Physics summary

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Beyond phase-II upgrade workshop

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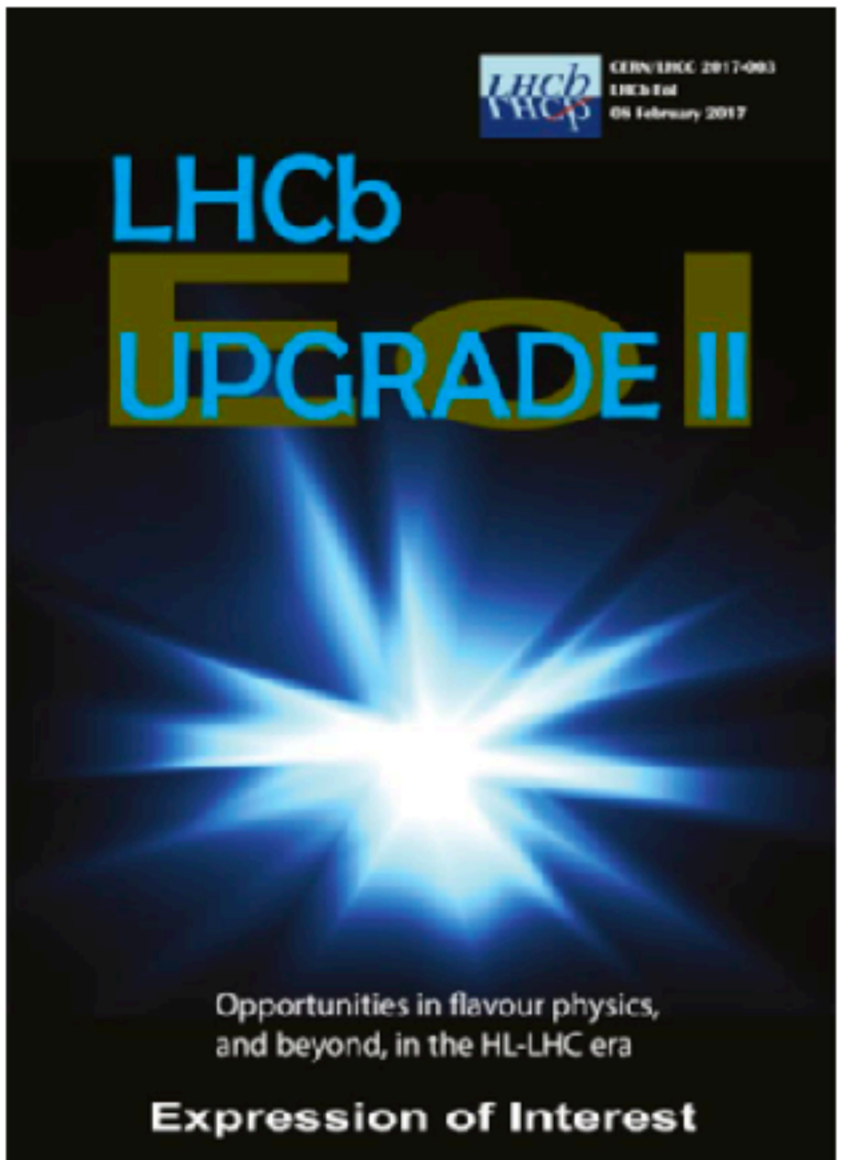
UNIVERSITY OF OXFORD

LHCb Phase-II Upgrade

Serious thinking began a couple of years ago, & in April 2016 a workshop was held in Manchester. This year an Expression of Interest was submitted to the LHCC.



[CERN-LHCC-2017-003]

- Install in LS4 (~2030), after Phase-I Upgrade.
- Integrate ~300 fb^{-1} within a couple of LHC runs.
- … requires detector to be able to operate at ~1-2 x 10^{34} $cm^{-2}s^{-1}$.
- Comprehensive flavour physics programme + general-purpose forward physics (as now), but targeting clean measurements currently limited by statistics, and new observables.

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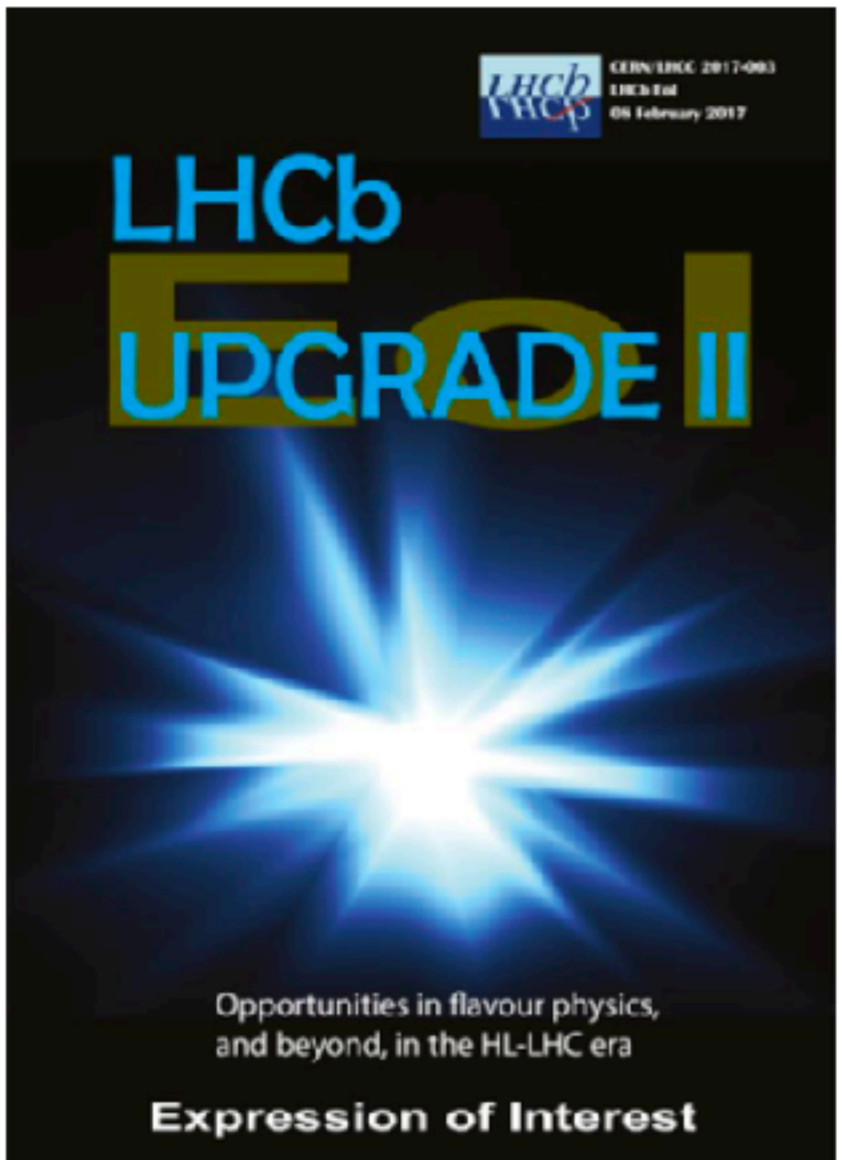


[CERN-LHCC-2017-003]

	Non-muonic modes	Muonic modes
Run 1	1	1
Run 2	4.3	4.3
Phase I	60.3	32.3
Phase II	393.6	199.0

Detector improvements could mean factors in effective luminosity.

LHCb Phase-2 upgrade: a clear case

Zoltan Ligeti

- Theoretical prejudices about new physics did not work as expected 10–20 yrs ago

  . . .

- Hierarchy puzzle: fine tuning measures off? Is NP an order of magnitude heavier?
  Flavor may be even more important (deviation from SM $\to$ upper bound on scale)

- New physics at LHC — MFV probably useful approximation
  $\Updownarrow$ "naturalness' loss = flavor's gain"
  New physics at $10 - 100\,\text{TeV}$ — less flavor suppression (MFV less motivated)

- Discovering deviations from the SM flavor sector is possible in either case (LHC-scale MFV-like, or heavier more generic scenarios)

  . . .

- Ample physics reasons to study much larger b hadron samples
  LHC is a one-time opportunity — aim for the most that technology might allow

The physics talks

CP-violation. *Luca Silvestrini and Dan Johnson*

Very rare decays and $b \to qll$, *David Straub, Jessica Prisciandaro, Tom Blake.*

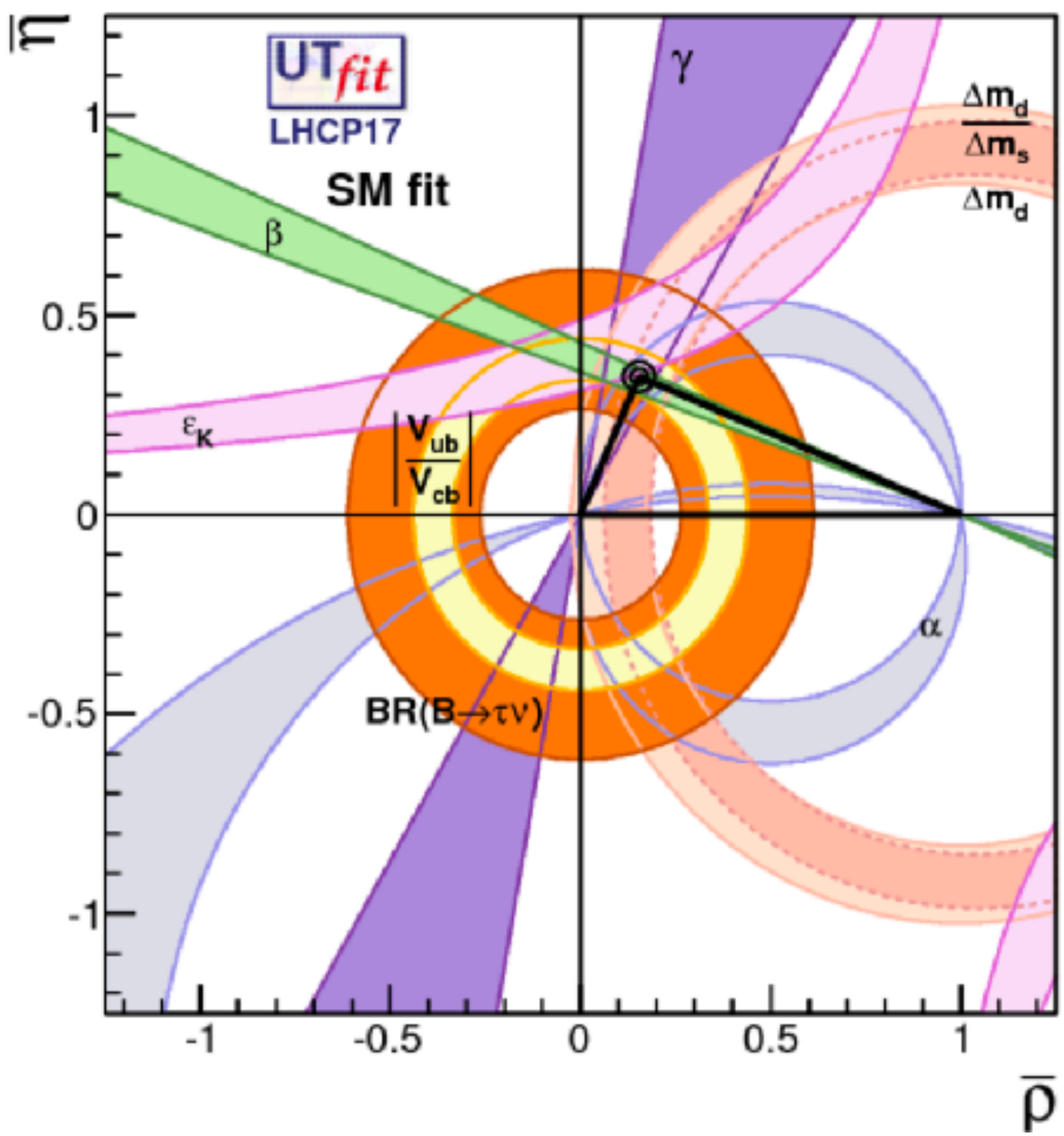
Radiative $b \to q\gamma$, *Ayan Paul, Preema Pais.*

Semileptonic decays, *Martin Jung, Patrick Owen.*

Spectroscopy, *Marek Karliner, Marco Pappagallo.*

Beyond flavour, *Uli Haisch, Mike Williams, Will Barter.*

CPV and CKM unitarity



levels @ 95% Prob

~10 %

$\bar{\rho} = 0.154 \pm 0.015$
$\bar{\eta} = 0.346 \pm 0.013$

~4%

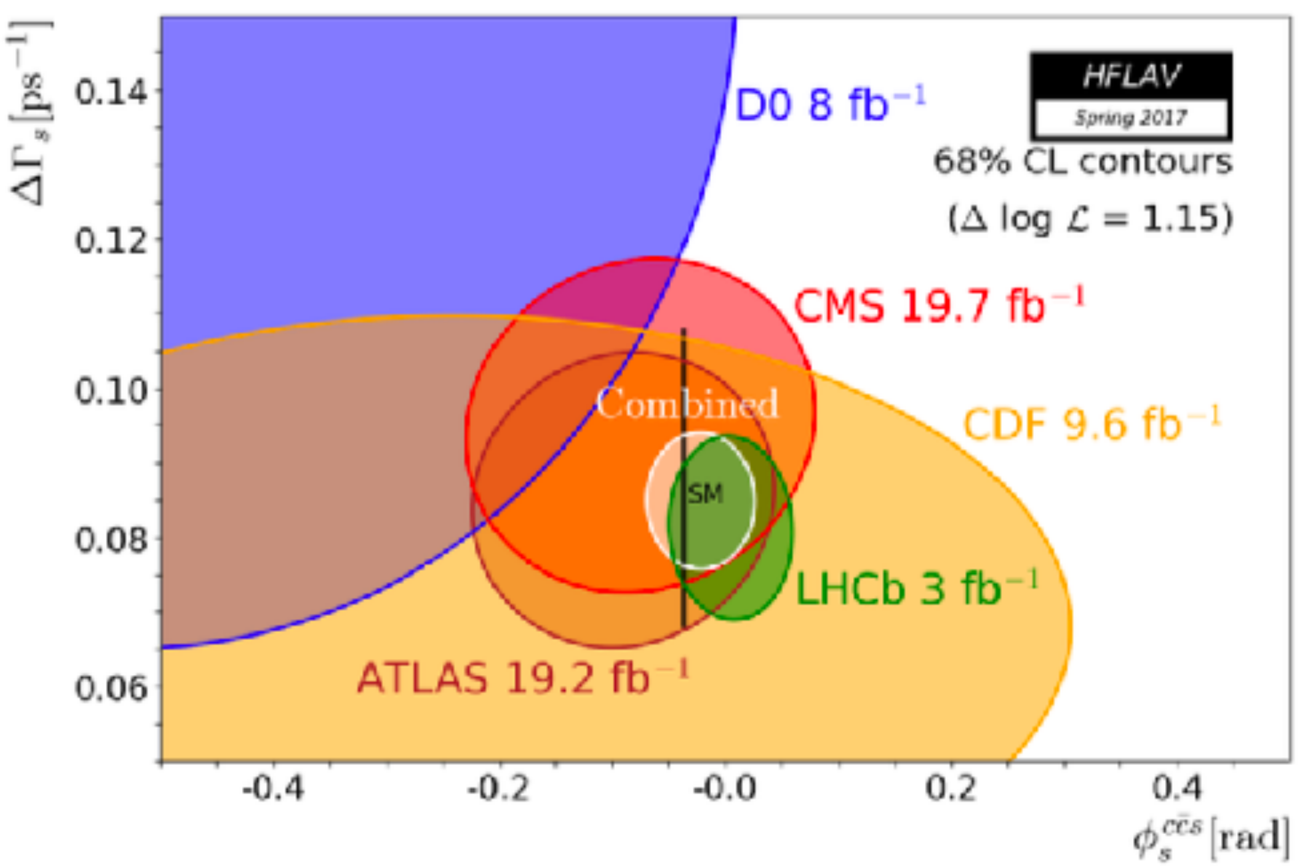
LHCb upgrade with 300/fb will allow to improve constraints on NP from the UT analysis without hitting the theoretical uncertainties wall

Some LHCb prospects

γ determination down to ~degree precision on individual modes.
Start to probe tree-level NP.

Sample	$\sigma_{stat}(\gamma)^{\circ}$
Run 1	8
Run 2	4
Upgrade	~ 1
Phase-2 upgrade	<0.5

Great case for BES-III run on Ψ(3770) to improve the D strong phase inputs.



