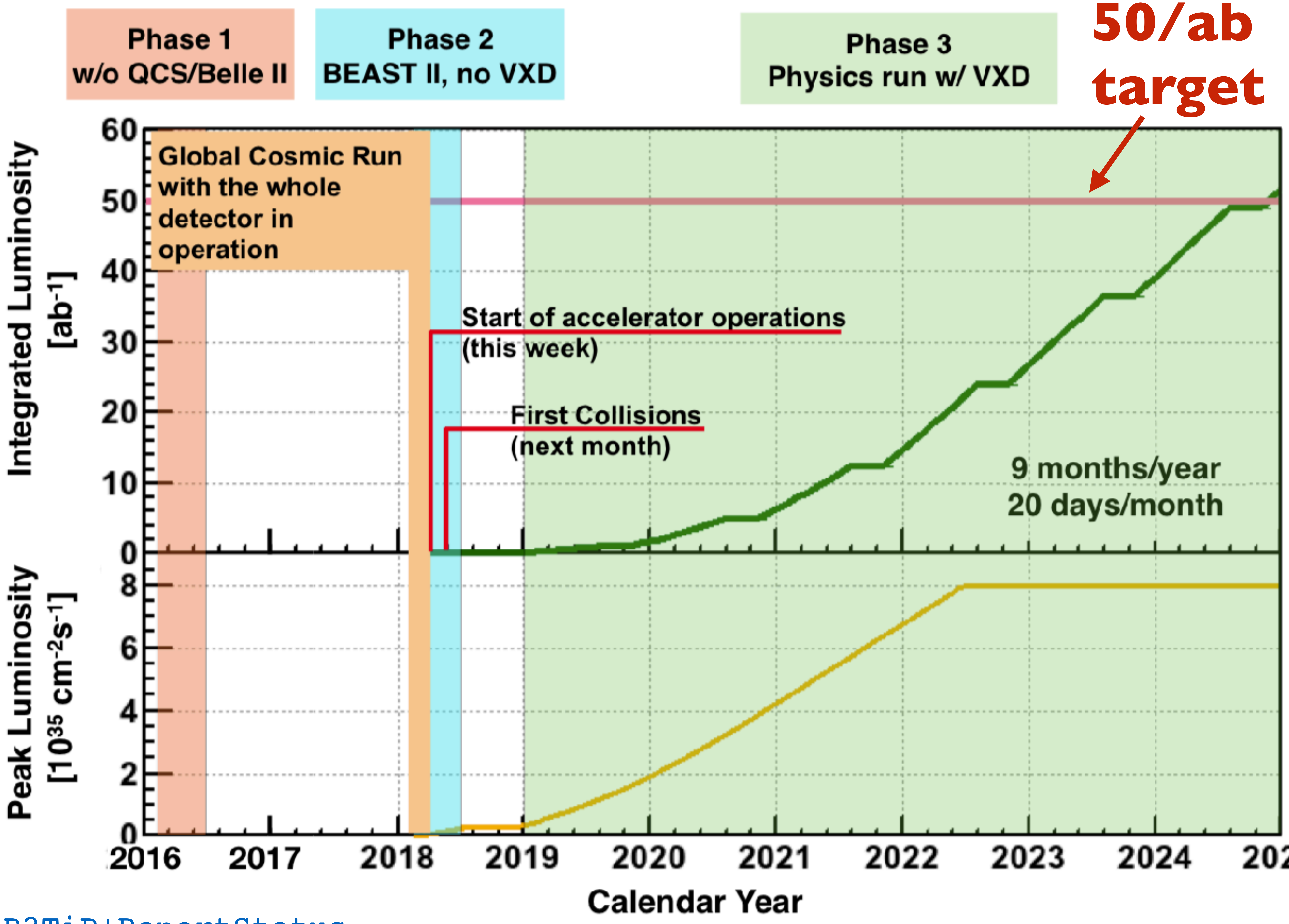
Beam energies less asymmetric to give longer beam lifetime, but smaller boost ($\beta\gamma$: 0.42 → 0.28)

Belle-II plan

Beast-II installed in the VXD volume to monitor backgrounds

Phase-II may open up some physics triggers, e.g., **dark photons**

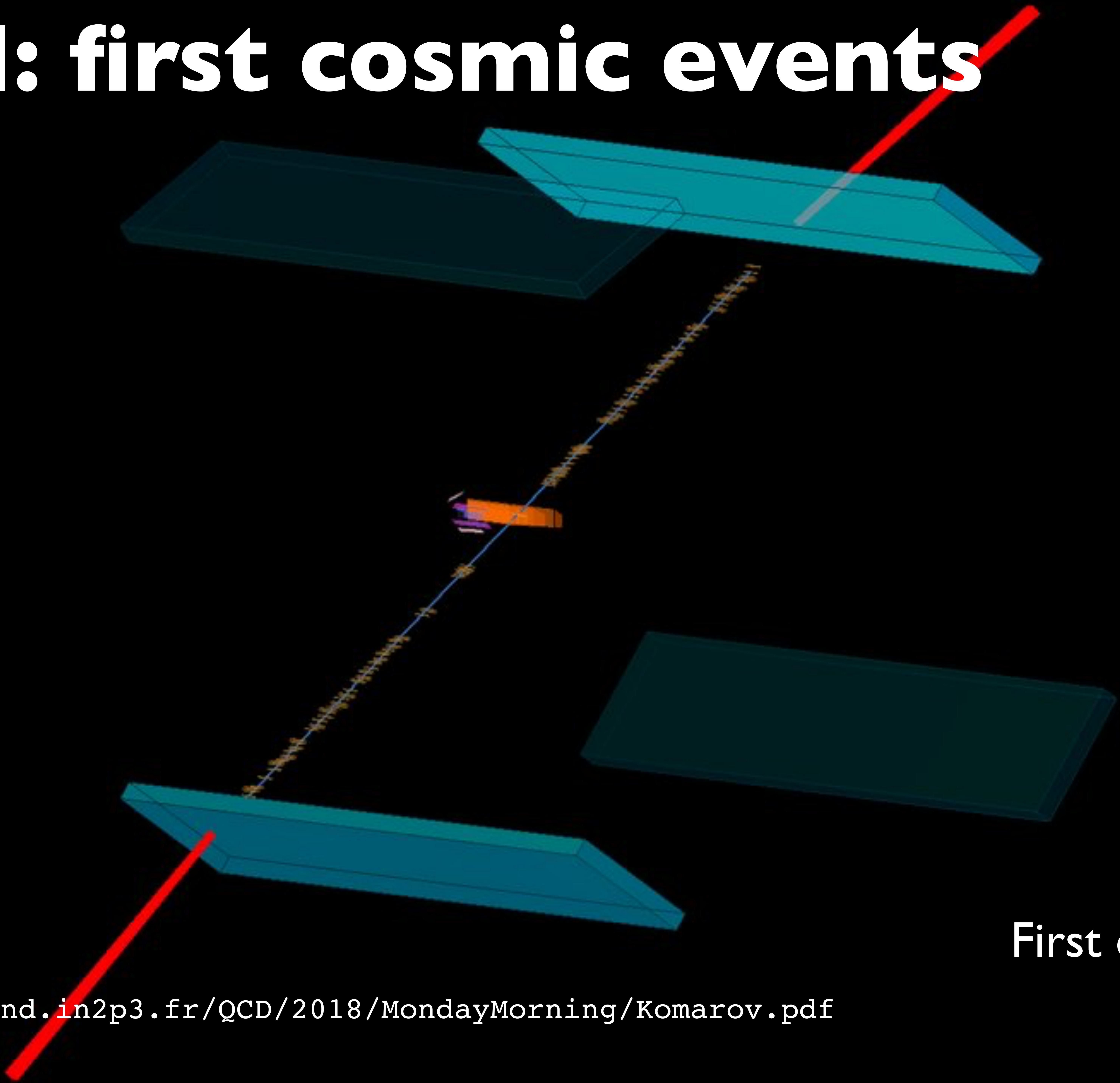
Will achieve significantly improved precision on many CPV observables



Physics document:
https://confluence.desy.de/display/BI/B2TiP+ReportStatus

Aim for **complementarity** with LHCb (modes with neutrals, electrons, $B \to \eta K^0$, LFV tau decays)

Belle-II: first cosmic events



http://moriond.in2p3.fr/QCD/2018/MondayMorning/Komarov.pdf

First collisions expected next month!

