The LHCb experiment at the LHC

Current status and future perspectives

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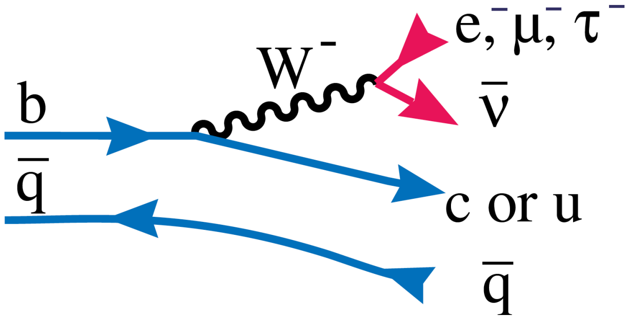
On behalf of the LHCb collaboration

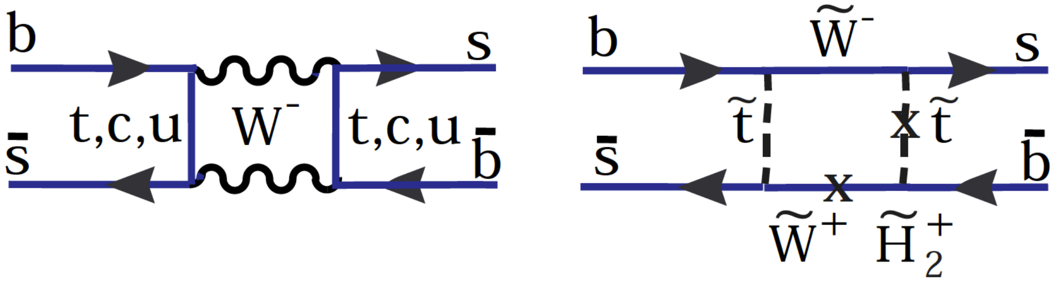
SYRACUSE UNIVERSITY
SUOS CULTORES SCIENTIA CORONAT
FOUNDED AD 1870

LHCb physics goals

- ☐ Broad and ever expanding
- ☐ Search for new physics manifest itself in beauty decays and charm decays



Tree diagram example



Loop diagram example

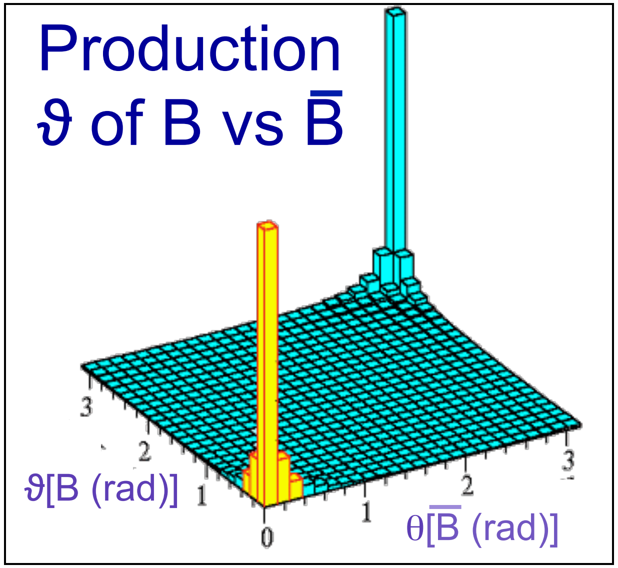
- ❑ Explore new manifestations of the strong interaction through the study of exotic states
- ❑ General purpose detector in the forward direction

The Forward Direction at the LHC

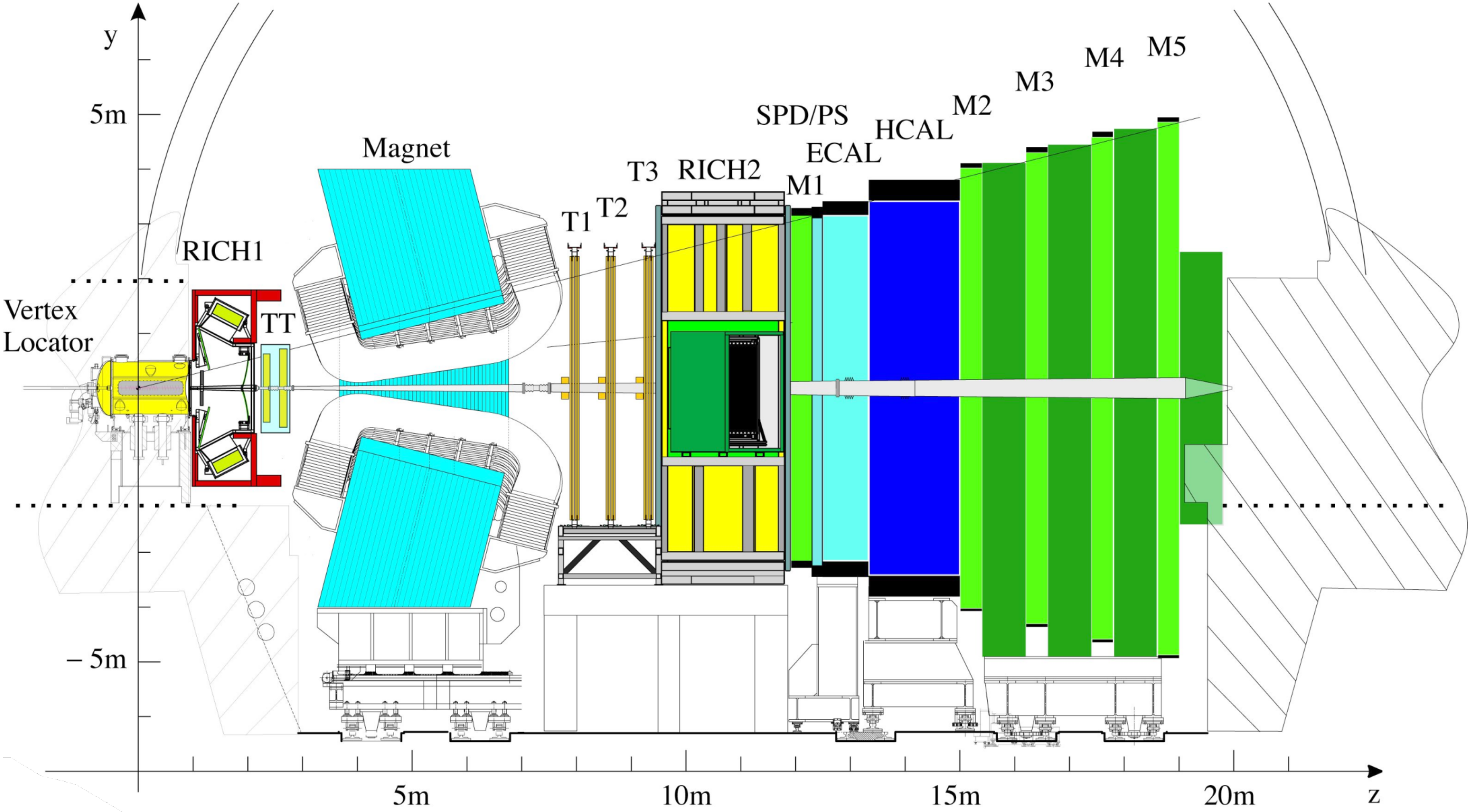
- In the forward region at LHC the $b\bar{b}$ production σ is large
- The hadrons containing the b & $\bar{b}$ quarks are both likely to be in the acceptance. Essential for "flavor tagging"
- LHCb uses the forward direction where the B's are moving with considerable momentum ~100 GeV, thus minimizing multiple scattering
- At $\mathcal{L}=4\times10^{32}/\text{cm}^2/\text{s}$, we get ~$10^{12}$ B hadrons in 10^7 sec in the LHCb acceptance.

arXiv:1009.2731

Measured cross section at 7 TeV in LHCb acceptance is ~90 μb



The LHCb detector



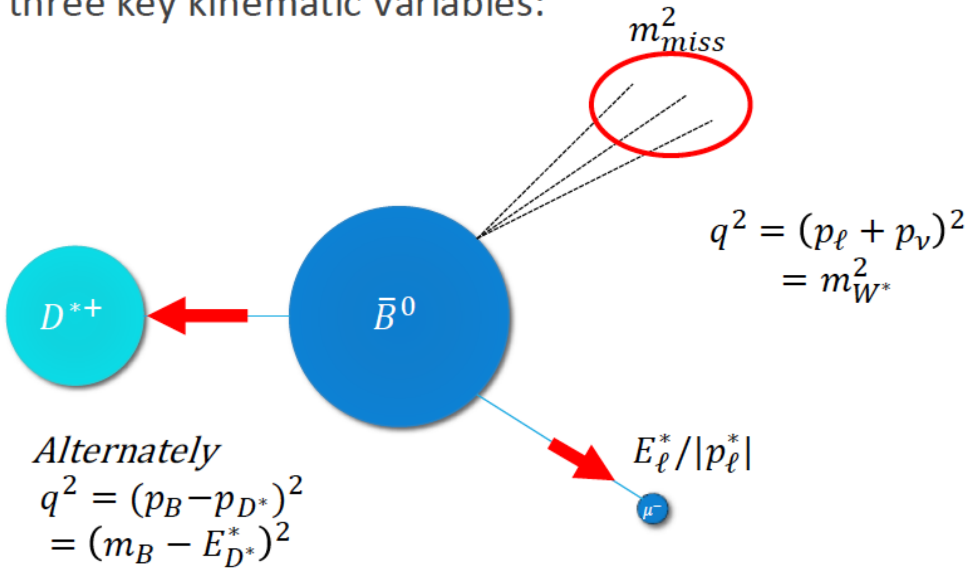
Many analyses still ongoing exploiting in novel ways the RUN I data set: new results expected at all the major conferences in 2016

LHCb physics: a snapshot based on RUN I

Violation of lepton universality

B→D*τν at LHCb

In B rest frame, three key kinematic variables:



Alternately

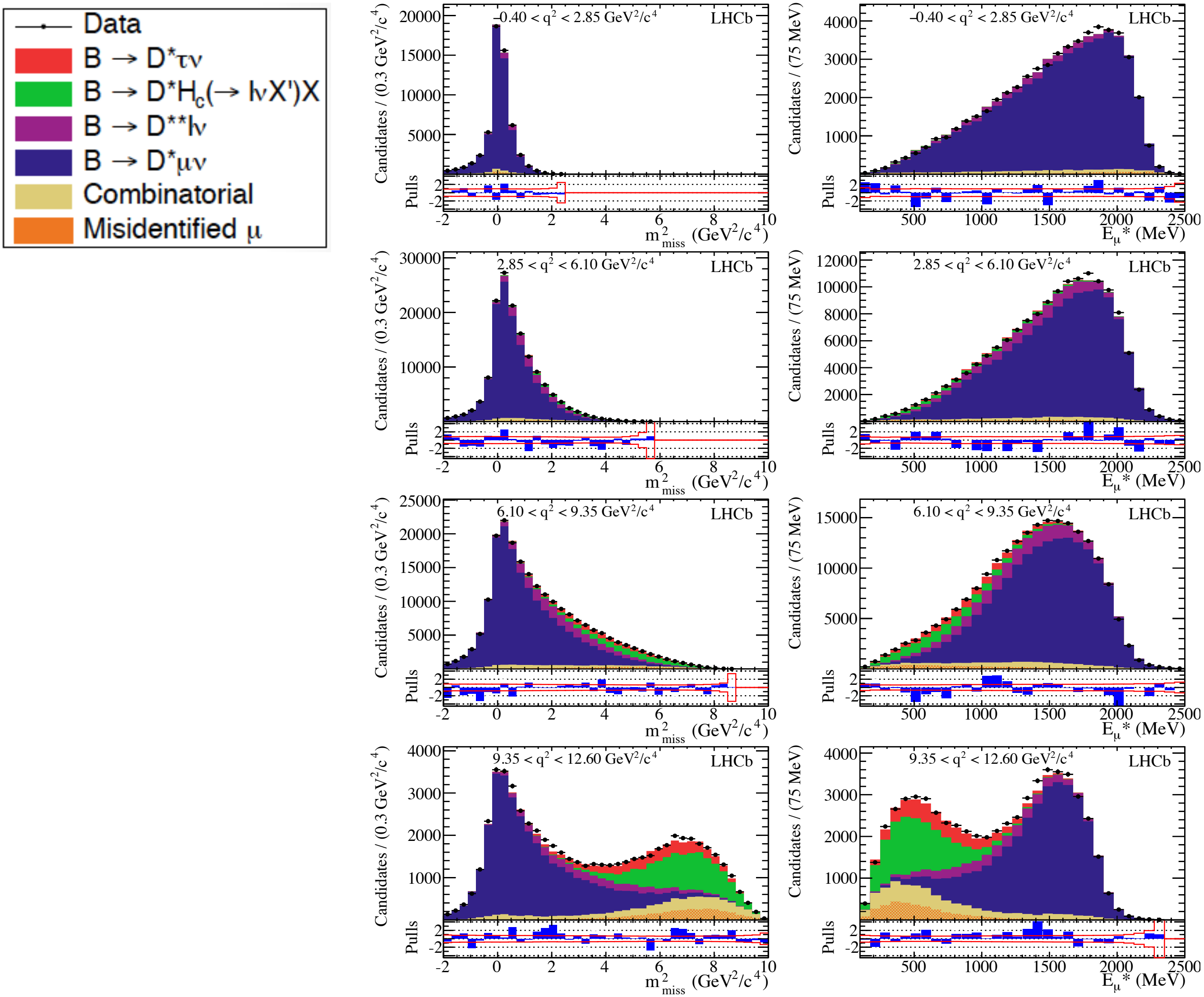
$$q^2 = (p_B - p_{D^*})^2 = (m_B - E^*_{D^*})^2$$

$\overline{B}^0 \to D^{*+}\tau^-\overline{\nu}$	$\overline{B}^0 \to D^{*+}\mu^-\overline{\nu}$
$m^2_{miss} > 0$	$m^2_{miss} = 0$
E^*_l spectrum is soft	E^*_l spectrum is hard
$m^2_\tau \leq q^2 \leq 10.6\ \mathrm{GeV}^2$	$\approx 0 \leq q^2 \leq 10.6\ \mathrm{GeV}^2$

- Use isolation TMVA to discriminate between signals and variety of backgrounds

B→D*τν fit

LHCb-PAPER-2015-025
arXiv:1506.08614

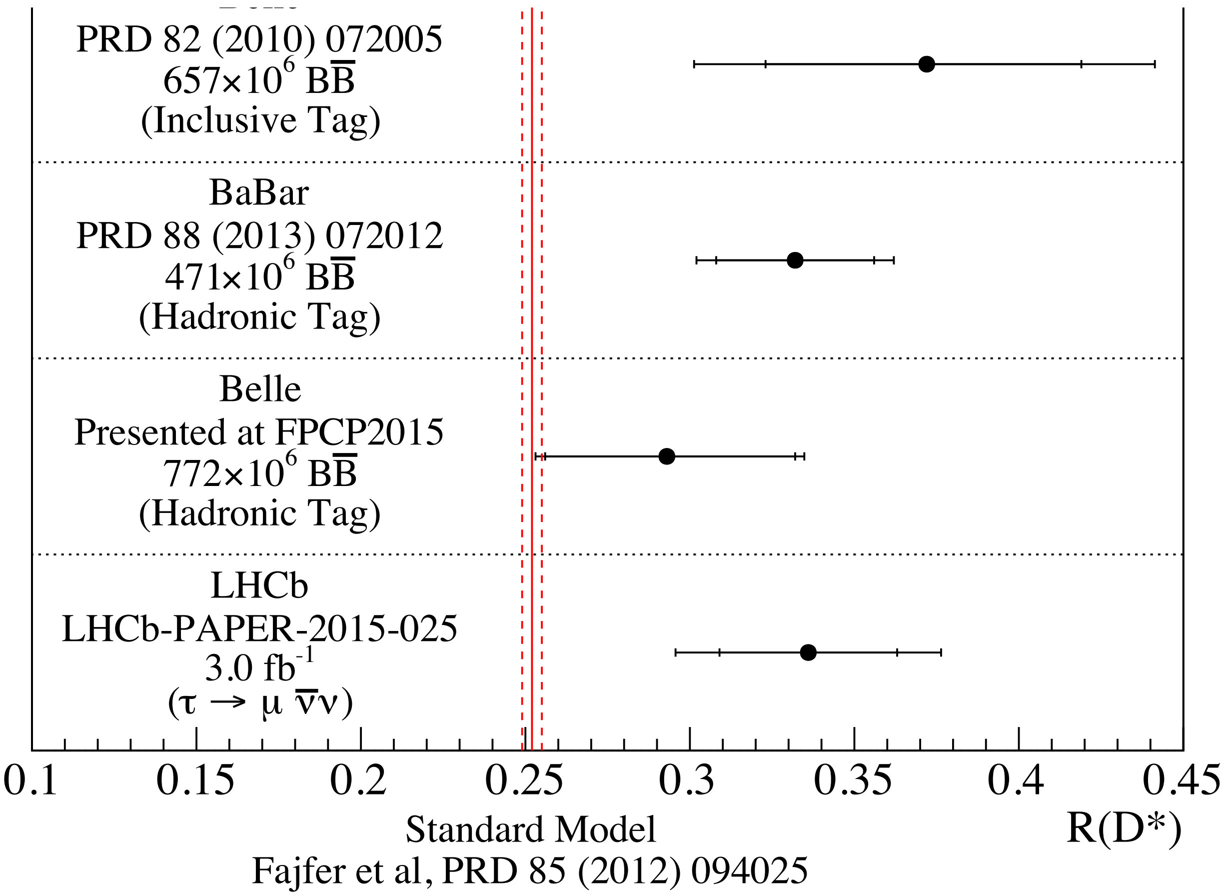


Fit in 4 q^2 bins: fit variables E_m(CM)& m_{miss}^2:

☐ templates for each component using approximate B momentum

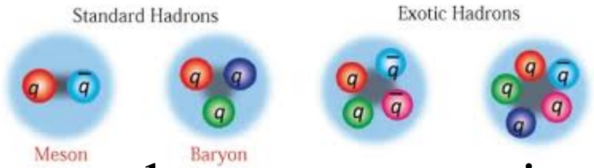
$B \to D^{(*)}\tau\nu$ summary

Belle semileptonic tag, $R(D^*) = 0.302 \pm 0.030 \pm 0.011$ [1603.06711,



In progress at LHCb $B\to D^*\tau\nu$, with $\tau\to3\pi(\pi^0)$…

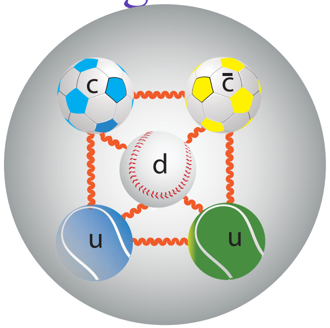
exotic hadrons & QCD



- ☐ theory perspective:
  - ☐ lattice QCD is poised to predict mass and decay properties of ordinary hadrons, but also exotica (glueballs, tetraquarks, pentaquarks…)

"Multiquark correlations inside hadrons can have a significant and in some cases even striking impact on the hadron spectrum. We show how such correlations in general, and mesons with a dominant tetraquark content in particular, emerge holographically in the AdS/QCD framework." Forkel arXiv:1206.5745

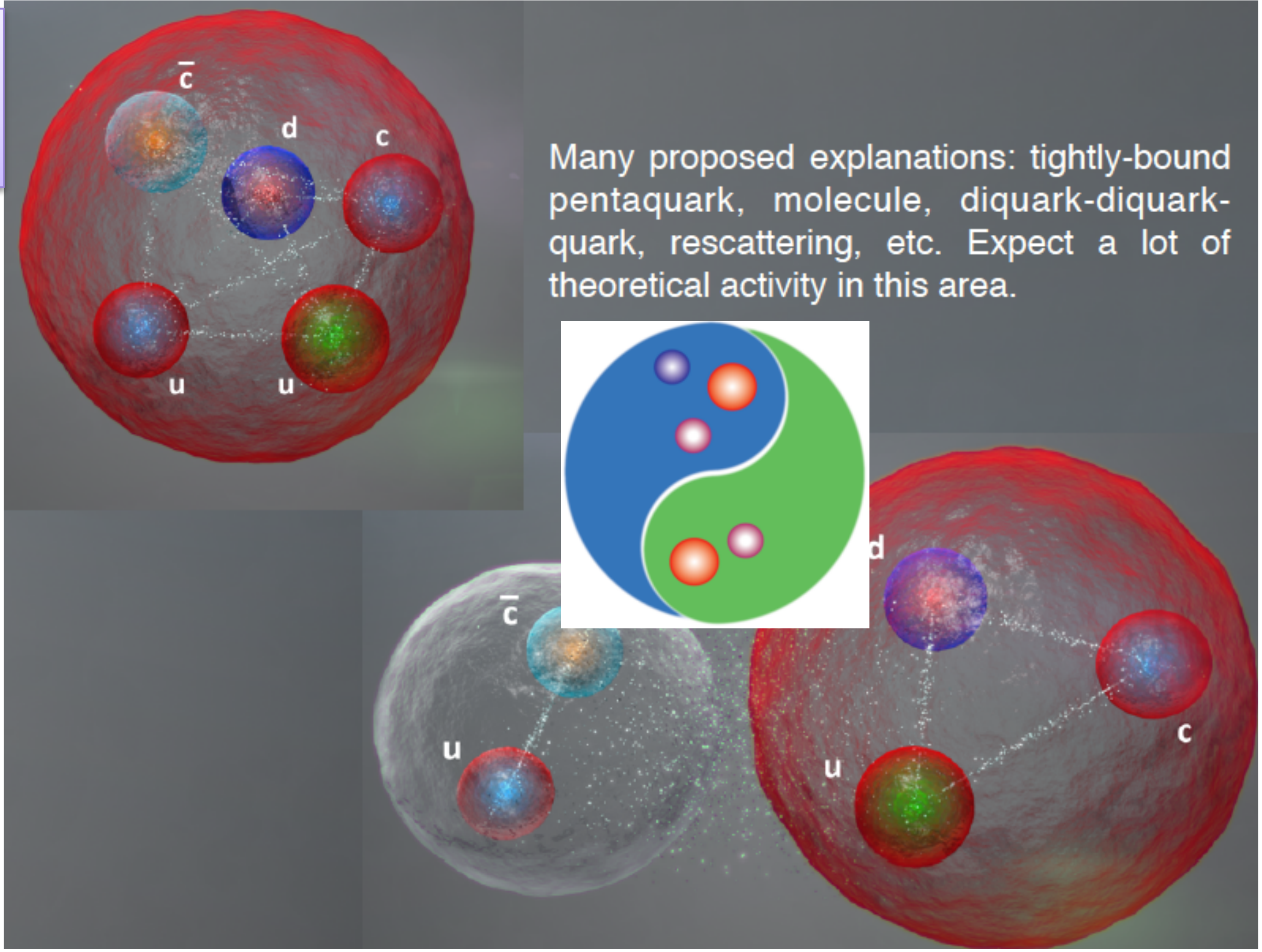
- ☐ experimental perspective:
  - ☐ Nature of scalar nonet still a mystery
  - ☐ zoo of exotic X,Y,Z particles containing b and c quarks are being discovered
  - ☐ Here is the summer sensation:



Physics World

One of the top 10 physics breakthrough of 2015

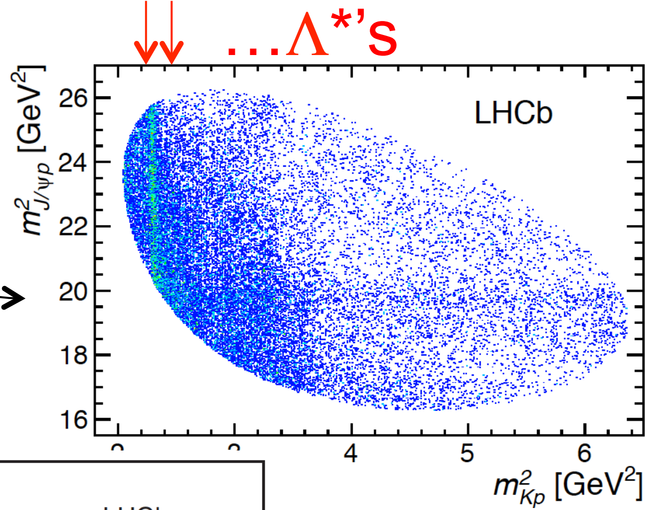
CERN VISUALIZATION, less sport oriented



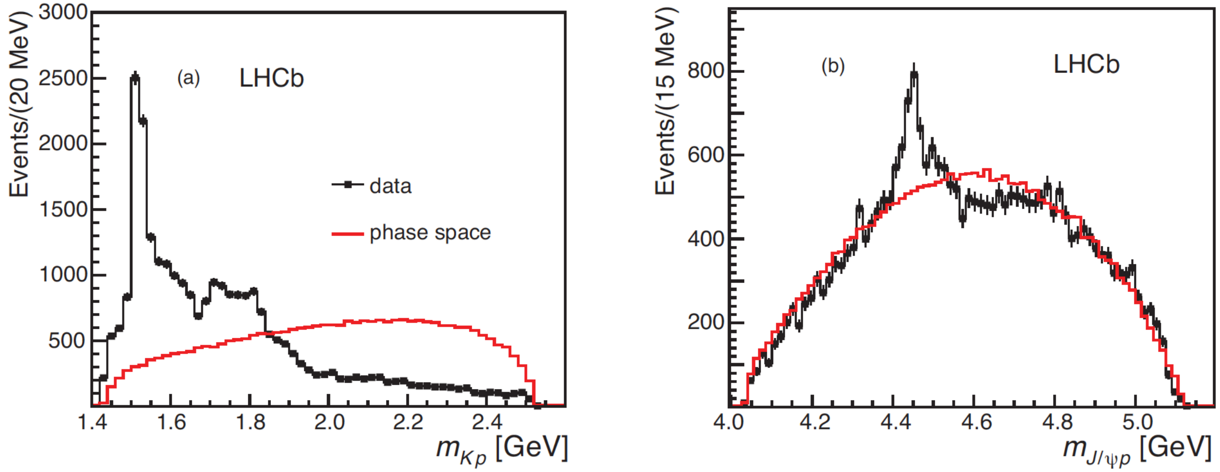
Many proposed explanations: tightly-bound pentaquark, molecule, diquark-diquark-quark, rescattering, etc. Expect a lot of theoretical activity in this area.

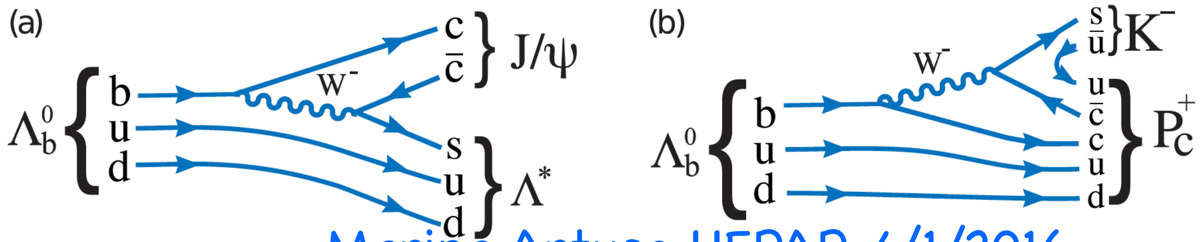
P_c states in $\Lambda_b \to J/\psi K^- p$

- ☐ Dalitz plot show an unusual feature
  [arXiv:1507.03414]



projections



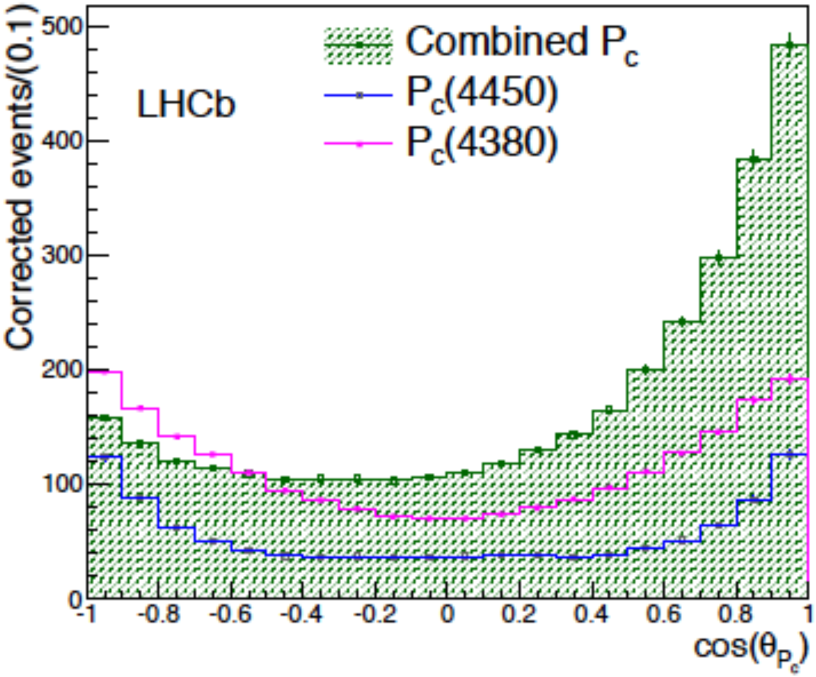


Decay amplitude analysis

- Are there "artifacts" that can produce a peak?
  - Many checks done that shows this is not the case: e.g. changing p to K, or π to K allows us to veto misidentified $B_s \rightarrow J/\psi K^- K^+$ & $B^0 \rightarrow J/\psi K^- \pi^+$
  - Clones & ghost tracks eliminated
  - Ξ_b decays checked as a source
- Can interferences between Λ* resonances generate a peak in the J/ψp mass spectra?
  - Implemented a decay amplitude analysis that incorporates both decay sequences

Pentaquarks

A 6-D amplitude analysis fails to describe the data without two charm pentaquark states (Pc). The asymmetric combined Pc angular distribution requires (at least) two states of opposite parity.



PRL 115 (2015) 072001
LHCb-PAPER-2015-029

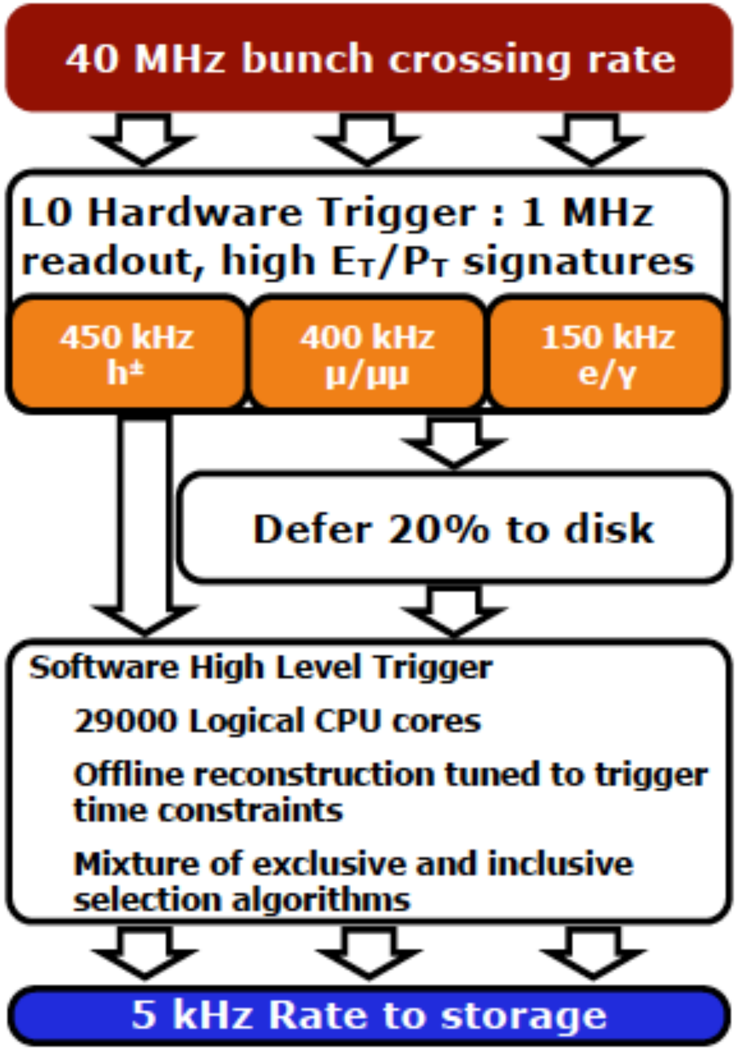
Model-independent analysis shows clear resonant behavior for both Pc states.

An important milestone towards the phase 1 upgrade

LHCb RUN II

The LHCb Trigger evolution

RUN I



40 MHz bunch crossing rate

L0 Hardware Trigger : 1 MHz readout, high E_T/P_T signatures

450 kHz $h^\pm$	400 kHz $\mu/\mu\mu$	150 kHz e/γ

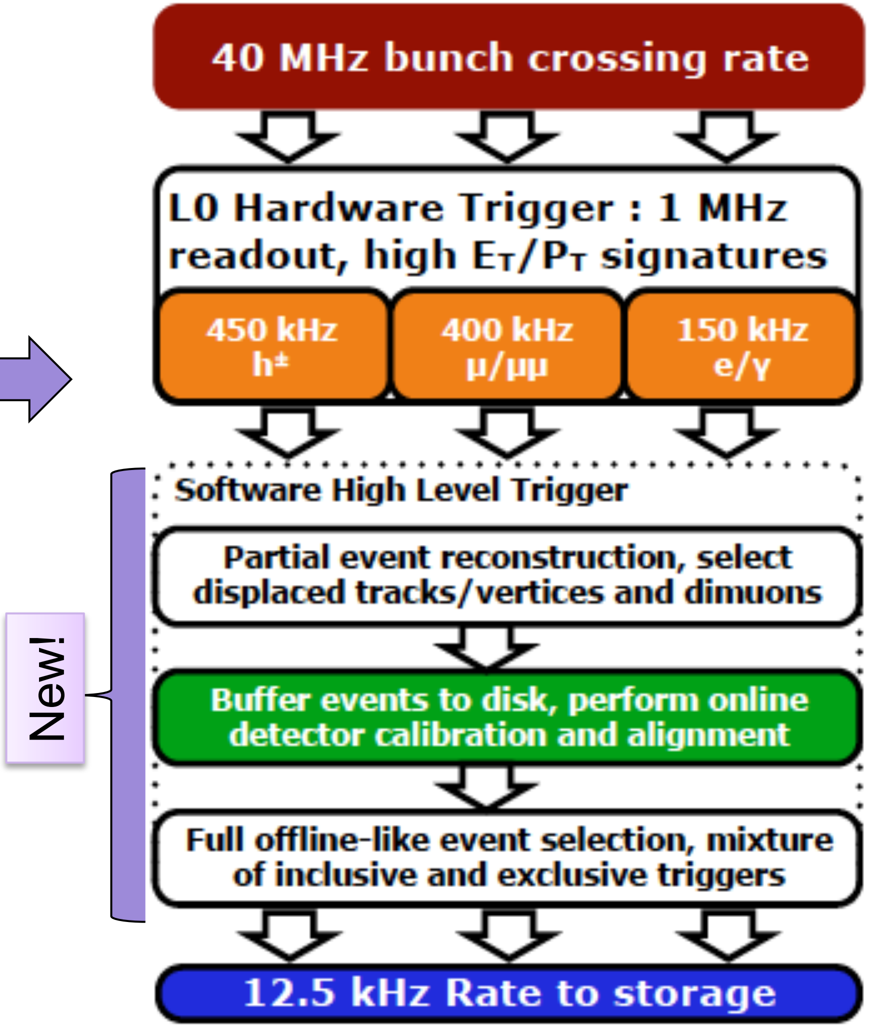
Defer 20% to disk

Software High Level Trigger

- 29000 Logical CPU cores
- Offline reconstruction tuned to trigger time constraints
- Mixture of exclusive and inclusive selection algorithms

5 kHz Rate to storage

LHCb 2015 Trigger Diagram



40 MHz bunch crossing rate

L0 Hardware Trigger : 1 MHz readout, high E_T/P_T signatures

450 kHz $h^\pm$	400 kHz $\mu/\mu\mu$	150 kHz e/γ

Software High Level Trigger

New!