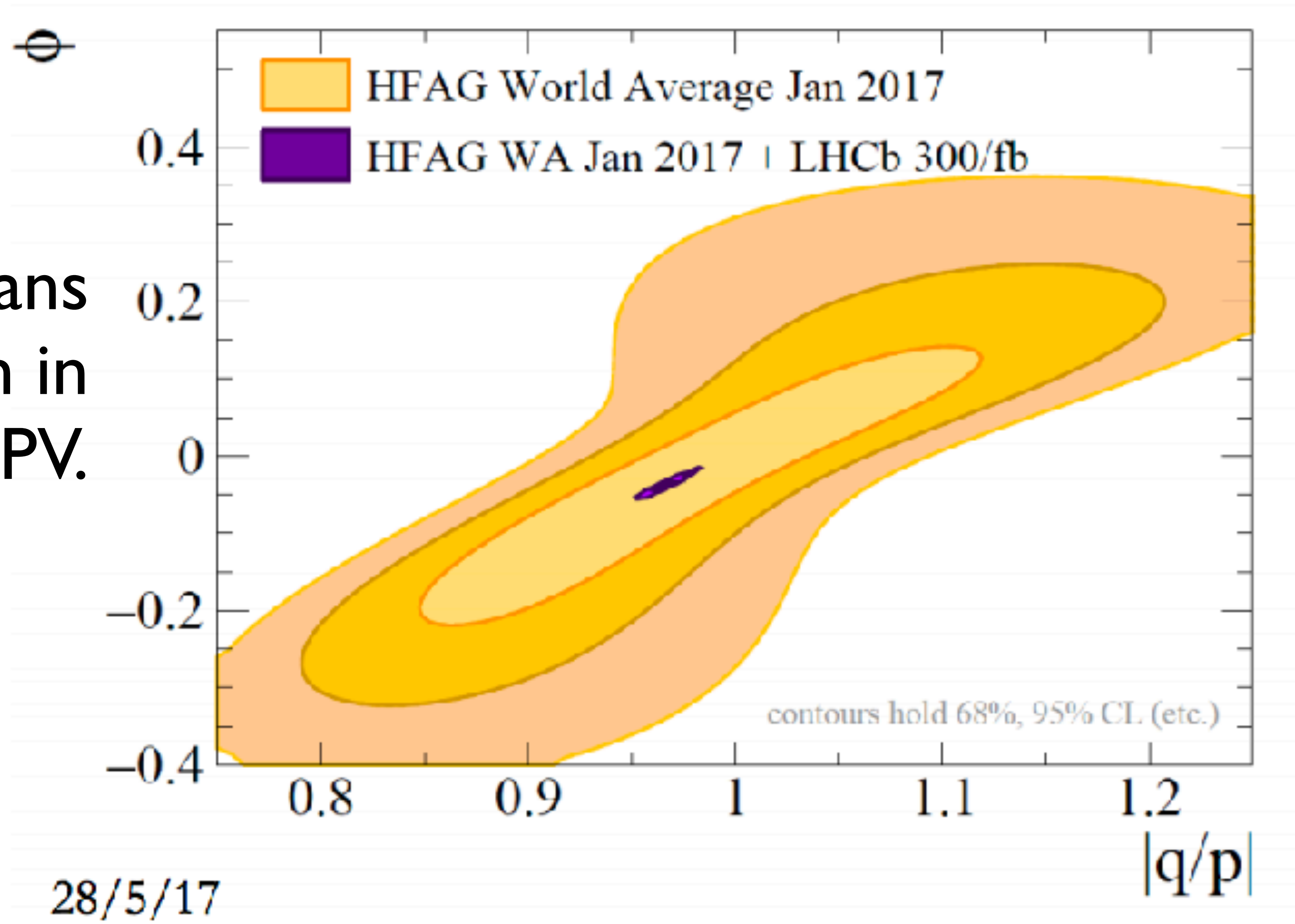
Expect statistical scaling of Φ_s to continue to 300+/fb.

A programme to control penguin pollution via SU(3) symmetries is developing.

Charm

Expect to reach unprecedented precision on direct CPV, but requires theory breakthrough to be NP sensitive — let's be optimistic though.

300/fb means tremendous reach in the clean indirect CPV.



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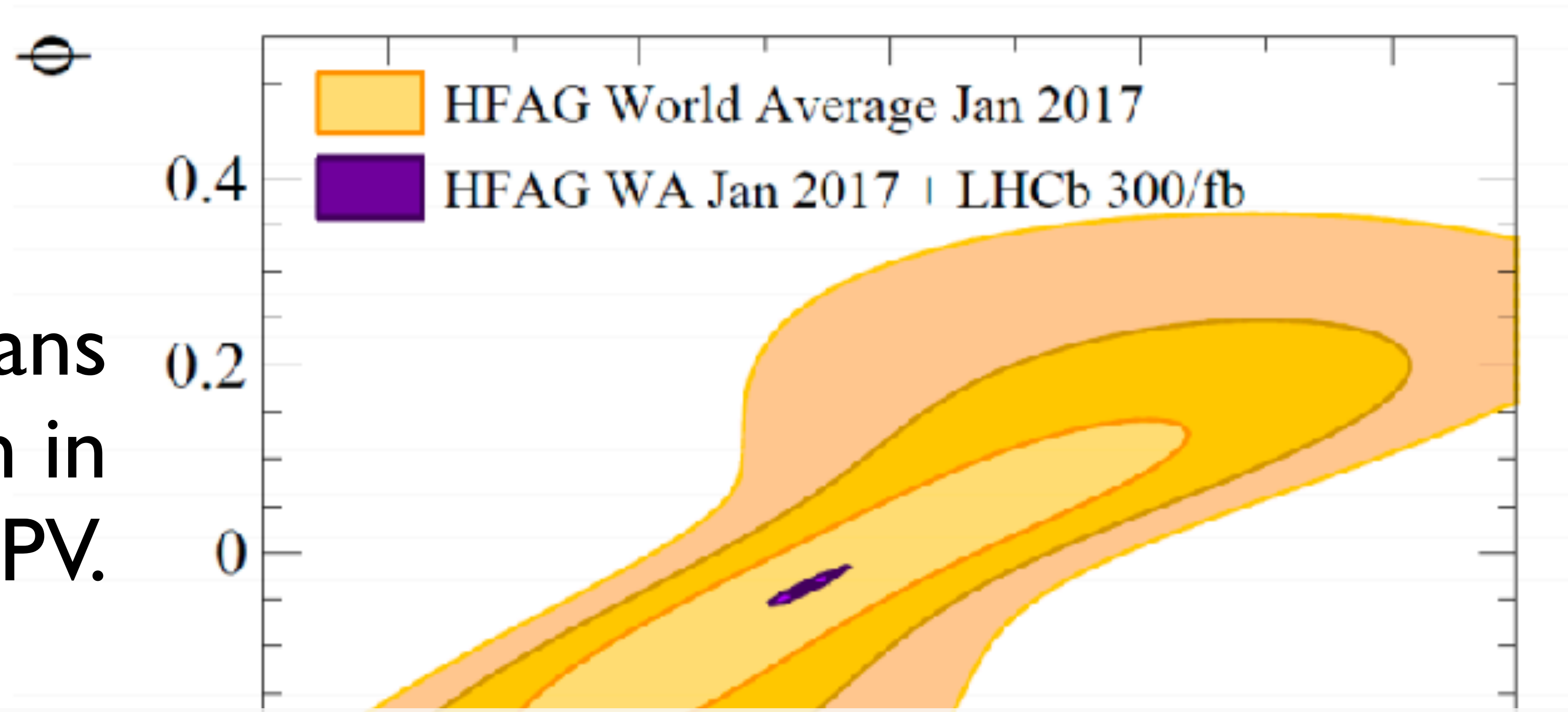
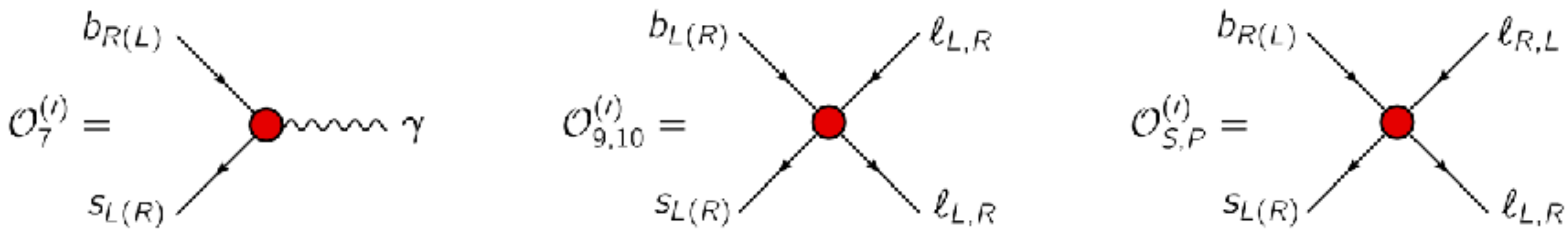


Some important experimental considerations. E.g., compromise between symmetry of magnet up-down luminosities, versus total luminosity.

Rare decays

$$\mathcal{H}_{\mathrm{eff}} = -\frac{4\,G_F}{\sqrt{2}}\frac{e^2}{16\pi^2}V_{tb}V_{ts}^{*}\sum_i C_i O_i + \mathrm{h.c.}$$



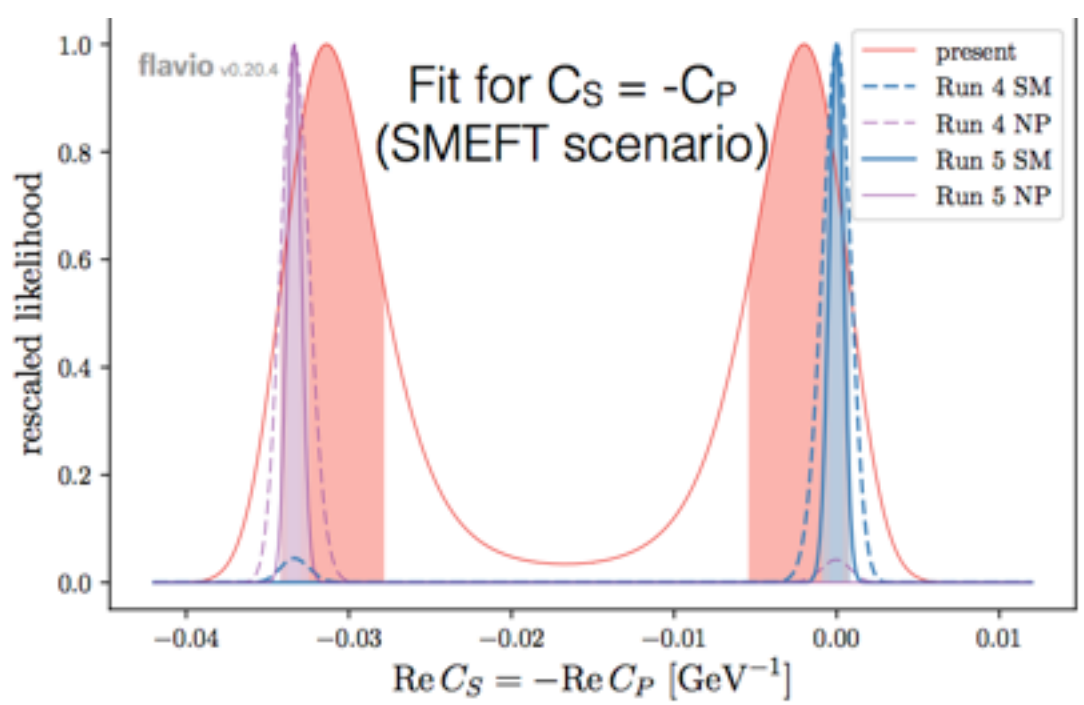
Decay	$C_7^{(\prime)}$	$C_9^{(\prime)}$	$C_{10}^{(\prime)}$	$C_{S,P}^{(\prime)}$
$B \to X_s\gamma$	X			
$B \to K^*\gamma$	X			
$B \to X_s\ell^+\ell^-$	X	X	X	
$B \to K^{(*)}\ell^+\ell^-$	X	X	X	
$B_s \to \mu^+\mu^-$			X	X

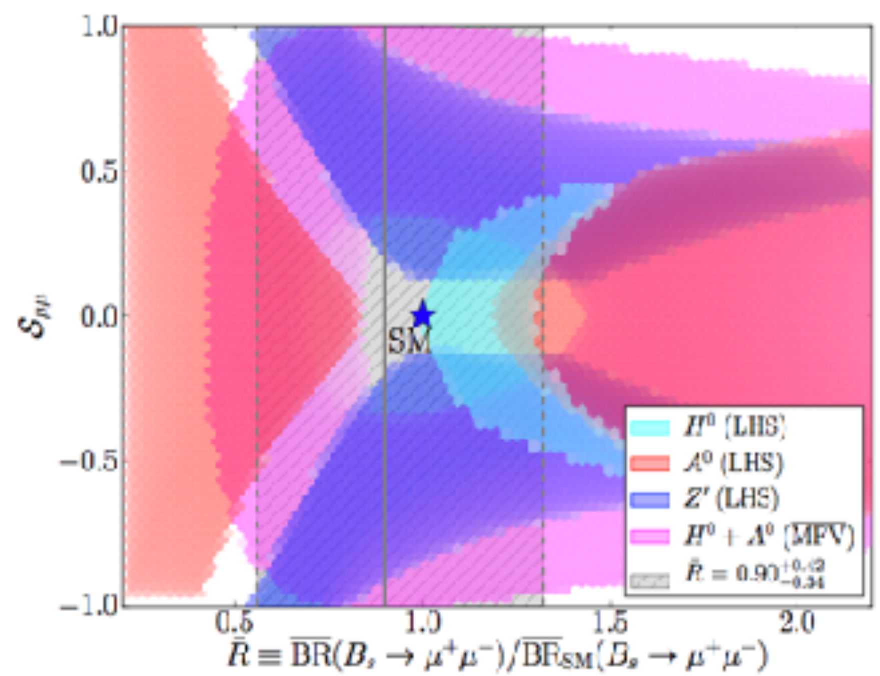
Complementarity of observables is the key.

Very rare decays

At 300/fb achieve ~20% on $B_d \to \mu\mu / B_s \to \mu\mu$ but we must consider competition from CMS.

Very clean and complementary new observables. With 300/fb measure $B_s \to \mu\mu$ effective lifetime to 2% and time dependent CPV parameter $S_{\mu\mu}$ to 30%.



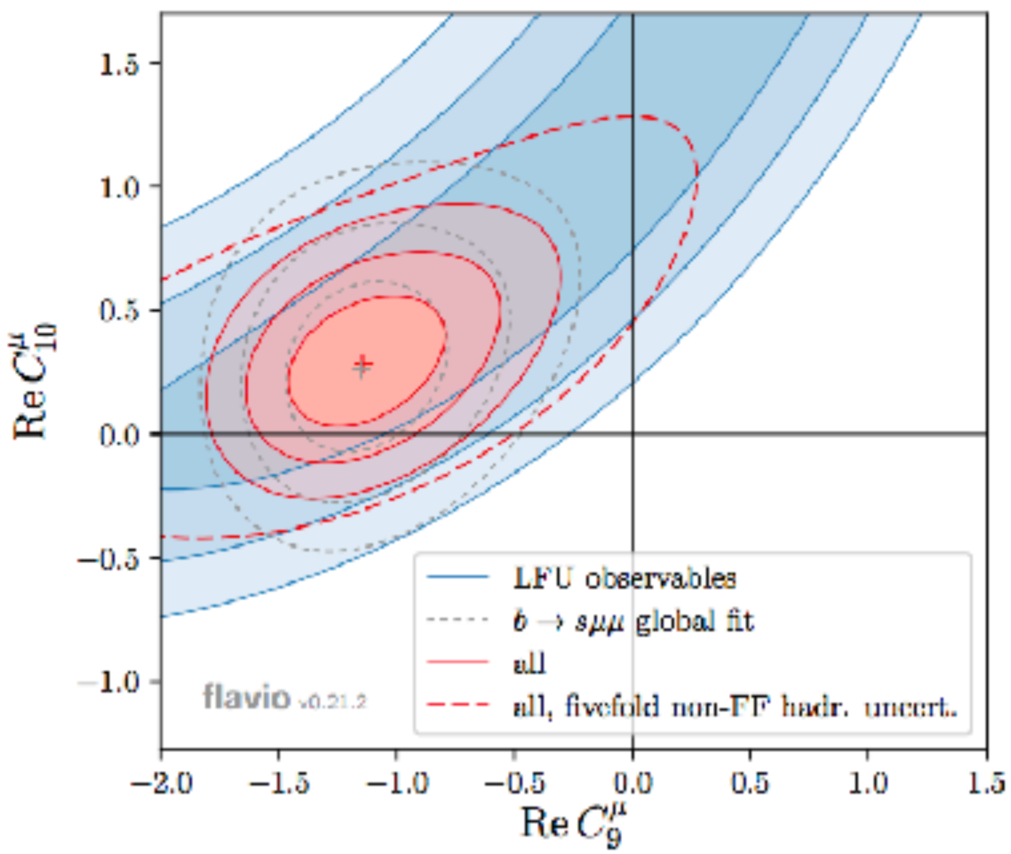


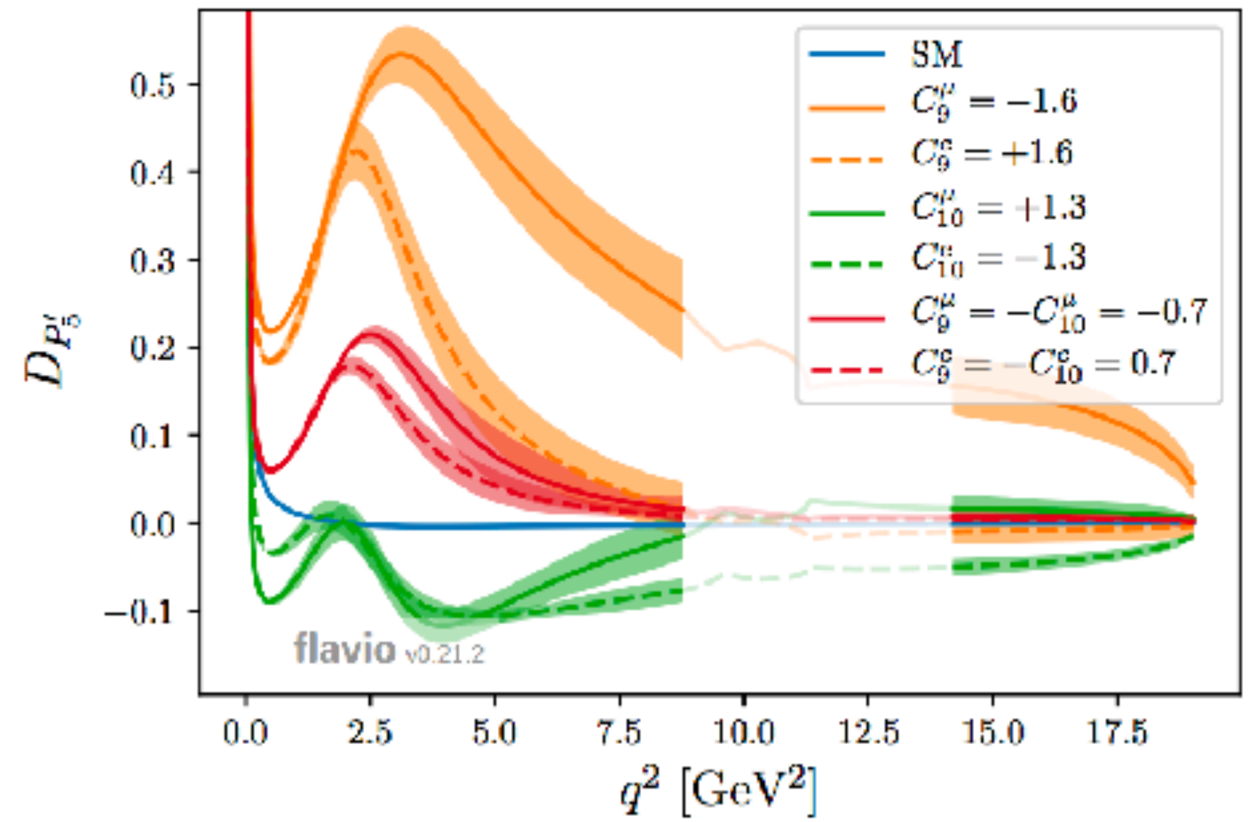
(A Buras et al, JHEP 1307 (2013) 77)

