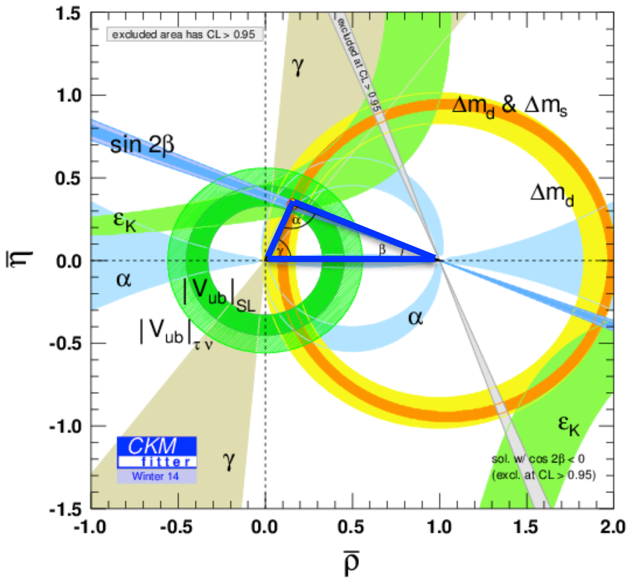
Depicting a Physics Case for Future Upgrades

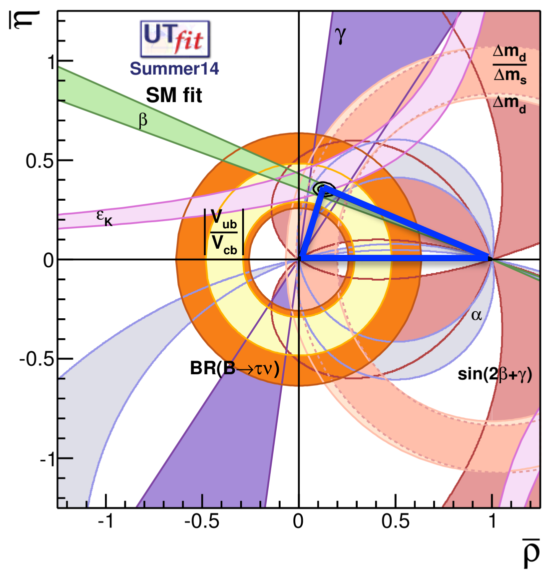
LHCb Italia

LNF - 13 Ottobre 2015

Consistency of global CKM fits

- Tremendous success of the CKM paradigm!
  - All of the measurements agree in a highly profound way





- We are leaving in a strange era
  - on the one hand we have been achieving great experimental success
  - on the other hand, we feel depressed as everything looks consistent with what we already knew

However...

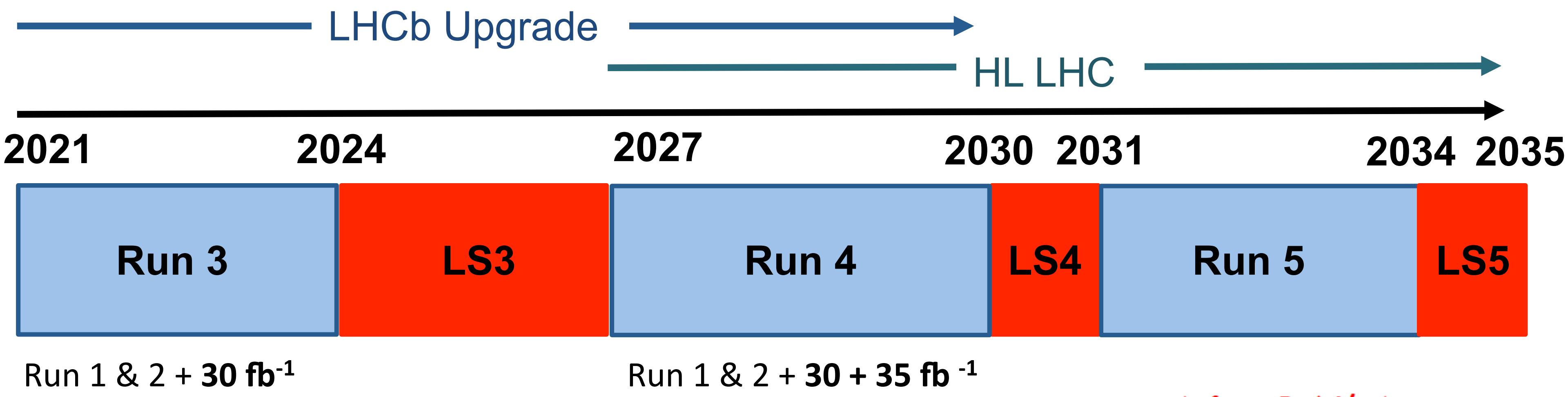
- There are good reasons to believe that the SM is incomplete
  - hierarchy
  - unification of gauge couplings
  - dark matter
  - baryonic asymmetry
  - ...
- Unfortunately these arguments do not provide stringent quantitative predictions, apart from hints that the NP scale should be “close” to the EW scale
- By studying *CP*-violating and flavour-changing processes we can accomplish two fundamental tasks
  - Identify new symmetries (and their breaking) beyond the SM
  - Probe mass scales not accessible directly

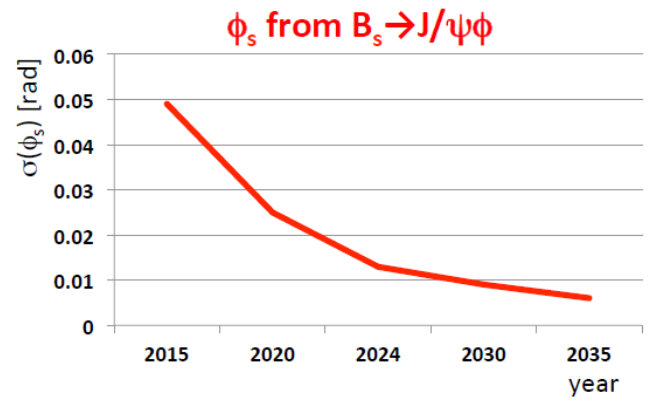
Think Tank for Future Upgrades

- The management has started since some time an effort to think to possible future upgrades
- TTFU is a discussion group that reports to the UPG and currently consists of
  - Pierluigi Campana, Monica Pepe Altarelli, Giovanni Punzi, Sheldon Stone, Frederic Teubert, Vincenzo Vagnoni, Guy Wilkinson
- This group has met several times and convened two open meetings (on 17/02/15 and 21/04/15)
- Healthy and necessary to start discussing next-step Upgrade(s)
  - Existing Upgrade activities are now sufficiently robust not to be vulnerable to these discussions