Partial event reconstruction, select displaced tracks/vertices and dimuons

Buffer events to disk, perform online detector calibration and alignment

Full offline-like event selection, mixture of inclusive and exclusive triggers

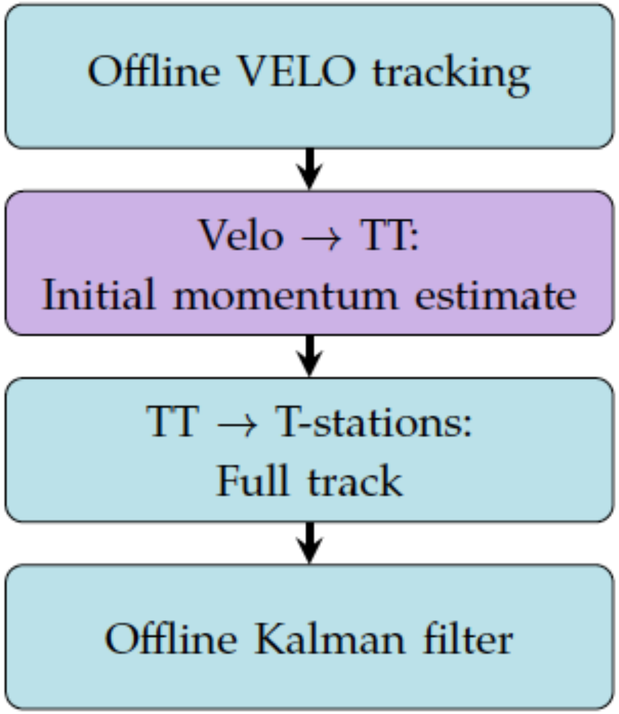
12.5 kHz Rate to storage

Run II Trigger overview

- LHCb detector read out at 1 MHz
- Hardware trigger (L0):
  - Based on multiplicity, calorimeter, and muon detectors
  - Fixed latency of 4 μs
  - Reduces rate to 1 MHz
  - Higher thresholds in Run II
- Software trigger (HLT):
  - Split into 2 applications (HLT1 & HLT2)
  - Events buffered after HLT1
  - Output rate 12.5 KHz
  - HLT software 40% faster

Tracking in HLT1

Tracking in HLT1 for Run II


Offline VELO tracking

Velo → TT:
Initial momentum estimate

TT → T-stations:
Full track

Offline Kalman filter

- Improved sequence forming Velo-TT tracks as an intermediate stage
- Momentum estimate allows a preselection on the p_T of tracks
- Charge estimate allows greatly reduced search windows downstream of the magnet
  - Vast reduction in both ghost rate (factor 4) and execution time (factor 3)

To be improved in the PHASE 1 upgrade with replacement of TT→UT with optimized acceptance and granularity, construction project lead by US institutions with NSF support

Real time calibration and alignment

- We want the trigger to be more efficient and selective

⇒same online and offline reconstruction

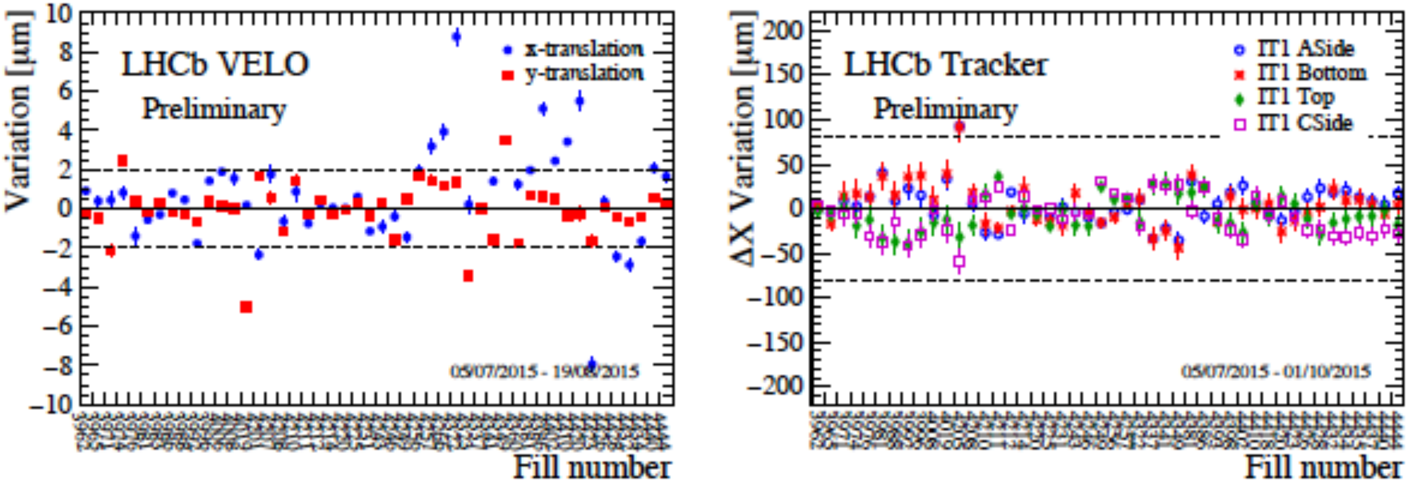
⇒ prompt alignment and calibration needed

- Alignment per fill:
  - Collect suitable data with dedicated HLT1 selections, e.g. $J/\psi \rightarrow \mu^+\mu^-$, $D^0 \rightarrow K^-\pi^+$
  - Run “alignment workers” on the HLT farm
  - Apply updates of VELO and/or tracker alignment if needed
  - RICH mirror alignment and muon alignment for monitoring
  - ECAL gain calibration
- Alignment per 1 h run (available in ~1 minute after data collection)
  - RICH and outer tracker t_0

Real time alignment

- VELO alignment and full alignment of tracking system,
- Straw-tube tracker drift time origin calibration,
- RICH refractive index calibration,
- RICH mirror alignment,
- Automatic calorimeter PMT voltage adjustment for detector aging,
- Muon detector alignment.

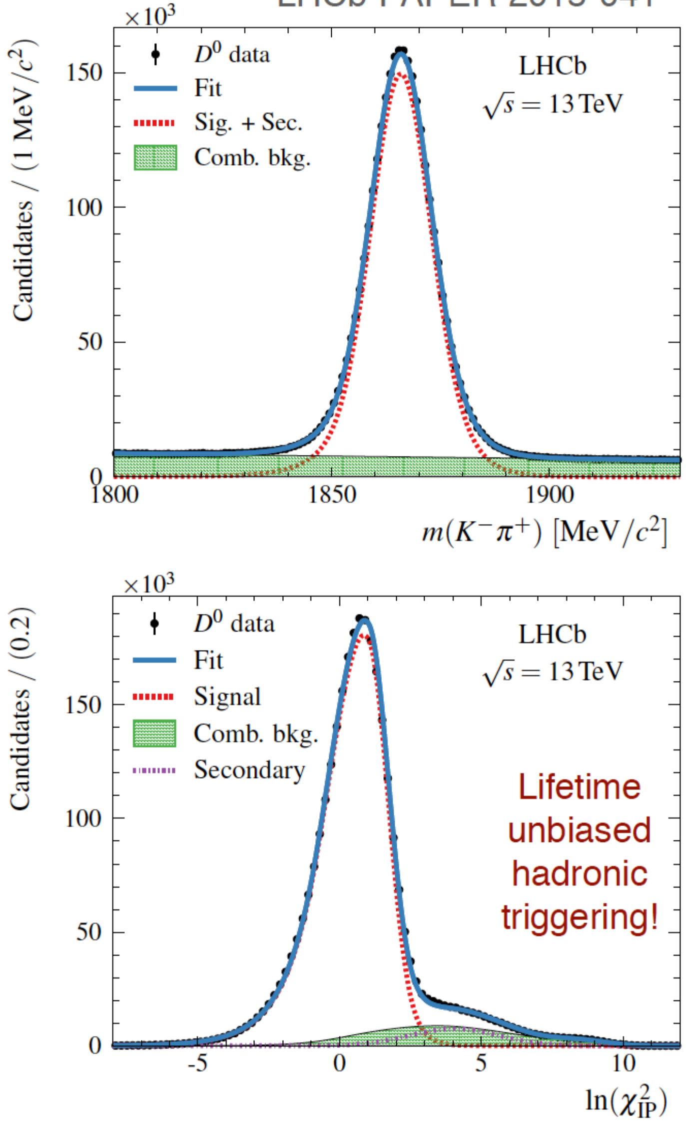
VELO and tracking alignment



Online reconstruction

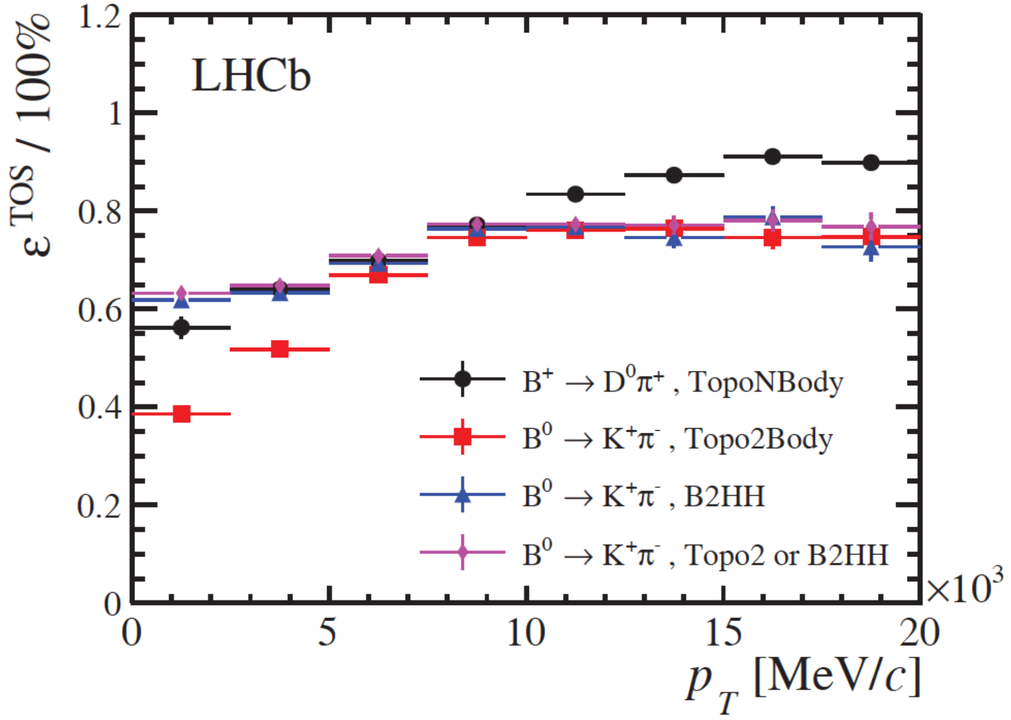
- Resolution obtained online in Run 2 comparable or better than Run 1 offline
- Data available to be analyzed 1 day after recording
- New HLT gains >50% efficiency for charm physics

LHCb-PAPER-2015-041



Lifetime unbiased hadronic triggering!

HLT2 selection (beauty)



- ❑Inclusive beauty selections:
  - ❑MVA based 2, 3, 4 body detached vertices
  - ❑Di-muon selections
  - ❑Exclusive beauty selection (e.g. B→γγ)

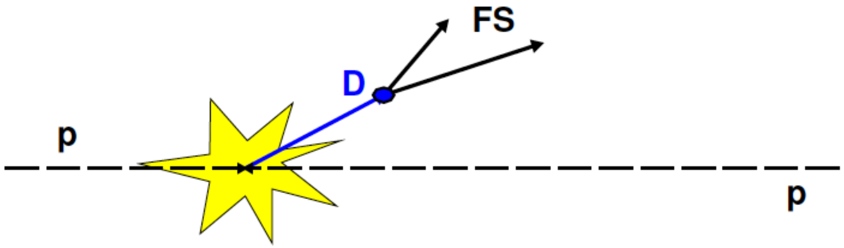
HLT2 & turbo stream

- Nearly 400 selections in total (beauty, charm, electroweak bosons..)
- 12.5 KHz to tape
- Offline reconstruction available online → do physics analysis with HLT candidates
- TURBO stream:
  - Substantial fraction of events have no raw information written: must be performed on the trigger output.
  - Space reduced by >90%
- Ideal for high-yield analyses
- *O*(24h) turn-around.

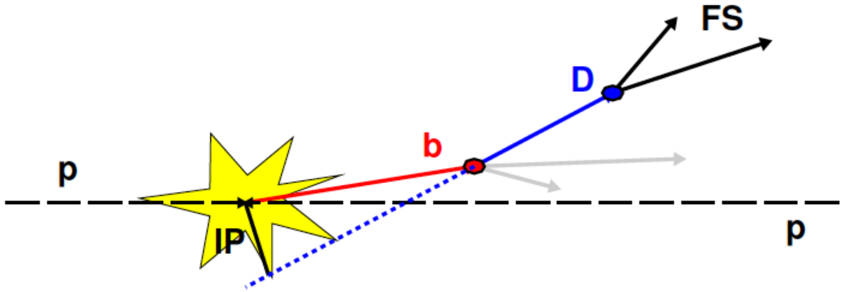
1st application of the turbo-stream

- The $b\bar{b}$ and $c\bar{c}$ cross sections at 13 TeV were presented at EPS 2015 within about 1 week of recording the data: they were measured using the trigger output.
- Some remarks:
  - Resolution obtained using online reconstruction in Run 2 comparable to (or better of) Run 1 offline reconstruction.
  - Data available ~24 hours after recording
  - New HLT gains >50% for charm physics
  - We expect 3-5 times increase in the flavor physics data sample in Run II, and about 20 times higher statistics for high-p_t final states like top

Charm hadrons at LHCb



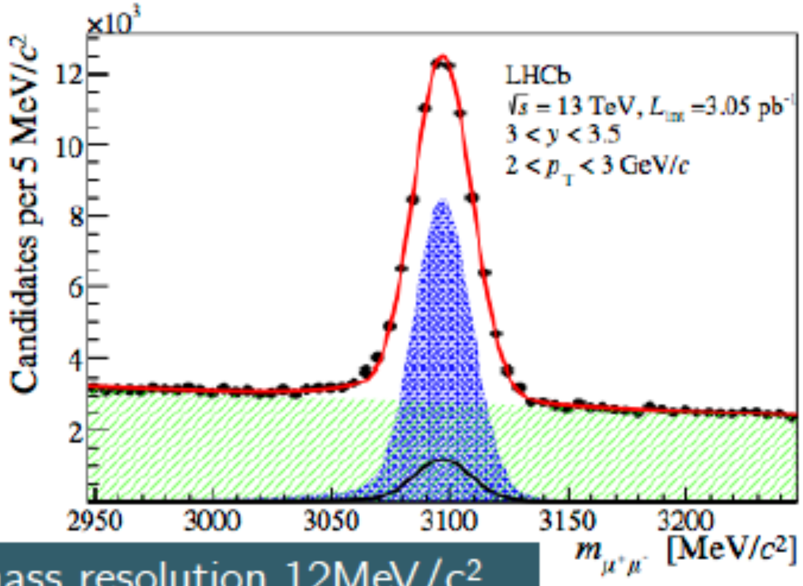
"prompt" charm



Charm from B

J/ψ sample separated into "prompt" to determine "**prompt J/ψ cross-section**" and "**J/ψ from b cross section**"

J/ψ selection



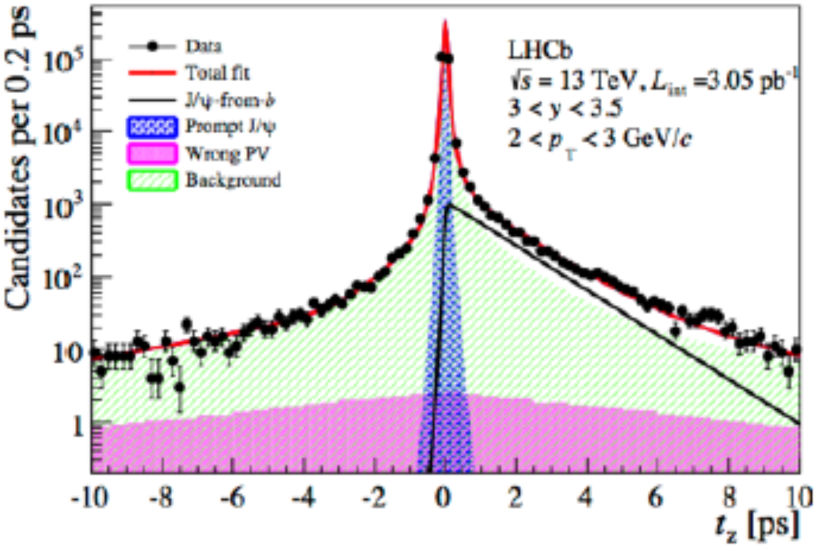
mass resolution 12MeV/c²
consistent with Run 1 offline

Analysis finds ~10^6 candidates directly from the trigger.