Belle-II: first cosmic events

Cherenkov ring visible in ARICH detector

https://twitter.com/belle2japan/status/975336909416235009

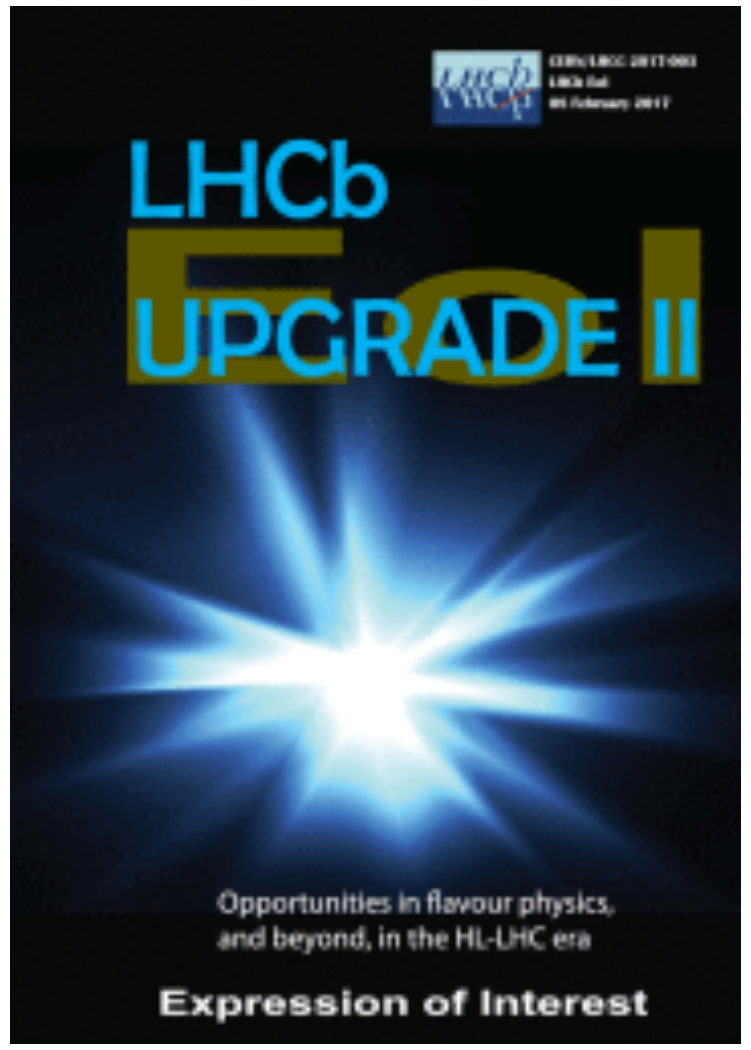
Upgrade II

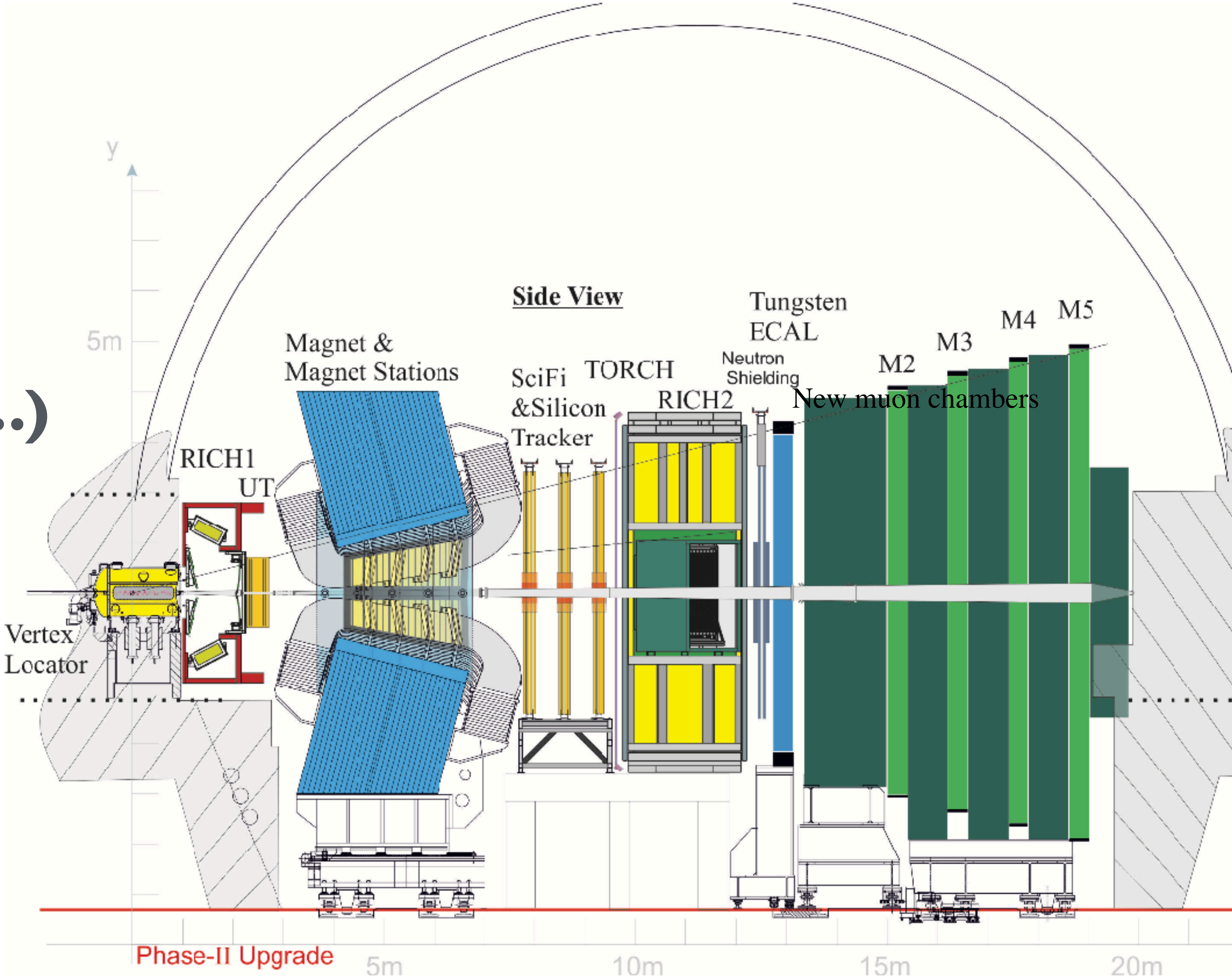
Installation in LS4

Operation during Run 5 (2031-…)