The steady-state syndrome

With $L = 2 \times 10^{33}$ cm^{-2}s^{-1} we can assume ~10 fb^{-1} per year





- The steady-state increase of luminosity is not optimal for keeping the collaboration committed and motivated for Run 4 and beyond
- We need a forward vision for then
- No very ambitious projects on scale of current Upgrade will be most likely possible in LS3 itself ← demands on FAs from phase-2 GPDs

Phase-1b Upgrade (LS3)

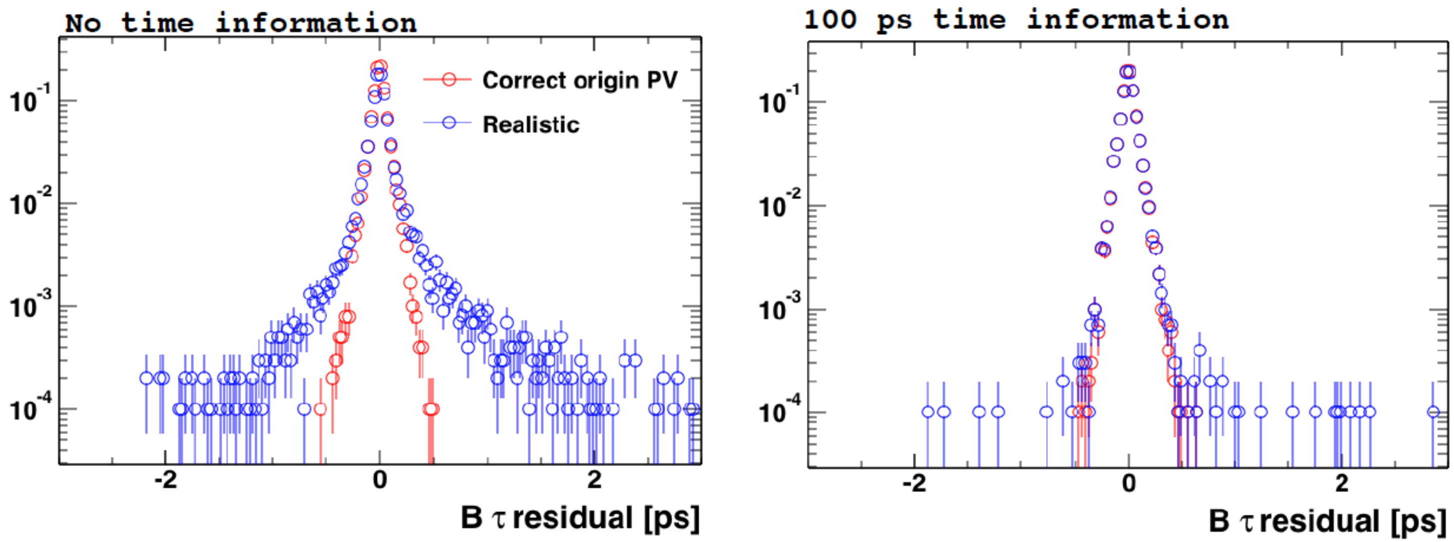
- LS3 comes too soon after phase-1 Upgrade to contemplate any paradigm shift in how we run LHCb, or installation of very expensive new system
- But there are many improvements worth investigating which have the potential to extend our physics capabilities in specific areas
- A non-exhaustive list notably includes
  - Magnet side chambers
  - TORCH
  - New shielding for muon system
  - New muon chambers in M2, M3…?
  - Inner region of ECAL will need replacing in LS3
    - Rather than using existing spares we could consider to install an option with higher performance, in order to improve current performance in Upgrade conditions
  - …
- Keep working at ~2 x 10^{33} $cm^{-2}s^{-1}$ → this would fall into the category of a (vigorous) improvement of the existing detector, let's call it "Phase-1b Upgrade"

Phase-2 Upgrade

- Let's move a step further: what sort of changes would be needed if go to ≥ 10^{34} cm^{-2} s^{-1} ?
  - Say, collect ≥ 300 fb^{-1} in a few years or running
- Beyond changes to the machine and to the shielding at the LHCb IP, relevant changes to the detector will be needed
  - New VELO mandatory and new tracker certainly needed
  - Data processing?
  - Displace interaction vertex? Without this need to solve very high occupancies, *e.g.* in RICH
- And what sort of physics would one do?
  - General purpose flavour physics or focusing on some key modes?
- To be done in LS4!?
  - in current LHC schedule LS4 is too short → need relevant changes in the machine schedule

Two words on how to mitigate pileup

- One obvious problem when working at extreme luminosity will be how to cope with the dramatic increase of pileup
  - Could we make time-dependent analyses with tens of simultaneous primary interactions?
- Possible solution → use time-tagged detectors
  - i.e. tag hits and tracks with time information to separate interactions happening at different times → a new powerful dimension!
  - not an easy task from the detector POV (also depending on what resolutions are needed and to what extent the information should be made available) → need robust R&D



Establishing a physics case for ≥ 300 fb^{-1}

- The physics WGs have been asked to start thinking of our further (physics) future for a Phase 2 upgrade
  – 300 fb^{-1} is a possible "realistic" scenario, but we can think even of larger numbers if there's a compelling physics reason
- How to do that?
  – we cannot afford any realistic simulation
  – we cannot distract too much ourselves from ongoing commitments
  – this has to come as an adiabatic effort...