No further reconstruction, all necessary information is persisted from the trigger

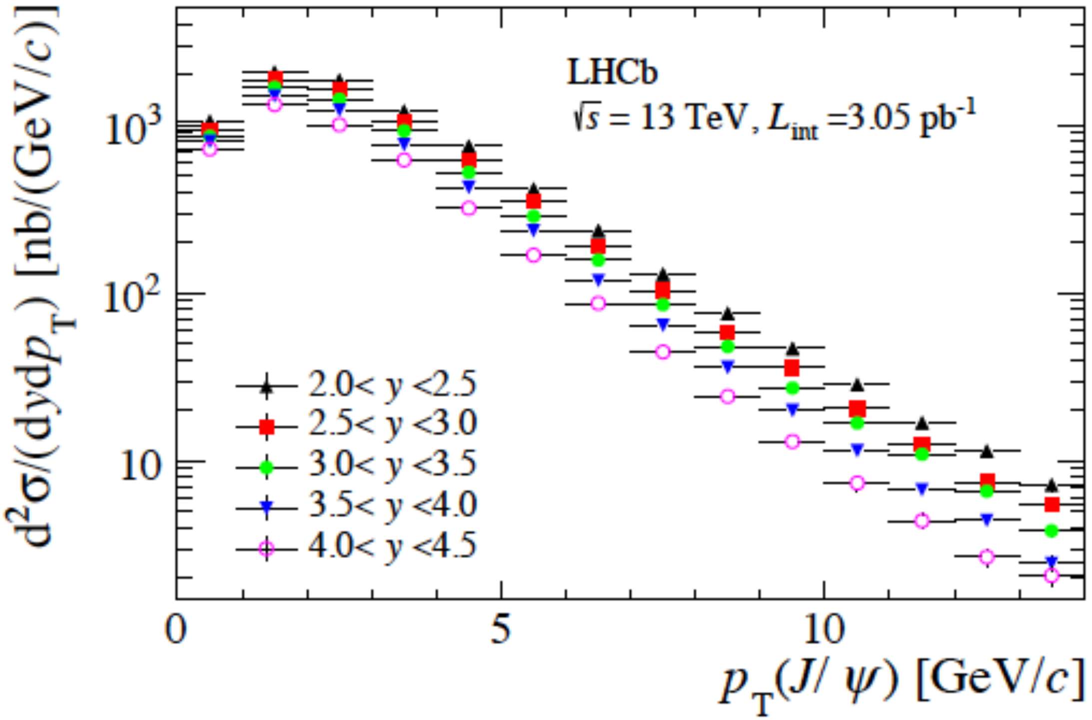
Component from B decays found from t_z distribution

$$t_z = \frac{(z_{J/\psi} - z_{PV})M_{J/\psi}}{p_z}$$



Prompt J/ψ cross-section

arXiV:1509.00771

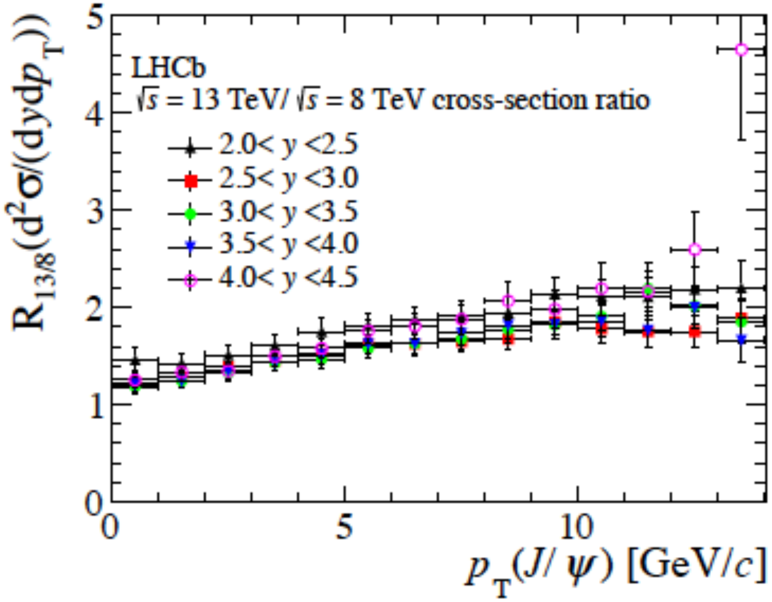


Double differential cross-sections, $d^2\sigma_i/dp_T dy$, of prompt J/ψ vs. p_T.

Integrated over the acceptance of the analysis

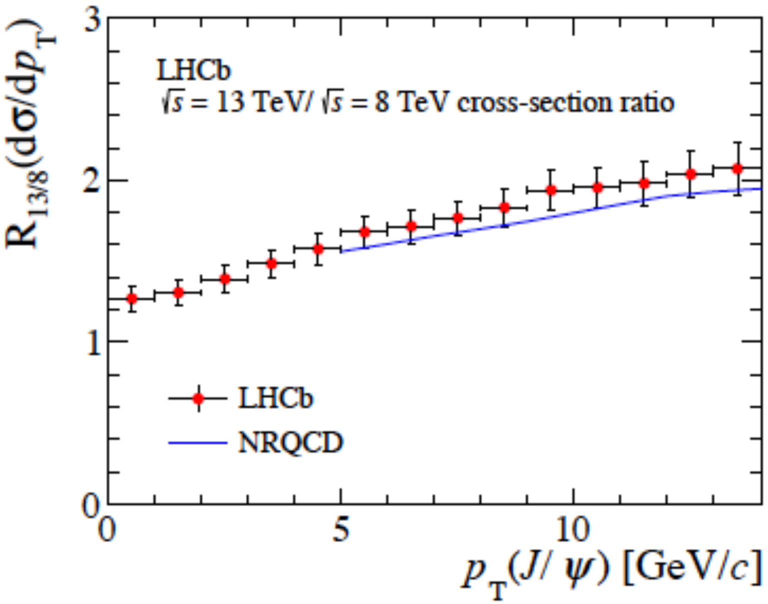
$$\sigma(\text{prompt } J/\psi, p_T < 14\,\text{GeV}, 2.0 < y < 4.5) = 15.30 \pm 0.03 \pm 0.86\,\mu\text{b}.$$

Comparison with 8 TeV data

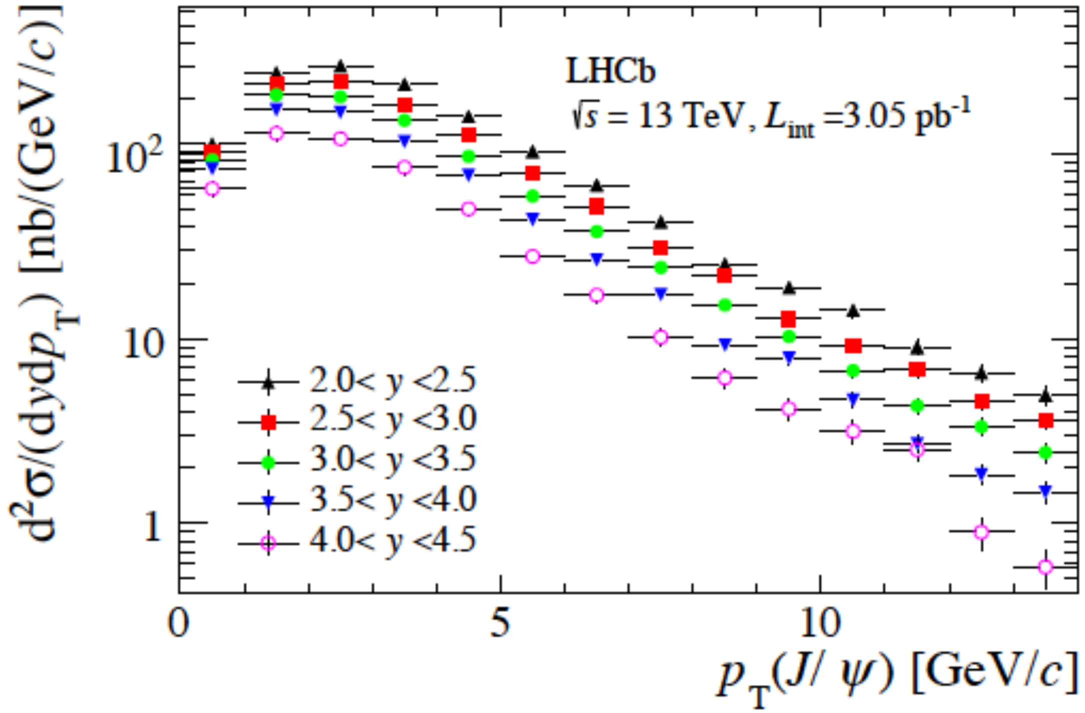


Ratios of double differential cross-sections, $d^2\sigma_i/dp_T dy$, between measurements at $\sqrt{s} = 13$ TeV and at $\sqrt{s} = 8$ TeV.

Ratios of differential cross-sections, $d\sigma_i/dp_T$, integrated over y between measurements at $\sqrt{s} = 13$ TeV and at $\sqrt{s} = 8$ TeV and compared to NRQCD calculations.



J/ψ from b cross-section

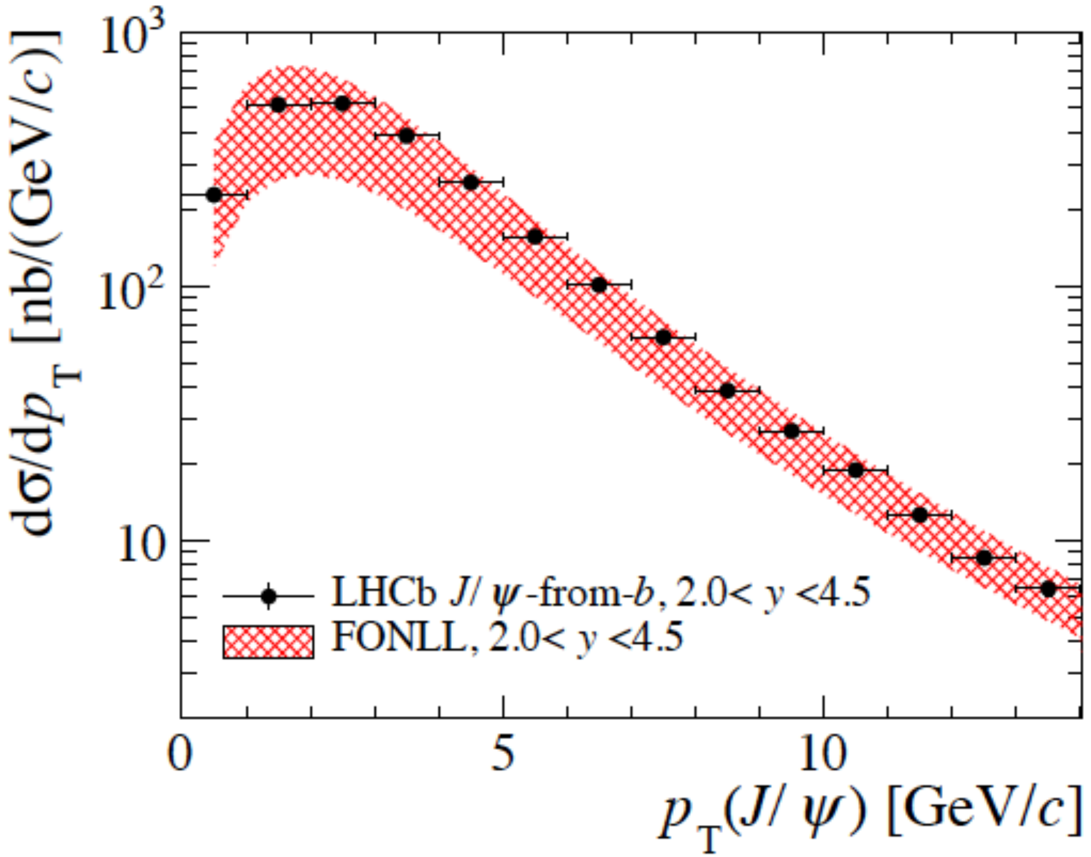


Double differential cross-sections, $d^2\sigma_i/dp_T dy$, of J/ψ-from-b vs. p_T.

Integrated over the acceptance of the analysis

$$\sigma(J/\psi\text{-from-}b, p_T < 14\,\text{GeV}, 2.0 < y < 4.5) = 2.34 \pm 0.01 \pm 0.13\,\mu\text{b}.$$

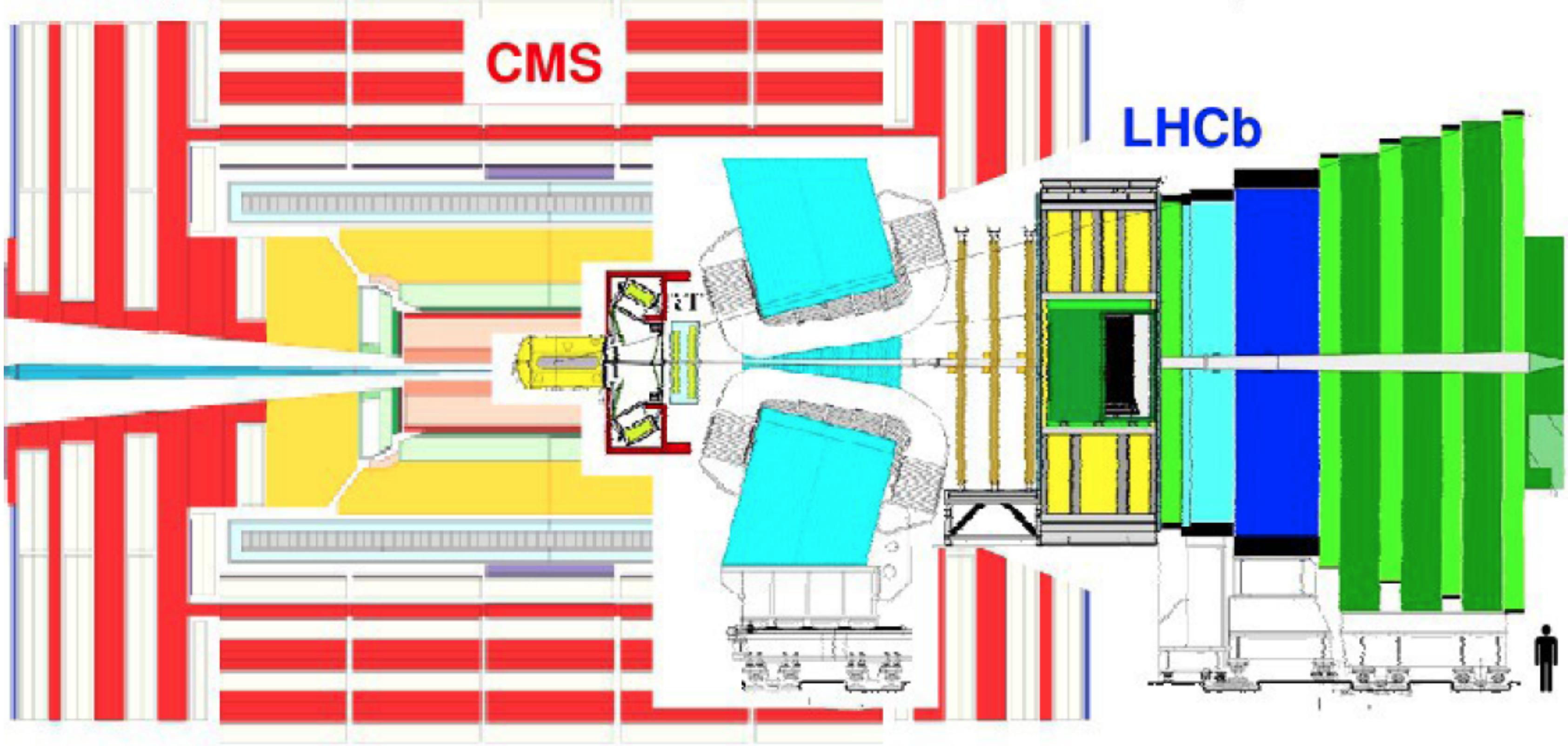
Comparison with theory



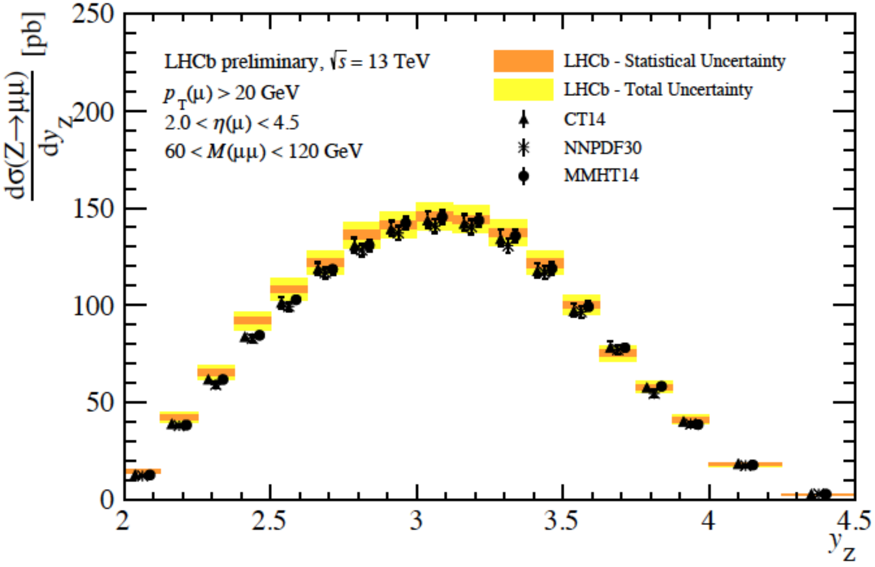
Differential cross-sections, $d\sigma_i/dp_T$, integrated over $2.0 < y < 4.5$ and compared to FONLL calculations (Cacciari *et al.*, arXiv:1507.06197).

