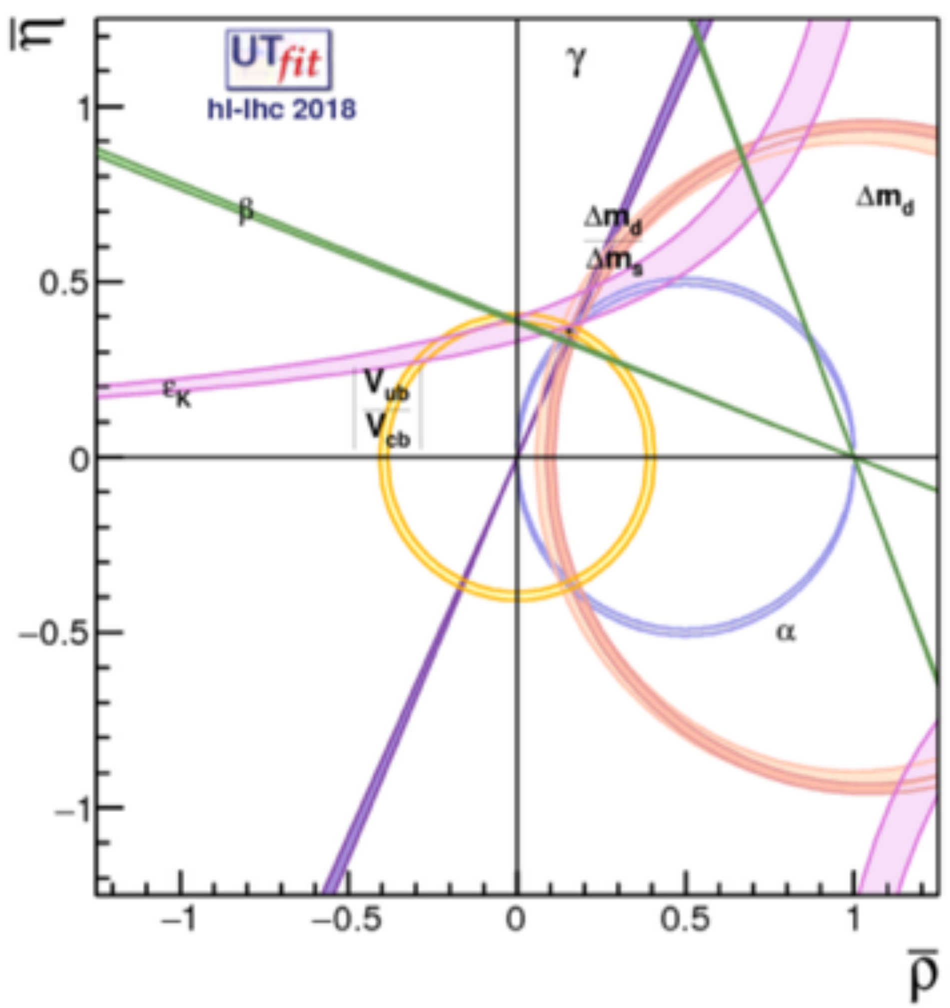
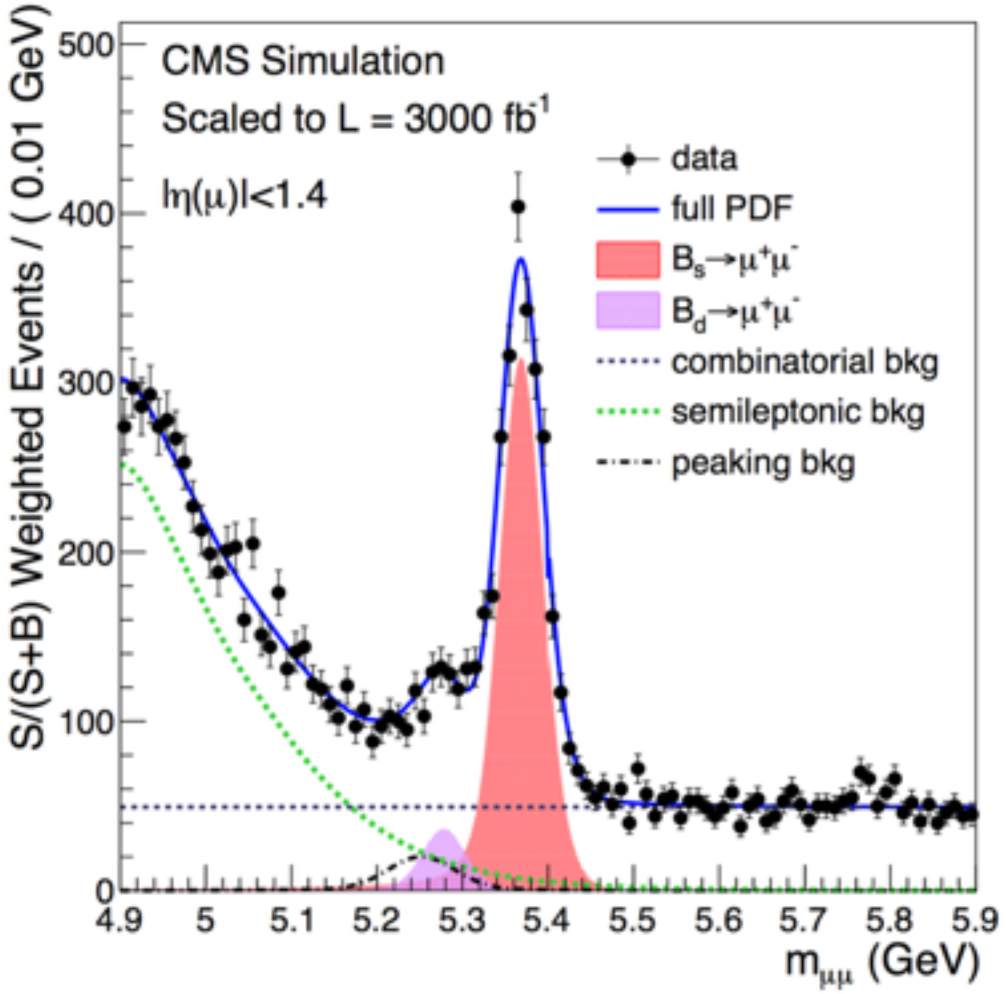
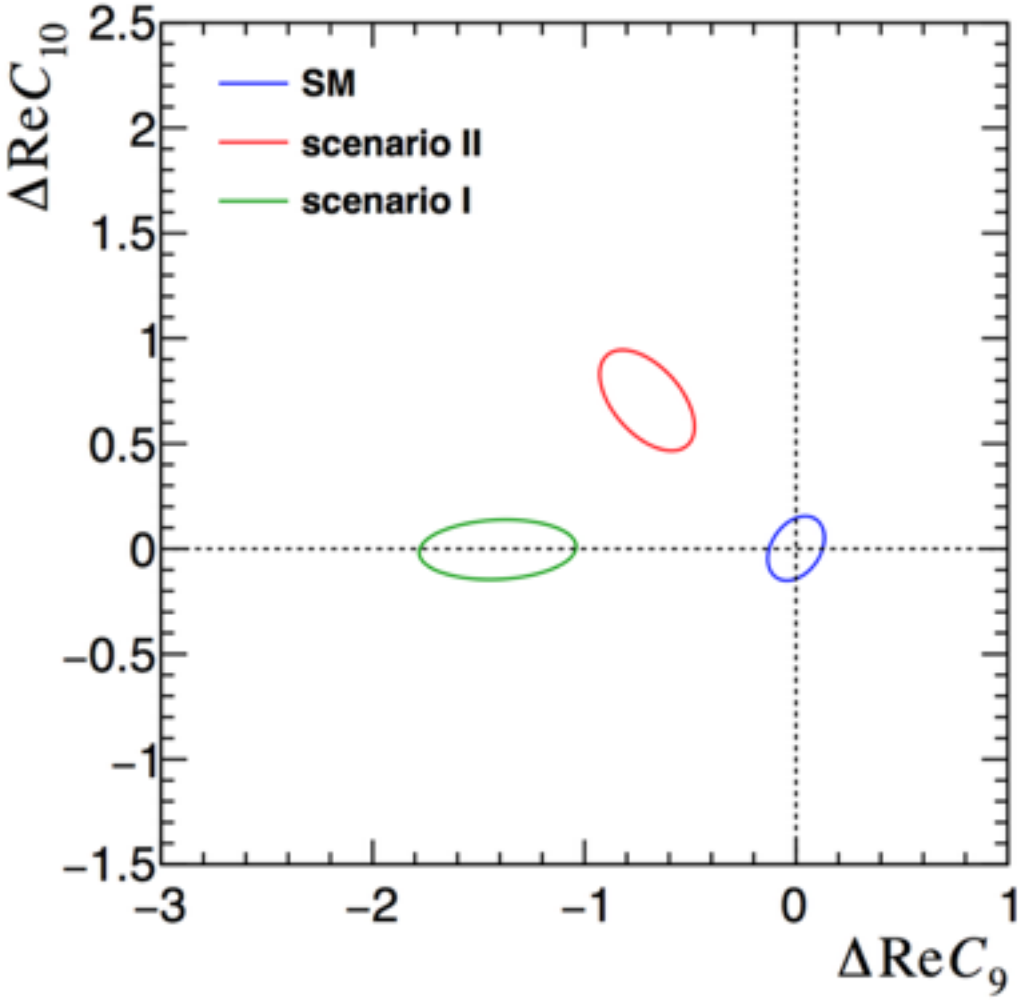
WG4 (Flavour) Summary



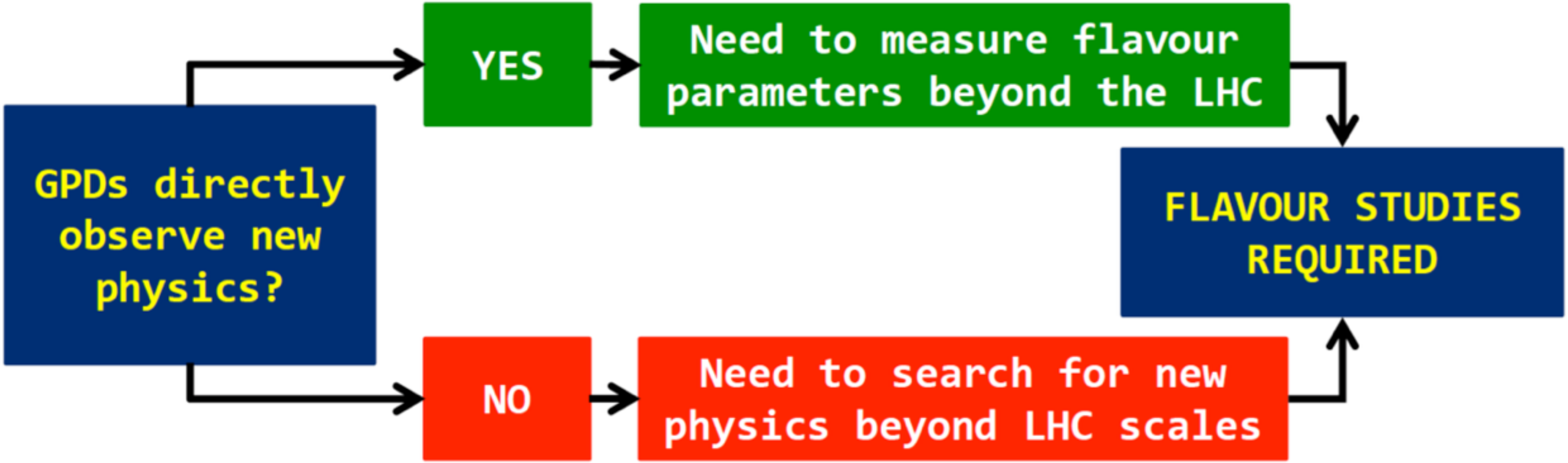




Vladimir V. Gligorov, CNRS/LPNHE
WG conveners : VVG, Alex Cerri, Sandra Malvezzi, Jure Zupan, Jorge Camalich

HL-LHC Workshop, CERN, 20.06.2018

Why flavour physics?