$\mathcal{L} \sim 1\text{-}2 \times 10^{34}\ \mathrm{cm^{-2}s^{-1}}$

Target: 300 $\mathrm{fb^{-1}}$





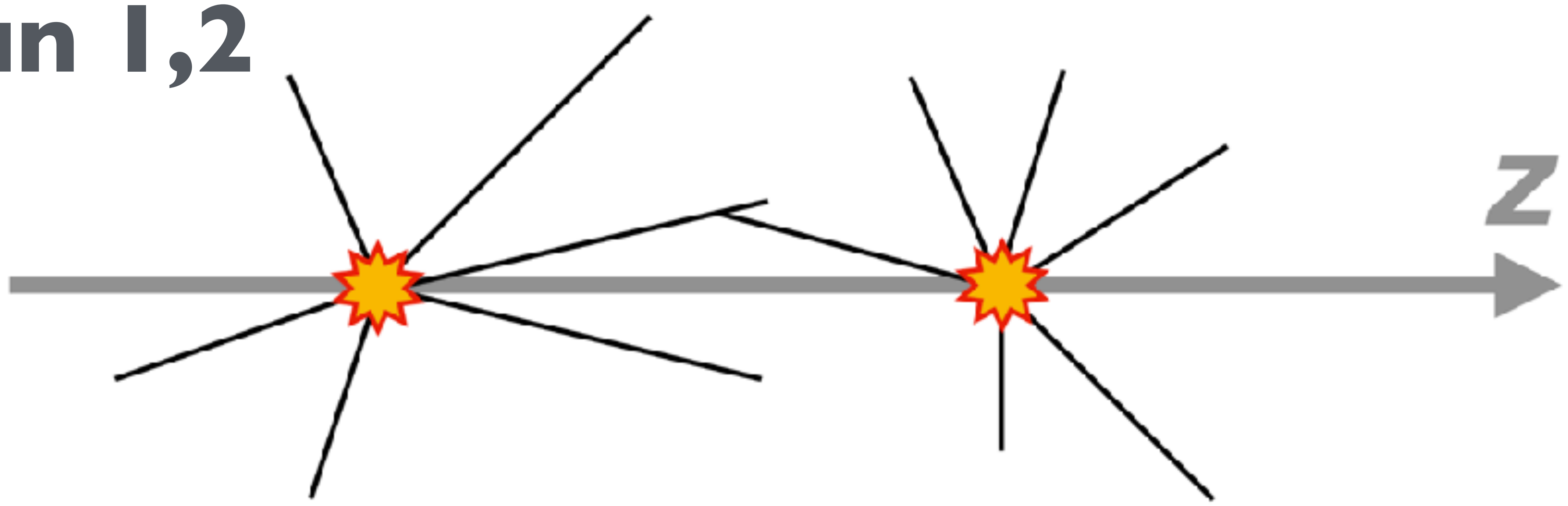
Looks similar to Upgrade I but substantial refit of existing sub-detectors

https://cds.cern.ch/record/2244311?ln=en

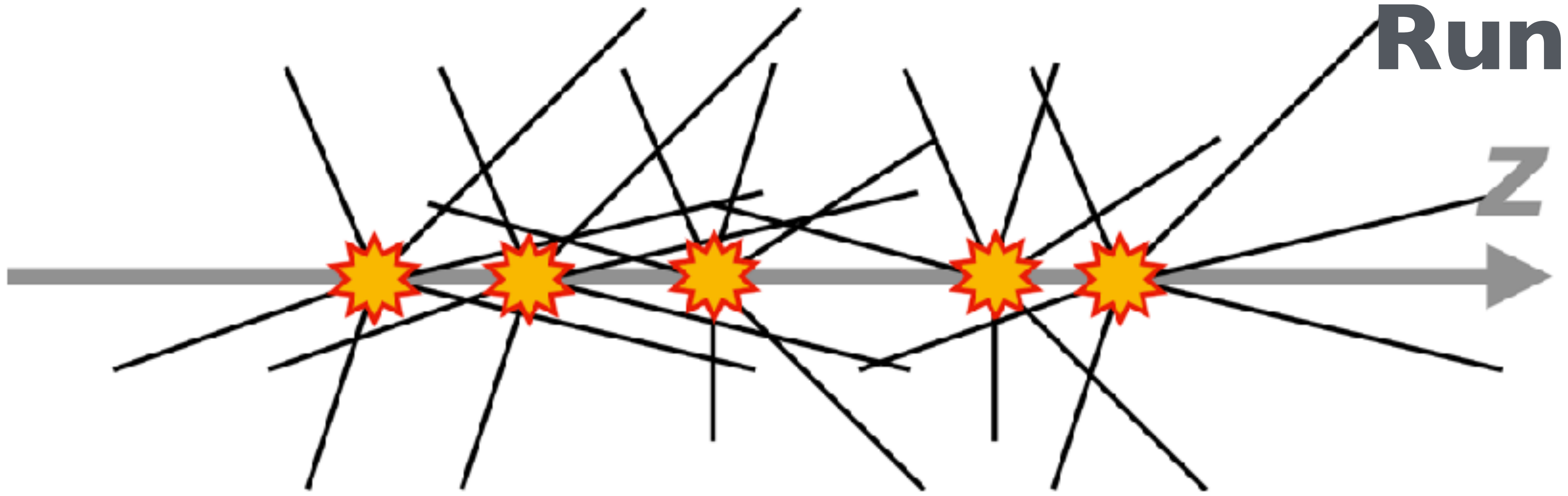
Challenges

Last week: 3rd workshop on LHCb upgrade-II
https://indico.in2p3.fr/event/16795/overview