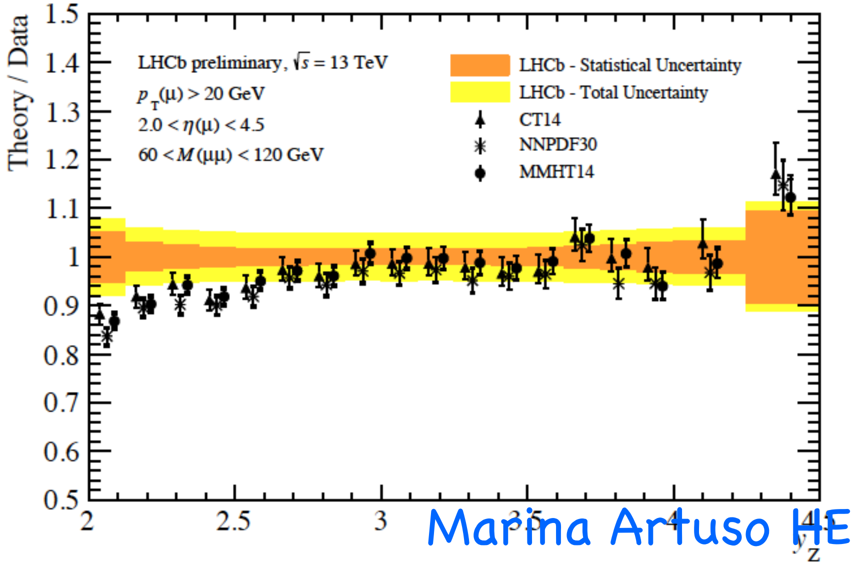
LHCb detector - another view

- Complementary to ATLAS & CMS
- Much less expensive



Z→$\mu^+\mu^-$ production cross-section at 13 TeV





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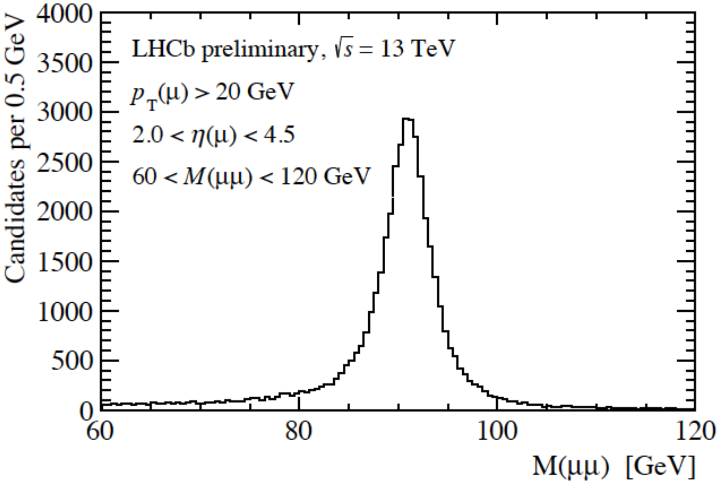


→ $\sigma = 198.4 \pm 1.0$ (stat) ± 4.2 (syst) ± 7.7 (lumi) pb

In good agreement with NNLO in pQCD from FEWZ

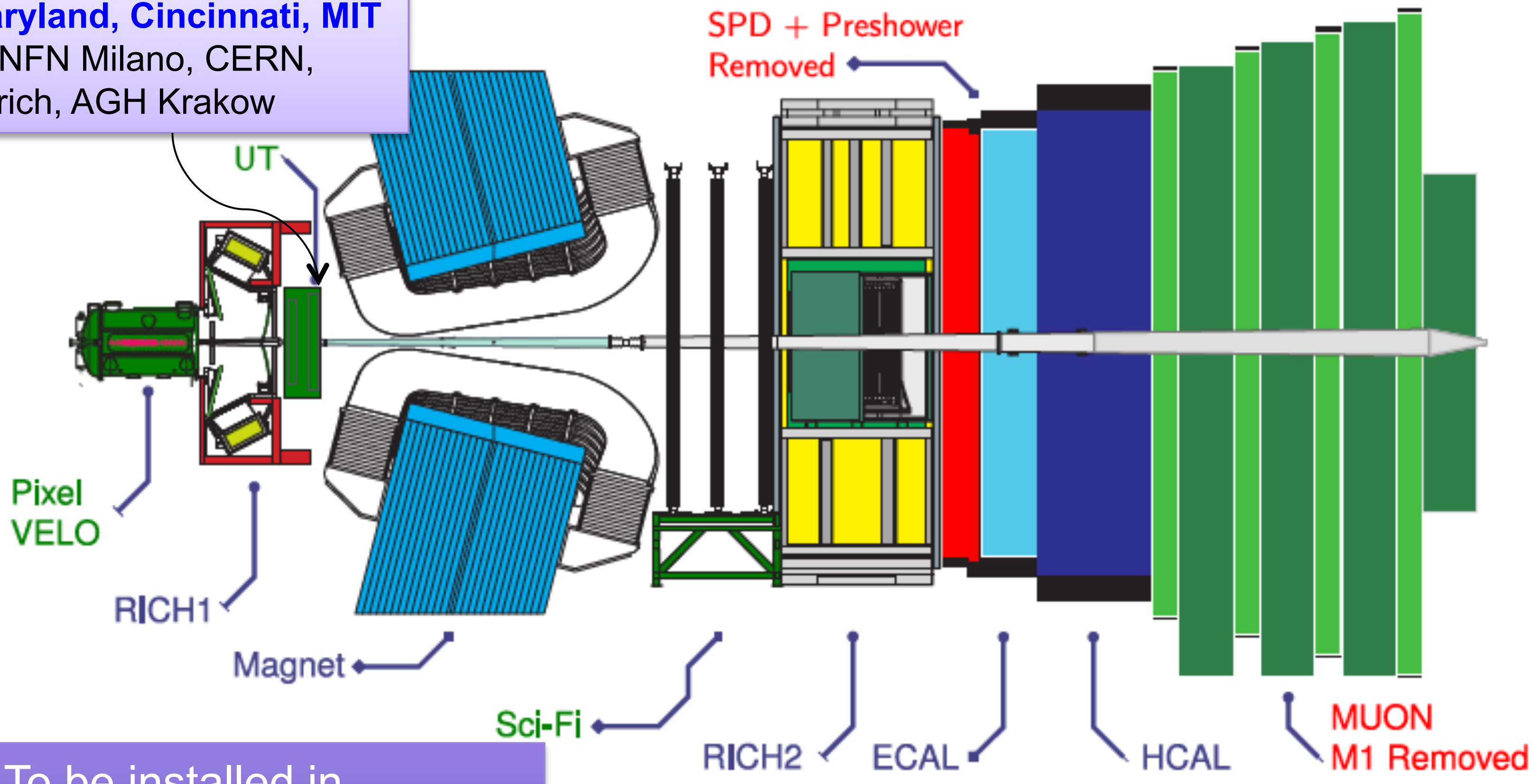
Taking strides towards the future

THE LHCB PHASE 1 UPGRADE

The LHCb PHASE 1 upgrade

Luminosity to increase by 5x, and we will move to a triggerless-readout system. Many detector elements being redesigned to make this possible.

US lead: **Syracuse, Maryland, Cincinnati, MIT** & INFN Milano, CERN, Zurich, AGH Krakow



To be installed in 2019-2020 shut down

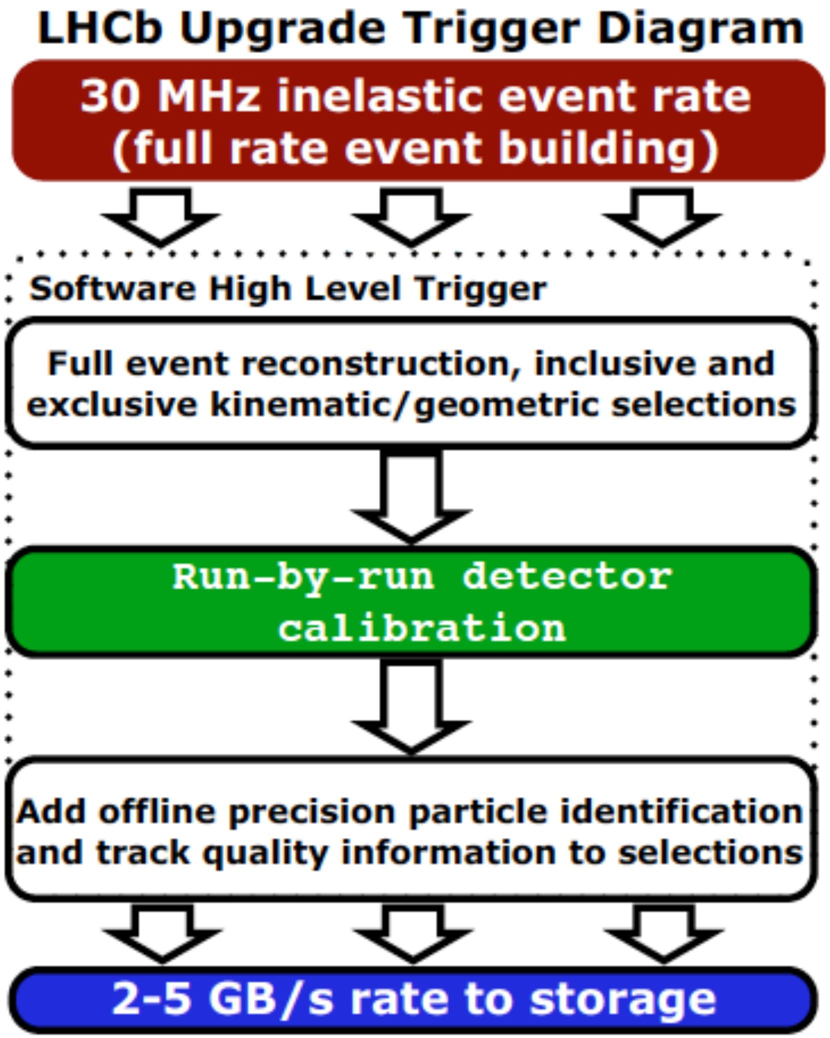
The LHCb Upgrade trigger concept

❑ Remove the 1 MHz L0 hardware trigger bottleneck

❑ Goal is to run the full tracking at 30 MHz and make some loose selection

❑ Many events expected to go to Turbo Stream

❑ Very effective approach to improve LHCb sensitivity in many BSM searches



LHCb Upgrade Trigger Diagram

30 MHz inelastic event rate (full rate event building)

Software High Level Trigger

Full event reconstruction, inclusive and exclusive kinematic/geometric selections

Run-by-run detector calibration

Add offline precision particle identification and track quality information to selections

2-5 GB/s rate to storage

Projected sensitivity to key observables

LHCb PUB-2014-040-7

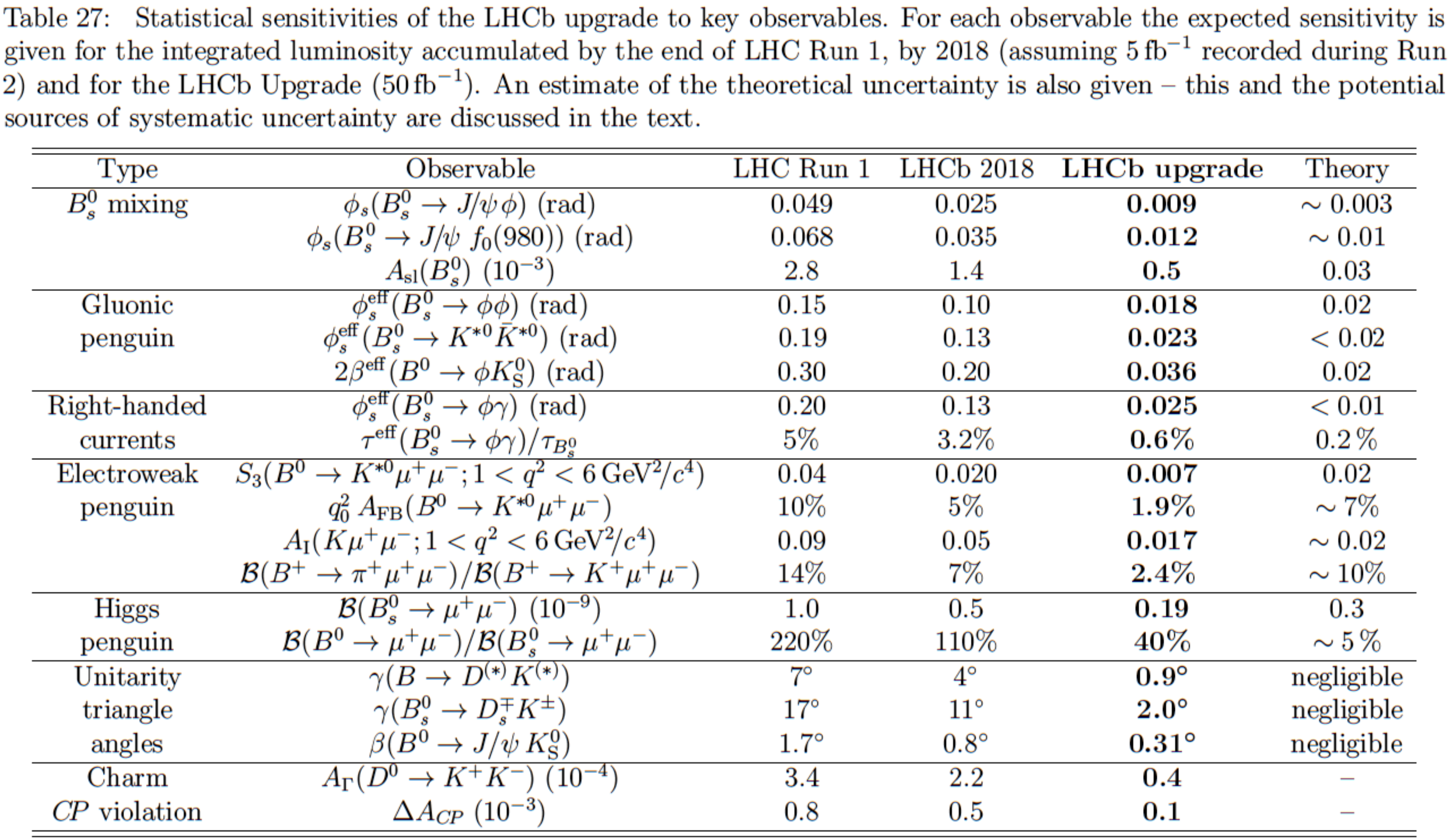


Table 27: Statistical sensitivities of the LHCb upgrade to key observables. For each observable the expected sensitivity is given for the integrated luminosity accumulated by the end of LHC Run 1, by 2018 (assuming $5\,\mathrm{fb}^{-1}$ recorded during Run 2) and for the LHCb Upgrade ($50\,\mathrm{fb}^{-1}$). An estimate of the theoretical uncertainty is also given – this and the potential sources of systematic uncertainty are discussed in the text.

Type	Observable	LHC Run 1	LHCb 2018	**LHCb upgrade**	Theory
B_s^0 mixing	$\phi_s(B_s^0 \to J/\psi\,\phi)$ (rad)	0.049	0.025	**0.009**	~ 0.003
	$\phi_s(B_s^0 \to J/\psi\ f_0(980))$ (rad)	0.068	0.035	**0.012**	~ 0.01
	$A_{\mathrm{sl}}(B_s^0)$ (10^{-3})	2.8	1.4	**0.5**	0.03
Gluonic penguin	$\phi_s^{\mathrm{eff}}(B_s^0 \to \phi\phi)$ (rad)	0.15	0.10	**0.018**	0.02
	$\phi_s^{\mathrm{eff}}(B_s^0 \to K^{*0}\bar{K}^{*0})$ (rad)	0.19	0.13	**0.023**	< 0.02
	$2\beta^{\mathrm{eff}}(B^0 \to \phi K_S^0)$ (rad)	0.30	0.20	**0.036**	0.02
Right-handed currents	$\phi_s^{\mathrm{eff}}(B_s^0 \to \phi\gamma)$ (rad)	0.20	0.13	**0.025**	< 0.01
	$\tau^{\mathrm{eff}}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	5%	3.2%	**0.6%**	0.2 %
Electroweak penguin	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	0.04	0.020	**0.007**	0.02
	$q_0^2\ A_{\mathrm{FB}}(B^0 \to K^{*0}\mu^+\mu^-)$	10%	5%	**1.9%**	$\sim 7\%$
	$A_{\mathrm{I}}(K\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	0.09	0.05	**0.017**	~ 0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	14%	7%	**2.4%**	$\sim 10\%$
Higgs penguin	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ (10^{-9})	1.0	0.5	**0.19**	0.3
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	220%	110%	**40%**	$\sim 5\,\%$
Unitarity triangle angles	$\gamma(B \to D^{(*)}K^{(*)})$	7°	4°	**0.9°**	negligible
	$\gamma(B_s^0 \to D_s^{\mp}K^{\pm})$	17°	11°	**2.0°**	negligible
	$\beta(B^0 \to J/\psi\ K_S^0)$	1.7°	0.8°	**0.31°**	negligible
Charm *CP* violation	$A_\Gamma(D^0 \to K^+K^-)$ (10^{-4})	3.4	2.2	**0.4**	–
	ΔA_{CP} (10^{-3})	0.8	0.5	**0.1**	–