I first used this slide around 9 years ago, wasn't original then and is still relevant now

The pillars of flavour physics

WG structure & business

Twiki : https://twiki.cern.ch/twiki/bin/view/LHCPhysics/HLHEWG4

Productive joint sessions with both BSM and SM WGs, allow links to HE-LHC studies — most WG activity on HL-LHC side.

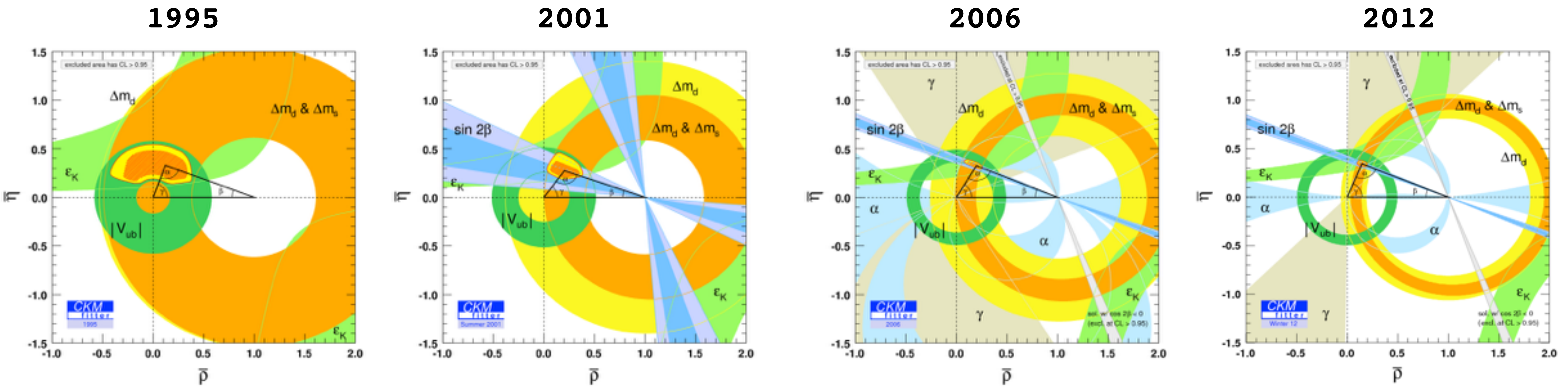
Global reminder of lumi assumptions for HL-LHC : 3000fb^{-1} for ATLAS/CMS, 300 fb^{-1} for LHCb Upgrade II.

WG report outline in place & people have been tasked with filling the sections, end of July as a deadline for the 0^{th} drafts.

A big thank you to all our speakers this week, my co-conveners, and apologies to everyone whose material was not used!

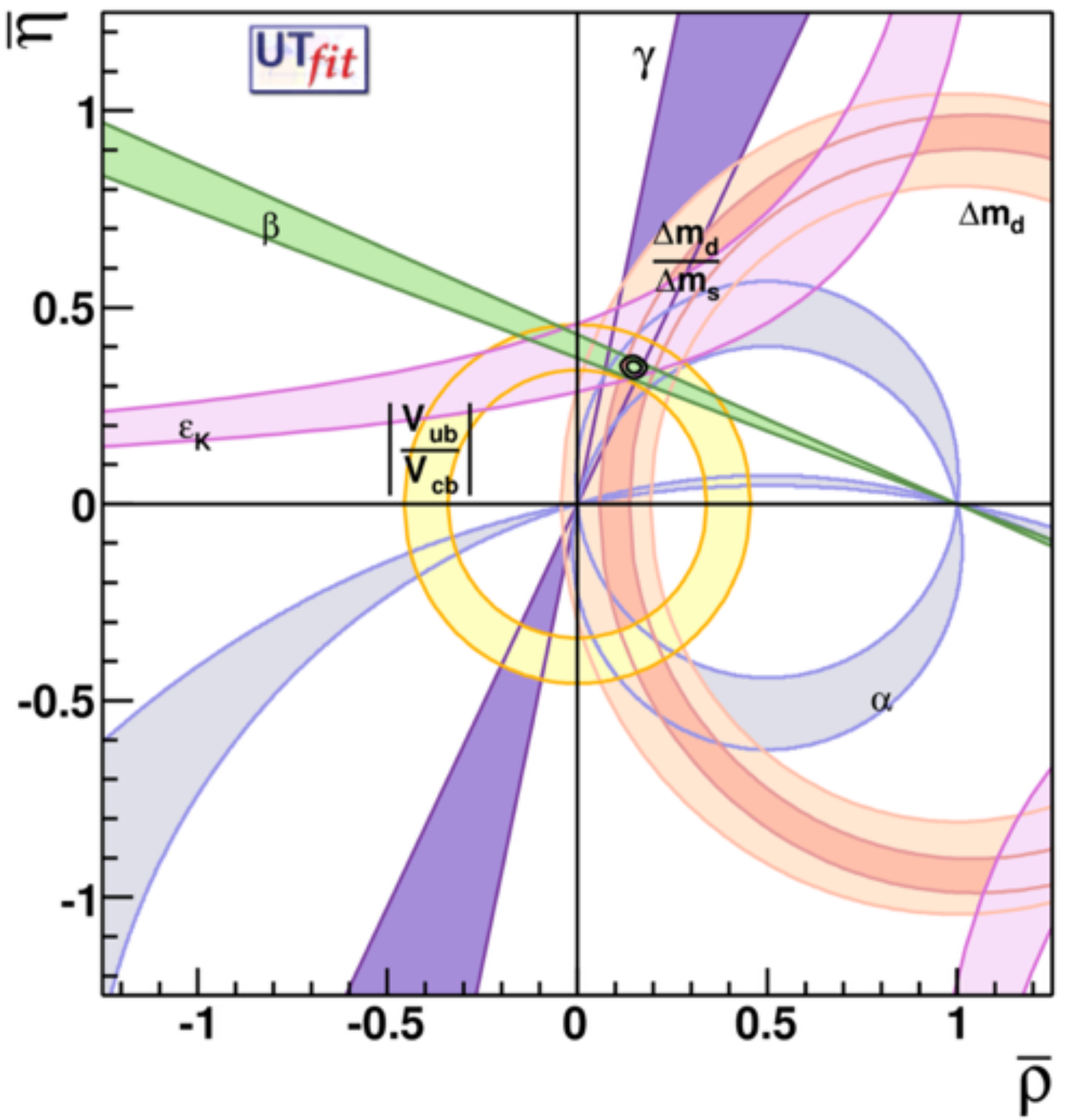
CKM metrology

The endurance of CKM metrology



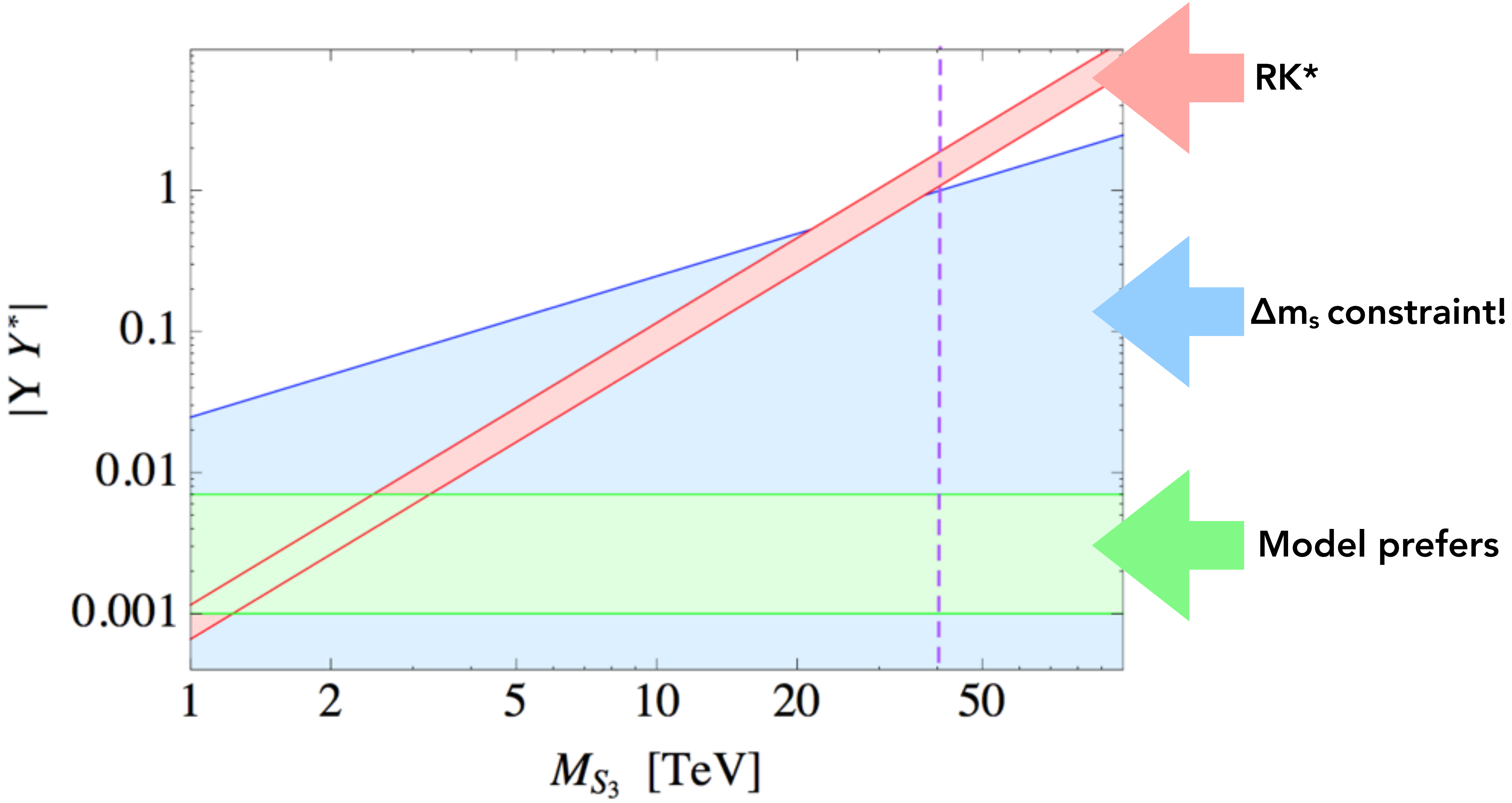
Test consistency of SM picture of quark mixing, breakdown in consistency indicates NP