Outcome of the first discussion

- Some of the working groups well understood the aim of the exercise, and came with a few selected topics
- Some other working groups came with a long list of possible modes
- What follows is a summary of what has been presented

Yasmine & Yuehong

Representing B2CC WG

B_s & B_d mixing phases

- Very precise measurement of ϕ_s
  - $B_s \to J/\Psi\phi$, $B_s \to J/\Psi\pi^+\pi^-$, $B_s \to J/\Psi K^+K^-$ with high KK mass mass
  - Eventually make experimental error of $\phi_s \sim$ theoretical uncertainty of *O*(0.001)
- Very precise measurement of $\sin 2\beta$
  - $B_d \to J/\Psi K_S$

Penguin effect in $b \to ccs$

- Control penguin shift on ϕ_s and 2β using SU(3) related $b \to ccd$ decays
  - $B_d \to J/\Psi\rho^0$, $B_s \to J/\Psi K^{*0}$, $B_s \to J/\Psi K_S$: well studied
  - $B^+ \to J/\Psi\pi^+$: 3 fb^{-1} update in progress
  - $B_d \to J/\Psi\pi^0$: study just started

A systematic study of many channels will be essential for a full understanding of SU(3) symmetry breaking

CPT violation

- $B_d \to J/\Psi K^0$ with $K^0 \to \pi\mu\nu$
  - Measure asymmetry as a function of B and K decay times, mentioned in "Implication document"

$$A_{bk} = \frac{\Gamma(B^0+\overline{B}^0 \to J/\psi\,[\pi^-\mu^+\nu] - \Gamma(B^0+\overline{B}^0 \to J/\psi\,[\pi^+\mu^-\overline{\nu}])}{\Gamma(B^0+\overline{B}^0 \to J/\psi\,[\pi^-\mu^+\nu] + \Gamma(B^0+\overline{B}^0 \to J/\psi\,[\pi^+\mu^-\overline{\nu}])}.$$

- $B_d \to J/\Psi K_S$
  - Ongoing work: looking for sidereal variation of

$$A_{CPT}(t) \equiv \frac{\overline{P}_{\bar{f}}(t) - P_f(t)}{\overline{P}_{\bar{f}}(t) + P_f(t)}$$

Other possibilities

- $B_s \to J/\Psi\gamma$: Effective lifetime and CP violation
- $\Delta\Gamma_d$ with $B_d \to J/\Psi K_S$ and $B_d \to J/\Psi K^{*0}$
- Measurement of properties of light f0 states
  - $B_{s/d} \to J/\Psi\pi^+\pi^-$
- CP violation in B_C decays
  - $B_c \to J/\Psi K^+$

Interesting topics to study in the future, but maybe not necessary for this very early discussion

Physics cases for high-luminosity running of LHCb: B2CC inputs

Yasmine & Yuehong

Representing B2CC WG

B-hadrons and B_c

- Bc → charmless
- Bc → Bs pi (Bs tagging)
- Bc →Ds D (gamma measurement)
- Bc radiative decay: Bc→Ds1(2536) gamma
- Search for Excited Bc**:
  - ✓ Bc** → Bc pi pi
  - ✓ Bc** → Bc gamma
  - ✓ Bc** → BD
- Search for the missing Bs0* and Bs1':
  - ✓ Bc → B K pi
  - ✓ Bc → Bs gamma pi
  - ✓ Bc → Bs pi0 pi

- Search for Xi_bc →J/psi Lc K
- Search for Omega_bc→J/psi Omegac
- Search for Xi_bb
- Exclusive Search for etab
  - ✓ etab → J/psi J/psi
  - ✓ etab → DDpi
  - ✓ etab → p pbar

B&Q HL-LHC Prospects (*Very Preliminary*)

M. Pappagallo & Z. Yang

On behalf of the B&Q WG

Production and Polarization

- Associative Production
  - ✓ Y(nS) + J/psi
  - ✓ Y(1S) + psi(2S)
  - ✓ Double open b (B + B)
  - ✓ Y(1S) + B

Exotics

- Charmonium(-like) spectroscopy in CEP
- Bc → DD Ds (Search for Doubly charmed tetraquarks)
- Bc → J/psi p pbar pi (Search for pentaquark)
- Y(1S) → J/psi p pbar (Search for pentaquark)
- B(s)0 →J/psi p pbar (Search for pentaquark)
- Ξb-→J/ψ Λ K- (Pentaquark in J/psi Lambda)
- Search for pentaquark →J/psi p (Prompt production)
- Λb→ηc p K- (Search for pentaquark → etac p)
- Λb→chic1 p K- (Search for pentaquark → chic1 p)
- Λb→Λc+ D0 K- (Search for pentaquark → Lc D0)

- Search for Z(4430)+
  - B+ → psi(2S) pi0 K+
  - B+ → psi(2S) pi+ Ks
- Search for $Z(4430)^0$
  - B0 → psi(2S) pi+ pi-
  - B0 → J/psi eta K+
- Search for chi_c1(2P)→chic1 pi+ pi-

B&Q HL-LHC Prospects (Very Preliminary)

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- Λb→ηc p K- (Search for pentaquark → etac p)
- Λb→chic1 p K- (Search for pentaquark → chic1 p)
- Λb→Λc+ D0 K- (Search for pentaquark → Lc D0)
- Search for exotic Zb+ →B+ anti-B0
- Bottomonium exotics decaying to:
  - ✓ Y(1S)phi
  - ✓ Y(1S)p
  - ✓ Y(1S)K
  - ✓ Y(1S) Lambda
  - ✓ Y(1S) Omega

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TTFU Physics Case: BnoC Input

Tom and Eduardo
on behalf of BnoC WG

2-body decays

- Extrapolations of direct CP asymmetries in $B_{d,s}$ -> $K\pi$ and Λ_b -> ph show statistical uncertainties of 0.03%, 0.2% and 0.1%, respectively
- Many systematics are data driven, so these measurements could remain statistically limited – indeed the current systematic uncertainty on B_d mode ~ the projected stat uncertainty on B_s mode
- Time-dependent asymmetries in B_d -> $\pi\pi$ and B_s -> KK should have statistical uncertainties below 1% but systematics much harder to extrapolate
- Interpretation in terms of gamma and β_s:
  - Precision does not scale linearly with inputs
  - Relies on several external inputs and isospin / U-spin symmetries
  - Difficult to extrapolate without dedicated studies (not yet performed)

3-body decays

- Again very rich physics:
- Time-dependent Dalitz-plot analyses of $B_{d,s}$ -> $K_S hh$ and $B_{d,s}$ -> $hh\pi^0$ modes measure mixing phases
- Combining measurements of phase differences between various K* states can also determine gamma
- Estimates of sensitivity are ongoing
- The B_s decays are particularly crucial since Belle 2 will not be able to do time-dependent measurements
- These modes could gain from possible improvements to calorimeter and K_S reconstruction
- As with VV decays, acceptance over DP is a key issue