Discussed exciting prospects in B→ee, B→ττ, LFV, LNU, rare charm, rare kaon, etc…

$b \to sll$ decays

Altmannshofer et al. 1703.09189, Altmannshofer et al. 1704.05435



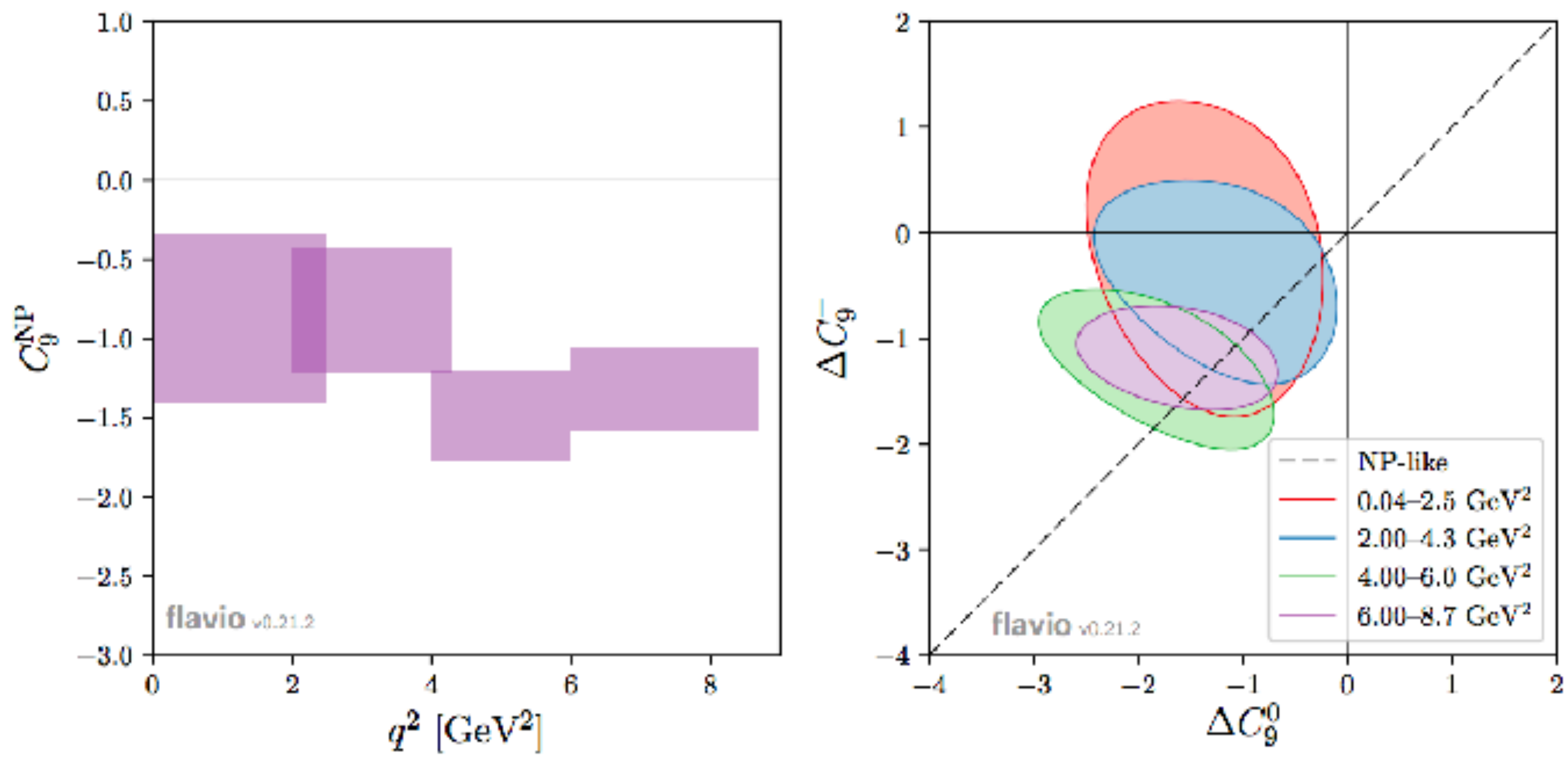


What if there is *no* violation of LFU?

What if the null tests remain null?

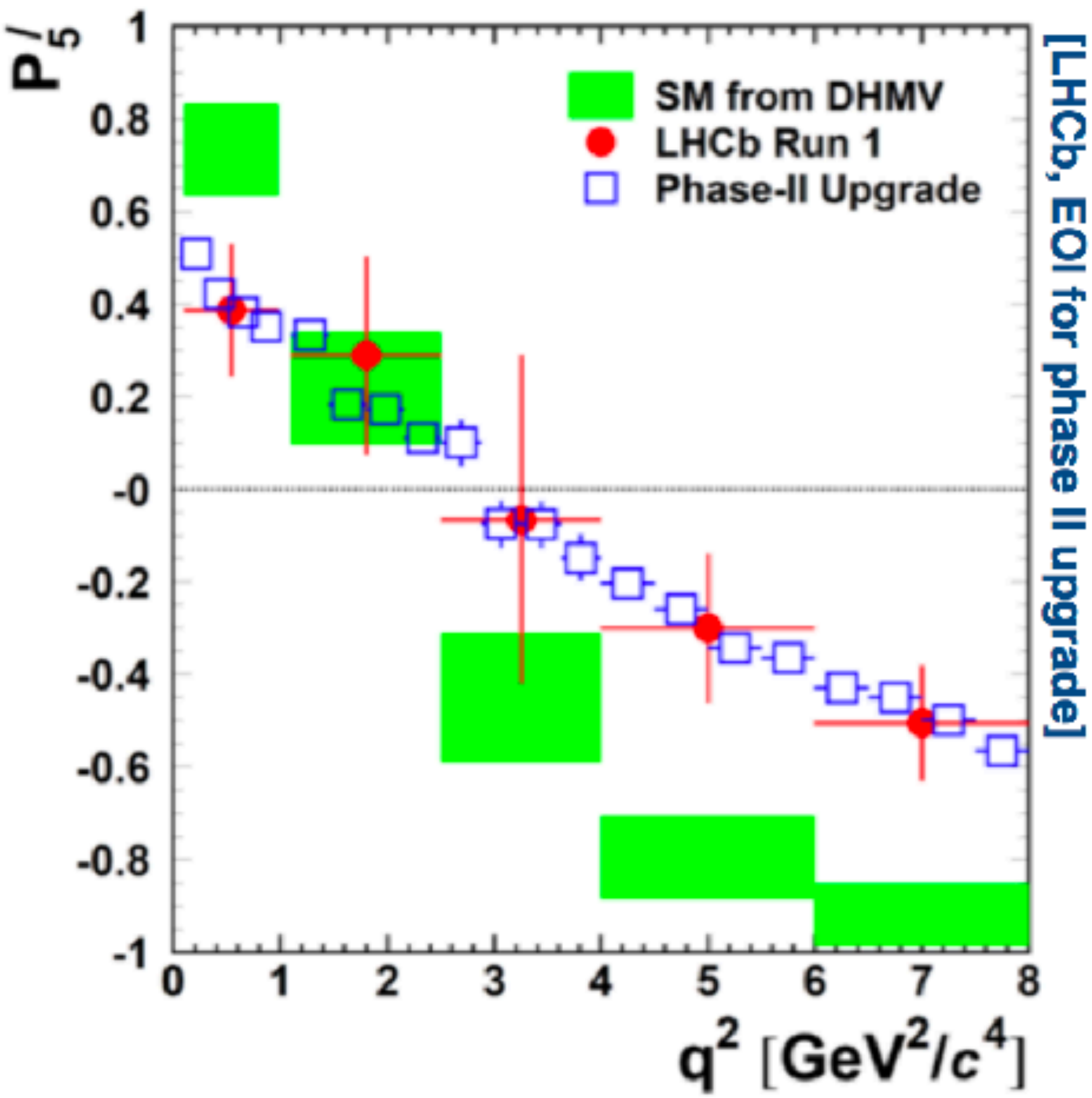
Clear strategies proposed in all scenarios

Example: q^2 dependence of C_9 best-fit



- Bin-by-bin fit to $B \to K^* \mu^+ \mu^-$ data Altmannshofer et al. 1703.09189
- NP in C_9 would give helicity and q^2 independent effect
- hadronic effect could be helicity and q^2 dependent
- See also more sophisticated Bayesian fits Ciuchini et al. 1512.07157, ...

300/fb possibilities



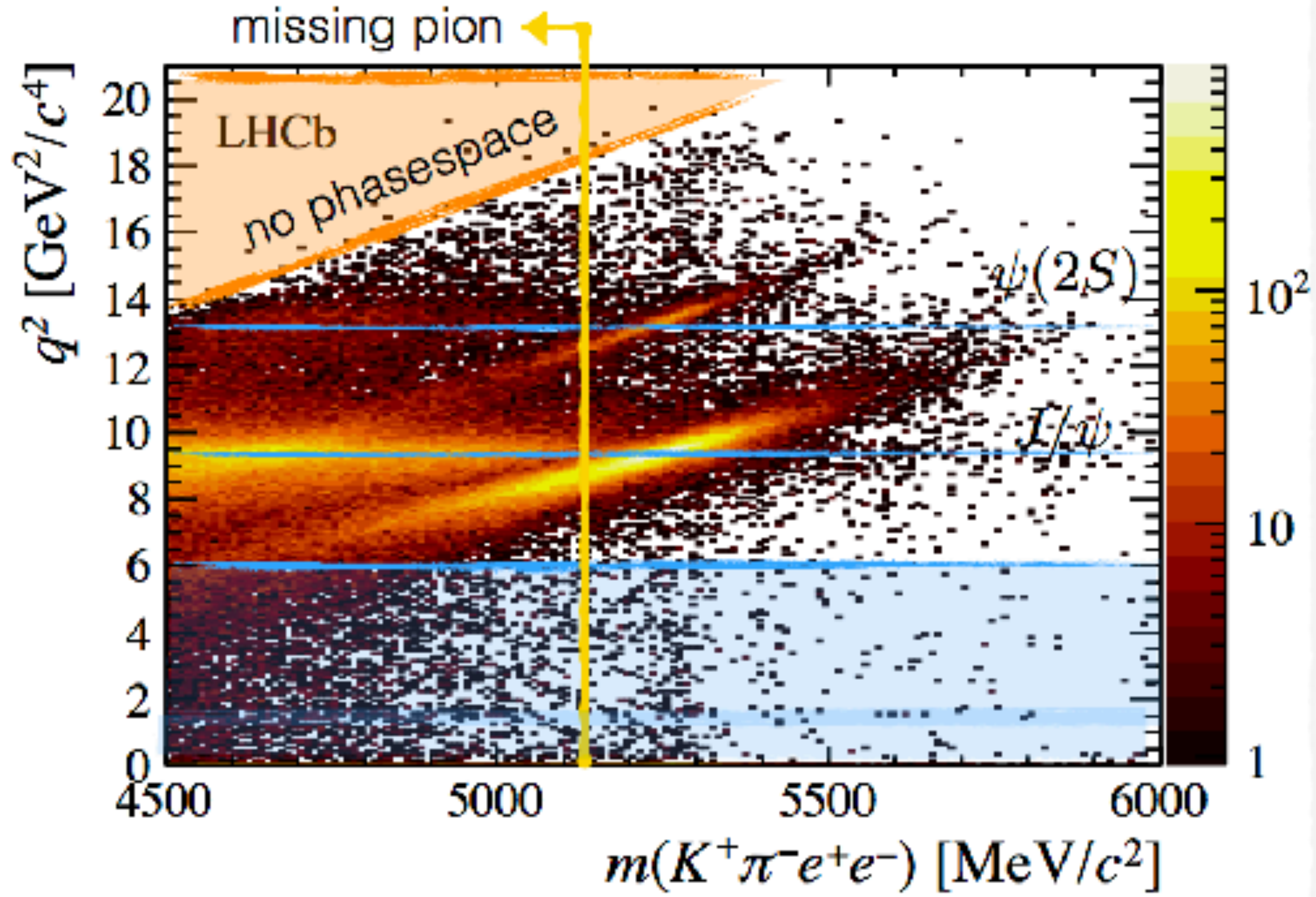
More ambitious possibilities, e.g., full amplitude analysis including resonances, and even fit for hadronic parameters.

And of course we can now do precision $b \to d\mu\mu$…

The LFU tests

- Main experimental challenges related to energy loss by electrons by Bremsstrahlung in the detector.
  - ➡ Recover energy loss using clusters with E_T > 75MeV in ECAL.

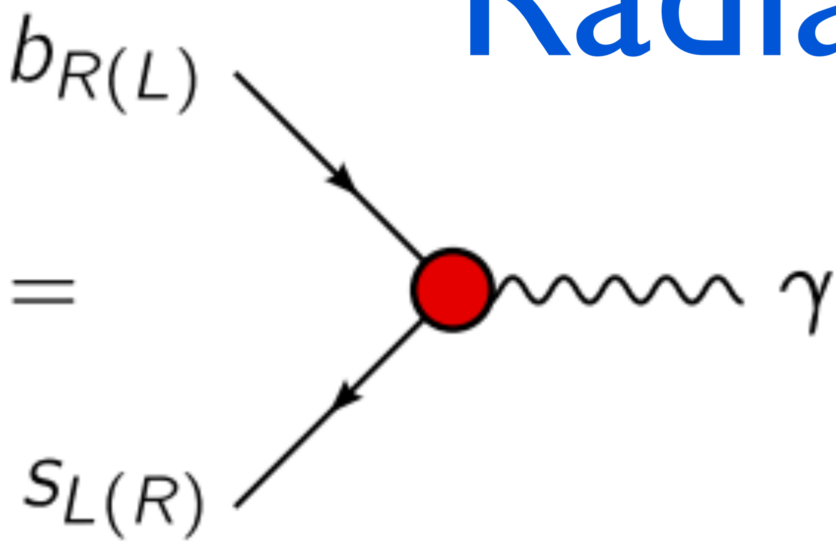
- Can we improve?
  - ➡ Reduce Bremsstrahlung by reducing material before the magnet.
  - ➡ Finer granularity ECAL or ECAL with better energy resolution.



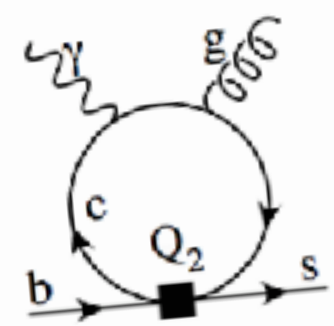
Crucial that we start fast simulation studies to really understand where we lose w.r.t the perfect detector.

Radiative decays

$\mathcal{O}_7^{(\prime)} =$



the charm loop



computation done with QCDF

A. Ali and A. Y. Parkhomenko, Eur. Phys. J. C **23** (2002) 89 [arXiv:hep-ph/0105302];
M. Beneke, T. Feldmann and D. Seidel, Eur. Phys. J. C **41** (2005) 173 [arXiv:hep-ph/0412400];
T. Becher, R. J. Hill and M. Neubert, Phys. Rev. D **72** (2005) 094017 [arXiv:hep-ph/0503263].

S. W. Bosch and G. Buchalla, Nucl. Phys. B **621** (2002) 459 [arXiv:hep-ph/0106081] and JHEP **0501** (2005) 035 [arXiv:hep-ph/0408231].

computation done with QCD sum rules

P. Ball and R. Zwicky, Phys. Lett. **B642**, 478 (2006), arXi
A. Khodjamirian, R. Ruckl, G. Stoll, and D. Wyler, Phys.
M. B. Voloshin, Phys. Lett. **B397**, 275 (1997), arXiv:hep-p

$S^{SM,s\rho} = -0.027 \pm 0.006(m_{s,b}) \pm 0.001(\sin(2\beta$

the form factors

LCSR:

$T_1(0) = 0.282 \pm 0.031$ for $B \to K^*\gamma$,

$T_1(0) = 0.309 \pm 0.027$ for $B_s \to \phi\gamma$,

LCSR + Lattice:

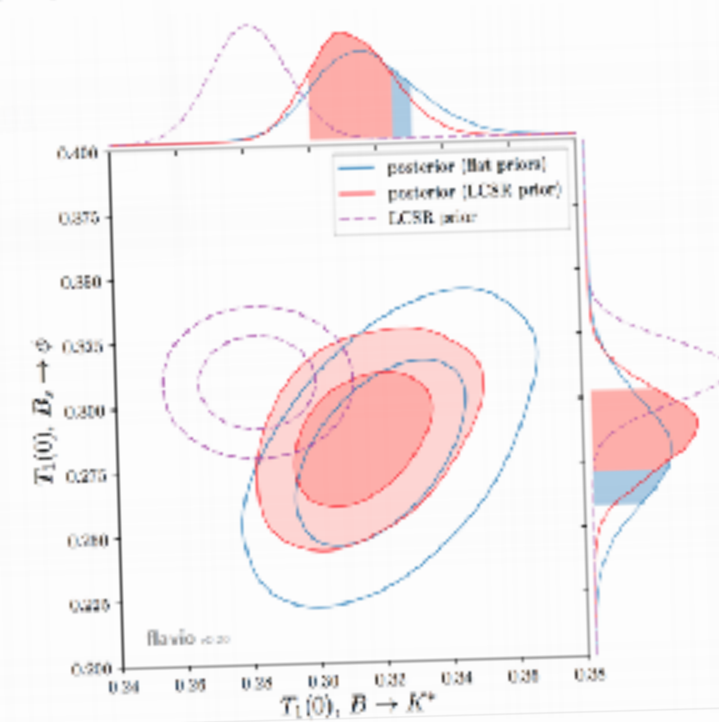
$T_1(0) = 0.312 \pm 0.027$ for $B \to K^*\gamma$,

$T_1(0) = 0.299 \pm 0.012$ for $B_s \to \phi\gamma$.