CKM metrology today



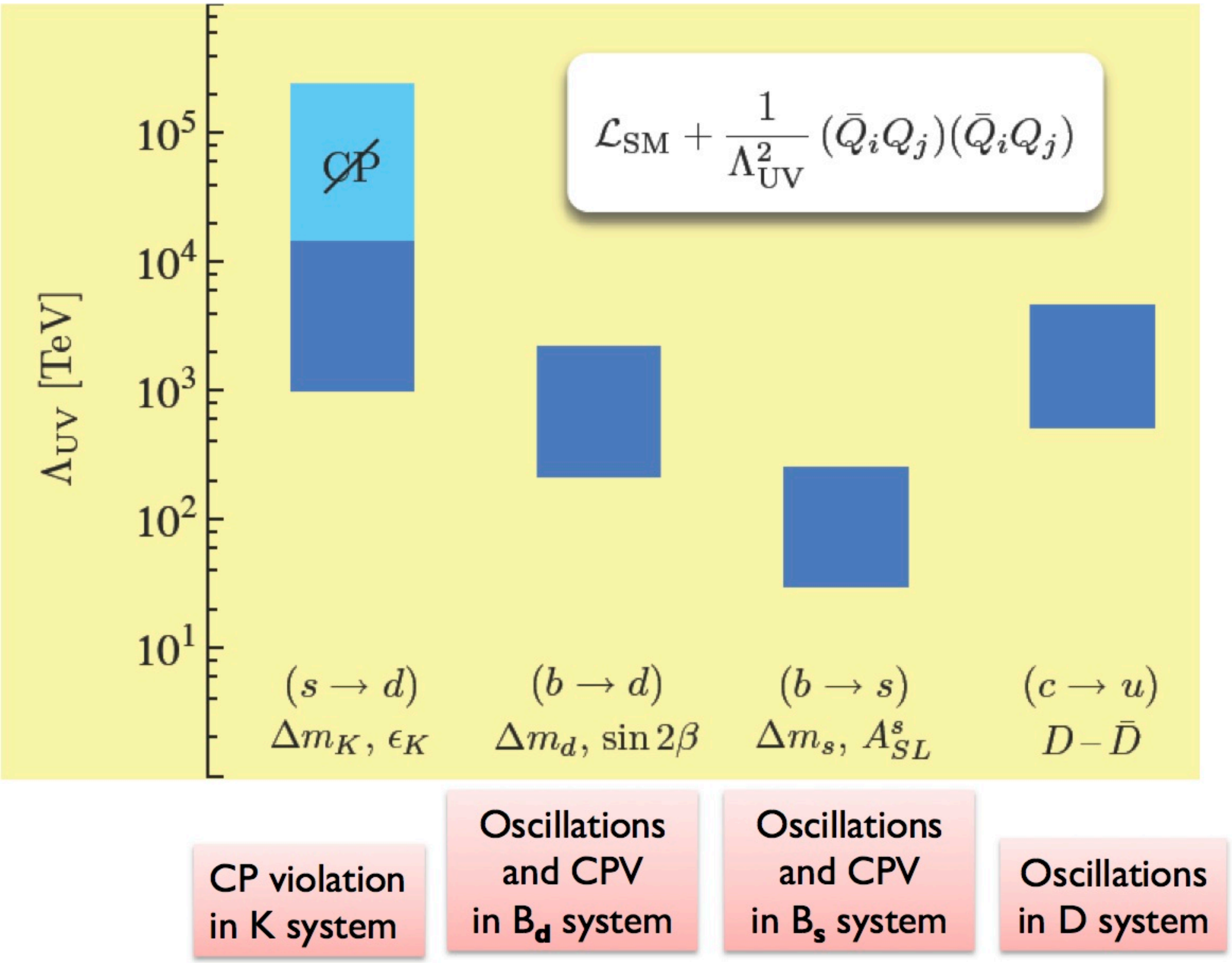
Entering the precision regime, SM picture solid but still room for O(10%) NP effects!

CKM metrology gives hard constraints



An example from Hiller & Nišandžić (arxiv 1704.05444) but applies generally

CKM metrology gives hard constraints



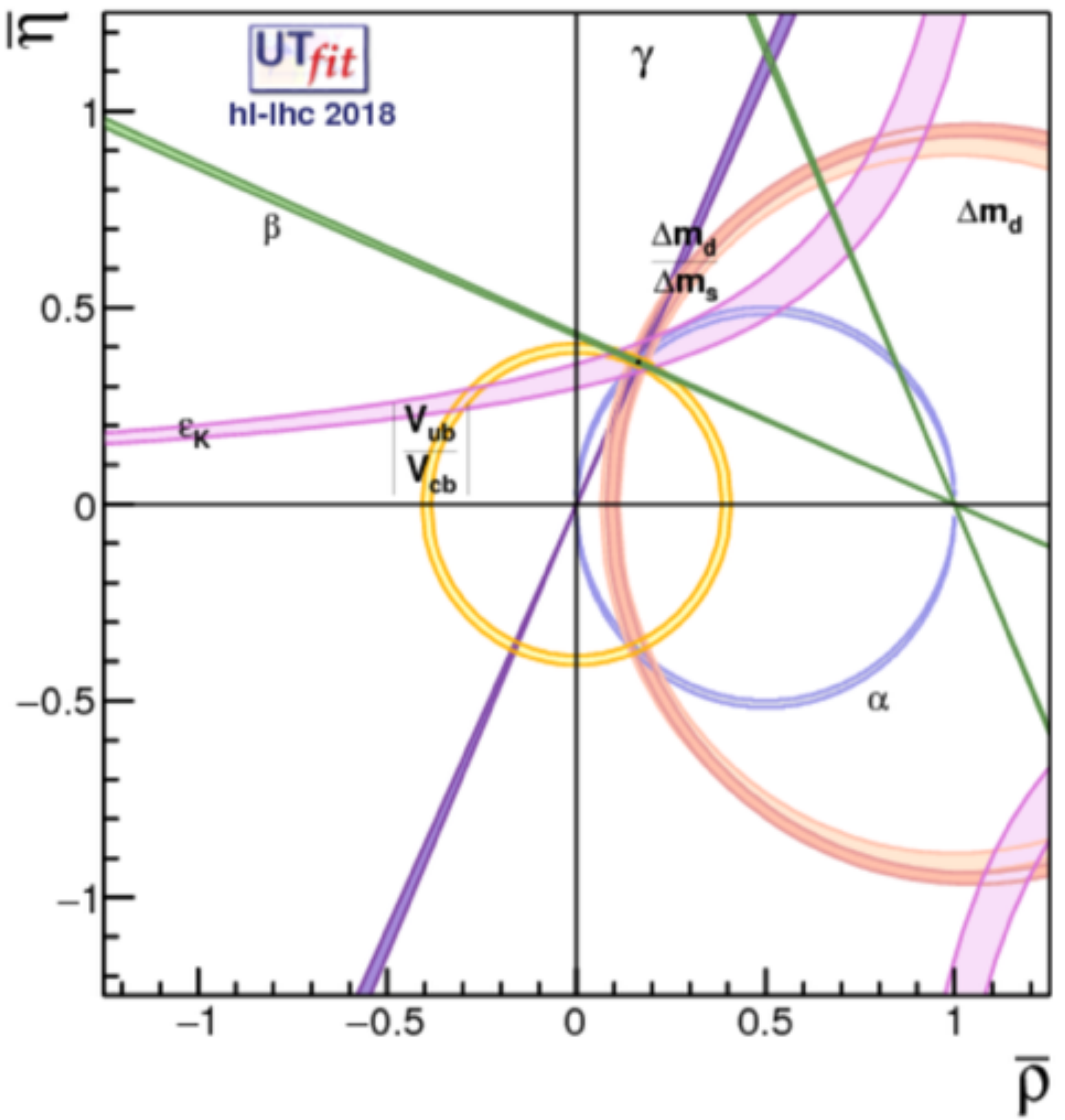
(Fig. Neubert, EPS-HEP'11

Isidori, Nir, Perez, Ann. Rev. Nucl. Part. Sci. 60 (2010) 355 [arXiv:1002.0900],
Isidori, arXiv:1302.0661

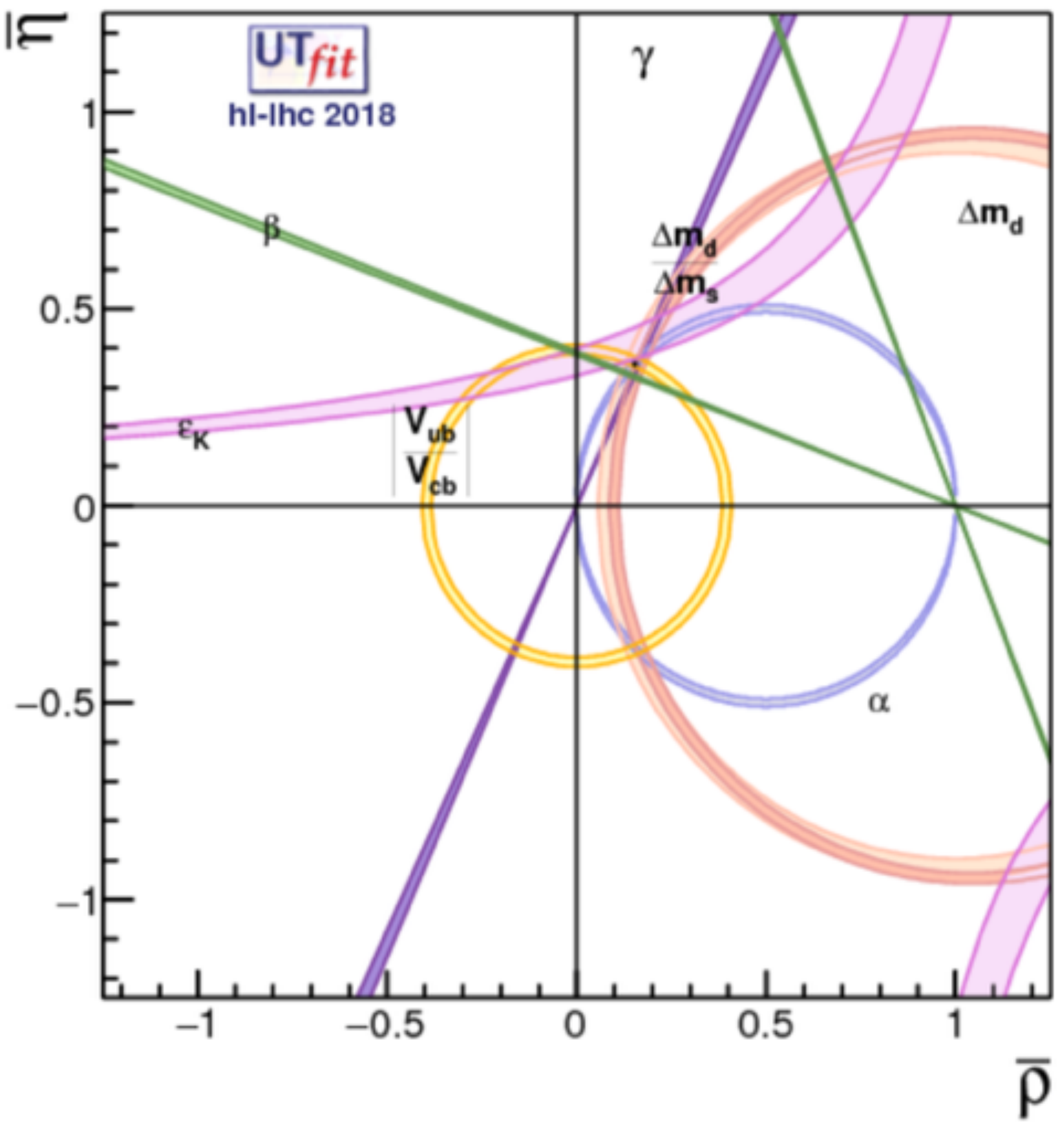
A more general (and older) way of seeing the same thing