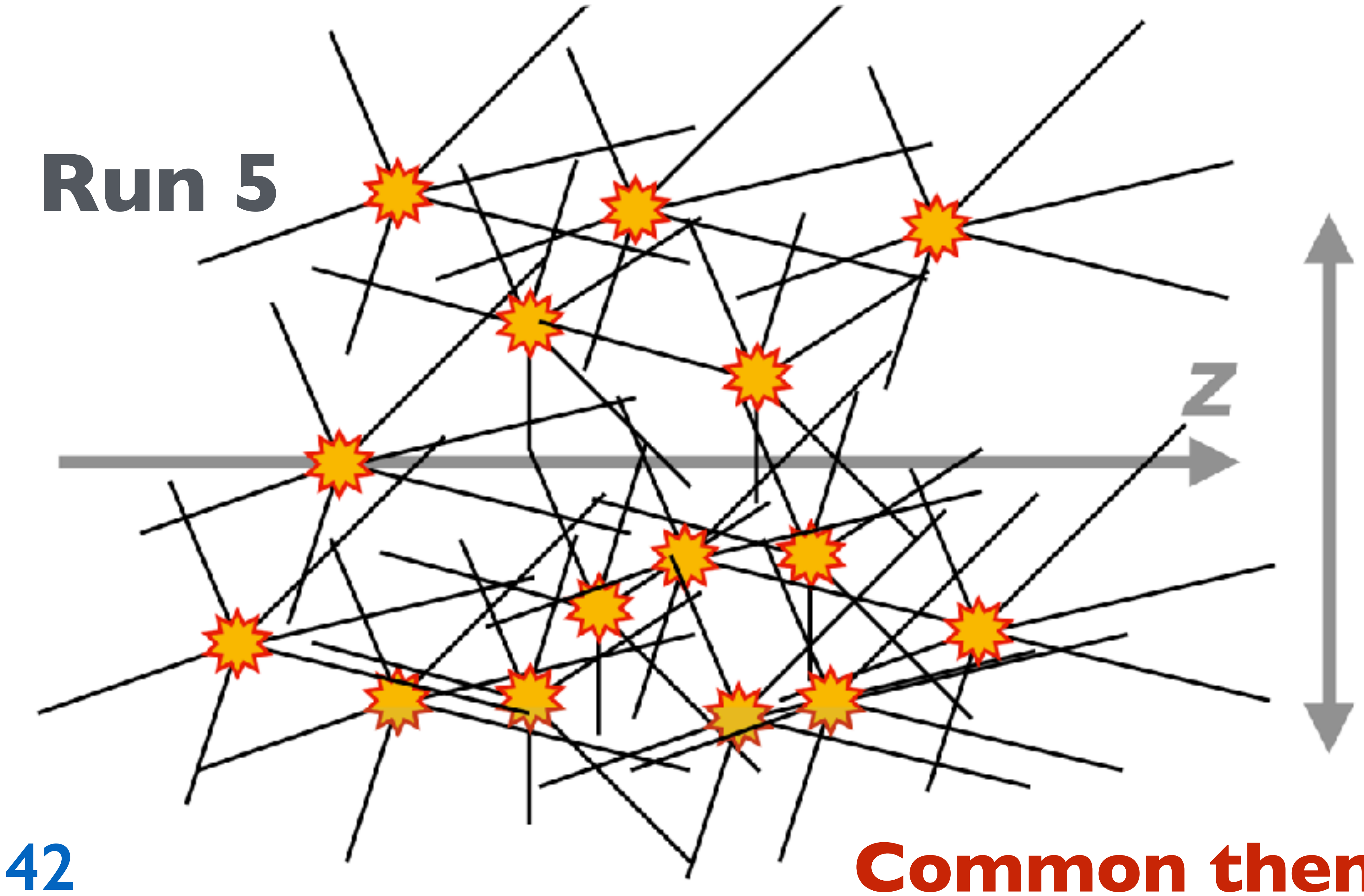
Run 1,2



Run 3,4



Run 5



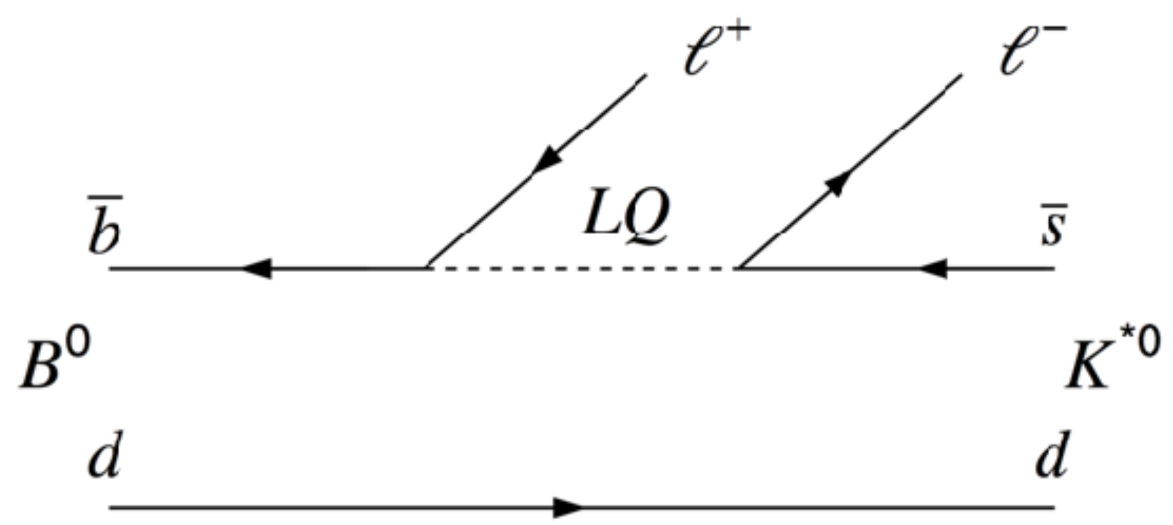
Δt ≈ 300 ps

x10 multiplicity
x10 pile-up
x10 radiation damage

} compared to Upgrade I

Common themes: timing, granularity, radiation hardness

Summary



Intruiging tensions/anomalies with the SM in FCNC and tree-level decays
⇒ Consistent picture of NP emerging (Z', leptoquarks)?

Precision of tree and loop-level CPV rapidly increasing
⇒ Tighter constraints on CKM mechanism and probing of **higher energy scales**

New (exotic) states in the **QCD spectrum** continue to be found

Huge potential with LHC upgrades, Belle-II and kaon physics in coming years

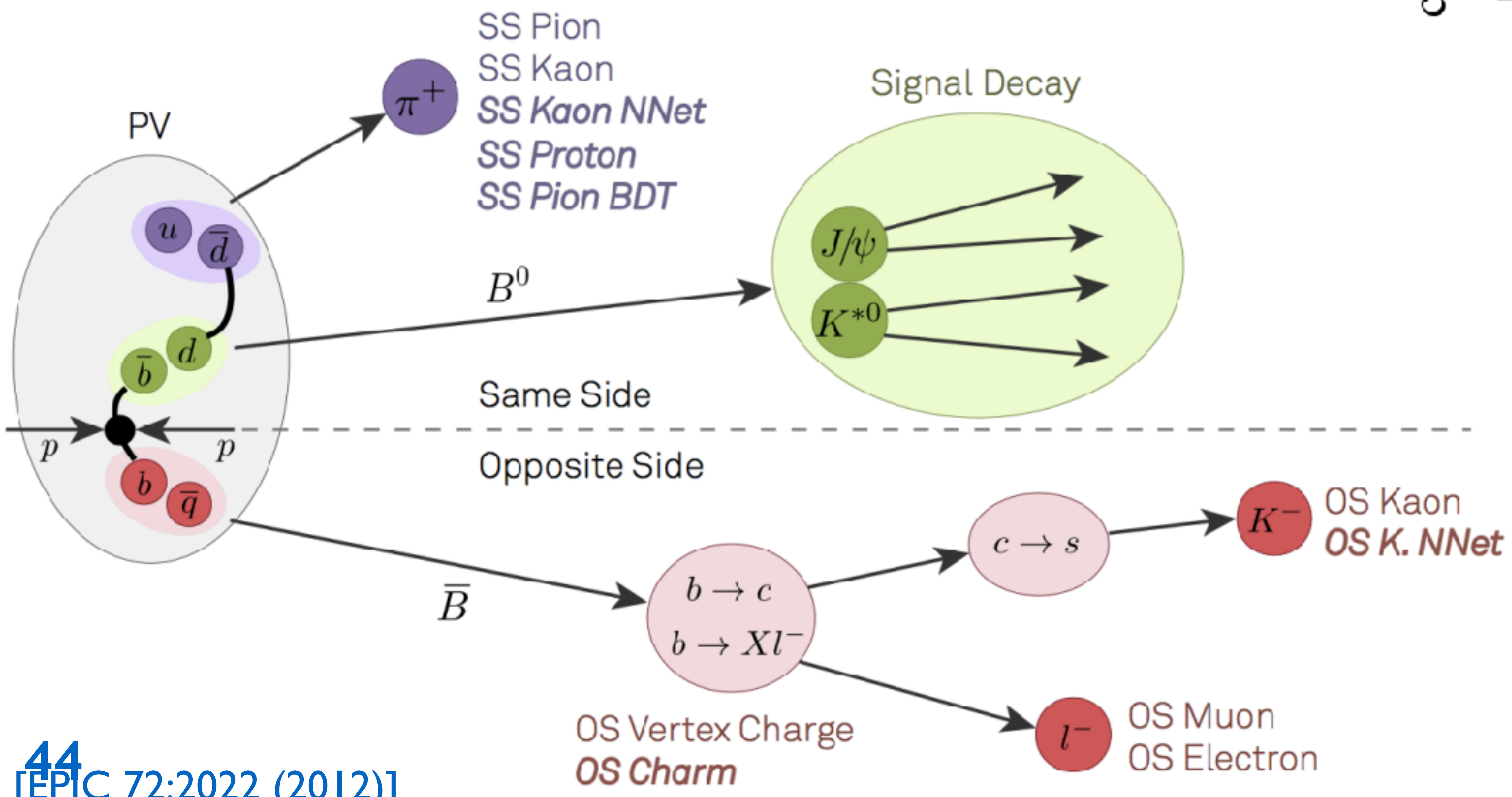
@LHCb_UK
www.lhcb.ac.uk

More details in the parallel sessions and Marco's prize talk tomorrow

Measuring B meson oscillations (+ CPV)