B -> VV

- A lot of physics here:
- B_s -> $\varphi\varphi$
  - Measures φ_s – preliminary extrapolation to 300fb^{-1} indicates uncertainty of 0.017
- $B_{d,s}$ -> K* K*
  - Again measure the mixing phases, for B_s extrapolated uncertainty is 0.020
  - Here can also make U-spin tests since have both the B_s and B_d decays
- B -> $\rho\,\rho$
  - Sensitivity to α
  - Potential from full amplitude analysis of 4π system to break ambiguities
  - Potential gain from improved neutral pion reconstruction
- Knowledge of angular acceptance crucial for these decays – implies very large MC samples and precise knowledge of data/MC corrections

Null tests

- Decays $B^- \to K^-K^-\pi^+$ and $B^- \to \pi^-\pi^-K^+$ are highly suppressed in SM, BFs $O(10^{-11})$ and $O(10^{-14})$
- Many New Physics models enhance these up to 10^{-9} (or even higher in a few cases)
- Run 1 analysis should set limits of ~4-6 x 10^{-8} (about to be unblinded)
- Extrapolation to 300fb^{-1} indicates sensitivity down to 1-2 x 10^{-9}, i.e. where the NP models should be
- Similar tests possible with modes like $B \to K^* K^*$ where the K*'s have the same strangeness

TTFU Physics Case: BnoC Input

Tom and Eduardo
on behalf of BnoC WG

B_c and b-baryons

- Both of these are areas where LHCb has essentially a monopoly – no competition from Belle 2 at least
- B_c decays to charmless final states (can potentially study 3h, $K_S h$ and $h\pi^0$) proceed via annihilation topologies
  - Both BF and A_{CP} sensitive to contributions of New Physics amplitudes
  - Perhaps have O(100) signal from 300fb^{-1}
- Could also consider using B_c tagging of B_s/B_d
- CPV in b-baryons is currently being searched for but hopefully well established by time of this future upgrade
  - Can it be interpreted in terms of CKM vs NP?
  - Hopefully with modes like $\Xi_b^- \to p^+h^-h^-$
  - Need input from theory

Detector improvements

- The programme in BnoC would definitely benefit from an improved ECAL
  - Better discrimination between π^0 and photons
  - Improved energy resolution
- At this stage it is hard to be quantitative because we have rather few studies of how these behave now – a TODO list item
- Improvement in the K_S reconstruction efficiency would also be very welcome – tracker in the magnet?

The charm TTFU task force

- Benoit Viaud
- Denis Derkach
- Stephen Ogilvy
- Matthew Charles
- Jolanta Brodzicka
- Any member of Charm WG.

https://twiki.cern.ch/twiki/bin/view/LHCbPhysics/CharmTTFU

What's an interesting mode at a 300 fb^{-1} FU ?

+ Luminosity + $\sqrt{(s)}$ = 14 TeV: Charm hadrons yield $\times$ 200 wrt Run I

+ Another factor (>3): trigger improvements already seen between Run I & II.
(Study by Mike Sokoloff [1])

==> Focused on observables which can take full advantage of a huge statistics.

- High sensitivity to NP
- Presently limited by σ_{stat}
- Not expected to be limited by σ_{syst}(ex: present can be reduced with more stat or new methods possible with more stat).
- Clean observables: not limited by σ_{th}

==> Natural priority to mixing, CPV in mixing, and rare decays

+ We don't know what the FU's detector will be.

- Assumed the same efficiency and reconstruction performance as the present detector.
- In particular, included modes with pi0 and e^- : benchmark for the design of the new detector.
- One big challenge: understand acceptance effects precisely enough (crucial at high stat)

The charm TTFU task force

- Benoit Viaud
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- Matthew Charles
- Jolanta Brodzicka
- Any member of Charm WG.

+ List A https://twiki.cern.ch/twiki/bin/view/LHCbPhysics/CharmTTFU

+ $D^0 \to KK/\pi\pi$ + $D^0 \to K\pi\pi^0$ + $D^0 \to K_s h^+ h^-$ + $D^0 \to K\pi\pi\pi$	Mixing + CPV in mixing.
+ $D^+ \to \pi\pi K^+$	CPV in decays
+ $D^0 \to \pi^+\pi^-\mu^+\mu^-$ + $D^0 \to \mu^+\mu^-$ + $D^+ \to \pi^+ e^+ e^-$ + $D^0 \to e^{+/-}\mu^{-/+}$ + $D^0 \to K^- \pi^- \mu^+ \mu^+$	Rare
+ $\Omega_{ccc}^{++} \to \Omega_{cc}^{+} \pi^+ / \Xi_{cc}^{++} K^- \pi^+$ + $\Lambda_c \to p\, \pi^- K^+$	Baryon physics

+ List B (other very interesting modes, included if List A not too long yet)

+ $D^0 \to K\pi$	Mixing + CPV in mixing.
+ $D^0 \to KK\pi\pi,\ \pi\pi\pi\pi$	CPV in decays
+ $D^+ \to \pi^- \mu^+ \mu^+$ + $\Lambda_c^+ \to (p/\mu)\mu\mu$	Rare
+ doubly-charmed Baryons ($\Xi_{cc}^{+/++}$) + Search for dibaryons	Baryons

PHYSICS CASE FOR THE FUTURE UPGRADE FROM B2OC

SNEHA & CONOR

Numerical estimates for 300 fb^{-1} are based on assumptions described in this talk

OBVIOUS CHOICE: GAMMA

- B → DK (and friends) γ
  - "Golden modes" : ADS/GLW, GGSZ, and DsK can all reach degree precision
  - Other B modes (e.g B→ DK*) with many D modes combined will also be capable of doing this.
  - Combination can be sub-degree
  - Ability to cross check at the degree level will be important
  - Expect current indirect uncertainties (+1, -3) to fall as the lattice becomes better – so the improved direct precision is desired.
  - DsK → 2βs or γ ?
  - BES-III inputs, using more data than they currently have would be the ideal scenario, but all is not lost if no results materialise.
  - Don't envisage other systematic showstoppers.