Conclusions

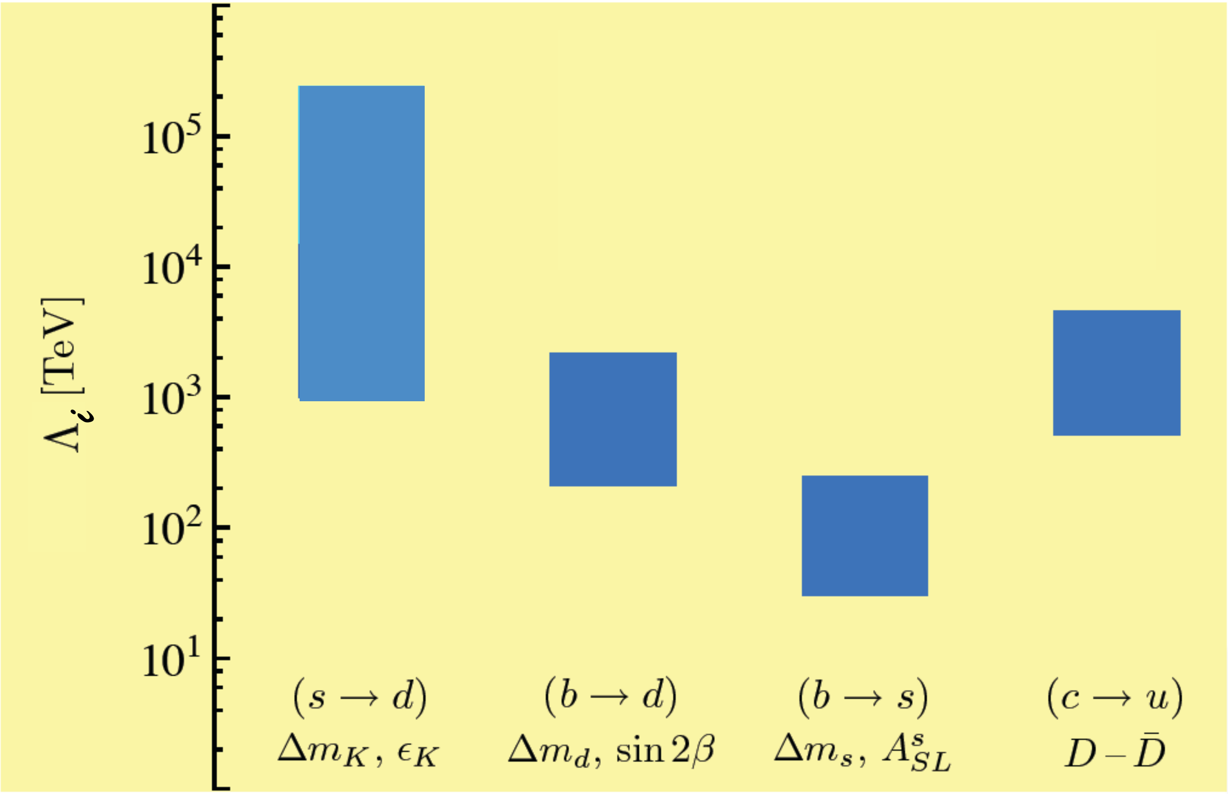
- The LHCb is poised to continue the exploitation of the rich Run I
- Run II is a key milestone towards the validation of the key trigger and DAQ philosophy for the phase I upgrade
- 2016 production year: expected 1.5 fb^{-1}
- Phase I detector construction is at a good start!

THE END

Flavor as a High Mass Probe

$$L_{\text{eff}} = L_{\text{SM}} + \frac{c_i}{\Lambda_i^2} O_i$$

☐ Already excluded ranges



Ways out

1. New particles have large masses >>1 TeV
2. New particles have degenerate masses
3. Mixing angles in new sector are small, same as in SM (MFV)
4. The above already implies strong constrains on NP

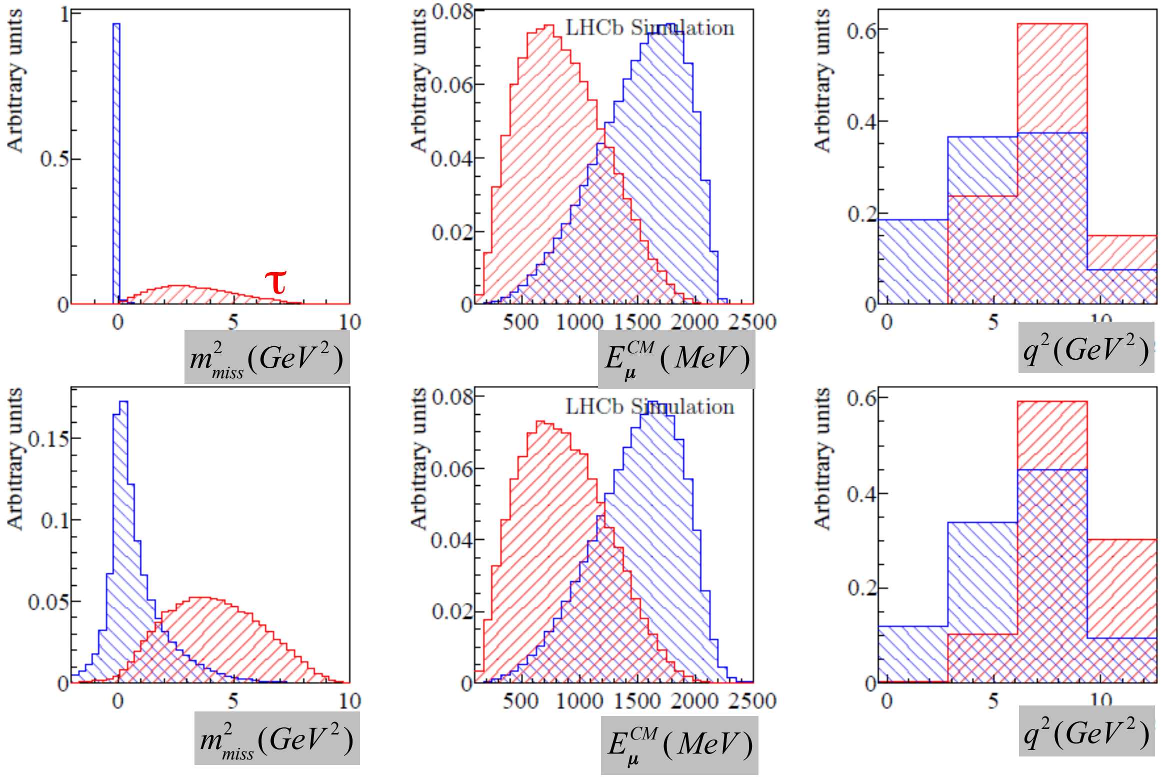
See: Isidori, Nir
& Perez arXiv:1002.0900;
Neubert EPS 2011 talk

B momentum approximation

LHCb-PAPER-2015-025
arXiv:1506.08614

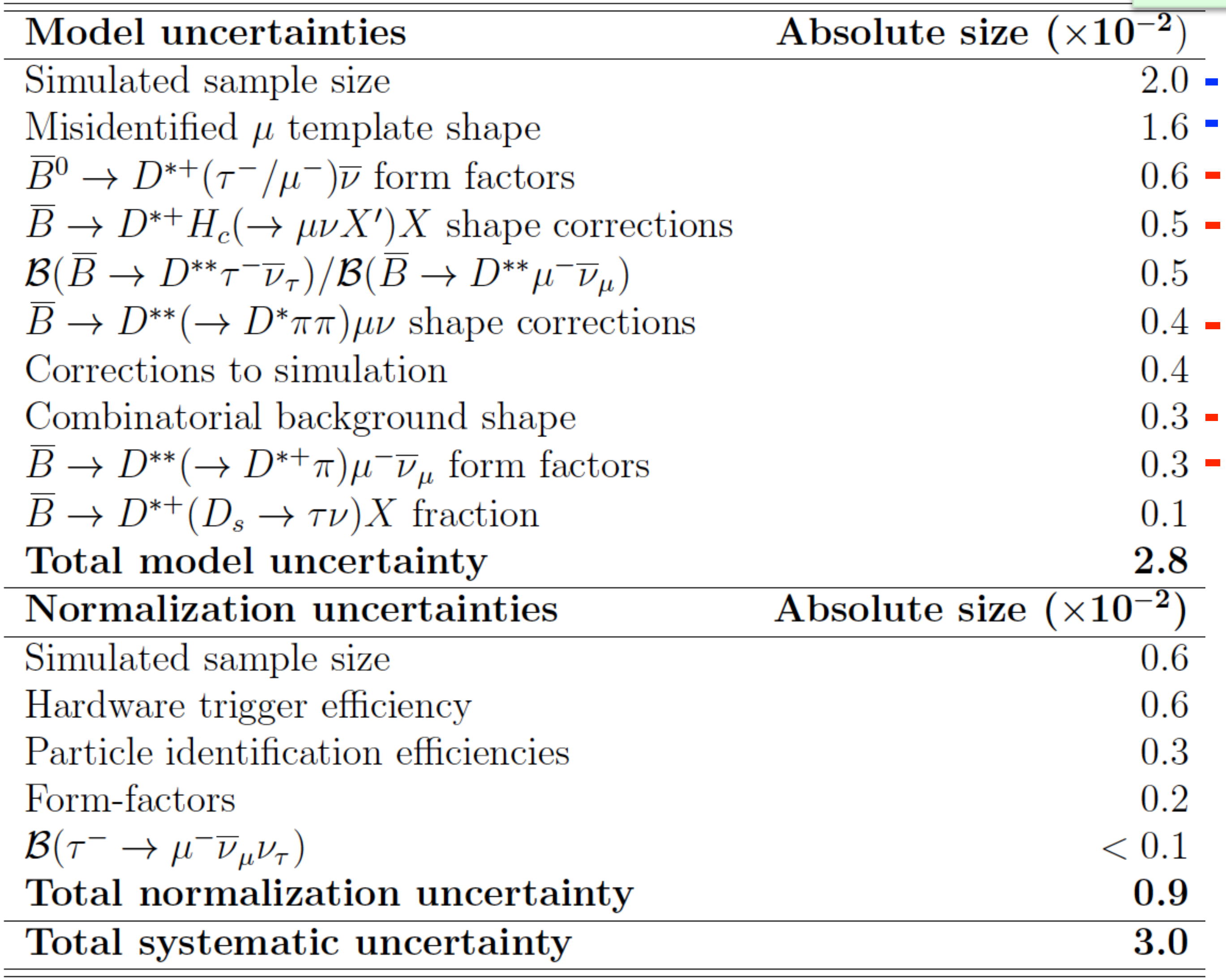
MC B momentum

Approximate B momentum



Systematic uncertainties

arXiv:1506.08614



Model uncertainties	**Absolute size ($\times 10^{-2}$)**	
Simulated sample size	2.0	🟦
Misidentified μ template shape	1.6	🟦
$\overline{B}^0 \to D^{*+}(\tau^-/\mu^-)\overline{\nu}$ form factors	0.6	🟥
$\overline{B} \to D^{*+}H_c(\to \mu\nu X')X$ shape corrections	0.5	🟥
$\mathcal{B}(\overline{B} \to D^{**}\tau^-\overline{\nu}_\tau)/\mathcal{B}(\overline{B} \to D^{**}\mu^-\overline{\nu}_\mu)$	0.5	
$\overline{B} \to D^{**}(\to D^*\pi\pi)\mu\nu$ shape corrections	0.4	🟥
Corrections to simulation	0.4	
Combinatorial background shape	0.3	🟥
$\overline{B} \to D^{**}(\to D^{*+}\pi)\mu^-\overline{\nu}_\mu$ form factors	0.3	🟥
$\overline{B} \to D^{*+}(D_s \to \tau\nu)X$ fraction	0.1	
Total model uncertainty	**2.8**	
Normalization uncertainties	**Absolute size ($\times 10^{-2}$)**	
Simulated sample size	0.6	
Hardware trigger efficiency	0.6	
Particle identification efficiencies	0.3	
Form-factors	0.2	
$\mathcal{B}(\tau^- \to \mu^-\overline{\nu}_\mu\nu_\tau)$	< 0.1	
Total normalization uncertainty	**0.9**	
Total systematic uncertainty	**3.0**	

Expected to be reduced for future R(D)+R(D*)

Will scale down with more data (Run2)

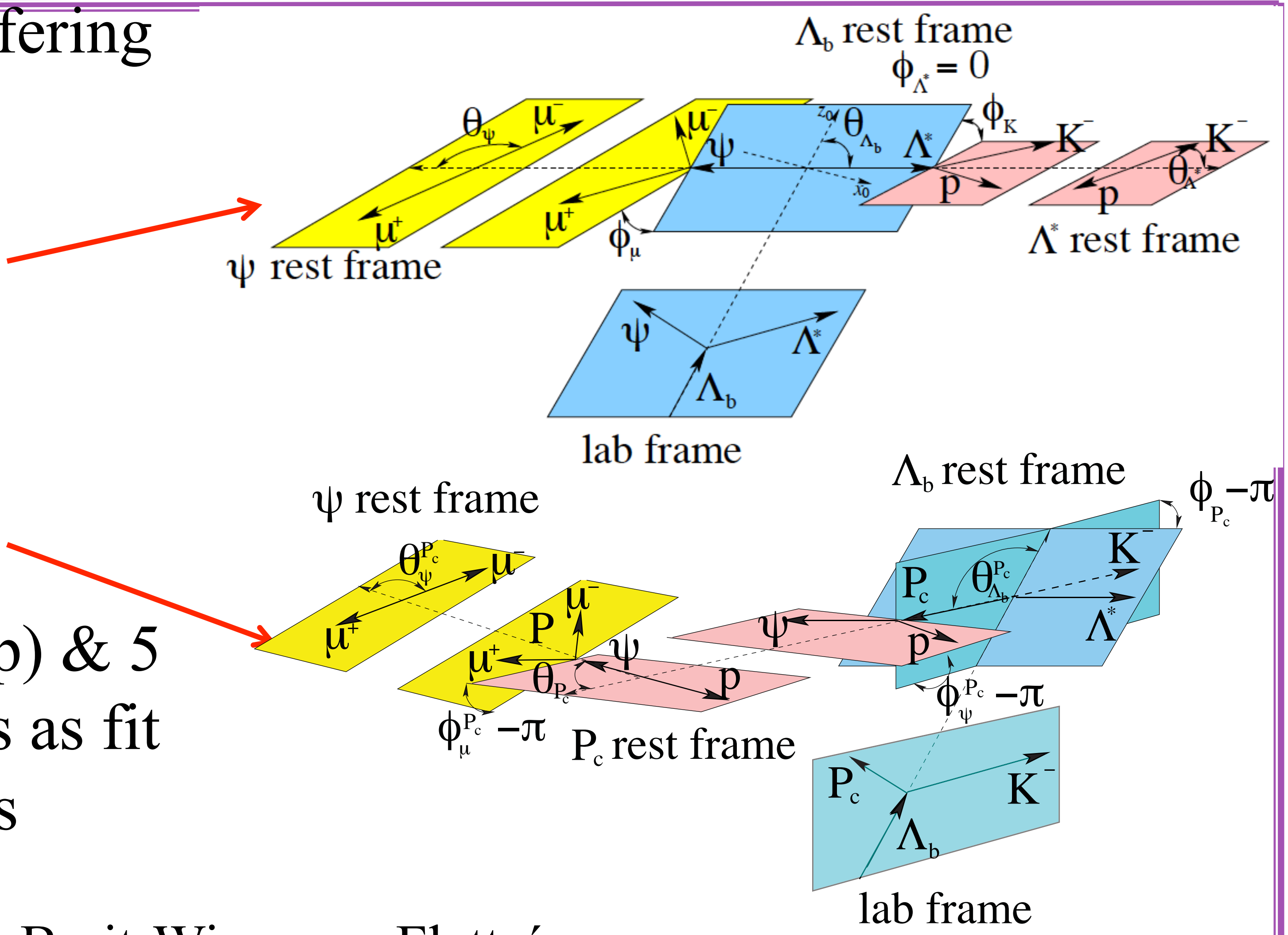
Matrix Element

- ☐ Two interfering channels:

$\Lambda_b \rightarrow J/\psi \Lambda^*$,
$\Lambda^* \rightarrow K^- p$

&

$\Lambda_b \rightarrow P_c^+ K^-$,
$P_c^+ \rightarrow J/\psi\ p$



- ☐ Use m(K⁻p) & 5 decay ∠'s as fit parameters

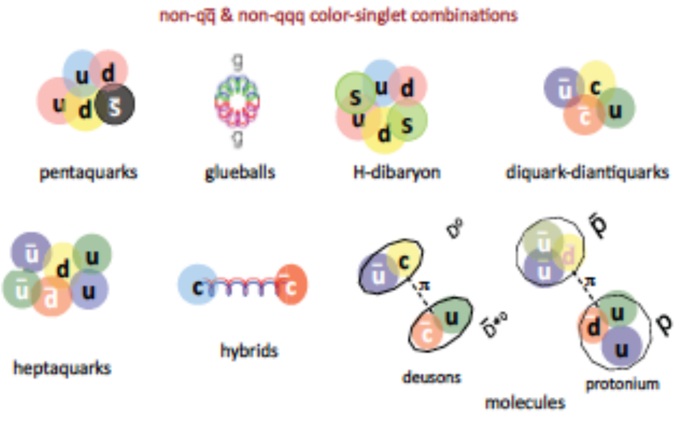
- Mass shapes: Breit-Wigner or Flatte´

From A. Hocker summary Moriond EW

Hadron zoo: XYZ mesons

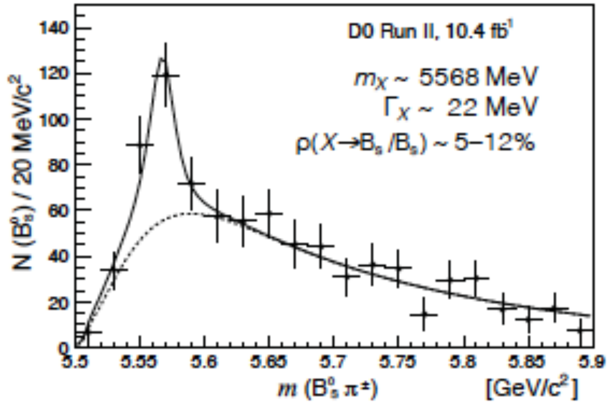
Topic of Moriond QCD, only this much…

Jeroen van Tilburg

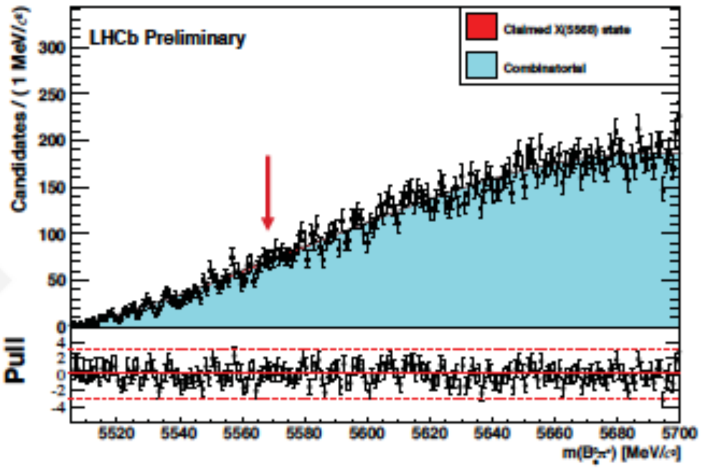


Picture from Stephen Lars Olsen, La Thuile 2016

D0 announced new state in $m(B_s(\to J/\psi\,\phi)\,\pi^{\pm})$ spectrum which may be a tetra-quark ($bsud$) [1602.07588, Feb 2016]