CKM metrology with HL-LHC

SM desert

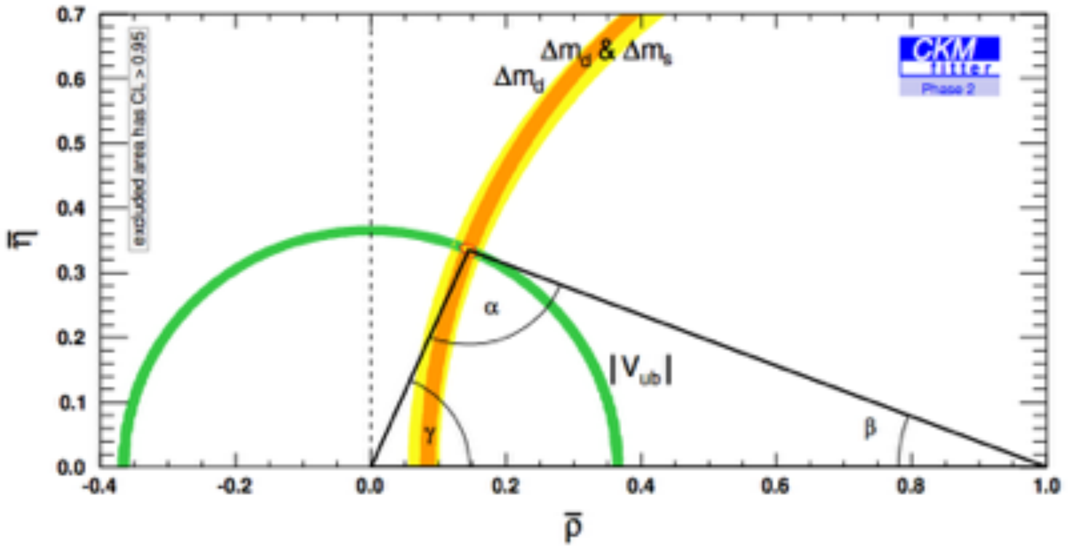


NP dream

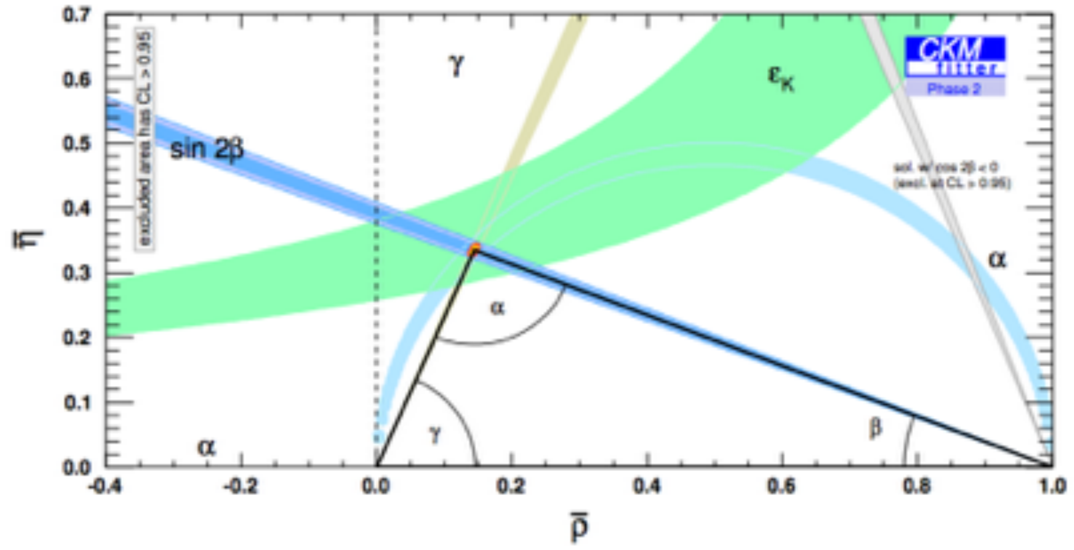


Understanding the flavour structure of quark mixing is critical whether NP is found or not

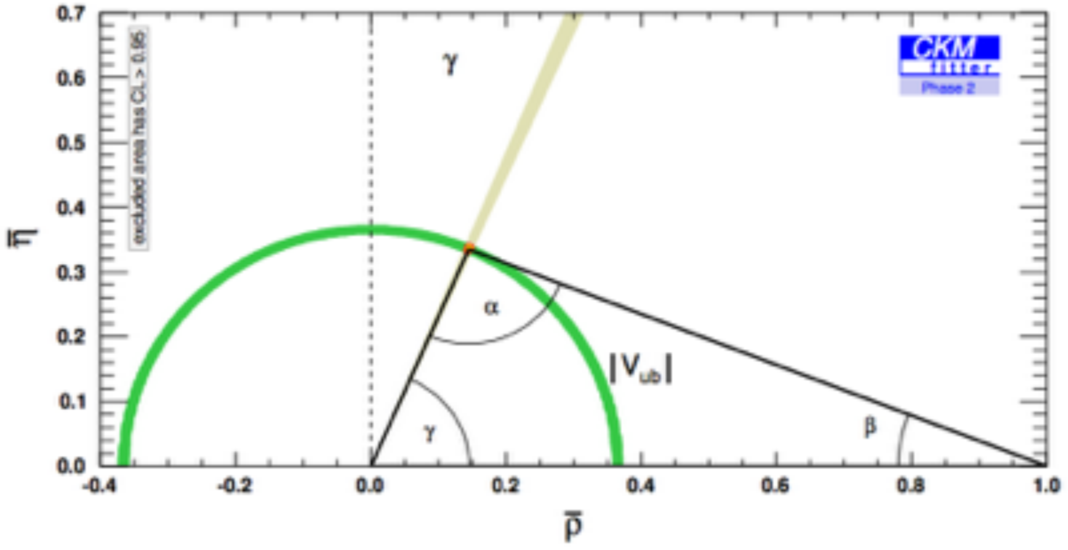
CKM metrology with HL–LHC



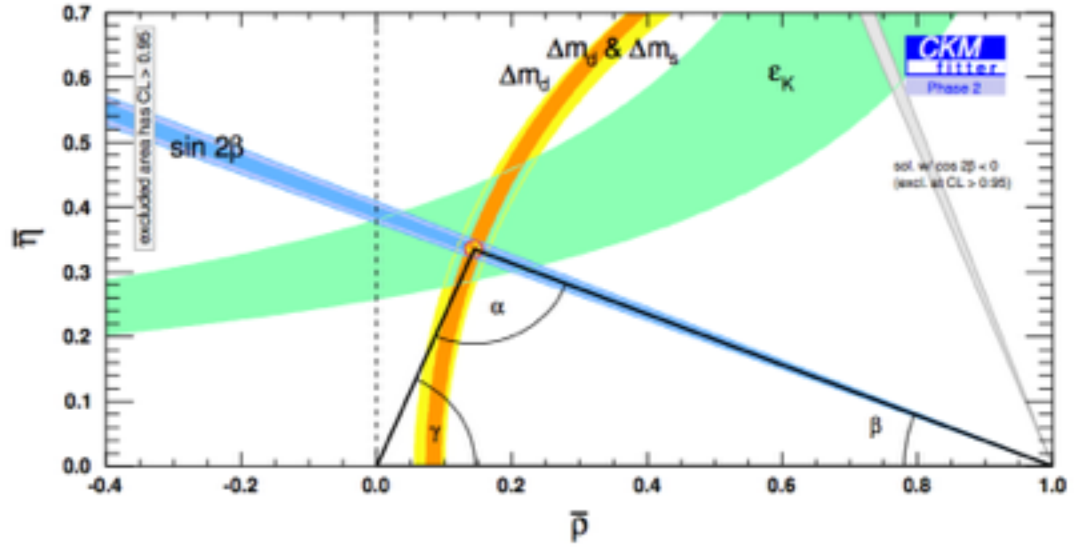
CP-allowed only



CP-violating only



Tree only



Loop only

With HL-LHC statistics can make precision determinations of UT apex with subsets of observables => powerful test of CKM consistency and check against systematic effects!

Interpreting at tree level

Theoretical issues

QUITE A FEW!

In the sub-percent era, many solid approximations used so far to compute hadronic amplitudes can't be relied on anymore (e.g. isospin symmetry, no QED corrections, no subleading amplitudes, no higher-dimensional operators, etc.)

Good news: the tree-level determination of γ from $B \to DK$ (GLW, ADS, GGSZ) safely extrapolates to the high precision. D mixing is manageble and EW corrections are still negligible

Brod, Zupan, arXiv:1308.5663

CKM angle gamma still solid "forever", other tree-level observables require more work!