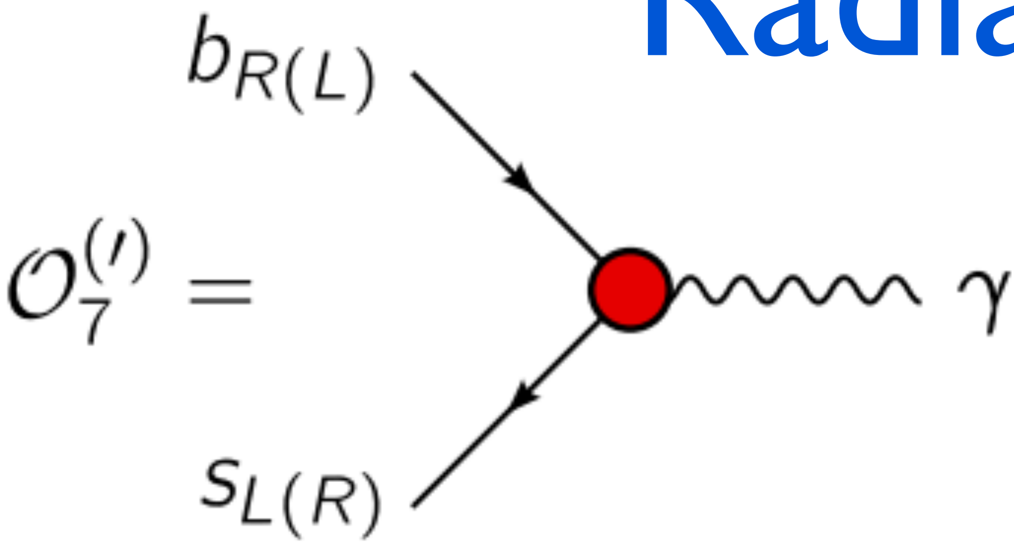
fit to experimental data:

$T_1(0) = 0.316^{+0.016}_{-0.015}$ for $B \to K^*\gamma$;

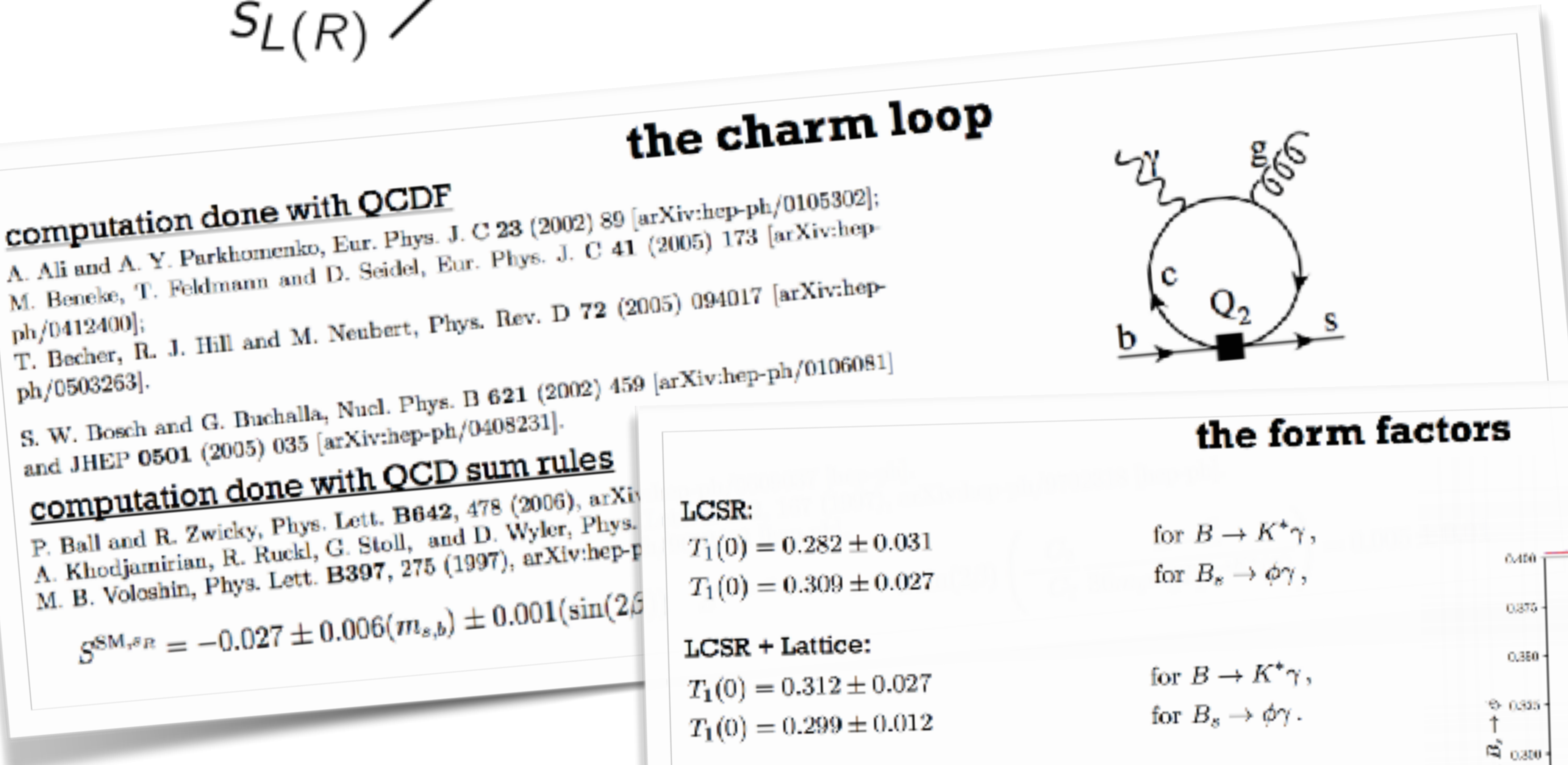
$T_1(0) = 0.280^{+0.020}_{-0.022}$ for $B_s \to \phi\gamma$.

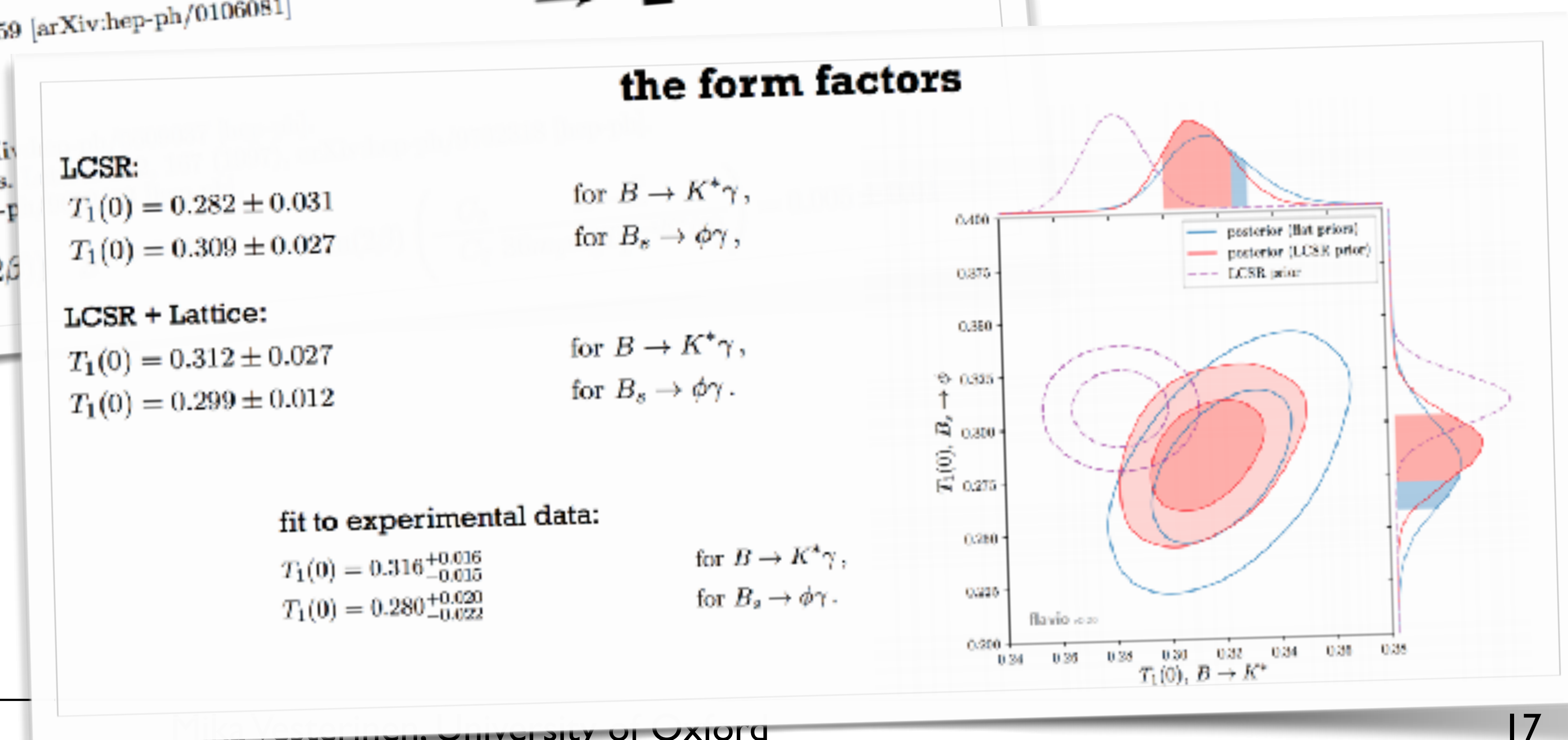


Radiative decays



Example: pinning down the photon polarisation…



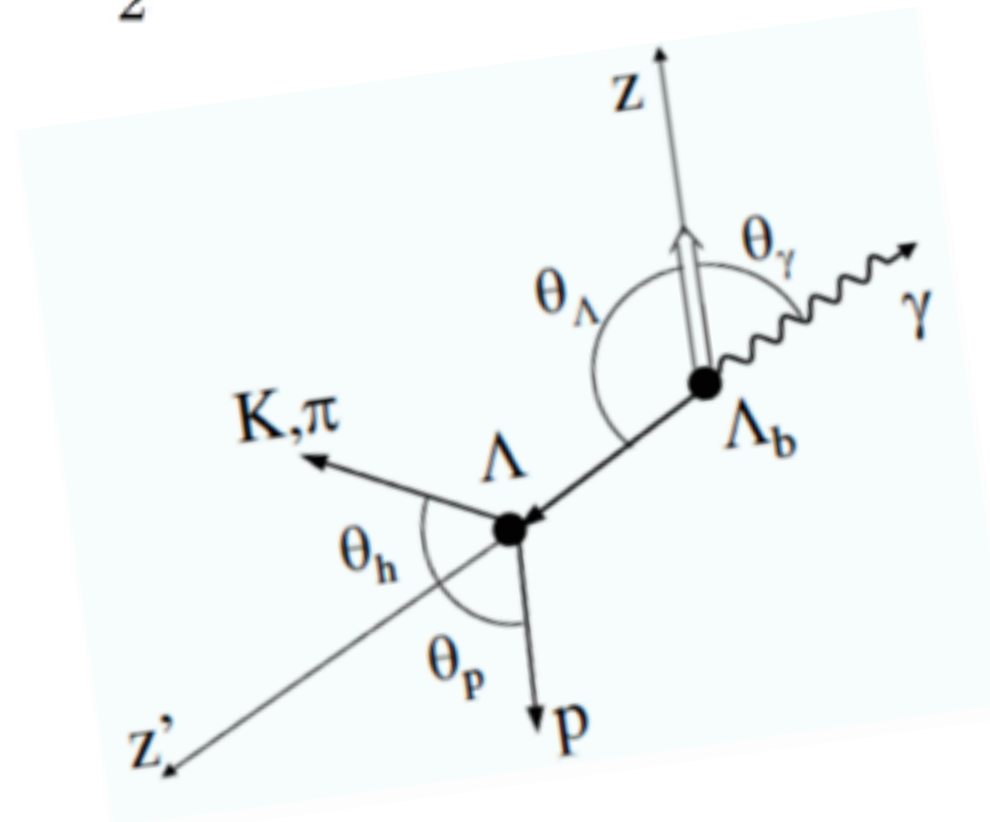


Some LHCb possibilities

Time dependent $B_s \to \Phi\gamma$

$$\Gamma(B^0_{(s)} \to f^{CP}\gamma) \sim e^{-\Gamma_{(s)}t}\left\{\cosh\frac{\Delta\Gamma_{(s)}t}{2} - \mathcal{A}^{\Delta}\sinh\frac{\Delta\Gamma_{(s)}t}{2} \pm \mathcal{C}\cos\Delta m_{(s)}t \mp \mathcal{S}\sin\Delta m_{(s)}t\right\}.$$

b-baryon angular distributions



$b \to hhh\gamma$ angular distributions

$$\mathrm{d}\Gamma(B^+ \to K^+\pi^-\pi^+\gamma) =$$

$$\left|\sum_i \frac{c_R^{(i)} A_R^{(i)}}{s - M_i^2 - iM_i\Gamma_i}\right|^2 + \left|\sum_i \frac{c_L^{(i)} A_L^{(i)}}{s - M_i^2 - iM_i\Gamma_i}\right|^2$$

$c_{R,L}$ - weak decay amplitudes

$A_{R,L}$ - strong decay amplitudes

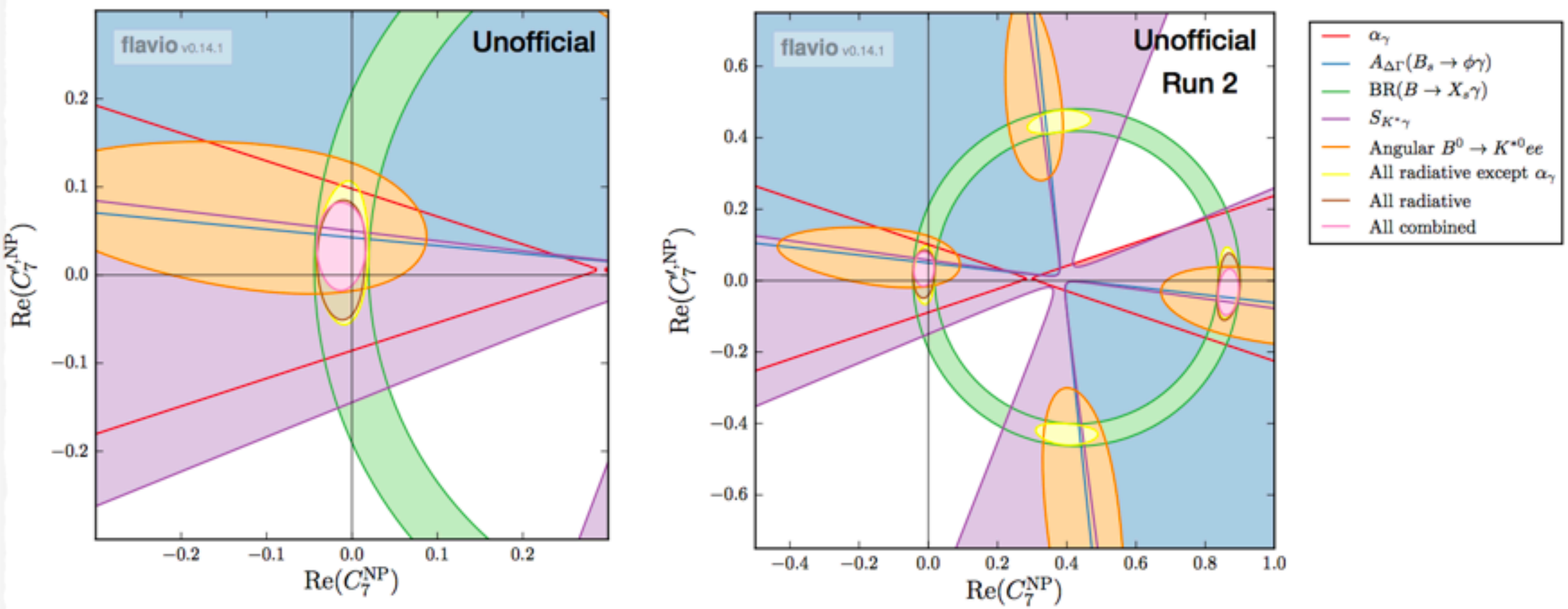
B_i - Breit Wigner propagator for resonance (i)

Must pay close attention to emphasise areas of complementarity with Belle-II.
Serious ECAL upgrade physics performance studies encouraged.