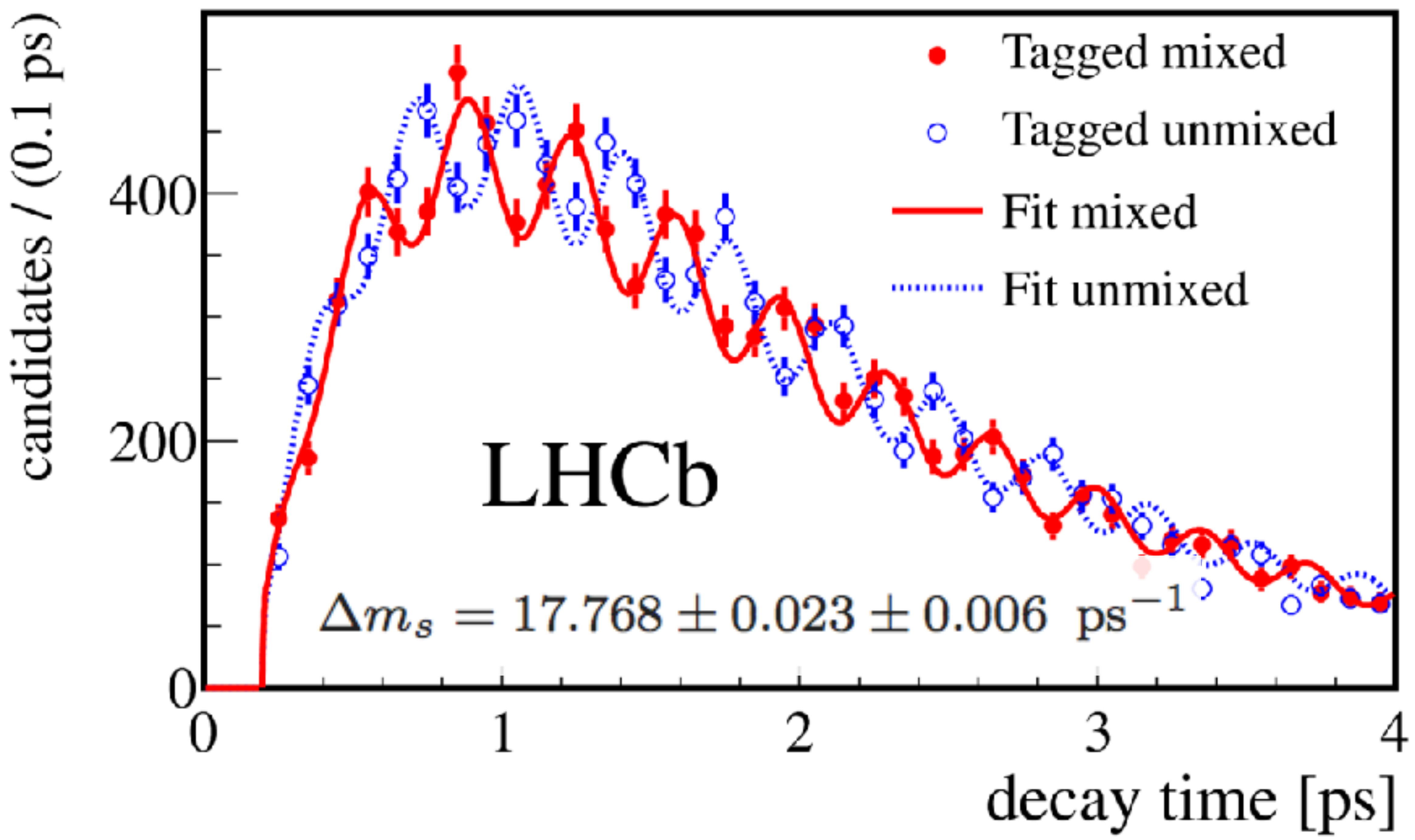
Typical analysis requirements:

- Excellent decay-time resolution (~45 fs)
- Modelling decay-time efficiency
- Production + detection asymmetries
- Tagging of meson flavour @ production



[EPJC 72:2022 (2012)]

$B_s^0 \to D_s^- \pi^+$ [NJP 15 (2013) 053021]