Interpreting at loop level

Loop-level constraints: th. prospects

→ Δm_d and Δm_s: decay constants and B parameters @1%
call for QED corrections

→ ε_K: QED corrections, long-distance contributions, RBC-UKQCD
dimension-8 operators need to be controlled MC et al., in progress

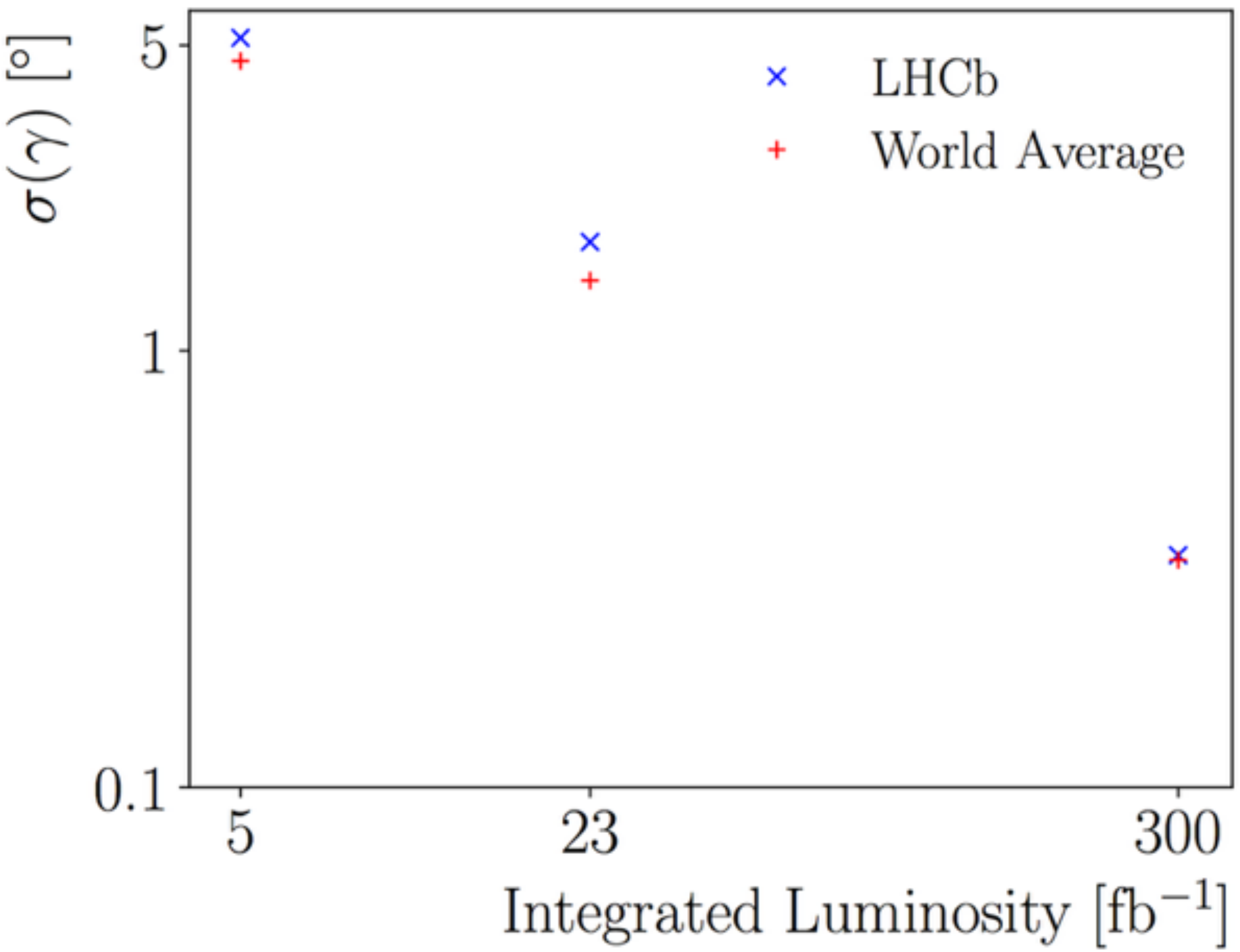
→ α: isospin breaking Gronau, Zupan, hep-ph/0502139 Charles et al., arXiv:1705.02981

→ β: subleading amplitude $A(B^0 \to J/\psi K) = V_{cb}^* V_{cs} T + \boxed{V_{ub}^* V_{us} P}$
bound using SU(3)-related b→d decays $B_s \to J/\psi K_S$ and $B \to J/\psi \pi^0$ where the 2nd term is not Cabibbo suppressed
th. error scales with the ones on control channels & matches the measurement accuracy Fleischer, hep-ph/9903455 MC et al., hep-ph/0507290, … De Bruyn, Fleischer, arXiv:1412.6834

→ β_s: same as β, but trickier (larger effect, ϕ is not a pure octet, …). Still likely controllable De Bruyn, Fleischer, arXiv:1412.6834

**Penguin effects need work but should be controllable throughout HL-LHC period.
Important that lattice is able to keep up with Δm_s and Δm_d for precision interpretation!**

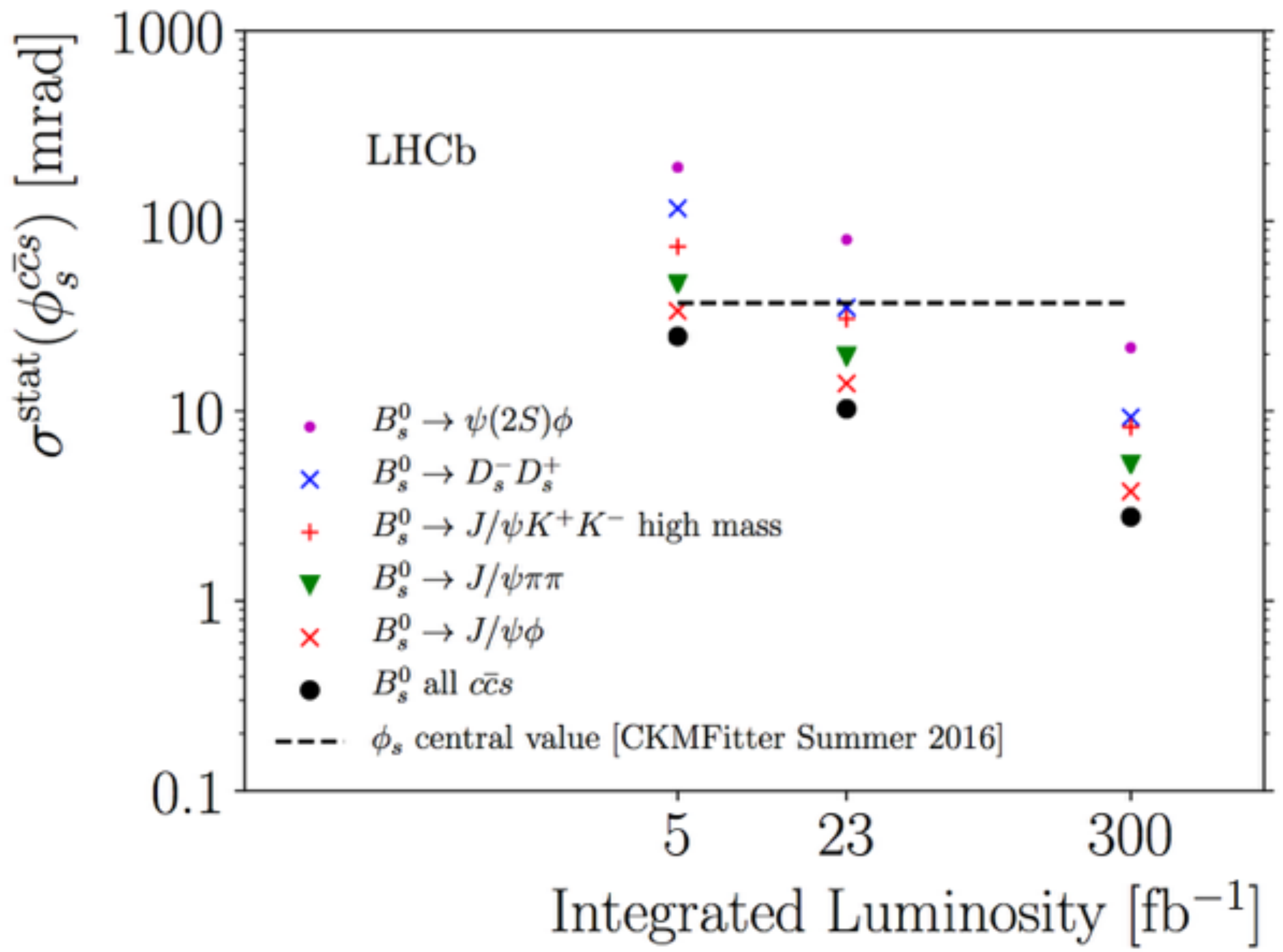
Key measurement : CKM angle γ

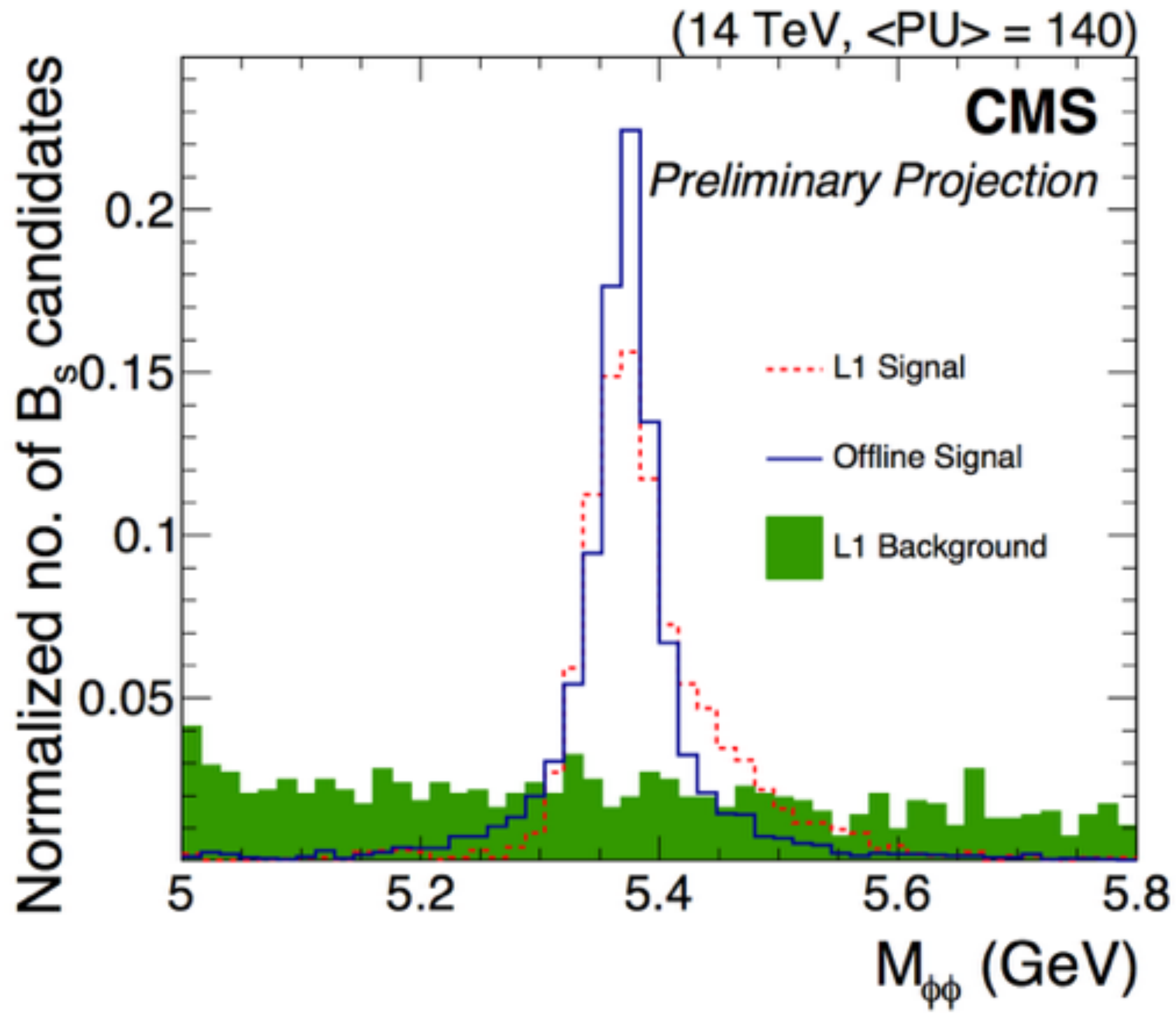


Parameters	$B_s^0 \to D_s^{\mp} K^{\pm}$ 23 fb^{-1}	300 fb^{-1}
S_f, $S_{\bar{f}}$	0.043	0.011
$A_f^{\Delta\Gamma}$, $A_{\bar{f}}^{\Delta\Gamma}$	0.065	0.016
C_f	0.030	0.007

LHCb's HL-LHC precision on γ will dominate world average. Unique opportunity to measure either γ or φs at 1° level using D_sK, only pure tree-level measurement of φ_s!