Some LHCb possibilities

Analysis ongoing with Run 2 (2015+2016) data:

- Dedicated HLT2 line developed for Run 2; uses long tracks only
- 770 signal events expected with 2 fb^{-1} (assuming a BR of 4.5×10^{-5}); expected sensitivity $\sigma(\alpha_\gamma)$ ~ 0.9



With 300fb^{-1}, should obtain O(10,000) signal events

- Uncertainty on α_γ (stat.) ~ 0.01
- Dominant uncertainty would be modeling of acceptance
- Yield could be improved with upgrade trigger + downstream track reconstruction

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Semileptonic decays

$|V_{xb}|$: Recent developments

V_{cb}:

Recent Belle $B \to D, D^* \ell \nu$ analyses

Recent lattice results for $B \to D$

[FNAL/MILC, HPQCD, RBC/UKQCD (ongoing)]

- $B \to D$ between incl. + $B \to D^*$

New lattice result for $B \to D^*$ [HPQCD]

- $V_{cb}^{\rm incl}$ cv, compatible with old result

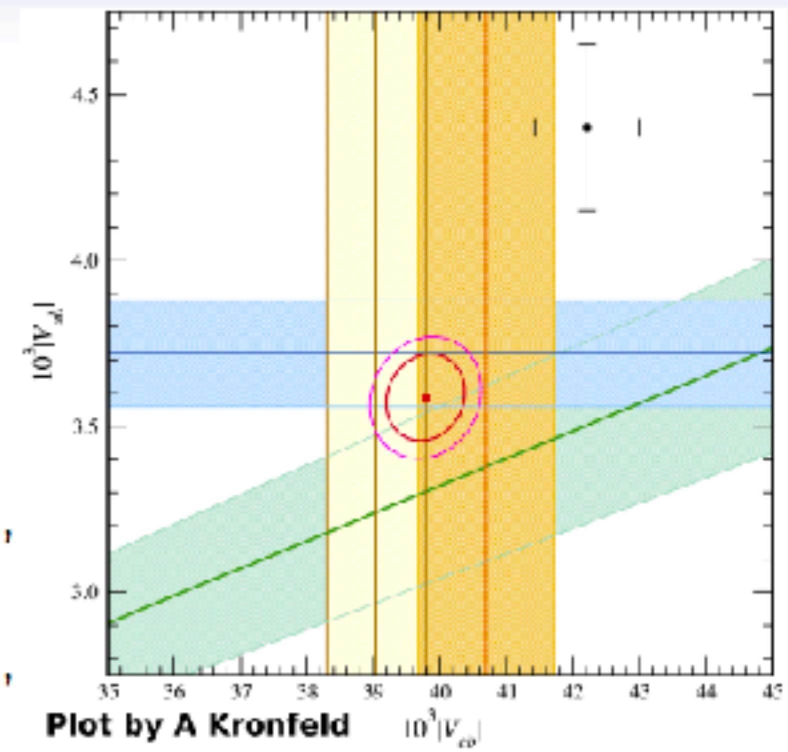
$B \to D^* \ell \nu$ re-analyses with CLN, $|V_{cb}| = 39.3(1.0)10^{-2}$ [Bernlochner+'17] + BGL [Bigi+,Grinstein+'17] (Belle only), $|V_{cb}| = 40.4(1.7)10^{-2}$

New BaBar analysis of V_{ub} incl.:

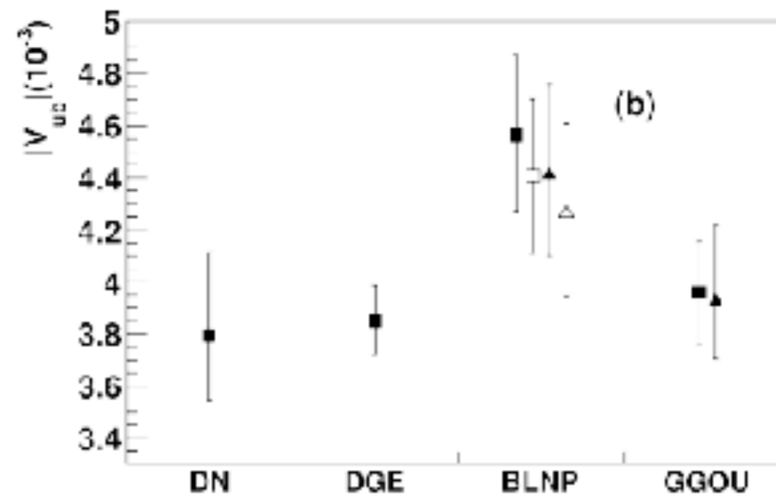
Dependence on theory treatment!

- GGOU 2σ lower than WA
- Compatible w/ PDG exclusive avg

Hints towards resolution, not yet conclusive



Plot by A Kronfeld



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Seems that these puzzles may be related to shapes…

LHCb possibilities

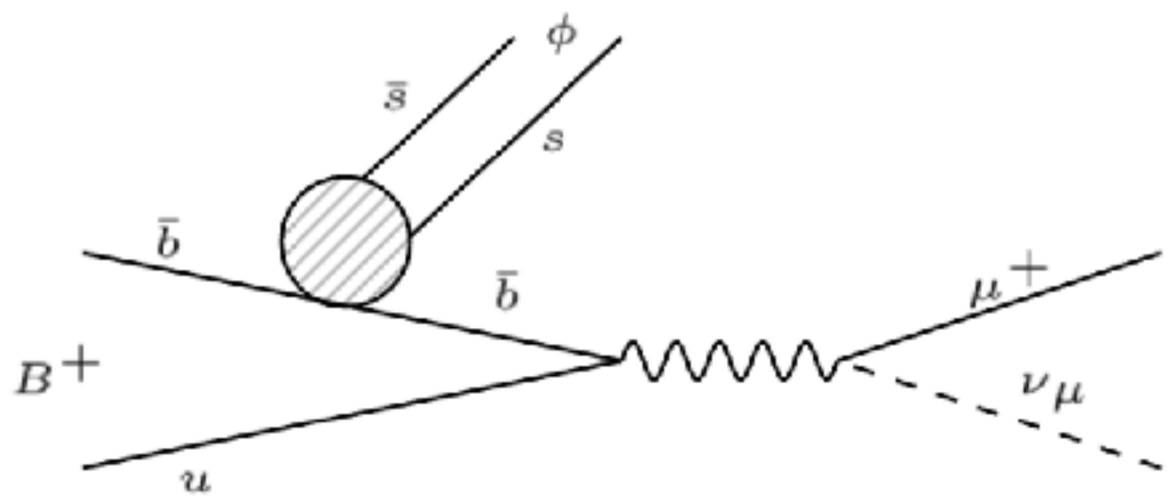
Imagine the shape constraining power of 10^9 $B \rightarrow D\mu\nu$ decays. And consider all of the possibilities with b baryons…

Likewise for the $|V_{ub}|$ modes — 10^7 $B_s \rightarrow K\mu\nu$ decays…

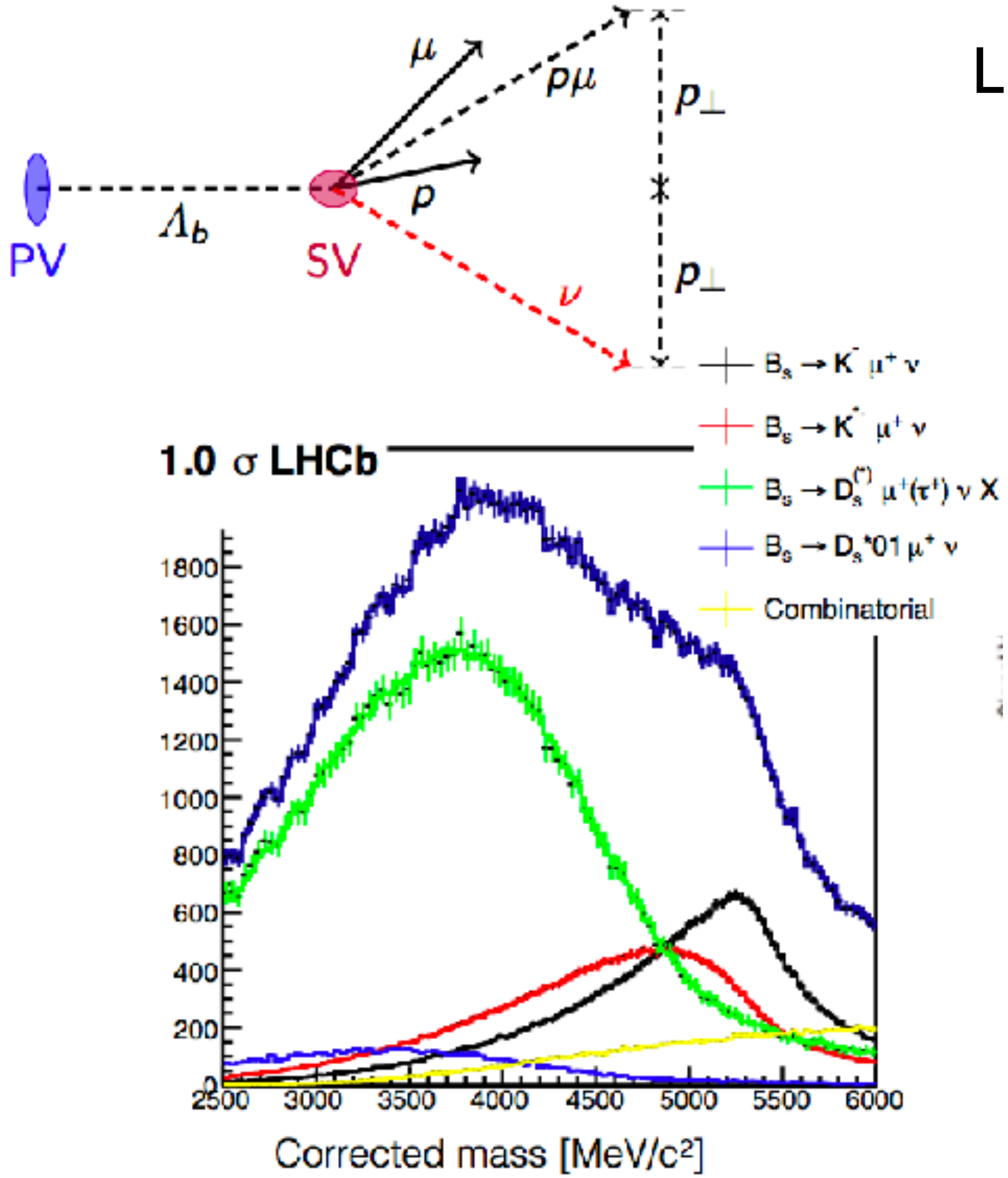
Rarer $|V_{ub}|$ decays like $B \rightarrow \mu\mu\mu\nu$, $\Phi\mu\nu$, $B_c \rightarrow D\mu\nu$.

$b \rightarrow u\tau\nu$ decays!

BF ~O(10^{-6})



Partial reconstruction

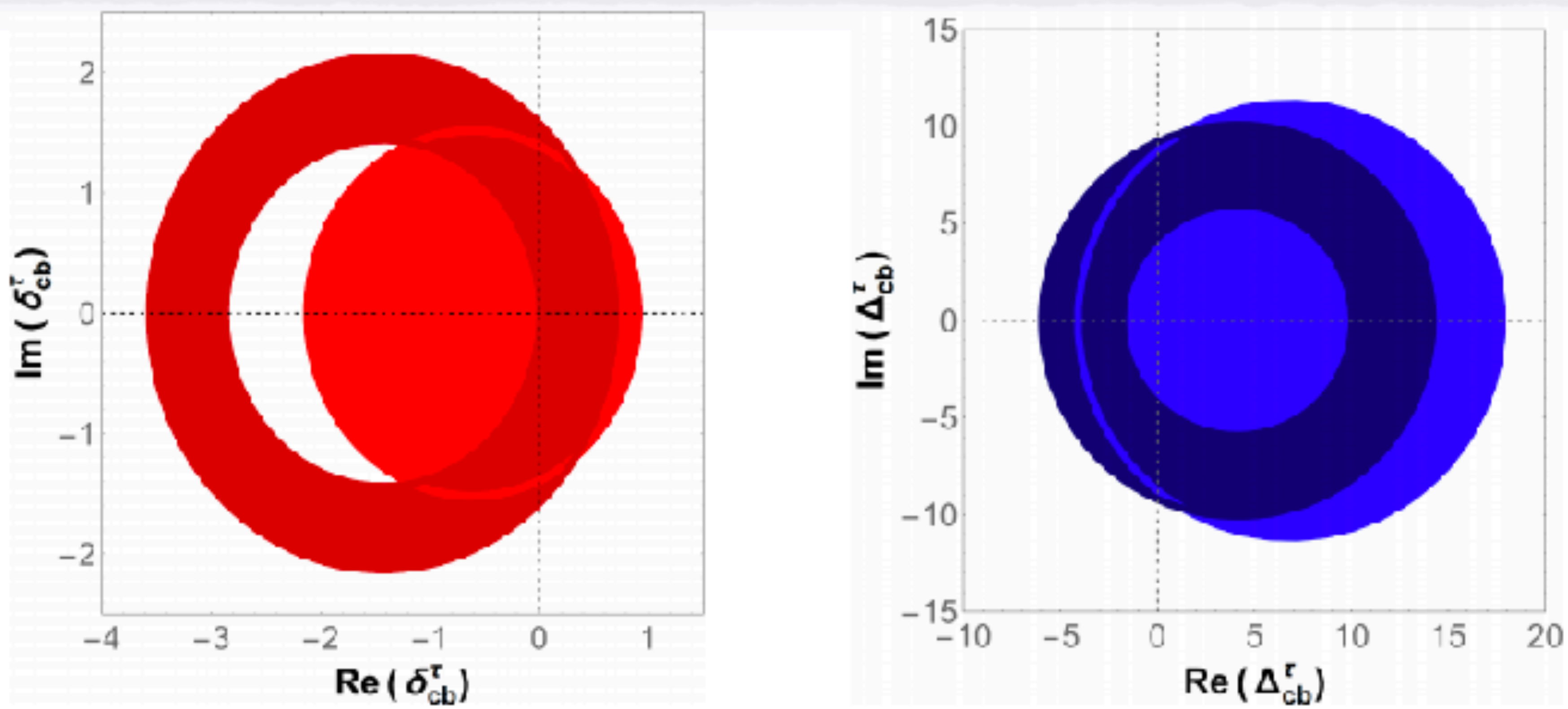


Limited by resolution in flight direction.

Study by Iwan Smith showed that a factor of 2 better vertex resolution can mean a factor of 2 in sensitivity to SL decays (factor of 4 in effective luminosity)!

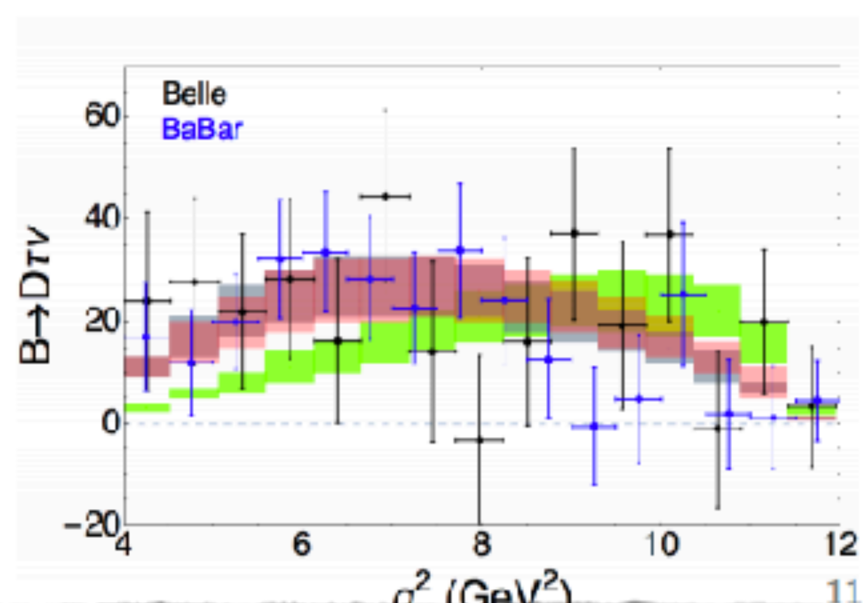
This is before considering the background rejection from the SV quality!

R(D(*)) and new observables



Differential rates:

- compatible with SM and NP
- already now constraining, especially in $B \to D\tau\nu$
- "theory-dependence" of data needs addressing [Bernlochner+'17]