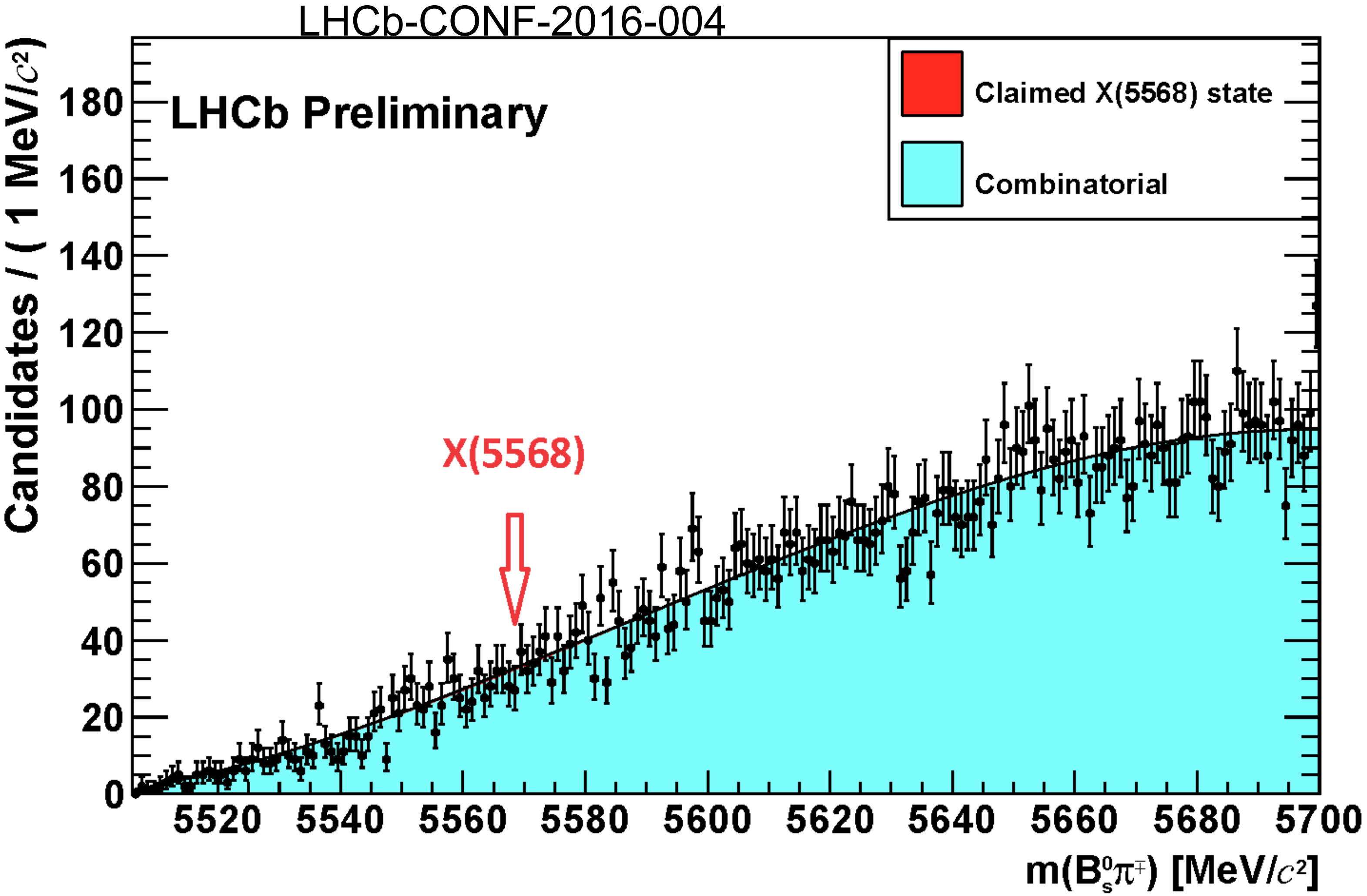


Prompt cross-check by LHCb did not confirm the observation in 20 times larger B_s sample. Upper limit on $\rho \sim 1\%$, but this may depend on beam/energy/analysis. No public material yet, but more information expected this week.

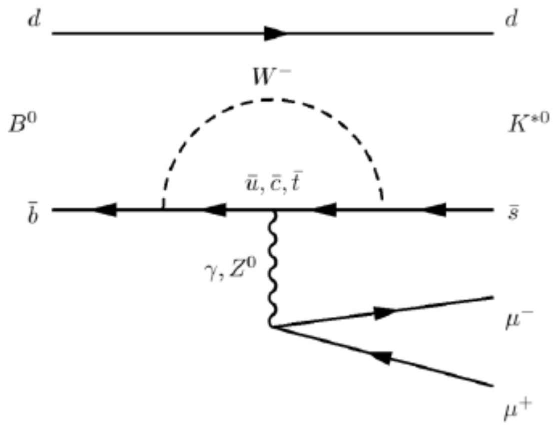


Other experiments are also looking

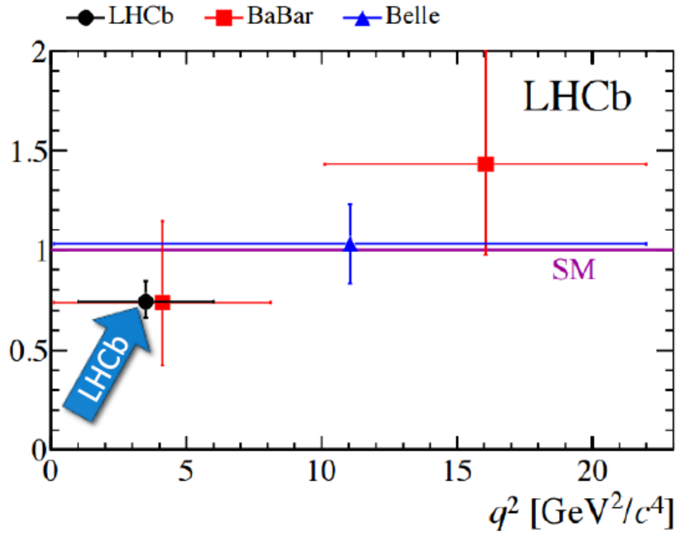
Non-confirmation of X(5568)

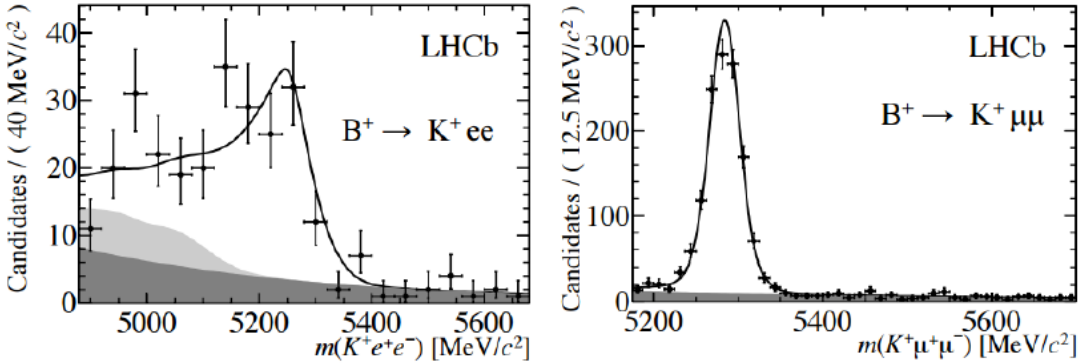


Lepton flavor violation in $B \rightarrow K^{(*)}\ell\ell$?



$$R_K = \frac{B(B^0 \to K^{*0}\mu^+\mu^-)}{B(B^0 \to K^{*0}e^+e^-)}$$





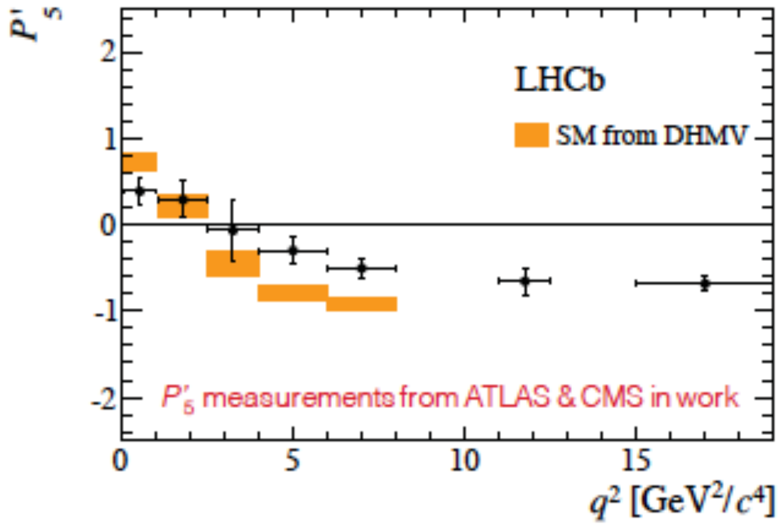
LHCb

(left: electron triggered category)

PRL 113 (2014) 151601

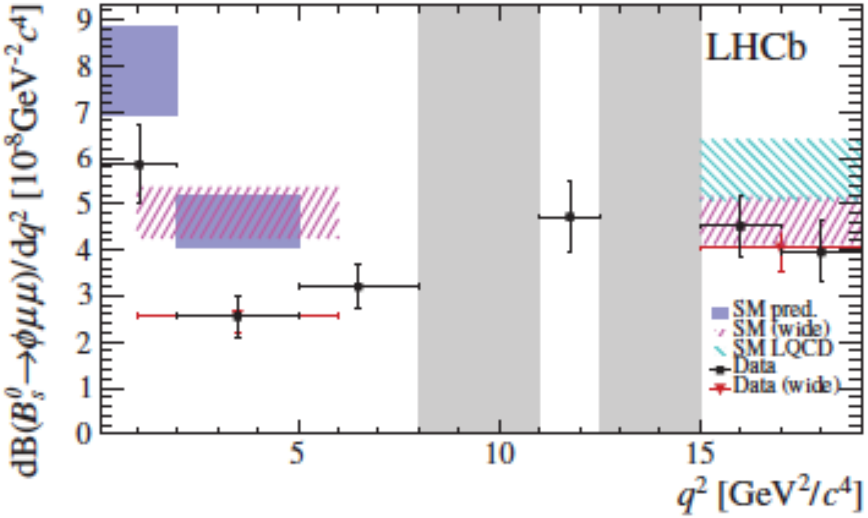
More anomalies in b→sℓℓ

Use ratio to cancel FF dependence: $P_5' = S_5/\sqrt{F_L(1-F_L)}$
Full Run-1 dataset and new analysis confirms discrepancy



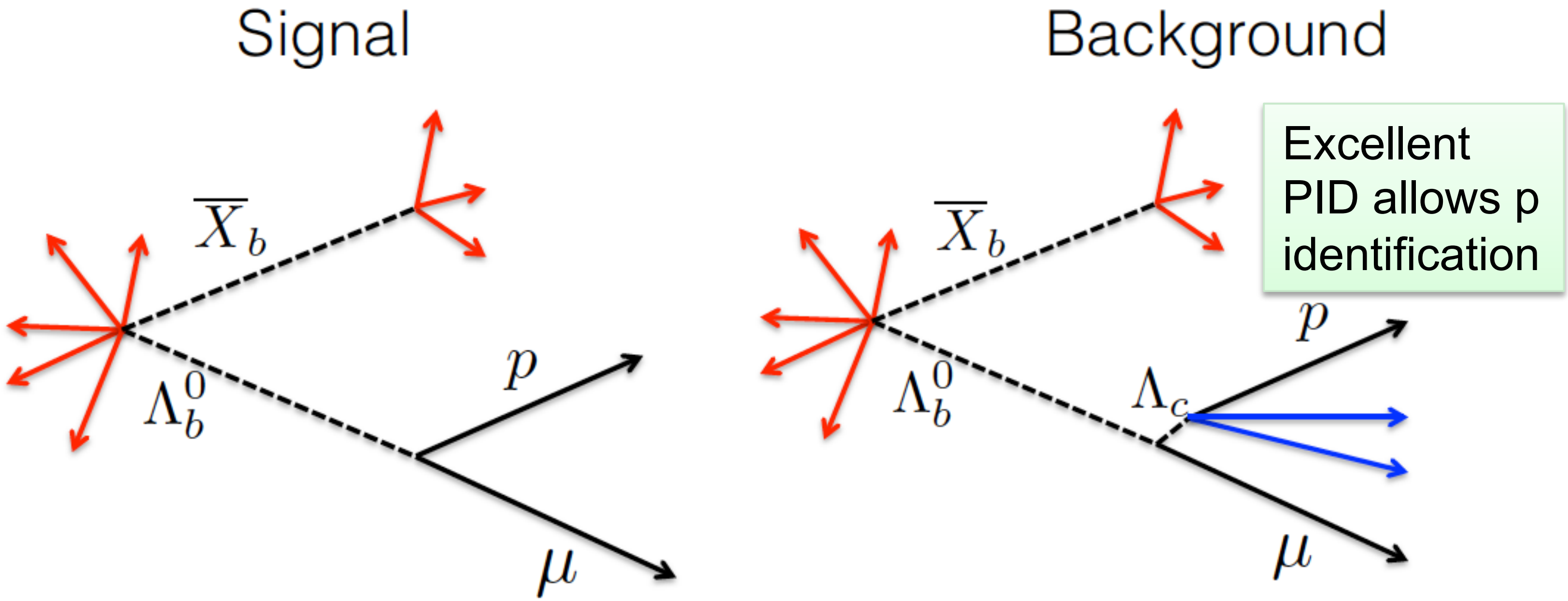
P'_5 measurements from ATLAS & CMS in work

Differential branching ratio of $B_s \to \phi\mu\mu$ decay



Global fit with new physics parameterisation (C_9^{NP}, C_{10}^{NP}) seems to reproduce observed discrepancy pattern

The $\Lambda_b \rightarrow p\mu\nu$ signal at LHCb



Excellent PID allows p identification

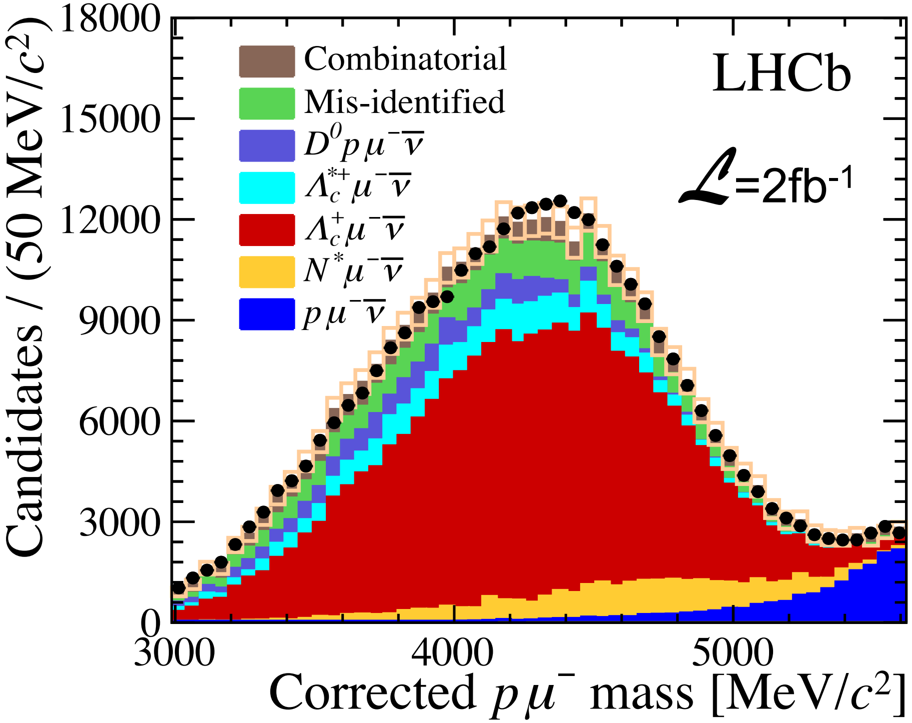
Cabibbo favored decays typically have additional tracks forming a good secondary vertex with the proton emitted in the semileptonic decay ⇨ train multivariate classifier to distinguish between these two configurations, get 90% rejection & 80% efficiency