Key measurement : φ_s





With HL-LHC stats LHCb has at least 5 independent ways of resolving the SM φ_s

CMS L1 track trigger hugely exciting! If $B_s \to \varphi\varphi$ is possible why not $B_s \to \varphi\gamma$?

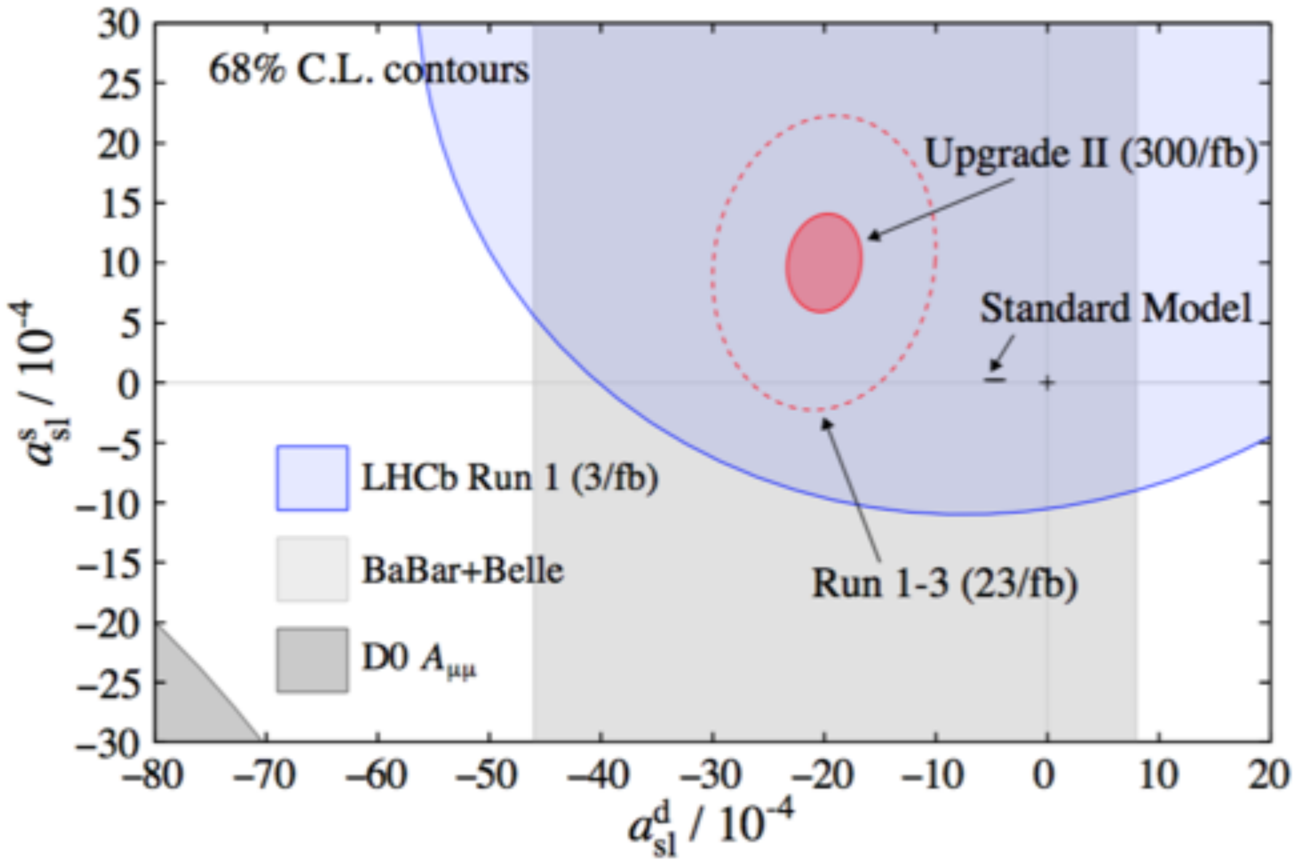
ATLAS & CMS projections for φ_s are being worked on for the yellow report chapter

Semileptonics @ HL–LHC

- LHCb already has the worlds best measurements, how far can we go?
  - Both will be measured to a few parts in 10^{-4}
  - Unprecedented sensitivity to new physics
  - Still far from the current theory uncertainties

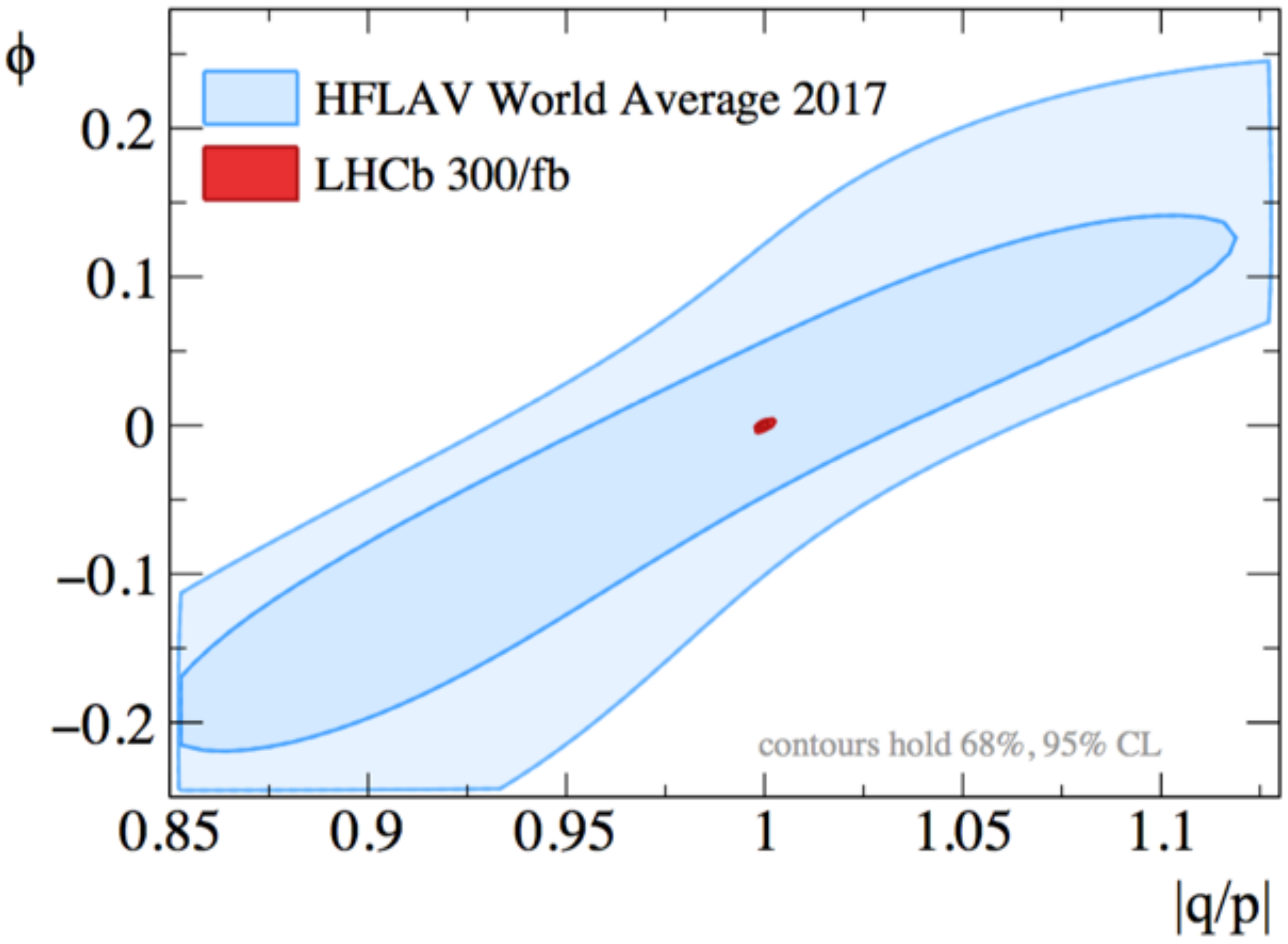
Sample ($\mathcal{L}$)	$\delta a^s_{\rm sl}/10^{-4}$	$\delta a^d_{\rm sl}/10^{-4}$
Run 1 (3 fb^{-1}) [193, 194]	33	36
Run 1-3 (23 fb^{-1})	10	8
Run 1-5 (300 fb^{-1})	3	2
Current theory [22, 185]	0.03	0.6

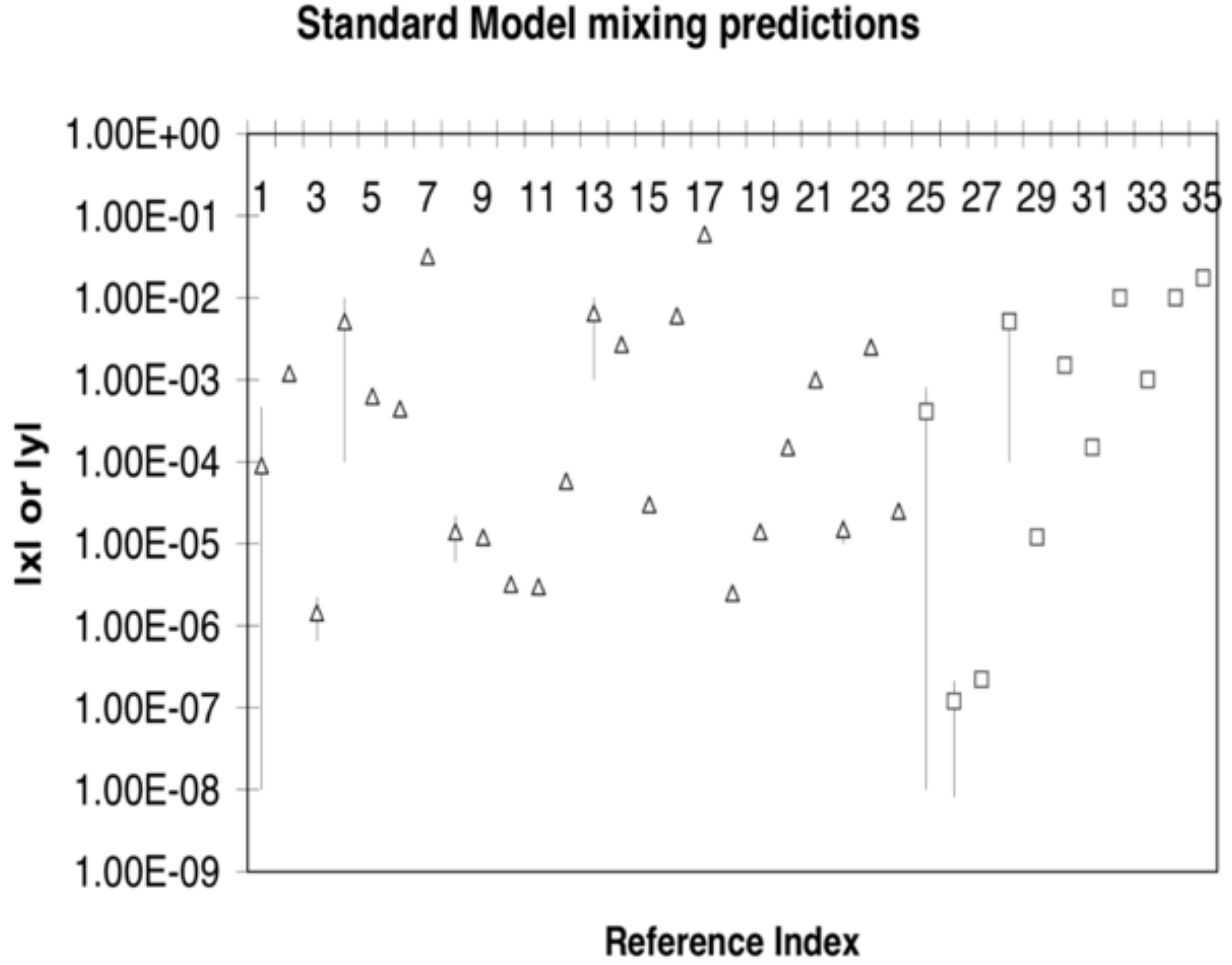
- Controlling systematics
  - Detection asymmetries should be controlled at the 1.0×10^{-4} level
  - Background asymmetries will be statistically subtracted by including a fit to the $D_q^- \mu^+$ corrected mass - uncertainty at the level of 1.0×10^{-4}