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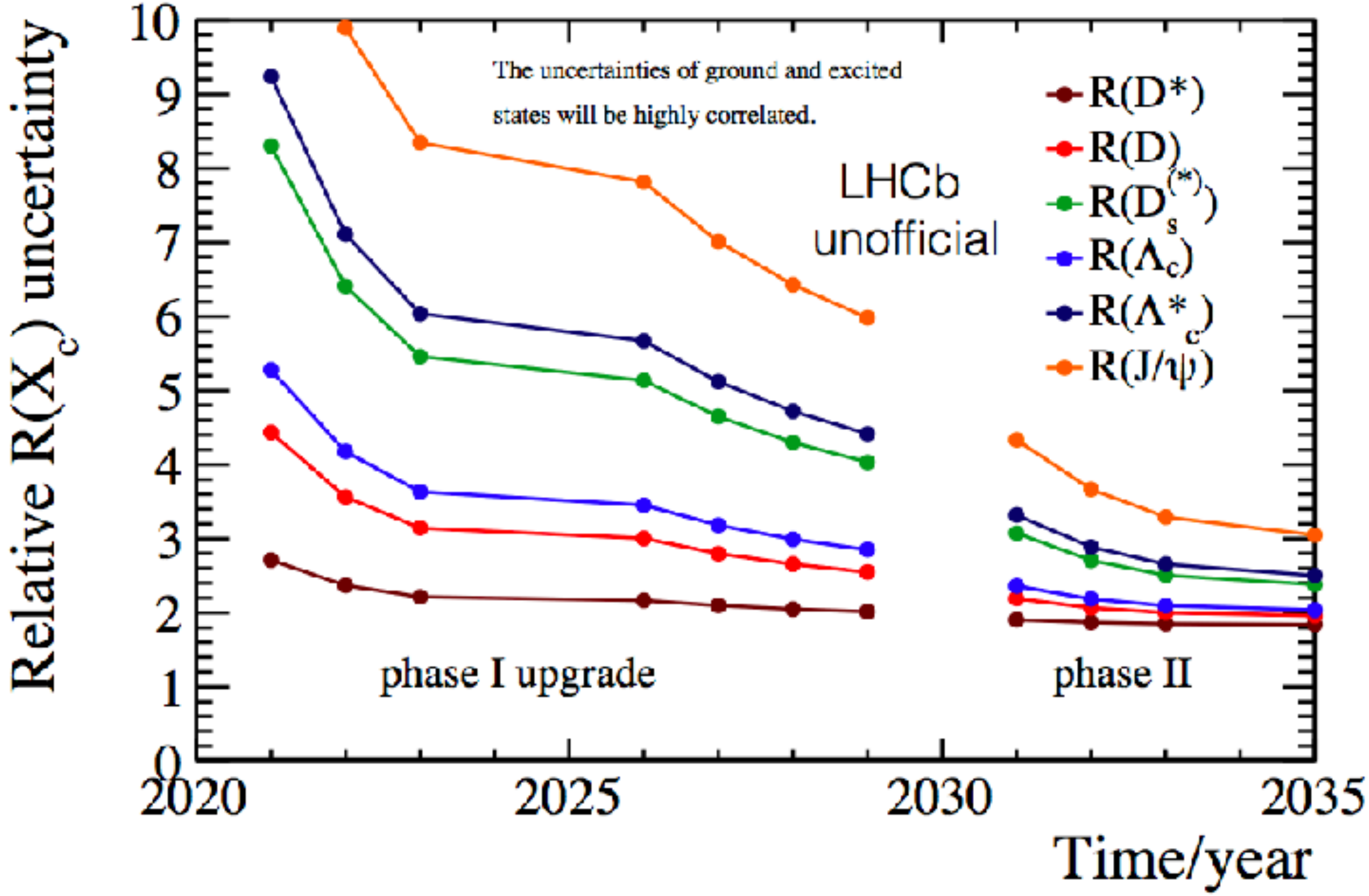
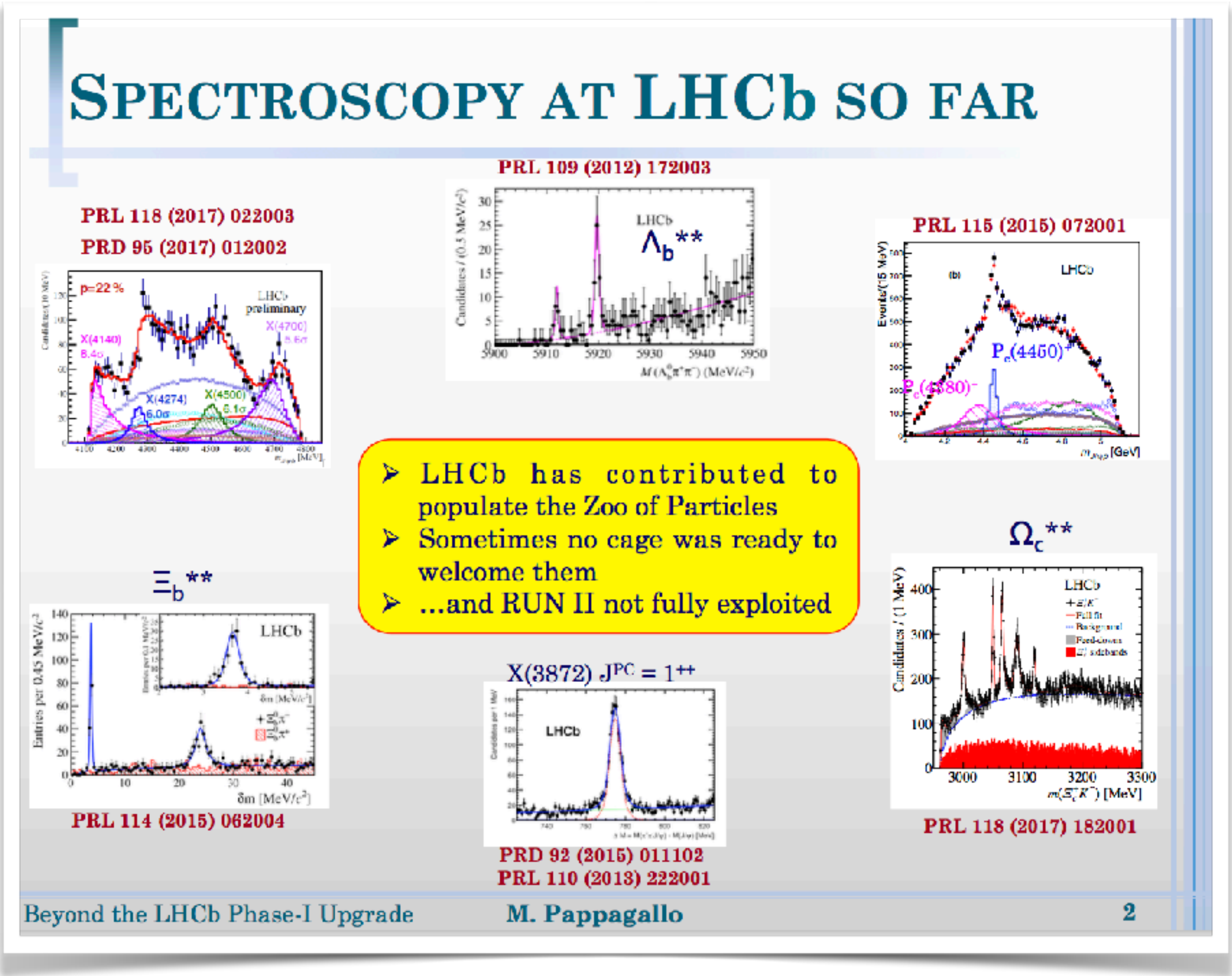
LHCb prospects



Physics performance question: what is the ultimate limit to neutral isolation performance?

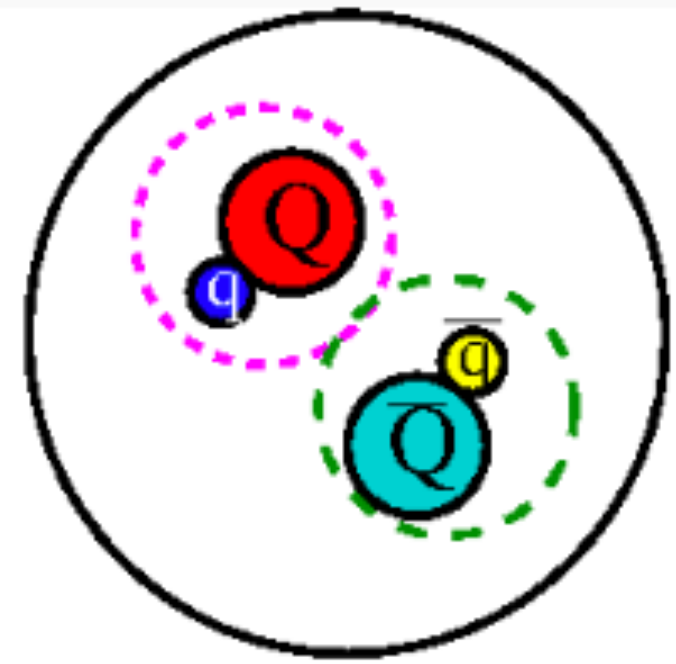

SPECTROSCOPY AT LHCb SO FAR
PRL 118 (2017) 022003
PRD 95 (2017) 012002
p=22 %
LHCb preliminary
X(4140) 8.4σ
X(4274) 6.0σ
X(4500) 6.1σ
X(4700) 5.6σ
PRL 109 (2012) 172003
LHCb
Λb**
PRL 115 (2015) 072001
LHCb
Pc(4450)+
Pc(4380)−
LHCb has contributed to populate the Zoo of Particles
Sometimes no cage was ready to welcome them
...and RUN II not fully exploited
Ξb**
LHCb
PRL 114 (2015) 062004
X(3872) JPC = 1++
LHCb
PRD 92 (2015) 011102
PRL 110 (2013) 222001
Ωc**
LHCb
PRL 118 (2017) 182001
Beyond the LHCb Phase-I Upgrade
M. Pappagallo
2

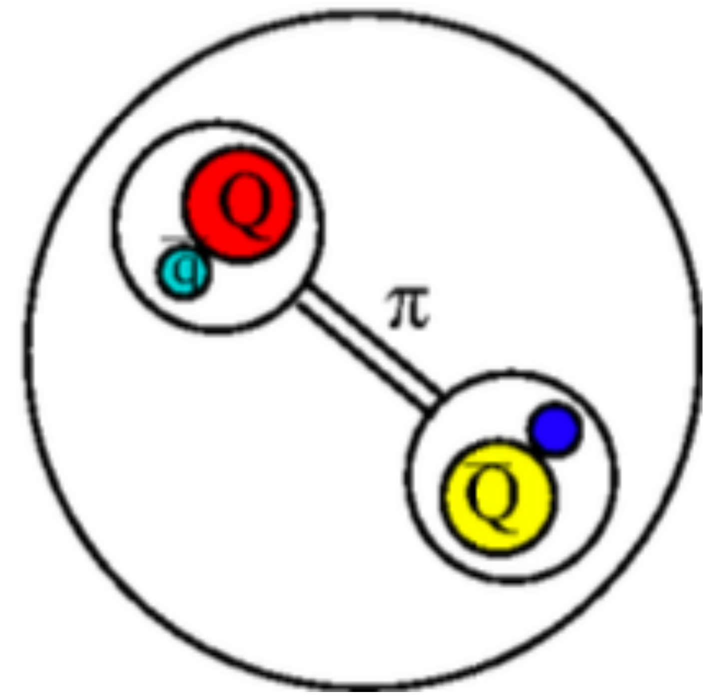
Example: QQ' states

Thresholds for $Q\bar{Q}'$ molecular states

Channel	Minimum isospin	Minimal quark content[a,b]	Threshold (MeV)[c]	Example of decay mode
$D\bar{D}^*$	0	$c\bar{c}q\bar{q}$	3875.8	$J/\psi\,\pi\pi$
$D^*\bar{D}^*$	0	$c\bar{c}q\bar{q}$	4017.2	$J/\psi\,\pi\pi$
D^*B^*	0	$c\bar{b}q\bar{q}$	7333.8	$B_c^+\pi\pi$
$\bar{B}B^*$	0	$b\bar{b}q\bar{q}$	10604.6	$\Upsilon(nS)\pi\pi$
$\bar{B}^*B^*$	0	$b\bar{b}q\bar{q}$	10650.4	$\Upsilon(nS)\pi\pi$
$\Sigma_c\bar{D}^*$	1/2	$c\bar{c}qqq'$	4462.4	$J/\psi\,p$
Σ_cB^*	1/2	$c\bar{b}qqq'$	7779.5	B_c^+p
$\Sigma_b\bar{D}^*$	1/2	$b\bar{c}qqq'$	7823.0	B_c^-p
Σ_bB^*	1/2	$b\bar{b}qqq'$	11139.6	$\Upsilon(nS)p$
$\Sigma_c\bar{\Lambda}_c$	1	$c\bar{c}qq'\bar{u}\bar{d}$	4740.3	$J/\psi\,\pi$
$\Sigma_c\bar{\Sigma}_c$	0	$c\bar{c}qq'\bar{q}\bar{q}'$	4907.6	$J/\psi\,\pi\pi$
$\Sigma_c\bar{\Lambda}_b$	1	$c\bar{b}qq'\bar{u}\bar{d}$	8073.3[d]	$B_c^+\pi$
$\Sigma_b\bar{\Lambda}_c$	1	$b\bar{c}qq'\bar{u}\bar{d}$	8100.9[d]	$B_c^-\pi$
$\Sigma_b\bar{\Lambda}_b$	1	$b\bar{b}qq'\bar{u}\bar{d}$	11433.9	$\Upsilon(nS)\pi$
$\Sigma_b\bar{\Sigma}_b$	0	$b\bar{b}qq'\bar{q}\bar{q}'$	11628.8	$\Upsilon(nS)\pi\pi$

[a]Ignoring annihilation of quarks. [b]Plus other charge states when $I \neq 0$.
[c]Based on isospin-averaged masses. [d]Thresholds differ by 27.6 MeV.





Doubly heavy baryons

QQq baryons are the simplest baryons:

hydrogen atom of baryon physics!

Reasonable estimate for Ξ_{bc} with 300/fb ~ 10^3 events.

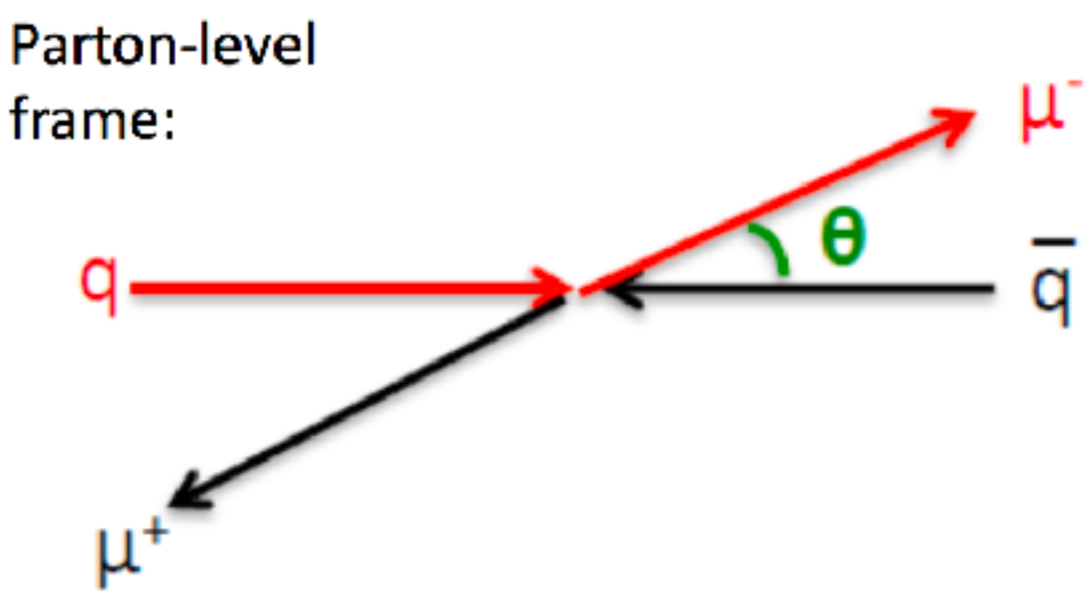
So, why have we not yet seen bcq baryons (Ξ_{bc})?

- Lower production rates, guess $\sigma(X_{bc}) \sim (0.1 - 0.5) \times \sigma(B_c^+)$
- In J/ψ modes, (usually) get a charm baryon: yield reduced by $BF(X_c) \times \varepsilon_{sel}(X_c)$
- Shorter lifetime (~0.15 – 0.4 ps range, compared to ~0.5 ps for B_c)
- Probably no single golden mode: several modes may be required for chance

How would improved IP resolution help with selection efficiency?

Precision EW

Weak mixing angle

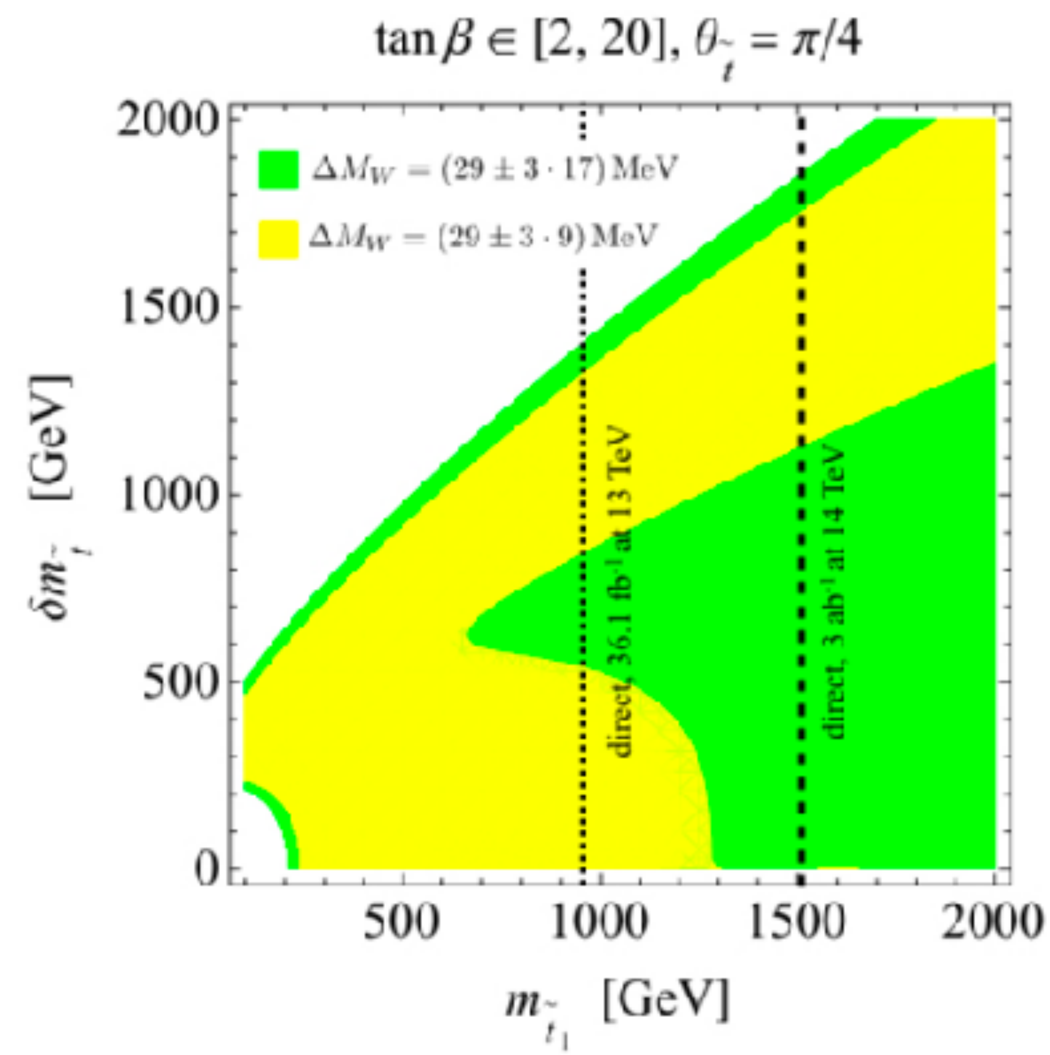


With 300/fb statistically precision 2x better than WA — can we make the necessary breakthrough in systematics?

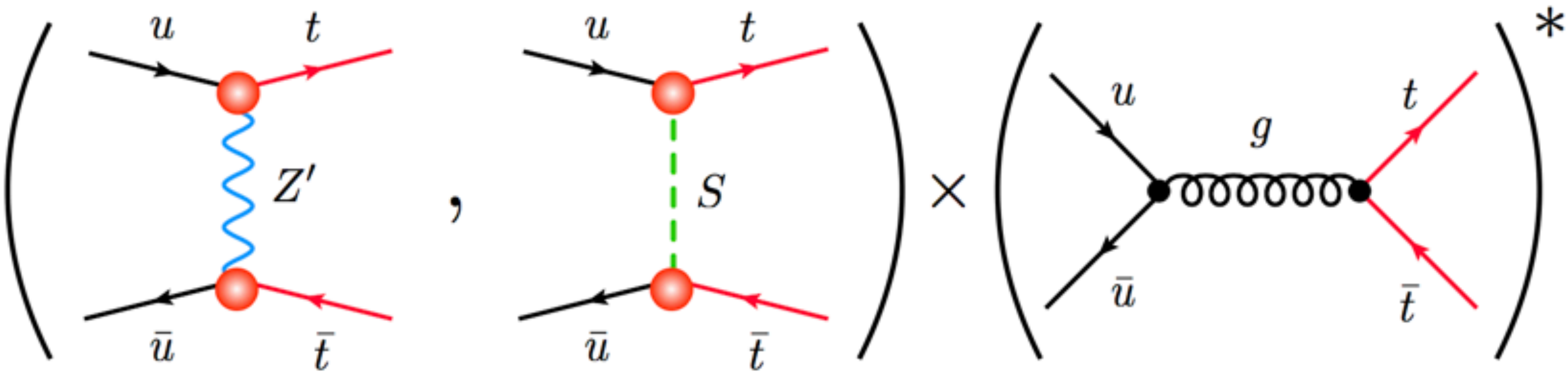
Electrons…

W mass.