Data	σ_γ (stat)
Run 1	6
Run II	3
Upgrade	0.9
Future up.	0.3

27/08/2015 Sneha Malde 2

$B_{(S)} \rightarrow D_{(S)} D_{(S)}$ FOR $\varnothing_S$ AND $BETA_{EFF}$

- Bs -> DsDs
  - Can access phi_s. Has a different penguin pollution to J/psiphi → Important to measure phi_s in this mode too.
  - The uncertainty on phi_s will become comparable to penguin pollution limits set by Jung & Schact (PRD, 91, 034027)
  - With DD can access β_{eff}
  - Provides data for theorists to improve calculations and predictions

Data	σ_phi_s(stat)
Run 1	0.17
Run II	0.085
Upgrade	0.024
Future up.	0.01

Data	σ_beta_eff(stat)
Run 1	0.26
Run II	0.13
Upgrade	0.037
Future up.	0.015

PHYSICS CASE FOR THE FUTURE UPGRADE FROM B2OC

SNEHA & CONOR

Numerical estimates for 300 fb^{-1} are based on assumptions described in this talk

NEW VENTURES

- Beta from B->Dpipi or Dpi0
  - From Dpipi the prediction is measurement of tree level β to precision of 1-2 degrees
- CP violation in Bc decays
  - Yields estimates ~150 in GLW modes for gamma (but interference could be v large in the Bc decays)
  - CP violation in Bc decays should go beyond gamma

SPECTROSCOPY

- B2OC have produced results on D spectroscopy through B dalitz plot analyses, and we've been observing new B baryons
- No single channel to "put forward" here but we can expect:
  - To observe more b baryons. Double b baryons and maybe even bbb?. The mass measurement of the bb baryons are wanted by the HQET community
  - Unlikely to have competition from other experiments
  - To continue the program of spectroscopy through the DP study of B decays. Potential observation of more tetra and penta quarks

Philip Ilten, Wouter Hulsbergen

Assumptions

- numbers modified from LHCb-TALK-2015-113
- physics objects with $p_\mathrm{T} > 20$ GeV and $2 < \eta < 5$
  - leptons (ℓ) are electrons and muons
  - jets are anti-k_T with $R = 0.5$
  - Z-boson mass within $60 < m < 120$ GeV
- theory predictions are performed with MCFM at NLO
  - fiducial definitions above used
  - these are estimates!
- detector performance similar to Run 1
  - lepton and jet reconstruction $\approx 95\%$
  - b-jet tagging $\approx 65\%$, c-jet tagging $\approx 25\%$
  - photon reconstruction $\approx 50\%$
  - hadronic τ reconstruction $\approx 60\%$, branching $\approx 65\%$
  - 100% trigger efficiency
- 300 fb^{-1} of integrated luminosity

Summary

- double differential precision measurements with W and Z
  - very low mass Drell-Yan, comprehensive data-set for PDFs
  - reduce ATLAS and CMS PDF uncertainty on Higgs couplings
- forward di-boson cross-section, particularly $WW[e, \mu]$
- precision differential $W + j, b, c$ measurements
- enough top events for interesting forward measurements
  - direct V_{ts}?
  - asymmetry
  - FCNC, $t \to Z + c$
- forward observation of the Higgs within reach
  - measure low p_{T} Higgs spectra?
  - diffractive Higgs production?
- vector boson CEP?
- exotica possibilities difficult to quantify
  - di-jet measurements, including emerging jets
  - revisit LEP limits for various couplings?

RD channels for TTFU

M-O. Bettler & T. Blake

What detector changes could impact RD analyses?

Mass resolution Important for rejecting peaking/partially reconstructed backgrounds, e.g. direct impact on $B^0 \to \mu\mu$.

Length of tracking volume Directly related to searches for long lived particles, e.g Majorana neutrino/Inflaton/etc and rare kaon decays.

Particle ID Changes to charged hadron PID performance can have important consequences *e.g.* $B \to K^* \mu\mu$ for which the peaking backgrounds from $B_s \to \phi\mu\mu$ and $\Lambda_b \to pK\mu\mu$ represent 10% of the signal in CMS.

Better calorimeter Electronic final states would benefit alot from an improved calorimeter (Bremsstrahlung correction and PID), radiative channel could then use converted photon more efficiently.

Higher instantaneous luminosity The name of the WG is rare decays, statistics is a limitation for the majority. A number of channel are insensitive to the degradation of the detector performance at high luminosity, the higher the better for them.

We are aware that those are incompatible changes.

Class of channels that are less sensitive to the detector choice

Mainly characterised by the fact that they are background-free.

- Majorana neutrinos searches,
- Dark Boson searches (can be improved by increased decay volume)
- $B \to 4\mu$ search (sensitive to C_9)

With improved calorimeter

Electrons final states, and radiative decays with converted photons.

- Whole list of $B \to Xe\mu$, $B \to ee$
- radiative $B_s \to \phi\gamma$, $B \to K^*\gamma$, $B \to \gamma\gamma$
- Lepton Flavor Universality tests, all involving electron final states.

The old players

- $B_{(s)} \to \mu\mu$, BF, ratio, lifetime, possible tagged-lifetime.
- $B \to K^{*0}\mu\mu$ could suffer from degraded PID.

Newcomers

- Rare kaons decays. Full software trigger can unleash the reach. Increased decay volume is a factor.
- B_c rare decays.

RD channels for TTFU

M-O. Bettler & T. Blake

And not to be forgotten: LFV with $\tau \to \mu\mu\mu$

CKM physics

Concezio Bozzi

$|V_{ub}|$ [More details here and here]

- $\Lambda_b \rightarrow p\mu\nu$ and $B_s \rightarrow K\mu\nu$
  - systematically limited by detector and lattice
  - Use high stats to constrain backgrounds and validate predicted lattice shapes
- $B^+ \rightarrow \mu\mu\mu\nu$
  - Very rare (10^{-8}) but potentially good theoretical control
  - Possibly disentangle background from $B \rightarrow (\omega,\rho \rightarrow \mu\mu)\mu\nu$ with enough statistics
- $B_c \rightarrow D(*)\mu\nu X$
  - 30k candidates in 300fb^{-1}
  - ...but huge background from $B^+ \rightarrow D^0\mu\nu X$ with a DCS D^0 decay!
  - Need prediction on theoretical sensitivity – lattice + checks on experimental data

$|V_{cb}|$ [More details here]

- $\Lambda_c\mu\nu$: dominant uncertainty due to normalization mode and background subtraction. To improve: better vertex definition and studies of hadronic systems with neutrals
- We should also look at $B_c \rightarrow \eta_c\mu\nu$ and other B_c semileptonic decays

$H_b \rightarrow H_c \tau \nu$

Concezio Bozzi

- More details here
- Careful extrapolation of current results on $D^*\tau\nu$ (leptonic mode) with assumptions on reconstruction and trigger based on upgrade TDRs

$$R(D^*)_{50} = x.xxx \pm 0.0052(\text{stat}) \pm 0.0071(\text{syst}) \pm 0.0051(\tau\ \text{bg})$$

$$R(D^*)_{300} = x.xxx \pm 0.0021(\text{stat}) \pm 0.0055(\text{syst}) \pm 0.0051(\tau\ \text{bg})$$