Charm @ HL-LHC

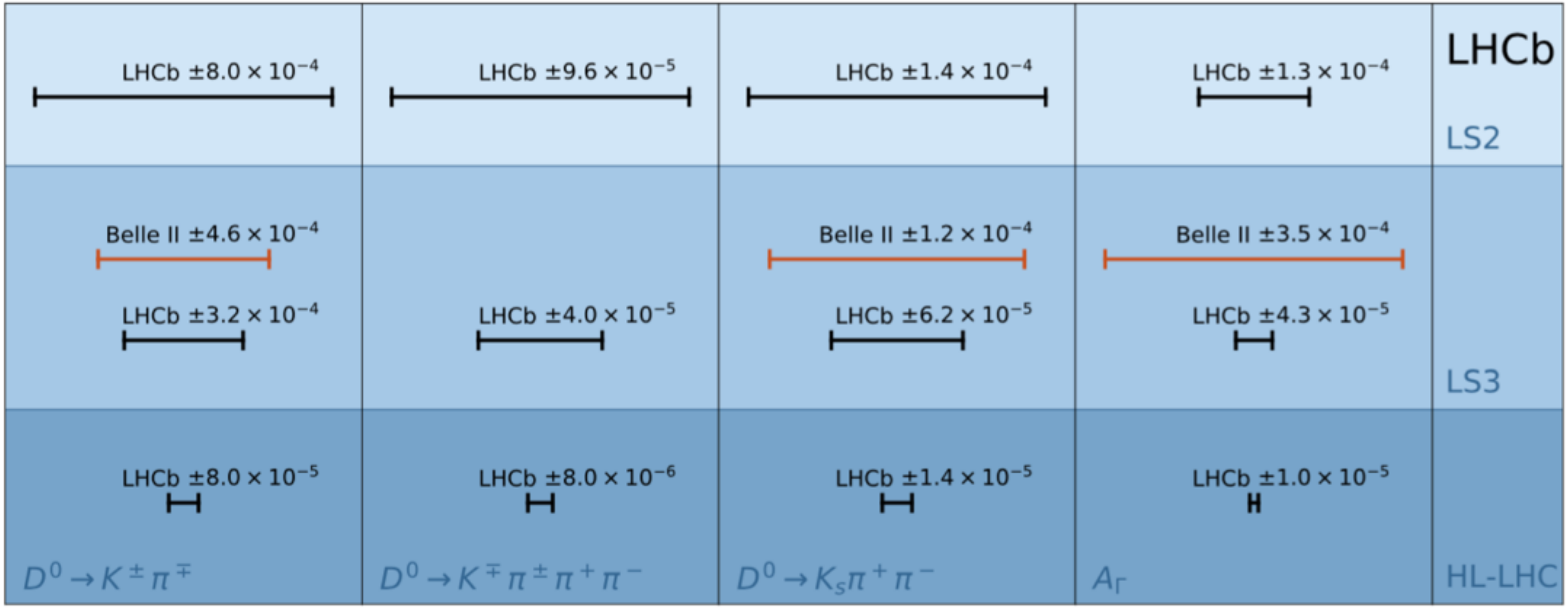
"Charm theory is notoriously difficult" – A Lenz
"If you want an easy life go sell internet ads" – V V Gligorov





HL-LHC is a potentially unique opportunity to probe charm CPV and mixing at the 10^{-5} level, will require a lot of work and progress on the theory side to interpret it properly!

Charm @ HL-LHC



Many other observables also available, opportunities abound also in rare charm decays

Unique opportunities in metrology

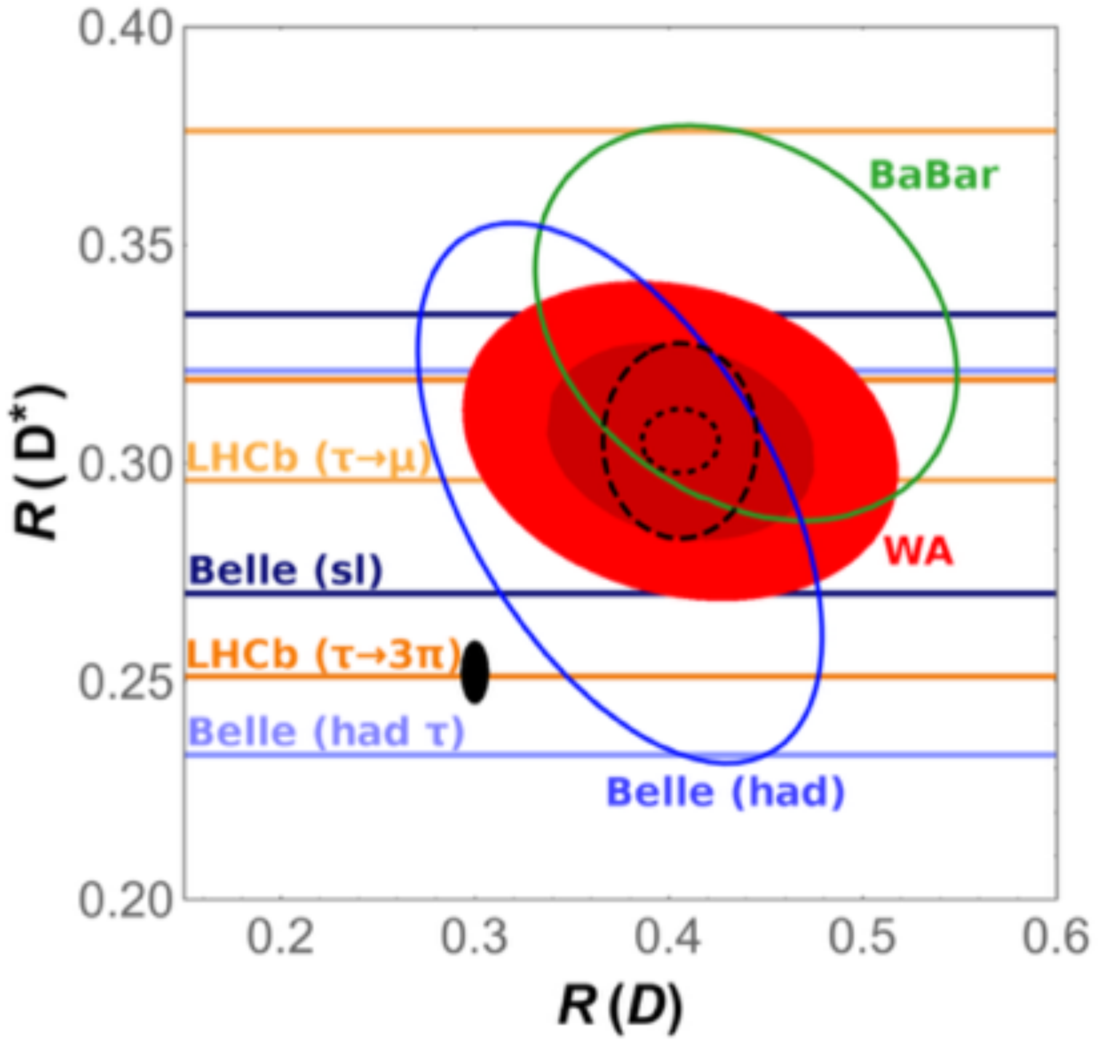
LHC experiments may be able to resolve SM $\Delta\Gamma_d$

LHCb in a unique position to precisely map out CPV in baryonic decays for the first time, as well as making unprecedented studies in B_c sector.

Rare processes & BSM

Anomalies here, anomalies there

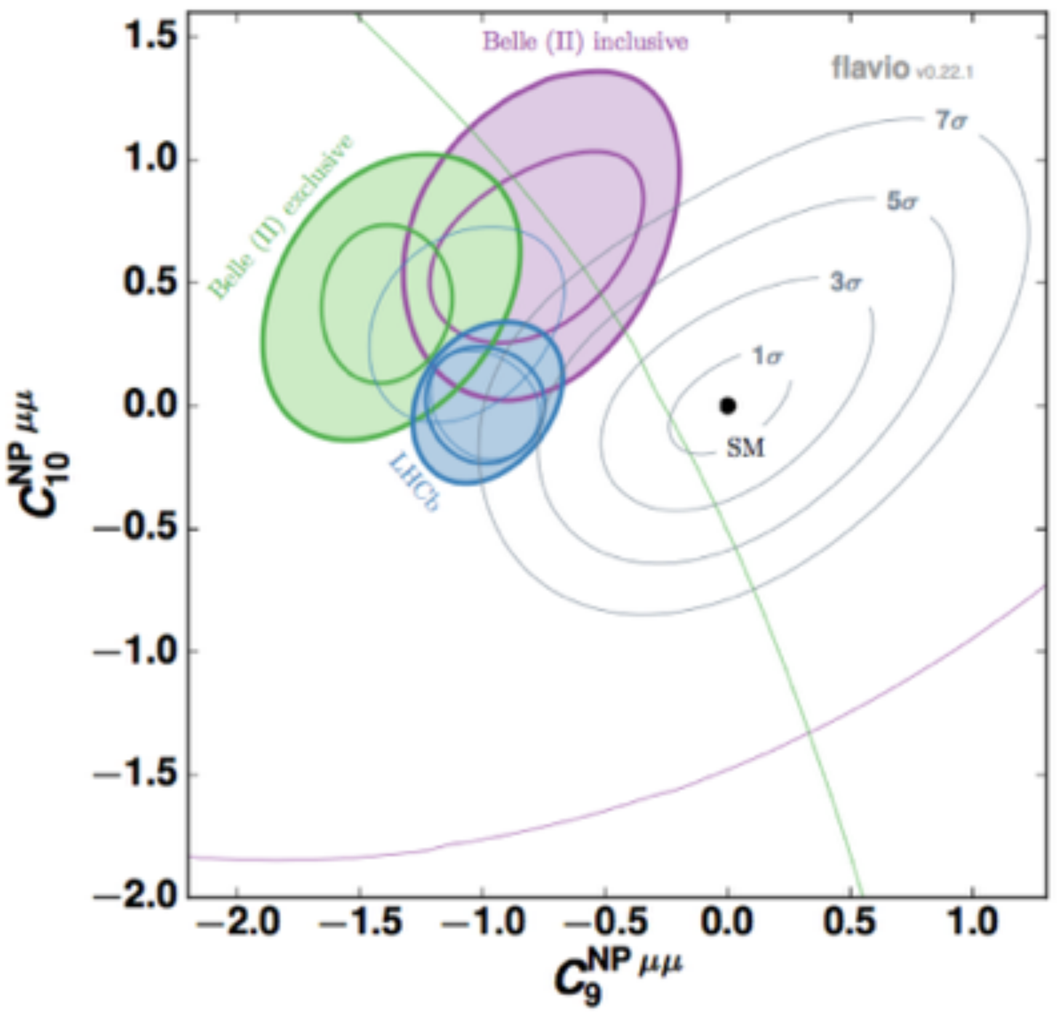
$\mathbf{b} \rightarrow \mathbf{c}\tau\nu$