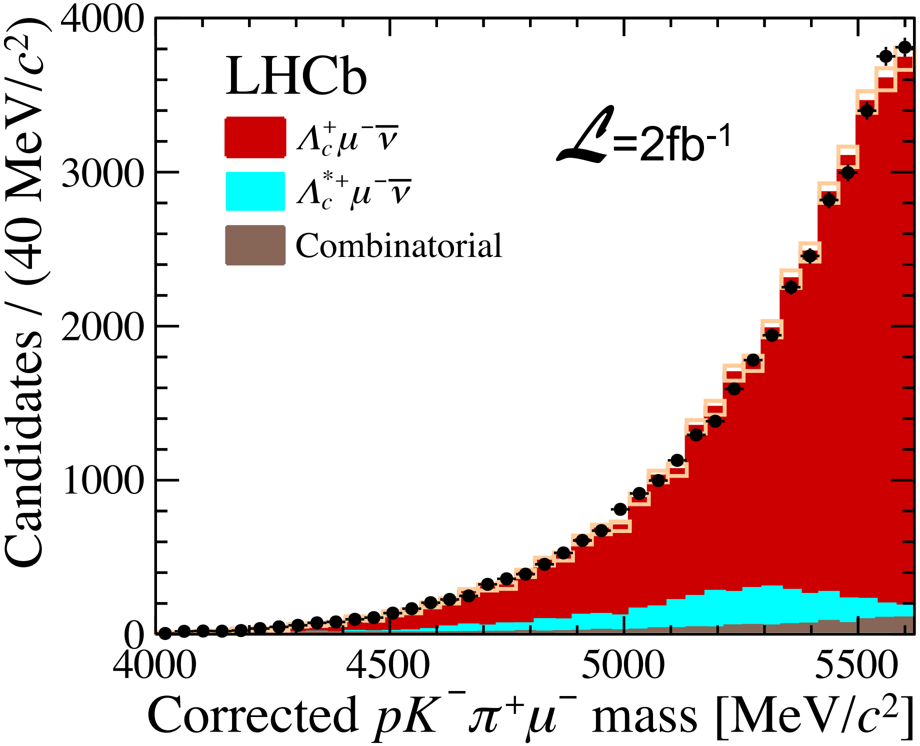
The signal fits

arXiv:1504.01568

$N(\Lambda_b \to p\mu\nu) = 17687 \pm 733$

$N(\Lambda_b \to \Lambda_c\mu\nu) = 34255 \pm 571$

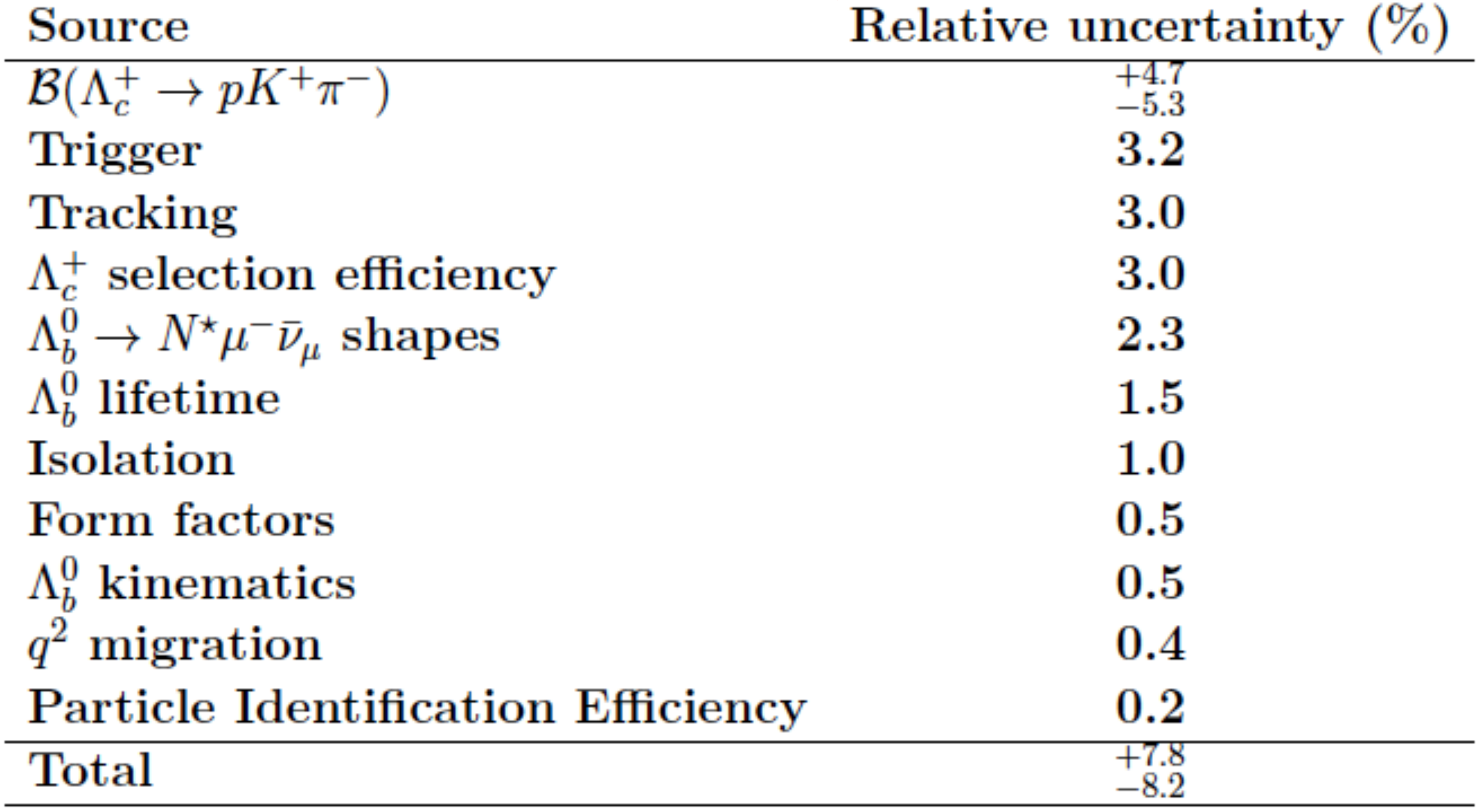




Experimental result

arXiv:1504:01568

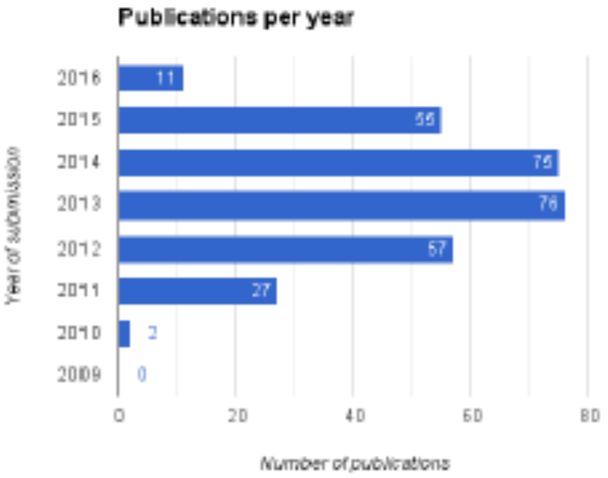
$$R_{\exp} \equiv \frac{\left.\mathcal{B}(\Lambda_b^0 \to p\mu^-\bar{\nu}_\mu)\right|_{q^2 \succ 15GeV^2}}{\left.\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\mu^-\bar{\nu}_\mu)\right|_{q^2 \succ 7GeV^2}} = \left(1.0 \pm 0.04(stat) \pm 0.08(syst)\right) \times 10^{-2}$$



Source	Relative uncertainty (%)
$\mathcal{B}(\Lambda_c^+ \to pK^+\pi^-)$	$^{+4.7}_{-5.3}$
Trigger	3.2
Tracking	3.0
Λ_c^+ selection efficiency	3.0
$\Lambda_b^0 \to N^\star\mu^-\bar{\nu}_\mu$ shapes	2.3
Λ_b^0 lifetime	1.5
Isolation	1.0
Form factors	0.5
Λ_b^0 kinematics	0.5
q^2 migration	0.4
Particle Identification Efficiency	0.2
Total	$^{+7.8}_{-8.2}$

Publication status pre-Moriond

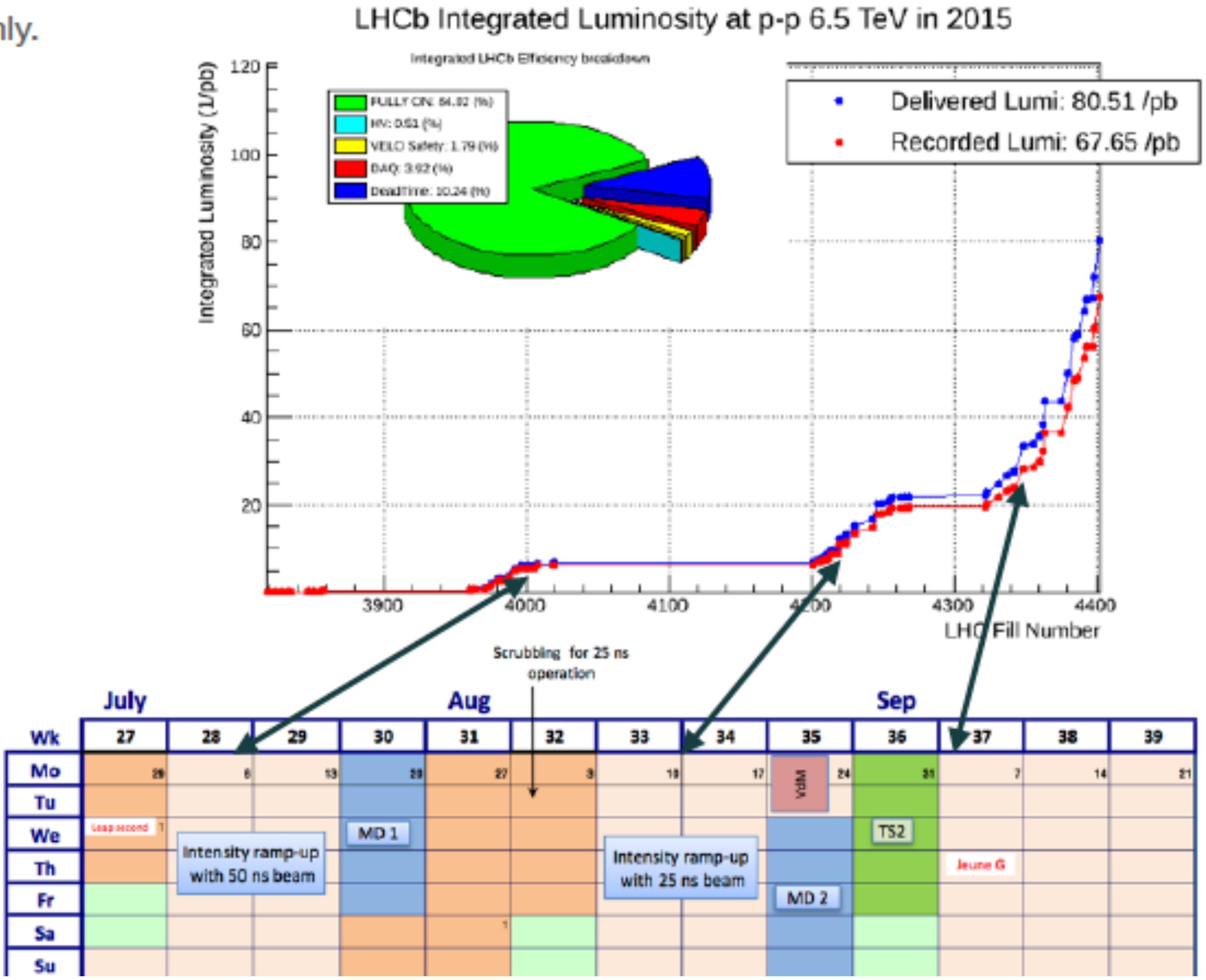
Publication status, as of Wednesday 9/3/2016



- Data taking running smoothly.

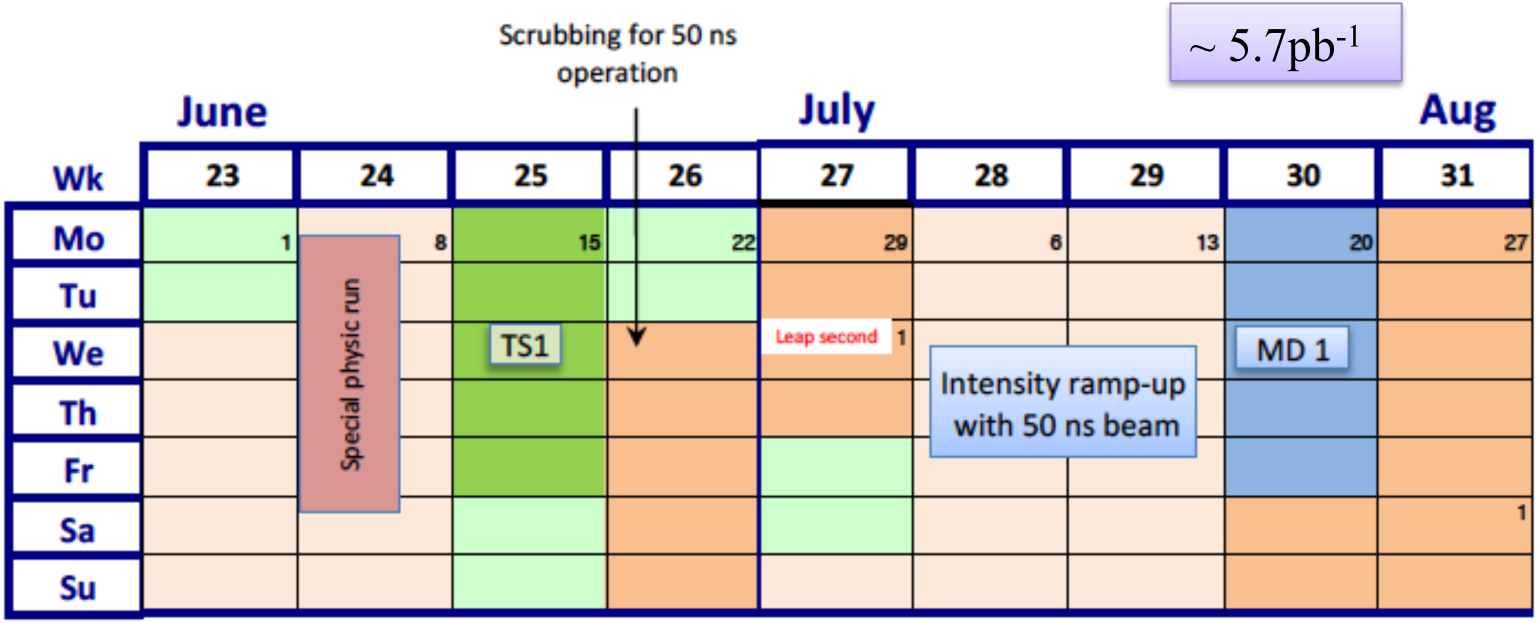
- Luminosity levelling at fixed pileup: μ=1.1

- Early measurements for 50ns ramp and part of 25ns ramp.
- Core physics program from end of August onwards.



2015 Early data collection

$\sim 5.7\text{pb}^{-1}$



Scrubbing for 50 ns operation

	June				July				Aug
Wk	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**	**31**
Mo	1	8 Special physic run	15	22	29	6	13	20	27
Tu									
We			TS1		Leap second 1	Intensity ramp-up with 50 ns beam		MD 1	
Th									
Fr									
Sa									1
Su									

The July 50 ns intensity ramp was used for primary data collection

- Calibration and full system validation with the June first collisions,
- Luminosity calibration with Beam Gas imaging also in June,
- Smaller collision rate ⇒ low-p_T triggers,
- Luminosity leveling ⇒ consistent collision conditions.

Charm meson cross section

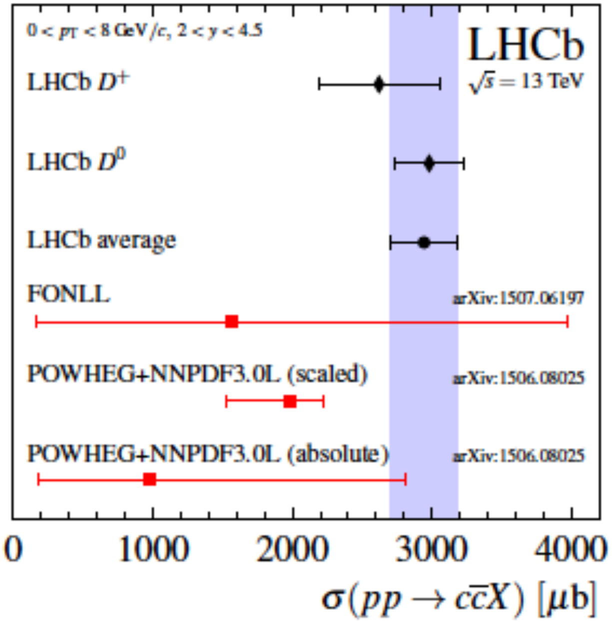
(arXiv:1510.01707)

The measured differential cross-sections are integrated over the analysis range

$p_{\mathrm{T}} < 8\,\mathrm{GeV}$
$2 < y < 4.5$

Integrated cross-sections are combined with fragmentation fractions measured at e^+e^- colliders.

The precise $\sigma(c\bar{c})$ estimates from the D^0 and D^+ modes are averaged.



Results are compared to theoretical predictions:

- FONLL (Cacciari *et al.*, arXiv:1507.06197),
- POWHEG+NNPDF3.0L (Gauld *et al.*, arXiv:1506.08025),
- GMVFNS (Kniehl *et al.*, Eur.Phys.J. C72 (2012) 2082).

$$\sigma(pp \to c\bar{c}X, p_{\mathrm{T}} < 8\,\mathrm{GeV}, 2 < y < 4.5) = 2940 \pm 3 \pm 180 \pm 160\,\mu\mathrm{b}.$$