Relatively new idea at LHCb.
QCD systematics anti-correlated with ATLAS/CMS.



Top



In new-physics models in which top production proceeds via t-channel exchange, cross section & asymmetry enhanced at large pseudo-rapidities not accessible at ATLAS & CMS

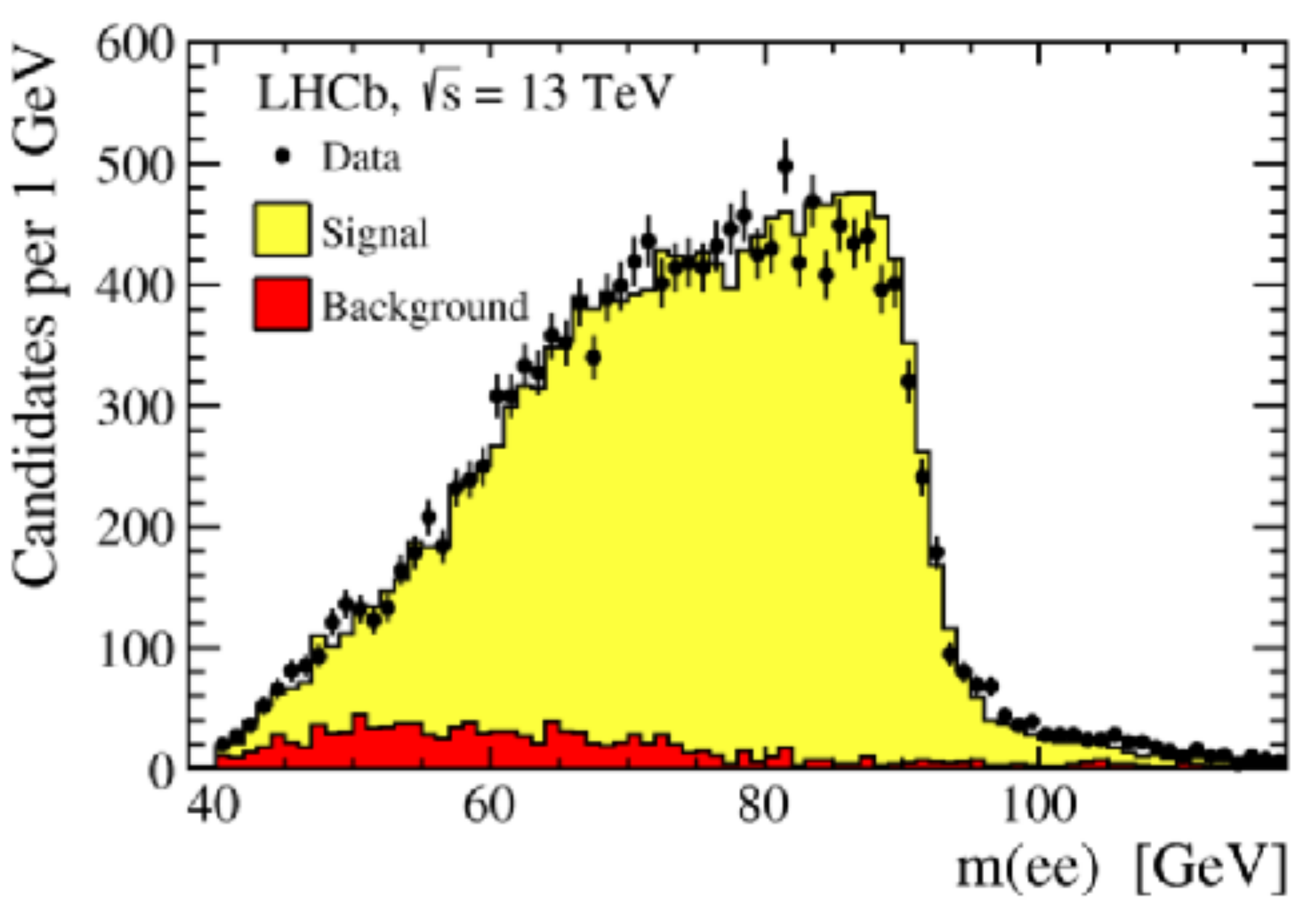
in LHCb context see Kagan, Kamenik, Perez & Stone, 1103.3747

Of high interest to study $A_{FB}(bb)$ too…

General Purpose Forward Detector

Many of LHCb's successes have been in unforeseen areas. Partly possible because of the solid general purpose capabilities of the apparatus.

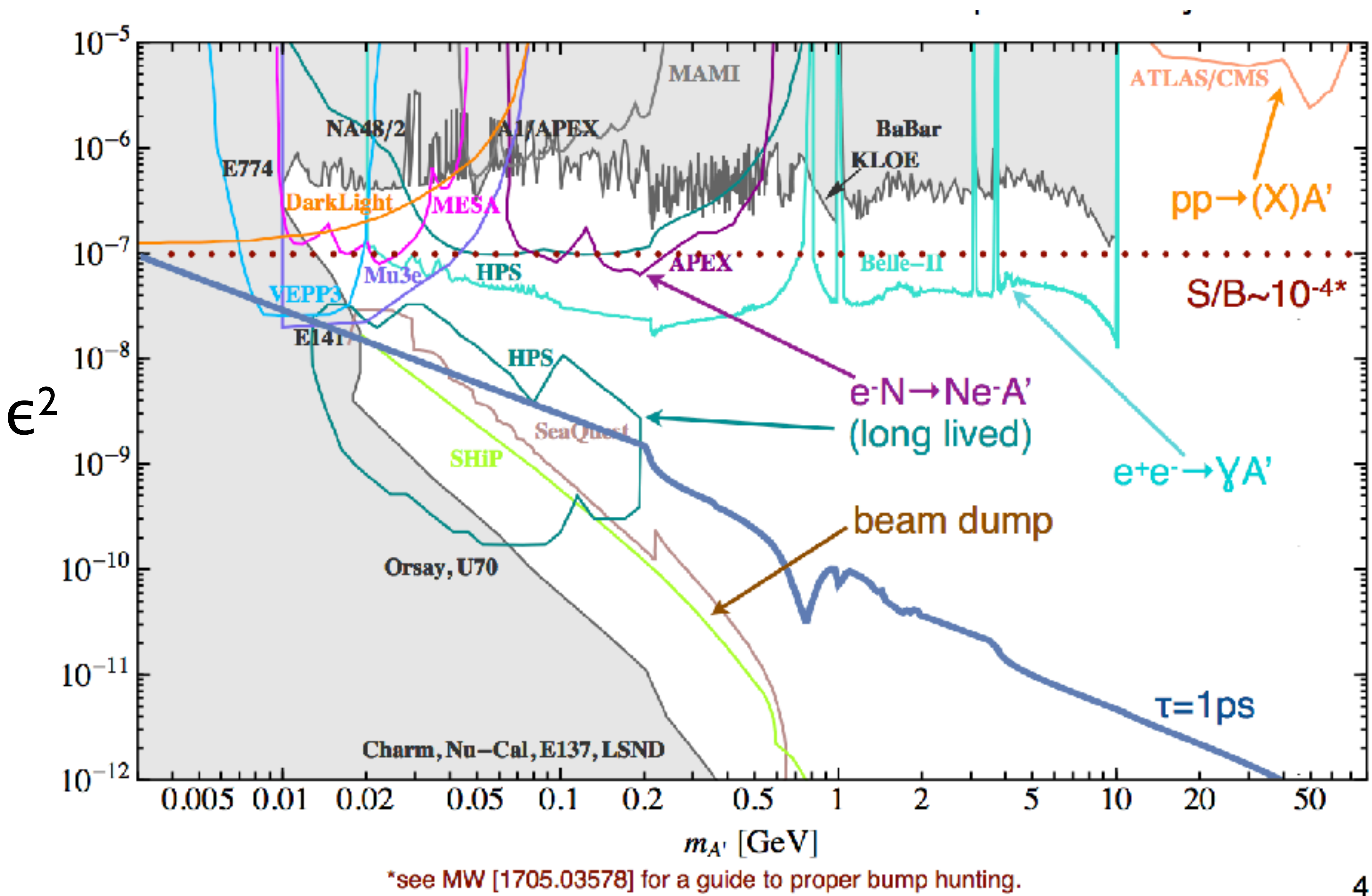
We should pay attention to the most general suite of physics performance metrics — even those that may not be relevant to our currently envisaged physics programme.



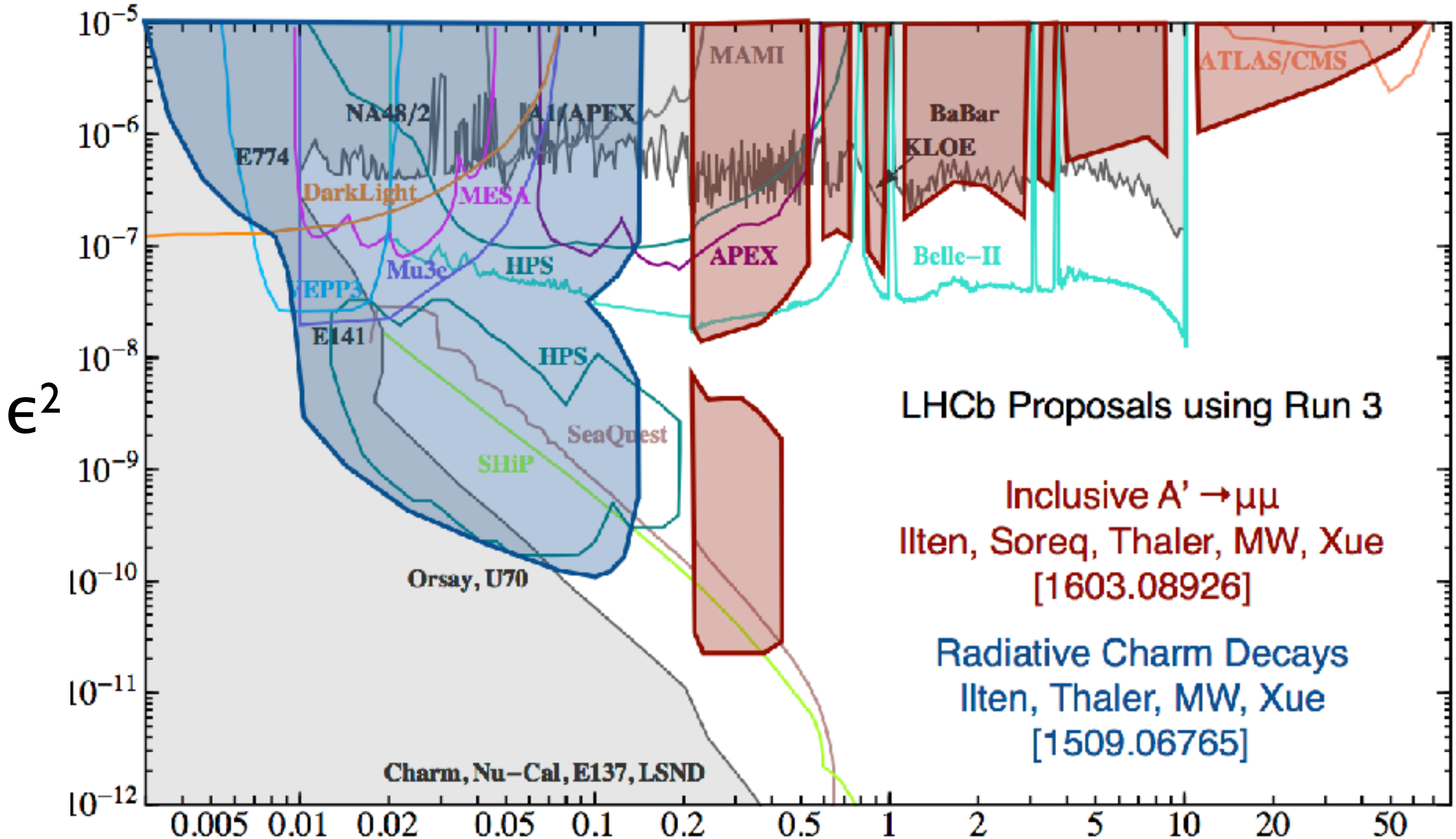
The ECAL saturation story…

Consider 4x dilepton top-pair, or LFU test with $\sin^2\theta_W$ etc..

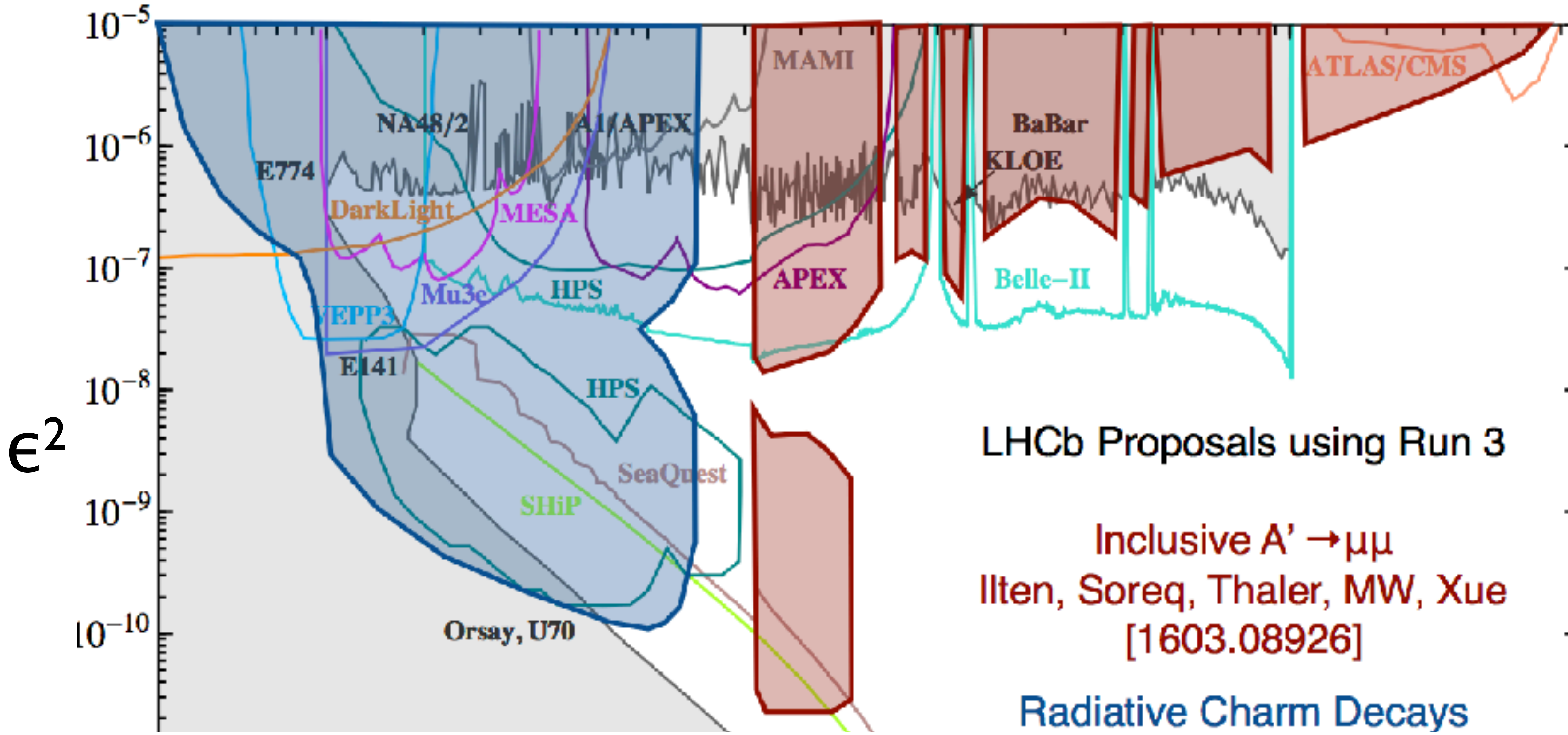
Dark photons



Dark photons



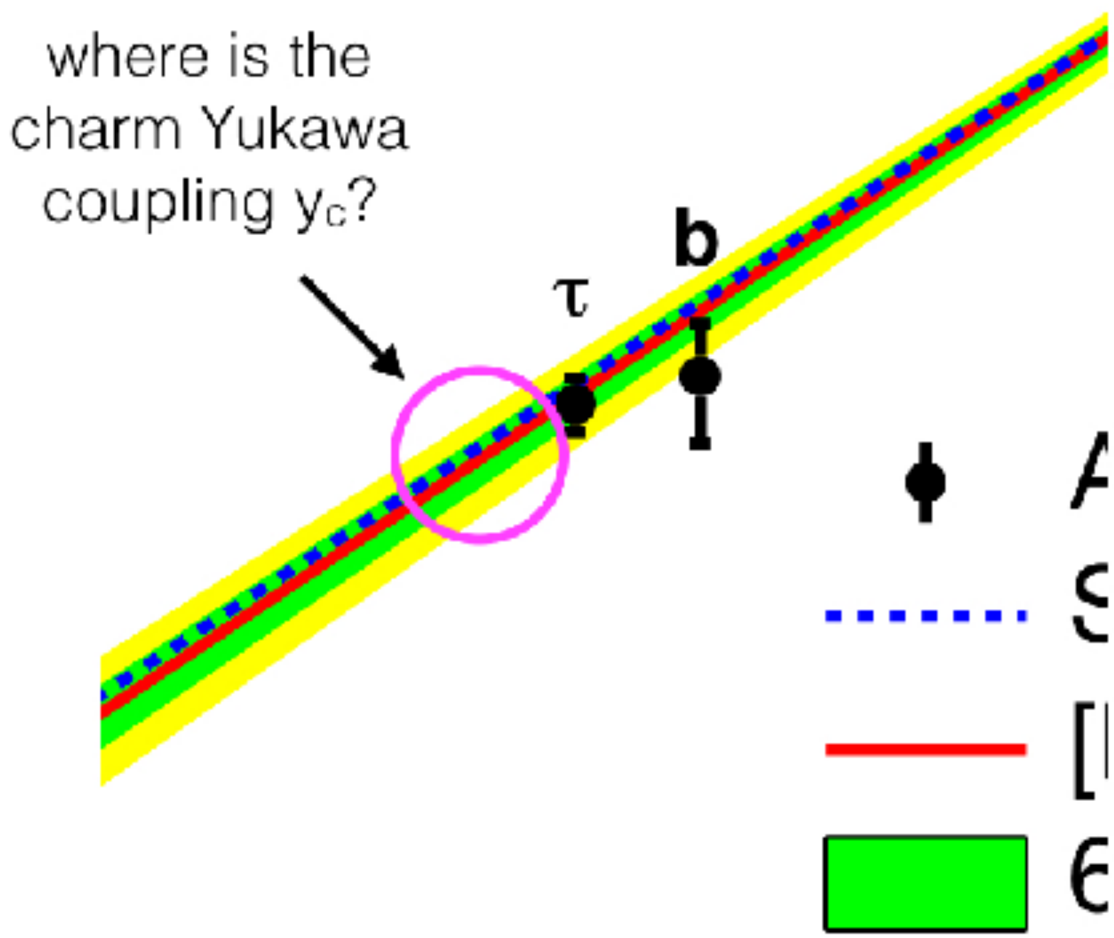
Dark photons



Heavy flavor BKGD scales as vertex resolution, transition to displaced region scales as lifetime resolution. Very-long-lived sensitivity depends on material budget, the volume occupied by material, and vertex resolution. Pathological cuts depend on pixel size, etc.