- Systematically dominated. Must improve on background knowledge and PID
- Lots of other channels and modes to be investigated.
- Uniqueness of 3-prong decays to access decay kinematics and fit distributions
  - Improving vertexing and isolation is vital

SL decays with 300fb^{-1}

a_{sl}^s, a_{sl}^d

Concezio Bozzi

Standard Model predictions

Lenz and Nierste, http://arxiv.org/abs/1102.4274

$a_{sl}^d = (-4.1 \pm 0.6) \times 10^{-4}$	$a_{sl}^s = (1.9 \pm 0.3) \times 10^{-5}$

$\delta_{theory} \sim \delta_{exp}/50$ $\delta_{theory} \sim \delta_{exp}/2000$

Naive $N^{1/2}$ scaling of current LHCb measurements assuming

- Total errors on are 100% statistical
- 2x cross section and same efficiency

$\delta_{LHCb} \sim 2 \times 10^{-4}$	$\delta_{LHCb} \sim 2 \times 10^{-4}$

$\delta_{theory} \sim \delta_{exp}/4$ $\delta_{theory} \sim \delta_{exp}/200$

Next steps

- Need to converge to a reasonable small list of topics to be followed up in more detail
  - no more than O(10) decays/topics
- Provide brief write-ups on each
  - These should be then collected in an internal LHCb note, to be scrutinised preparing for further work
- Organise a workshop, preferably before start of 2016 run, to catalyse thinking

Additional material

Mixing and CPV in mixing: List A

+ $D^0 \to KK/\pi\pi$

Flagships of the current physics program. Can be used in the context of the 300 fb^{-1} FU to improve A_Γ and y_{CP} . Also useful to update DA_{CP}. 30M/12M events per fb-1.

+ $D^0 \to K\pi\pi^0$

Channel that allows to exploit the CPV/mixing effects to a new level.
π0: requires an excellent calorimeter.
Expected yield are similar to the ones above for RS decays and ~100 times lower for WS.

+ $D^0 \to K_s hh$

Direct access to x and y.
Additional complication comes from Ks in the decay chain.
The effects of Kaon CPV and regeneration should be taken into account.

+ $D^0 \to K\pi\pi\pi$

With the rise in statistics this channel could become a very powerful one. Recent analyses of this mode at LHCb [2,3,4] suggest the time acceptance and the amplitude structure could be determined precisely enough. Large BF's also allow to use secondary D* to further reduce acceptance effects.

The RS decays will reach a very statistics and help controlling this.

Again a direct access to x and y. Expect 10M per fb^{-1}

Mixing and CPV in mixing: List B

+ $D^0 \rightarrow K\pi$

Interesting for mixing, less for CPV. Performance at the FU can be inferred from other two-body modes.

CPV in decays: List A

+ $D^+ \rightarrow \pi\pi K^+$

CPV in decays is less clean theoretically. Ideally, should measure many modes.
Focus on suppressed modes (more sensitive to NP) and modes where is σ_{th} is minimal or can be constrained (ex: isospin relations).

If at the end of Run III our sensitivity to CPV in SCS decays reached the level expected in the SM, we can turn to DCS decays like $D^+ \rightarrow \pi\pi K^+$.
Bigi [5]: " in DCS charm decays, SM provices only one amplidude → no CPV"
Expect 2M events per fb^{-1}.

CPV in decays: List B

+ $D^0 \rightarrow KK\pi\pi$, $\pi\pi\pi\pi$

$D^0 \rightarrow \rho\rho$ can be used in isospin analyses.

Angular asymmetries are also powerful probes of NP.
The potential of the FU for this type of observable must be studied in detail.
Less sensitivity to detection asymmetries than in $D^+ \rightarrow h^+h^-h^+$ decays.

Rare decays

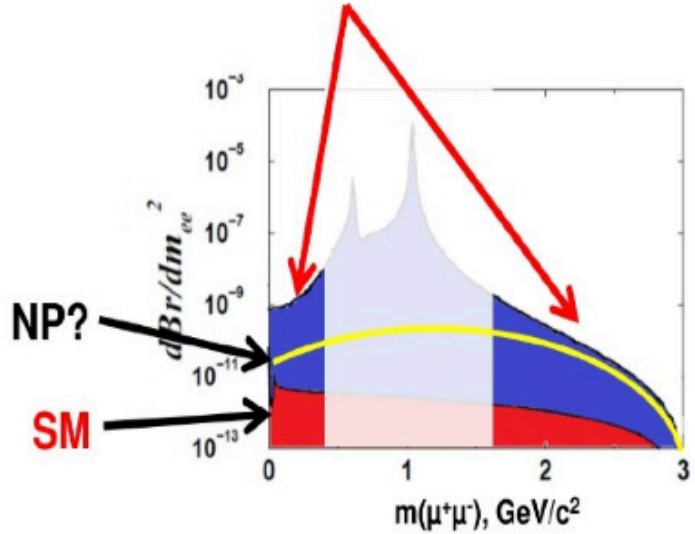
+ $D^0 \to \pi^+\pi^-\mu^+\mu^-$

Short Distance contributions to $D \to h(h)\mu^+\mu^-$ decays very suppressed in SM <=> sensitive to NP

Can be probed via using two approaches:

(1) BF outside the resonant regions in m(μμ), where Long Distance dominates

(2) Asymmetries (CP, A_FB, ...) anywhere in m(μμ)



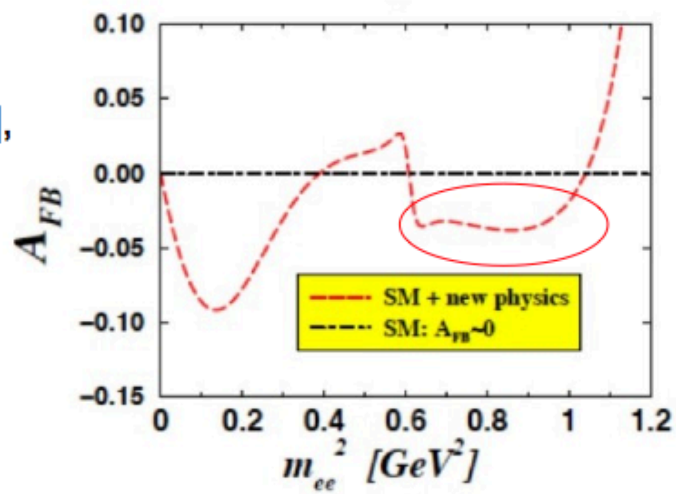
In most of the modes, approach (1) will reach its limits at the end of Run III: any signal could be due to resonance leakage.