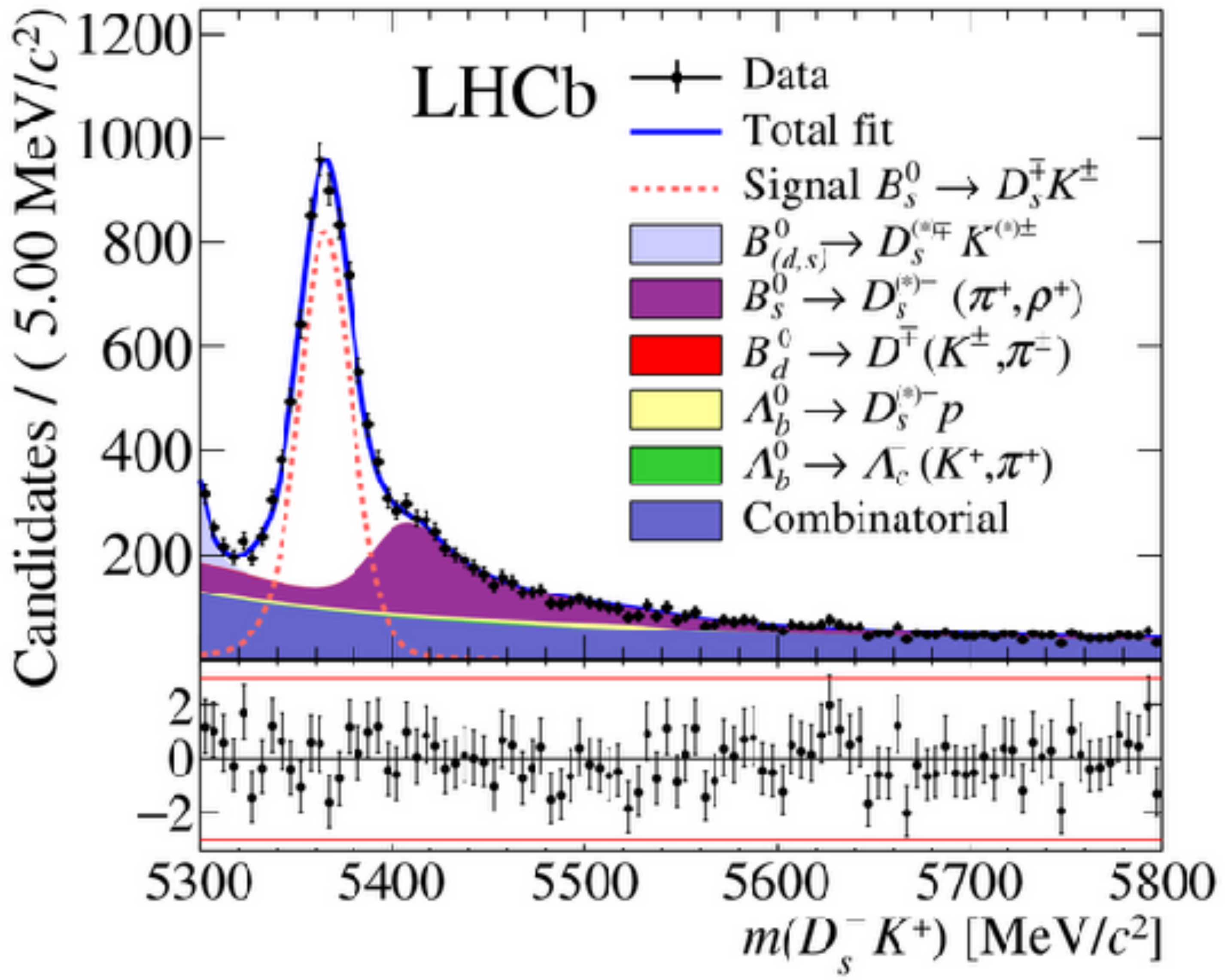


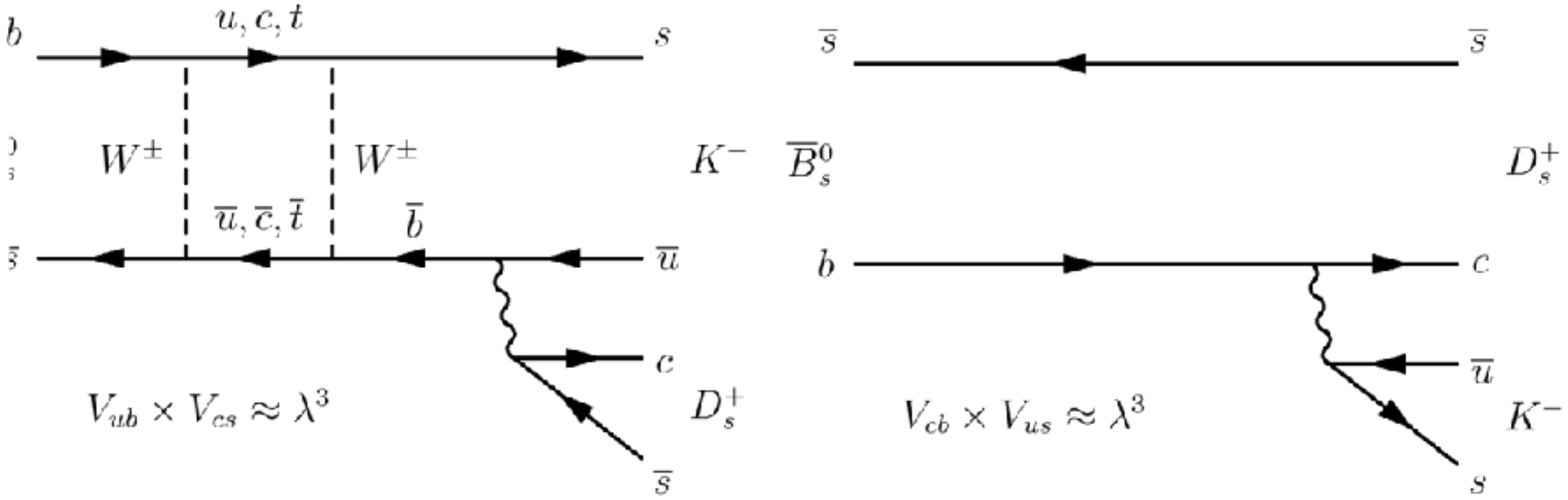
Typical tagging power

~ 4% LHCb (J/ψ modes)
~ 8% LHCb (open-charm modes)
~1.5% ATLAS/CMS
~ 30% B-factories

CPV in $B^0_s \to D^{\mp}_s K^{\pm}$

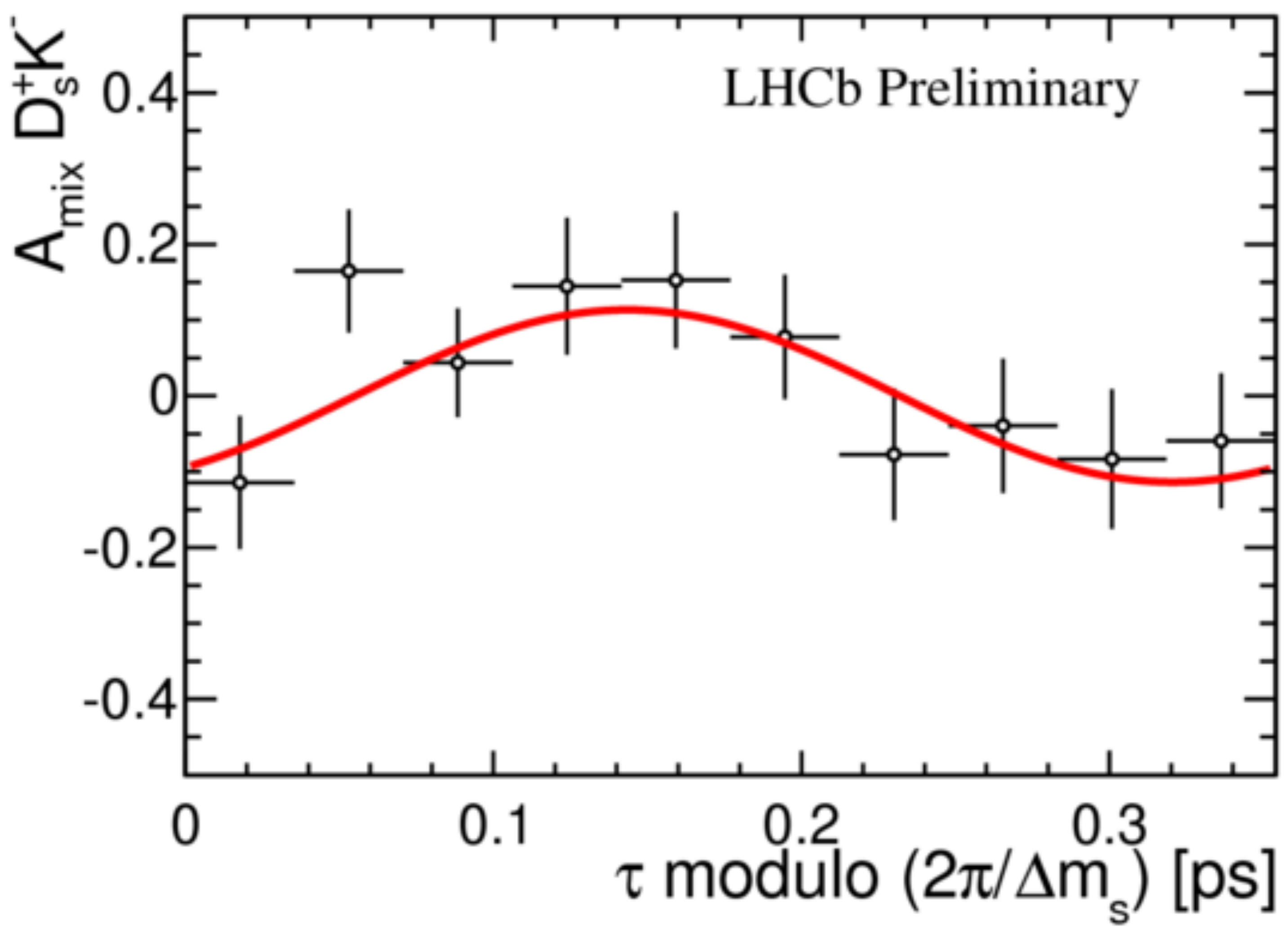
[arXiv:1712.07428]