Magnet chambers would help with soft A' decays to e+e- (efficiency and/or resolution).

The charm Yukawa

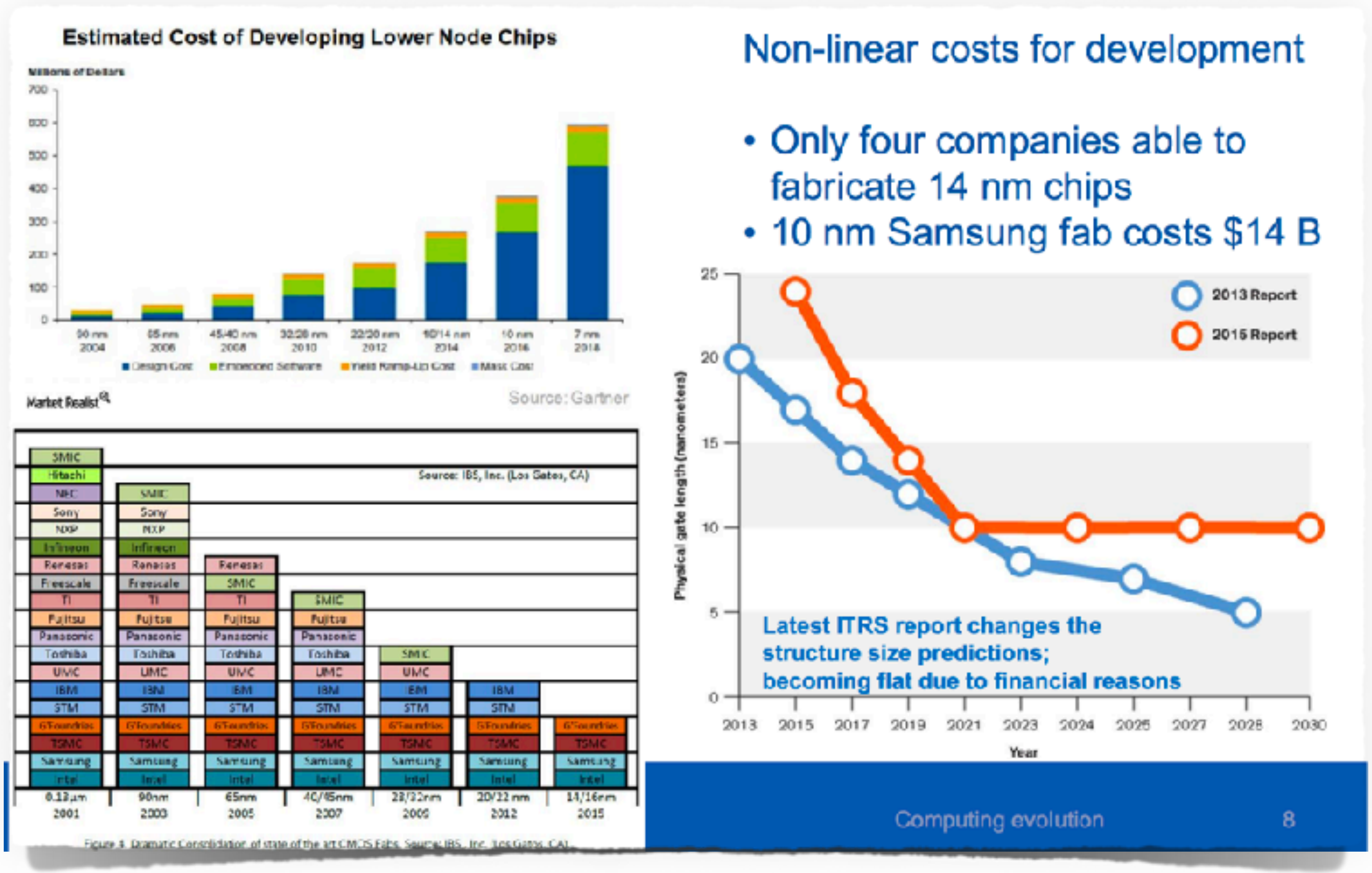


- 300 fb^{-1} at 14 TeV: $|\kappa_c| \lesssim 7$
- 30% di-c-tagging efficiency: $|\kappa_c| \lesssim 4$
- better electron reconstruction: $|\kappa_c| \lesssim 3$
- further improvements: $|\kappa_c| \lesssim 2.2$

This would be competitive with all other foreseen determinations on the same timescale!
And at 2-3x SM, this gets very interesting.

Computing is critical

Our successful and diverse physics program is dependent on a flexible and “real-time” data processing scheme.



Conclusions and outlook

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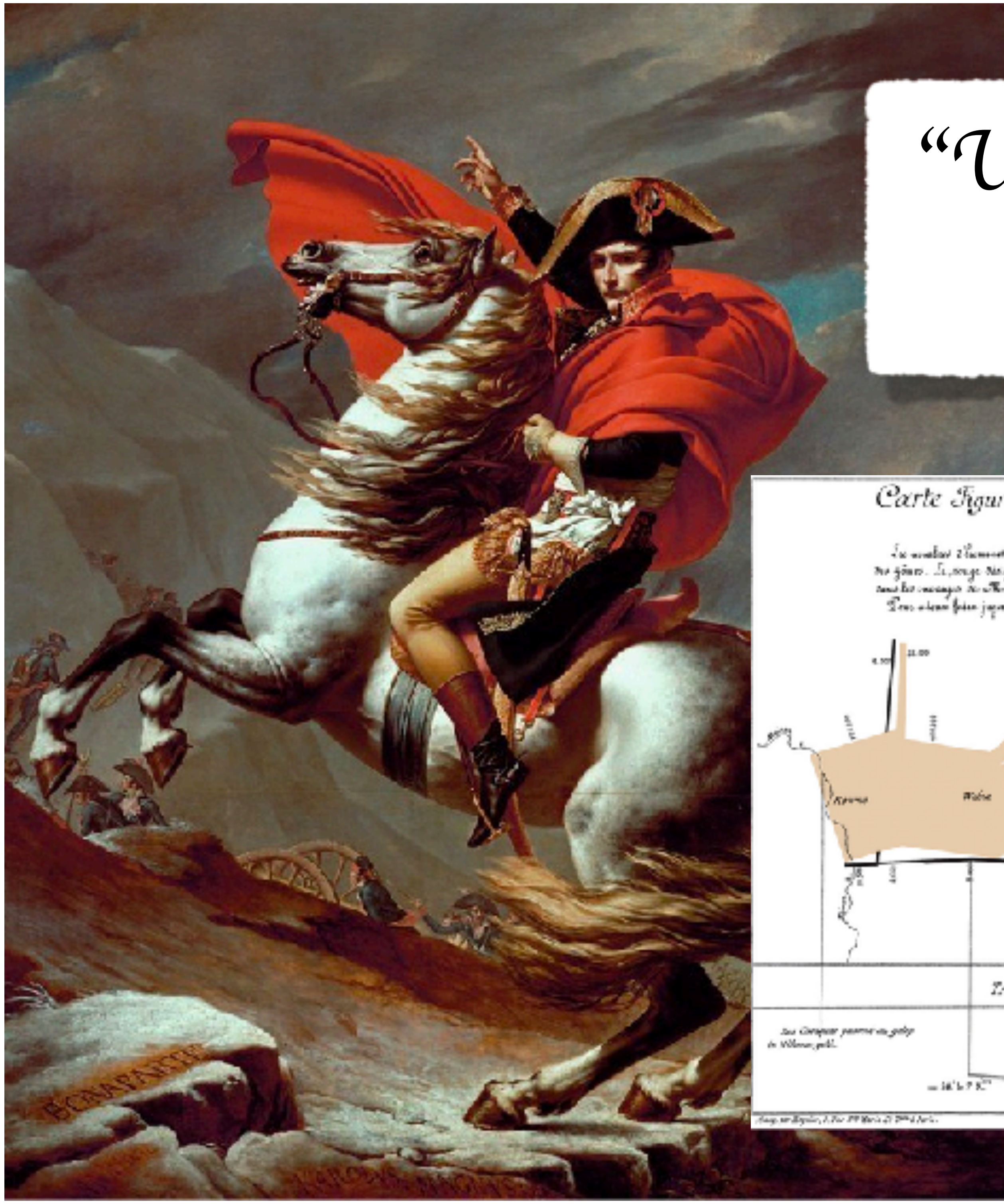
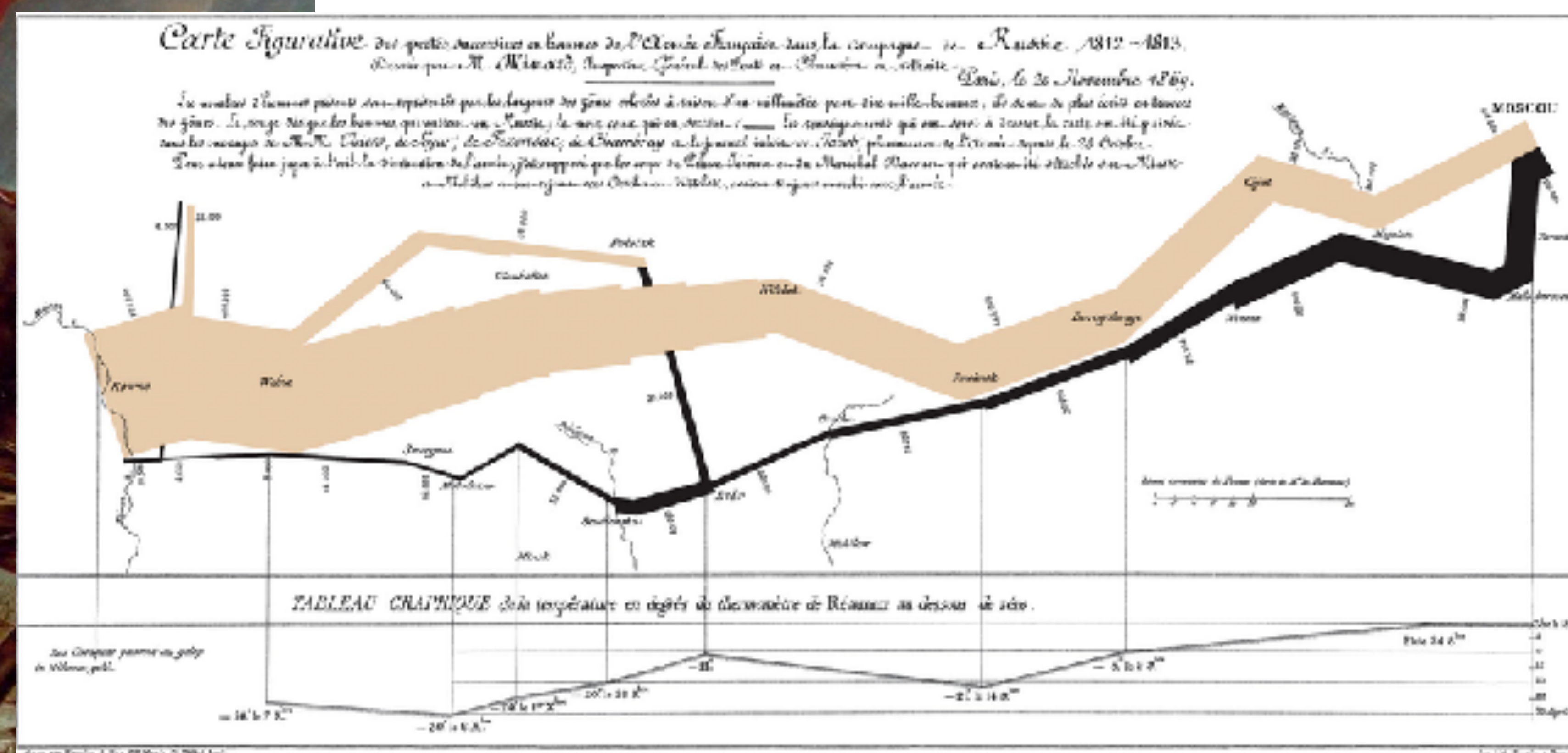
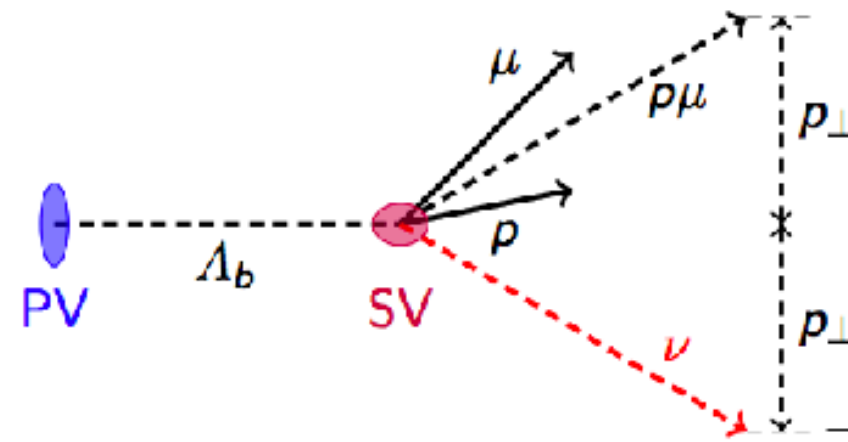


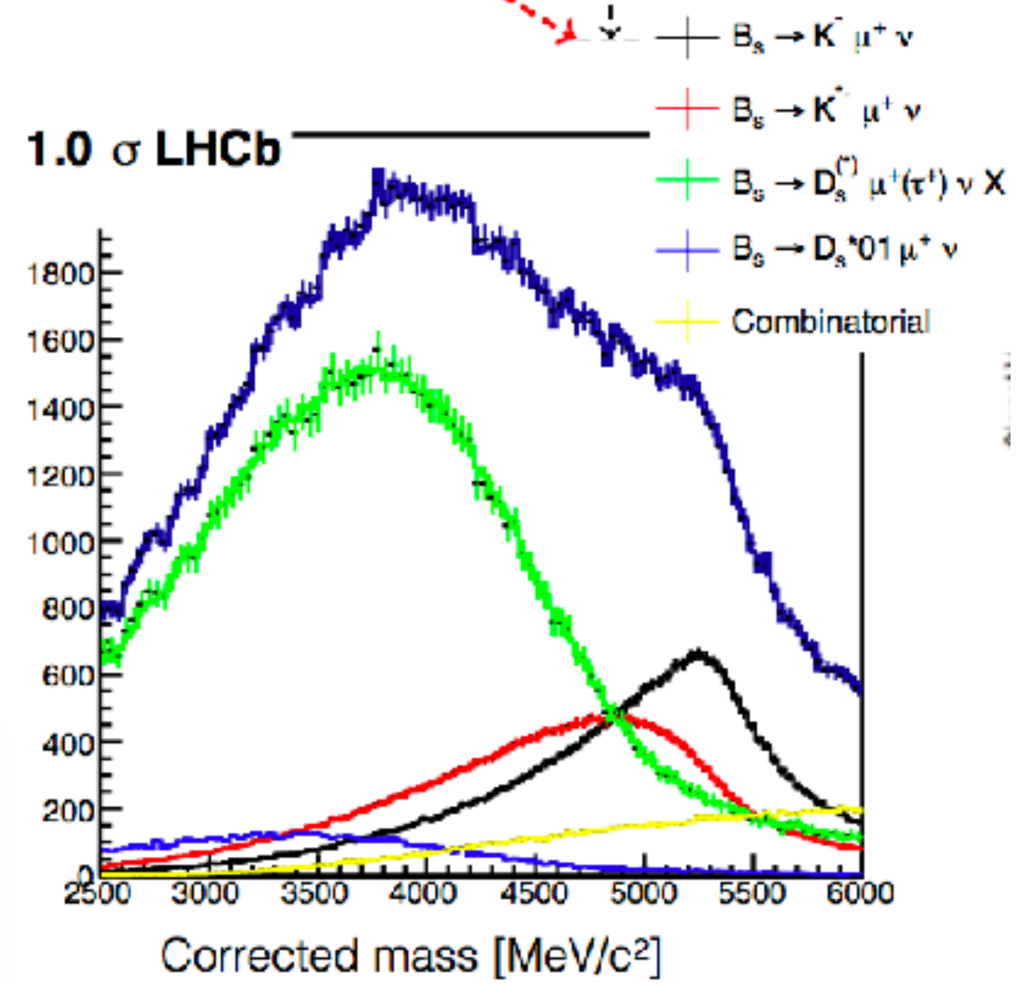
“Un bon croquis vaut mieux qu’un long discours”



Conclusions and outlook

“A physics performance study is better than speculation”





Conclusions and outlook

At this workshop we had stimulating discussions on the physics. We must now move forward with physics performance studies with detector improvements.

We must prepare a physics document for the LHCC in ~one year. And contribute to a Yellow report on the HL-LHC physics opportunities in late 2018 - early 2019, following a kickoff meeting in late 2017.

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Let's seize the opportunity that LHCb-phase-II presents to science!

Backup slides start here…