Approach (2) seems more promising.

Ex: In $D^0 \to \rho^0\mu^+\mu^-$ s, $A_{FB} \sim 3\%$ in 800 <m(μμ)< 975 MeV/c^2 [6]

Based on yields observed in the 2011 $D^0 \to \pi^+\pi^-\mu^+\mu^-$ analysis [7],

$\sigma A_{FB} \lesssim 1\%$ possible with the 300 fb^{-1} FU.



+ $D^0 \to \mu^+\mu^-$

The mode that provides the most stringent constraints.

BF>10^{-10} would be a <u>clean</u> sign of NP.

Present limit: BF < 7.6×10^{-9} @ 95% CL with 1 fb^{-1}

300 fb^{-1} FU: BF < 3×10^{-10} @ 95% CL

Rare decays

+ $D^+ \to \pi^+ e^+ e^-$

Recent results in B decays give hope to see beyond the SM via Lepton Universality. Interesting to extend this to charm decays. Chose an experimentally favorable mode.

Never studied at LHCb, so nothing to extrapolate. Assuming the sensitivity to this mode is an order of magnitude worse than in dimuon modes (seems reasonable): BF < 10^{-8} at the 300 fb^{-1} FU.

+ $D^0 \to e^{+/-} \mu^{-/+}$

Very clean NP signal if measured.

Present Limit at LHCb (3 fb^{-1}): $B(D^0 \to e^{+/-} \mu^{-/+}) < 1.59 \times 10^{-8}$ @ 90% CL
At the 300 fb^{-1} FU : $B(D^0 \to e^{+/-} \mu^{-/+}) < 1 \times 10^{-9}$ @ 90% CL
(assumes a calorimeter maintaining today's performance in a harsh environment)

Note: Don't think Belle II or a super tau-charm factory could do better.

+ $D^0 \to K^- \pi^- \mu^+ \mu^+$

For some masses of the Majorana ν, D decays should be better than B decays.

Ex: [8] predicts $B(K^- \pi^- \mu^+ \mu^+)$ for various masses

m_N	Γ/Γ_{tot}
150	–
200	–
250	1.6×10^{-9}
300	1.3×10^{-9}
350	4.5×10^{-10}
400	5.0×10^{-9}
450	3.0×10^{-9}

It seems these BF's are in the reach of the FU.

In [9]

$$\mathcal{B}(D^0 \to K^- \pi^+ \mu^+ \mu^-) = (4.17 \pm 0.12\,(\text{stat}) \pm 0.40\,(\text{syst})) \times 10^{-6}.$$

~15000 L0muon TOS events in 2 fb^{-1}

Will have to adapt to include the finite lifetime of the Majorana neutrino in future analysis.

Charm Baryons: List A

+ Triple Charm production: Ω_{ccc}^{++}

Very interesting place to study HQET – entirely new regime to explore.
Predicted cross-sections are very low: a 300 fb^{-1} FU might be the first opportunity for these studies.

Can use thse decays modes:

- $\Omega_{ccc}^{++} \to \Xi_{cc}^{++} K^- \pi^+$ (Cabibbo Favored, easier to select in a "see of pions")
- $\Omega_{ccc}^{++} \to \Omega_{cc}^{+} \pi^+$

Both modes require a large sample of doubly-charmed baryons.
Finding Ξ_{cc}^{++} and Ξ_{cc}^{+} first would help to determine the best mode to look for Ω_{cc}^{+}
Feasibility studies and guessed on BF's necessary before predicting anything.

+ CPV in DCS decays: $\Lambda_c \to p\, \pi^- K^+$

Bigi [4] : in DCS charm decays, SM provides only one amplitude → no CPV.
This suppression also gives more sensitivity to NP. Low branching fraction: natural target for this FU.

Charm Baryons: List B

+ Doubly-charmed Baryons ($\Xi_{cc}^{+/++}$)

Production and spectroscopy

+ Search for dibaryons

Classical example of di-baryon [11]: H-dibaryon (udsuds) searched for as (Λ,pπ) or (Λ,Λ) [12]
Ex: of such physics in the charm sector: (L_c,L), (L_c,p), (D_s^-, p)

Rare decays

+ $D^+ \to \pi^+ e^+ e^-$

Recent results in B decays give hope to see beyond the SM via Lepton Universality. Interesting to extend this to charm decays. Chose an experimentally favorable mode.

Never studied at LHCb, so nothing to extrapolate. Assuming the sensitivity to this mode is an order of magnitude worse than in dimuon modes (seems reasonable): BF < 10^{-8} at the 300 fb^{-1} FU.

+ $D^0 \to e^{+/-} \mu^{-/+}$

Very clean NP signal if measured.

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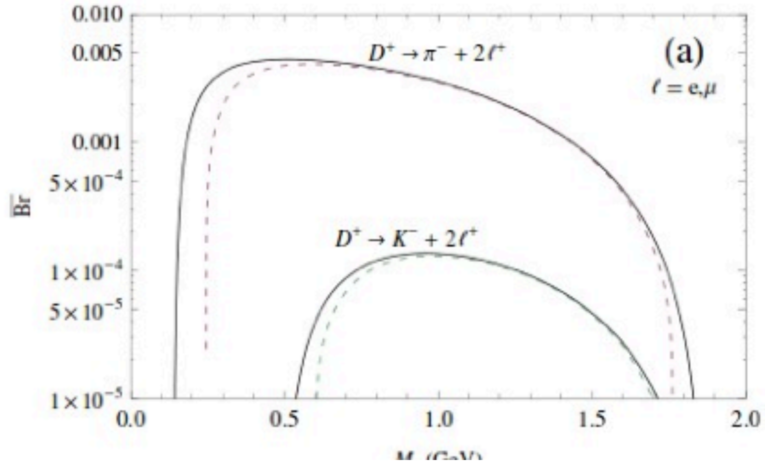
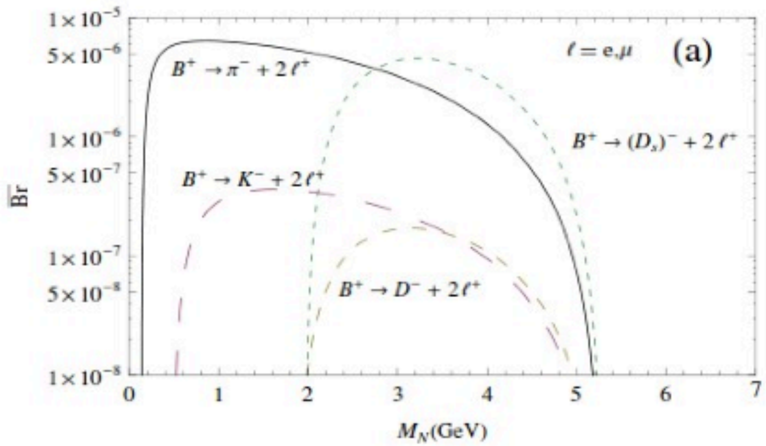
At the 300 fb^{-1} FU : $B(D^0 \to e^{+/-} \mu^{-/+}) < 1 \times 10^{-9}$ @ 90% CL
(assumes a calorimeter maintaining today's performance in a harsh environment)