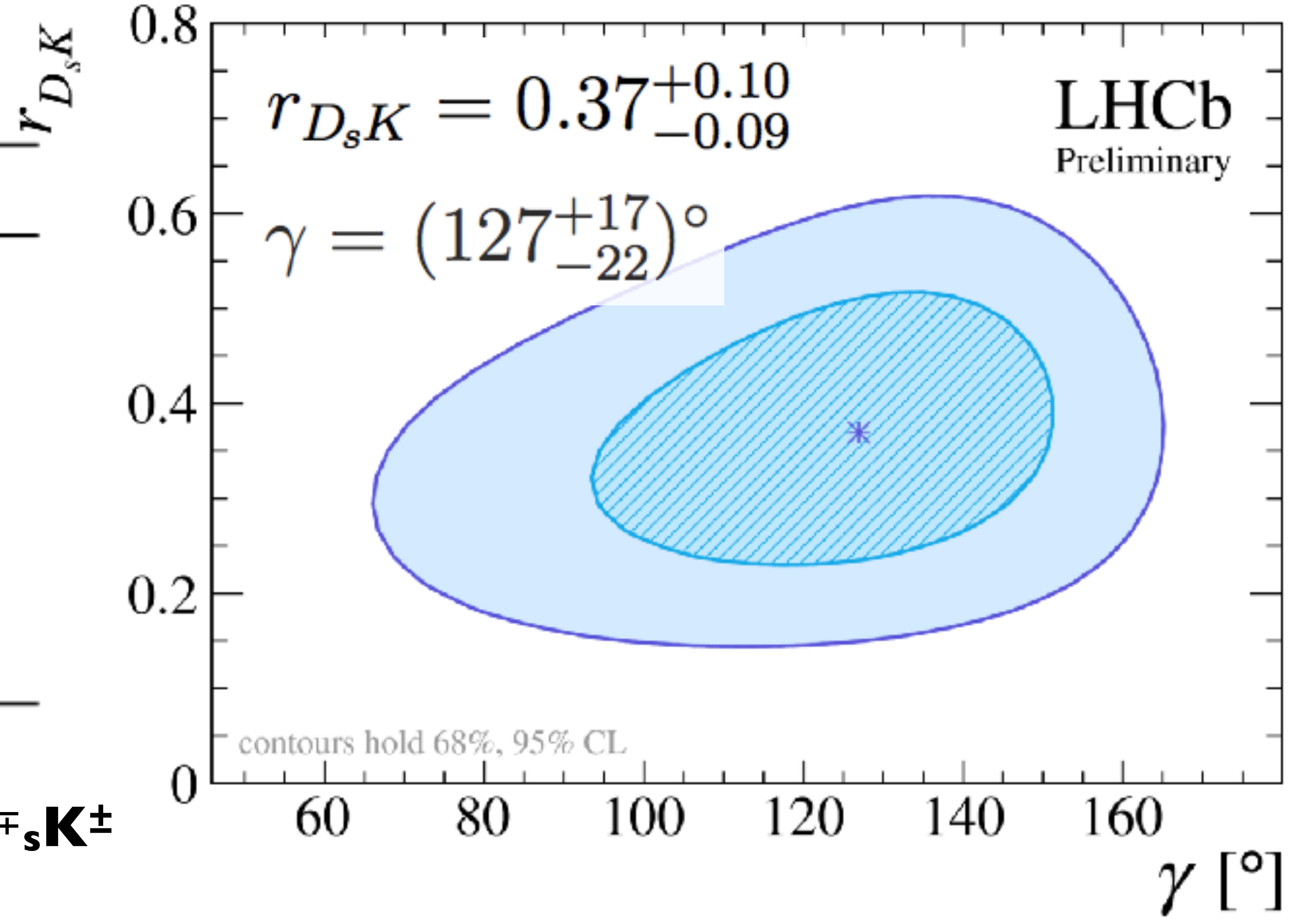
Both decay amplitudes are $O(\lambda^3)$
→ LARGE INTERFERENCE

$$A_{CP}(t) \equiv \frac{\Gamma_{\overline{B}^0 \to f} - \Gamma_{B^0 \to f}}{\Gamma_{\overline{B}^0 \to f} + \Gamma_{B^0 \to f}} = \frac{S_f \sin(\Delta m\, t) - C_f \cos(\Delta m\, t)}{\cosh(\Delta\Gamma\, t/2) + A_{\Delta\Gamma} \sinh(\Delta\Gamma\, t/2)}$$



Parameter	Value
C_f	$0.730 \pm 0.142 \pm 0.045$
$A_f^{\Delta\Gamma}$	$0.387 \pm 0.277 \pm 0.153$
$A_{\bar{f}}^{\Delta\Gamma}$	$0.308 \pm 0.275 \pm 0.152$
S_f	$-0.519 \pm 0.202 \pm 0.070$
$S_{\bar{f}}$	$-0.489 \pm 0.196 \pm 0.068$

3.8σ evidence for CP violation in $B^0_s \to D^{\mp}_s K^{\pm}$



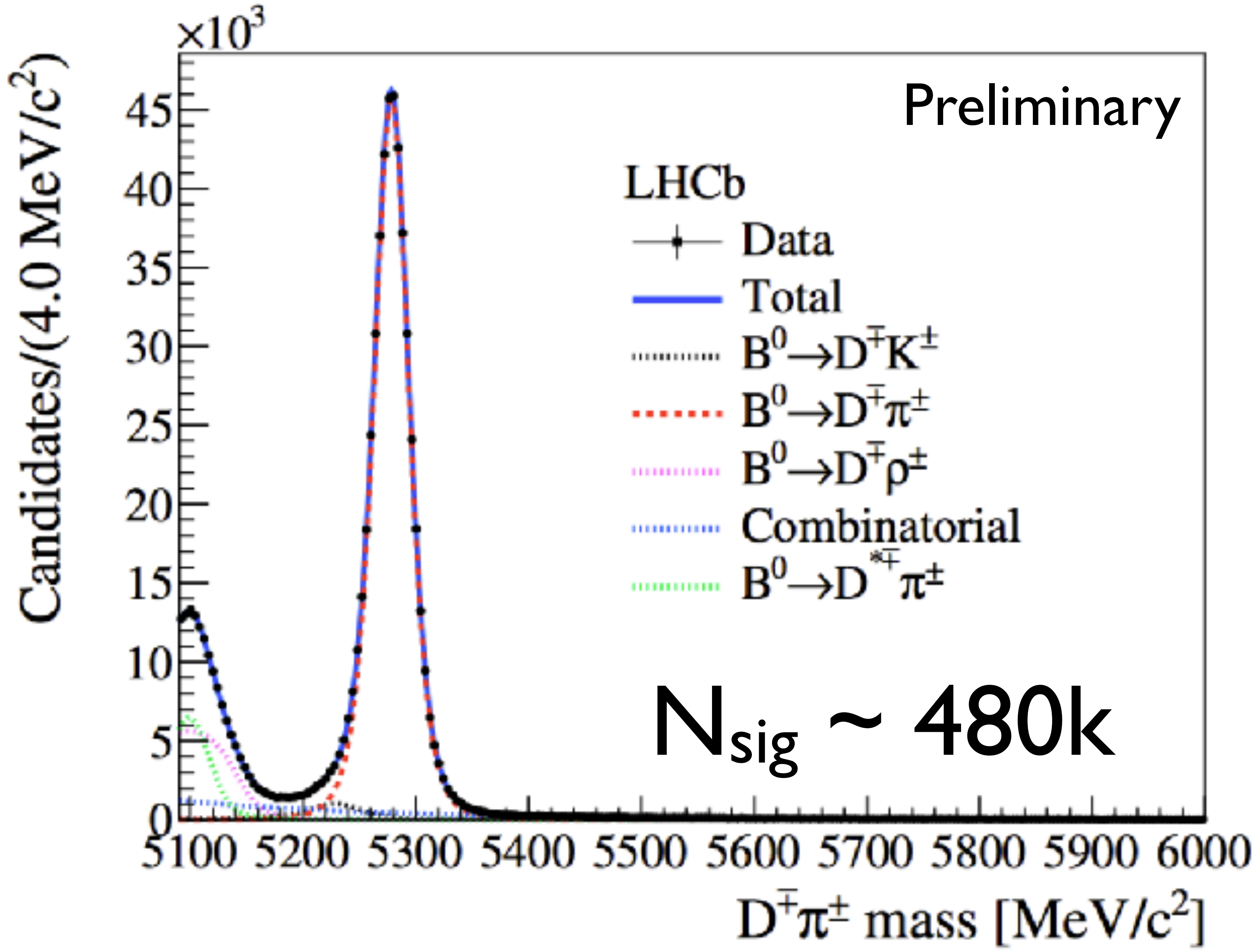
CPV in $B^0 \to D^{\mp}\pi^{\pm}$

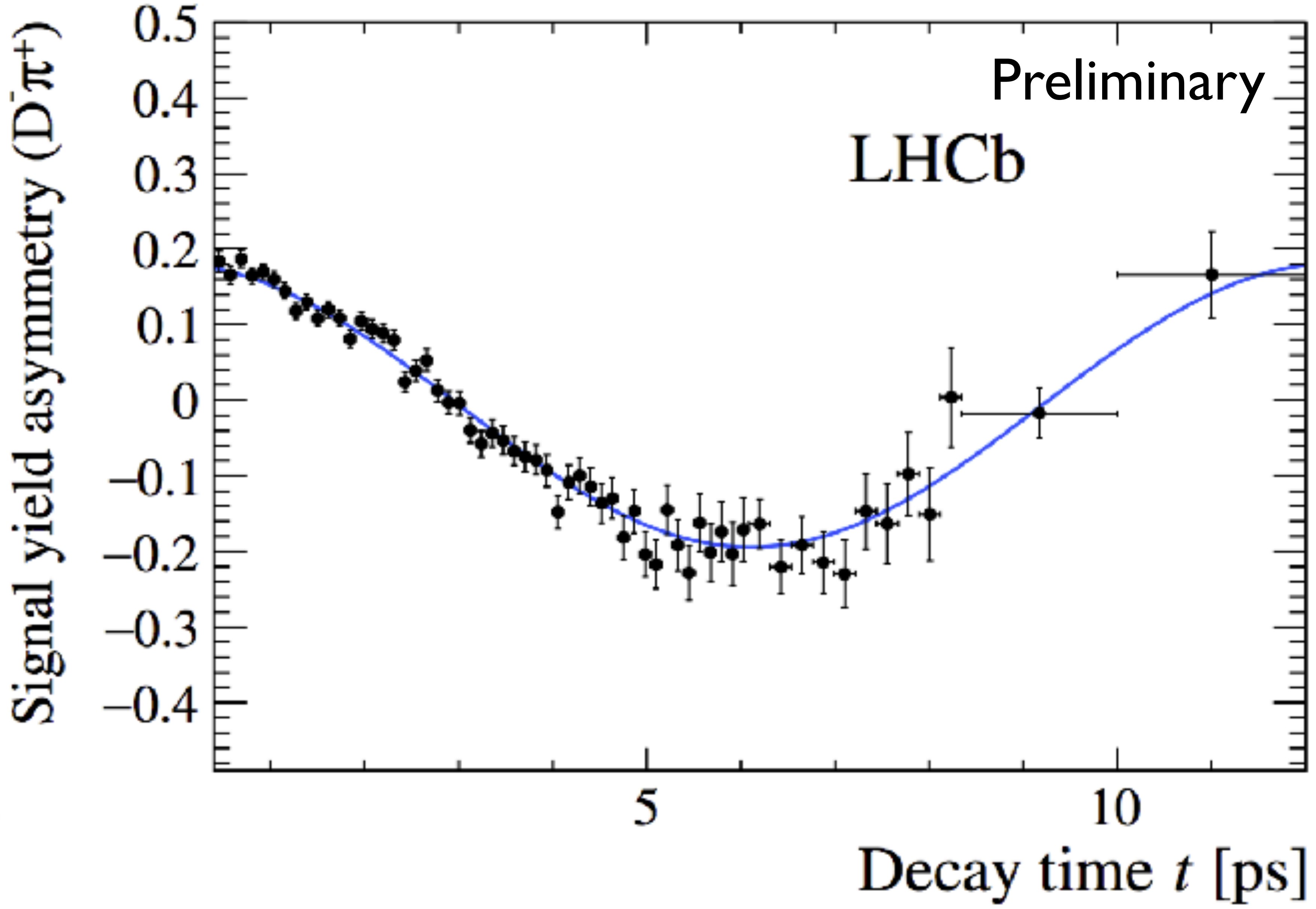
Measurements are sensitive to $2\beta+\gamma$

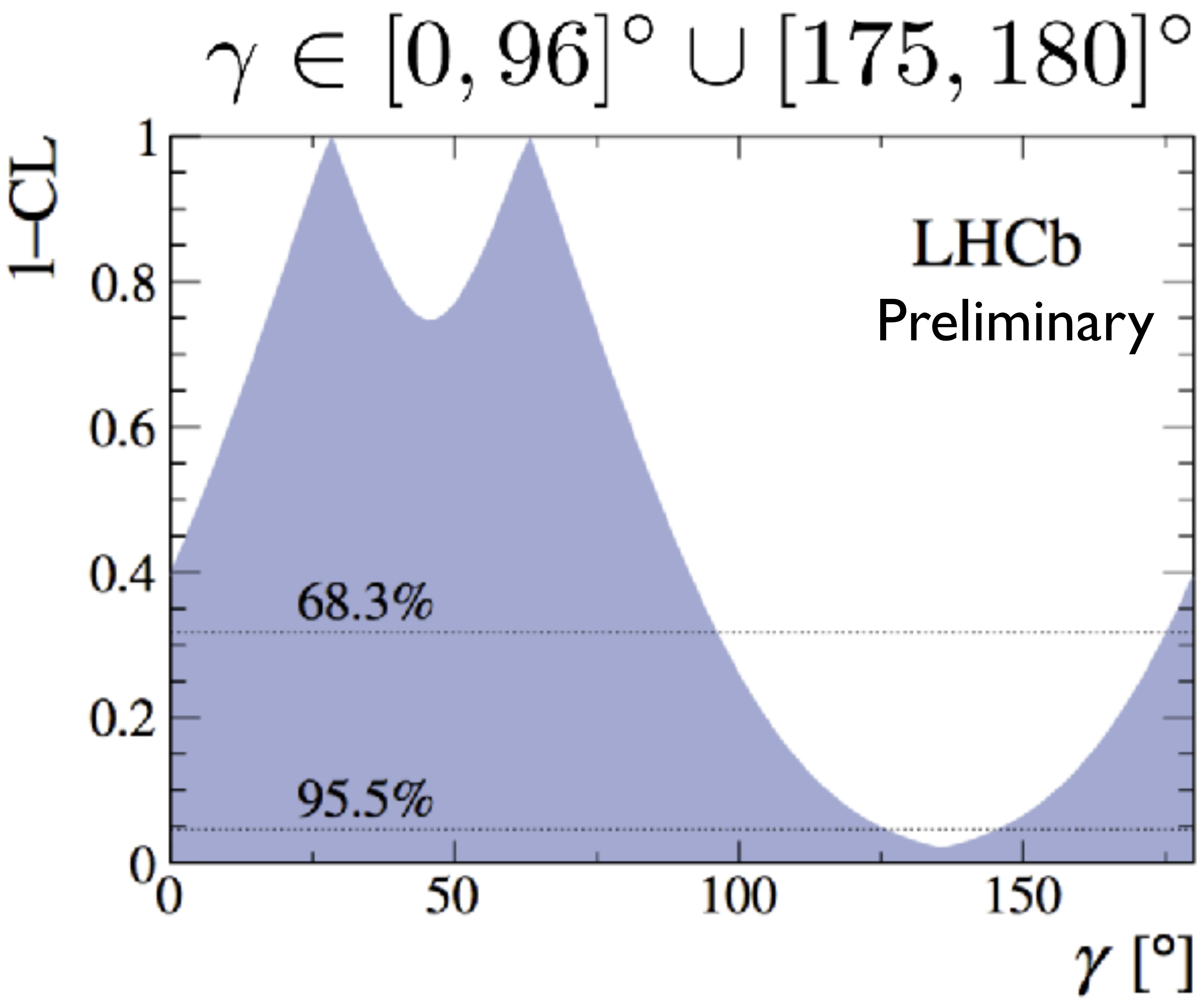
Limited sensitive to γ since $r^{D\pi} \sim 0.02$, but huge event yields.

Measure Sf, Sfbar and use external input for $r^{D\pi}$ (Belle/BaBar) and β (HFLAV)

	S_f[%]	$S_{\bar{f}}$ [%]
Belle [11]	$6.8 \pm 2.9 \pm 1.2$	$3.1 \pm 3.0 \pm 1.2$
Babar [10]	$-2.3 \pm 4.8 \pm 1.4$	$4.3 \pm 4.8 \pm 1.4$
This analysis	$5.8 \pm 2.0 \pm 1.1$	$3.8 \pm 2.0 \pm 0.7$







Hadronic uncertainties

[Capdevilla et al., arXiv:1704.05340]

Coloured bands represent different NP scenarios

Size of band indicates size of hadronic uncertainty

In models with LFUV this gets larger as there is no long a cancellation for e/mu