Note: Don't think Belle II or a super tau-charm factory could do better.

+ $D^+ \to \pi^- \mu^+ \mu^+$

For some masses of the Majorana ν, D decays should be better than B decays. Ex: see [10].





Rare decays

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+ $D^+ \to \pi^- \mu^+ \mu^+$

For some masses of the Majorana ν, D decays should be better than B decays. Ex: [10]

decay	$\mathcal{C}$	m_N at maximum	$Br <$
$D^+ \to \pi^- \ell^+ \ell^+$	$4.5 \cdot 10^{-3}$	0.51 GeV	$4.5 \cdot 10^{-10}$
$B^+ \to \pi^- \ell^+ \ell^+$	$6.3 \cdot 10^{-6}$	0.86 GeV	$6.3 \cdot 10^{-13}$

Extrapolating from 2011 results: $B < 2.5 \times 10^{-8}$ @ 95% CL → $B < 1 \times 10^{-9}$ @ 95%

Will have to adapt to include the finite lifetime of the Majorana neutrino in future analysis.

$Z[\ell\ell]$ and $W[\ell, \tau]$

- expected $Z[\ell\ell]$ cross-section 4.7×10^5 fb
  - $\rightarrow 1.2 \times 10^8$ events
- expected $W[\ell]$ cross-section 7.9×10^6 fb
  - $\rightarrow 8.6 \times 10^8$ events
- expected $W[\tau]$ cross-section 4.0×10^6 fb
  - $\rightarrow 3.2 \times 10^6$ hadronic τ events

WW, WZ, ZZ, $W\gamma$, and $Z\gamma$ Production

- expected $WW[\ell,\ell]$ cross-section 300 fb
  - $\rightarrow 4.0 \times 10^4$ events ($[e,\mu]$ final state)
  - clean signature, precision measurement
  - backgrounds primary systematic uncertainty ($Z \rightarrow \tau\tau[e,\mu]$)
- expected $WZ[\ell,\ell,\ell]$ cross-section 16 fb
  - $\rightarrow$ 4000 events
- expected $ZZ[\ell,\ell,\ell,\ell]$ cross-section 3.1 fb
  - $\rightarrow$ 760 events

- $V\gamma$ measurements difficult with current detector (ECAL response)
  - current studies from Zurich show feasibility
  - can use converted photons
- expected $W\gamma[\ell,\gamma]$ cross-section 3700 fb
  - $\rightarrow 5.2 \times 10^5$ events
- expected $Z\gamma[\ell,\ell,\gamma]$ cross-section 780 fb
  - $\rightarrow 1.1 \times 10^5$ events

$W + j, b, c[\ell]$

- expected $W + j[\ell, j]$ cross-section 9.4×10^5 fb
  - $\rightarrow 2.6 \times 10^8$ events
- expected $W + c[\ell, c]$ cross-section 6.9×10^4 fb
  - $\rightarrow 4.6 \times 10^6$ events
- expected $W + b[\ell, b]$ cross-section 7300 fb
  - $\rightarrow 1.2 \times 10^6$ events

Top Production

- lepton and b-jet final state
  - expected $t\bar{t}[\ell, b]$ 2600 fb
    - 5.0×10^5 events
  - expected $t[\ell, b]$ (t-channel) 1800 fb
    - 3.0×10^5 events
  - expected $t[\ell, b]$ (s-channel) 210 fb
    - 3.6×10^4 events
  - expected $Wt[\ell, b]$ 60 fb
    - 1100 events

- expected $Wt[\ell, \ell, b]$ 20 fb
  - 3200 events
- expected $t\bar{t}[\ell, \ell, b, b]$ 317 fb
  - 3.2×10^4 events

V_{ts}

- best indirect (single) result from precision $B_s^0 - \bar{B}_s^0$ measurement by LHCb, New J. Phys. **15** (2013) 053021
  - $|V_{ts}| = (40.0 \pm 2.7) \times 10^{-3}$
- no tree level measurements (yet)
- look for s-channel production with lepton and 2 b-jet final state
  - requires s-jet tagging with excellent b-jet rejection
  - needs further investigation
- expected $t[\ell, b, b]$ (s-channel) 150 fb
  - assume 10% s-tag efficiency, 0.1% fake rate
  - 100 s-tagged signal, 20 mis-tagged b-jet events
  - ignoring other backgrounds ...

Higgs Production

- four-lepton modes still largely out of reach

- expected $H[b, b, j]$ (VBF) cross-section 70 fb
  - $\rightarrow$ 6600 events
- expected $H[\tau, \tau, j]$ (VBF) cross-section 7.9 fb
  - $\rightarrow$ 300 events
- expected $H[c, c, j]$ (VBF) cross-section 3.6 fb
  - $\rightarrow$ 54 events
- expected $H + W[b, b, \ell]$ cross-section 12 fb
  - $\rightarrow$ 1360 events
- expected $H + W[\tau, \tau, \ell]$ cross-section 1.4 fb
  - $\rightarrow$ 60 events

a_{sl}^{s}, a_{sl}^{d}

- The name of the game is to keep systematics at the 10^{-4} level
  - Detection asymmetries: control samples + fast MC
  - B+ background: fit for it