- Presently $\sim 4\sigma$ from SM
- Relative to tree-level

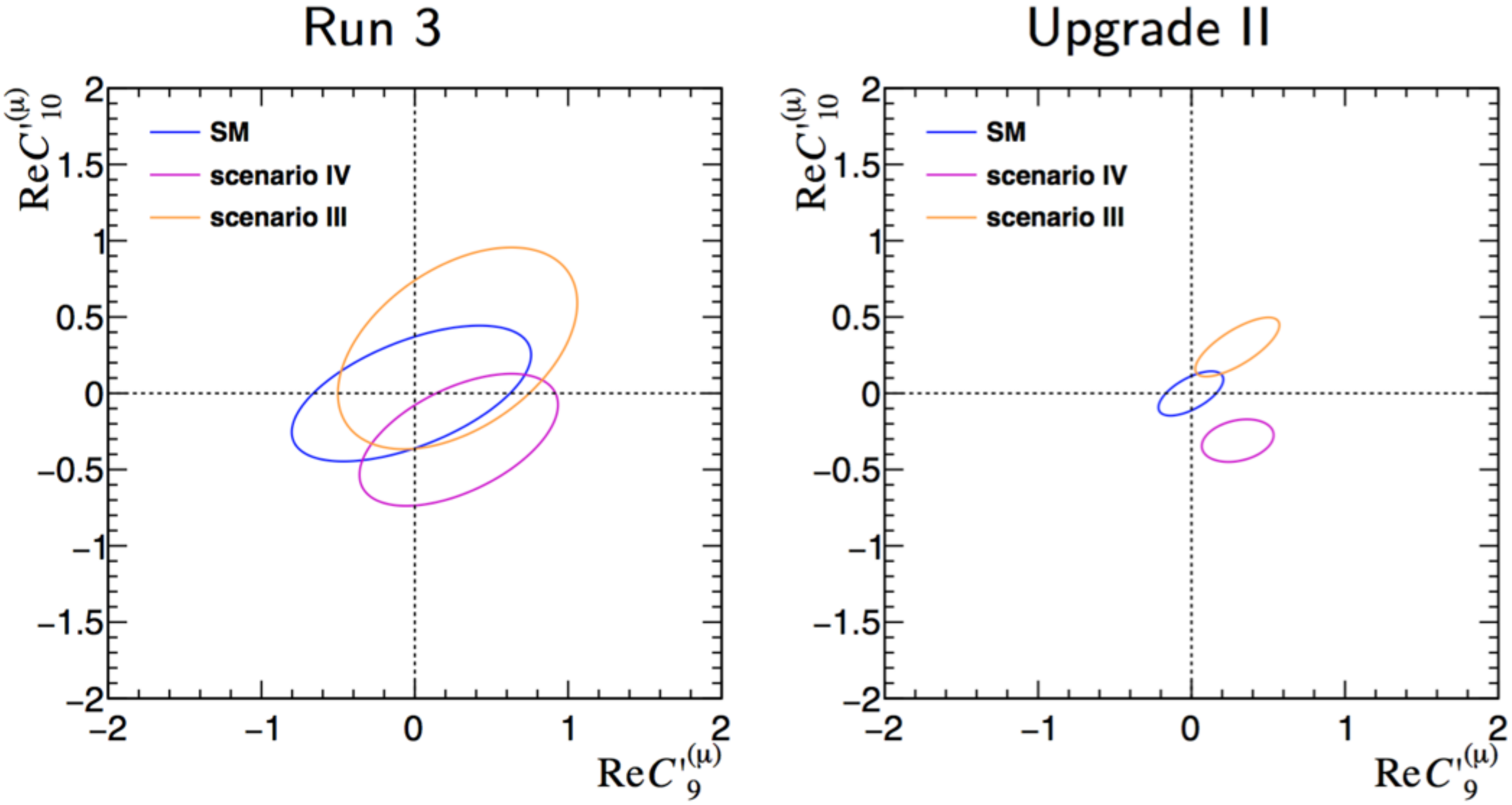
➥ Low NP scale?

$\mathbf{b} \rightarrow \mathbf{s}\ell^+\ell^-$ [Albrecht+'17]



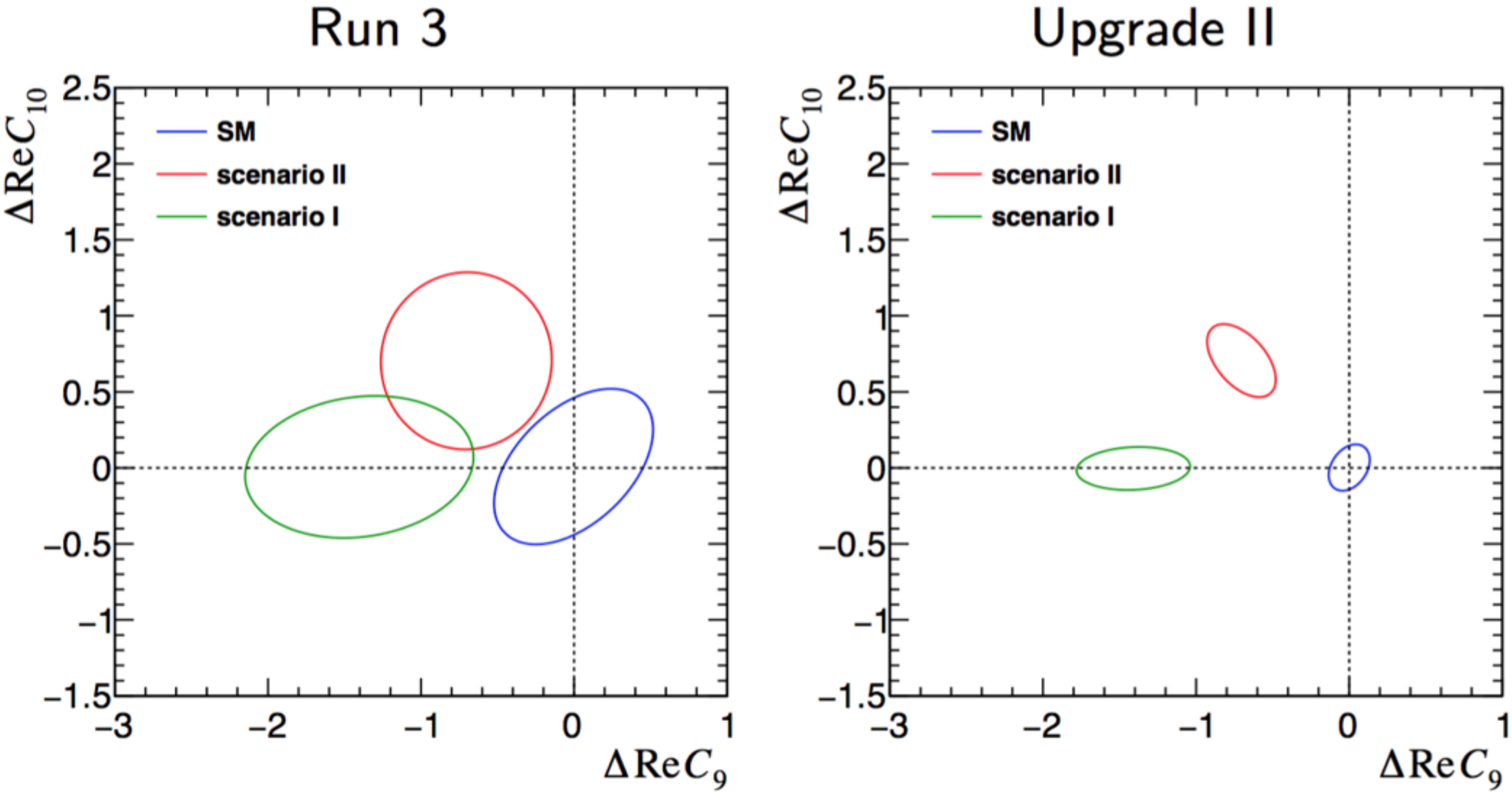
- $\sim 5\sigma$ from SM
- Relative to EW penguin loop
- Consistent BR, angular + LFU data

Anomalies @ HL-LHC with muons



ATLAS and CMS studies for $K^*\mu\mu$ are ongoing for HL-LHC

Anomalies @ HL-LHC with electrons

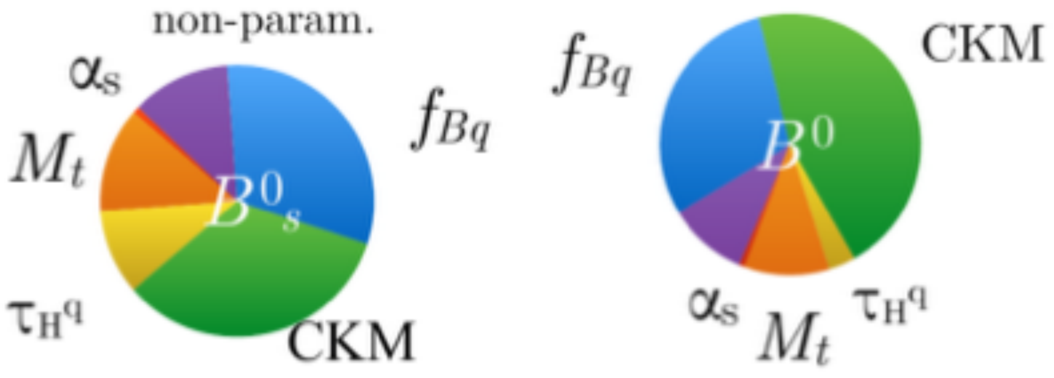


What can ATLAS and CMS do for K^*ee?

Connection to $B_s \to \mu\mu$

Current Experimental Systematics	
Source	size
Hadronisation fraction f_s/f_d	5.8%
Normalisation modes	3%
Particle identification	2%
Track reconstruction	2%

Current Theory Systematics



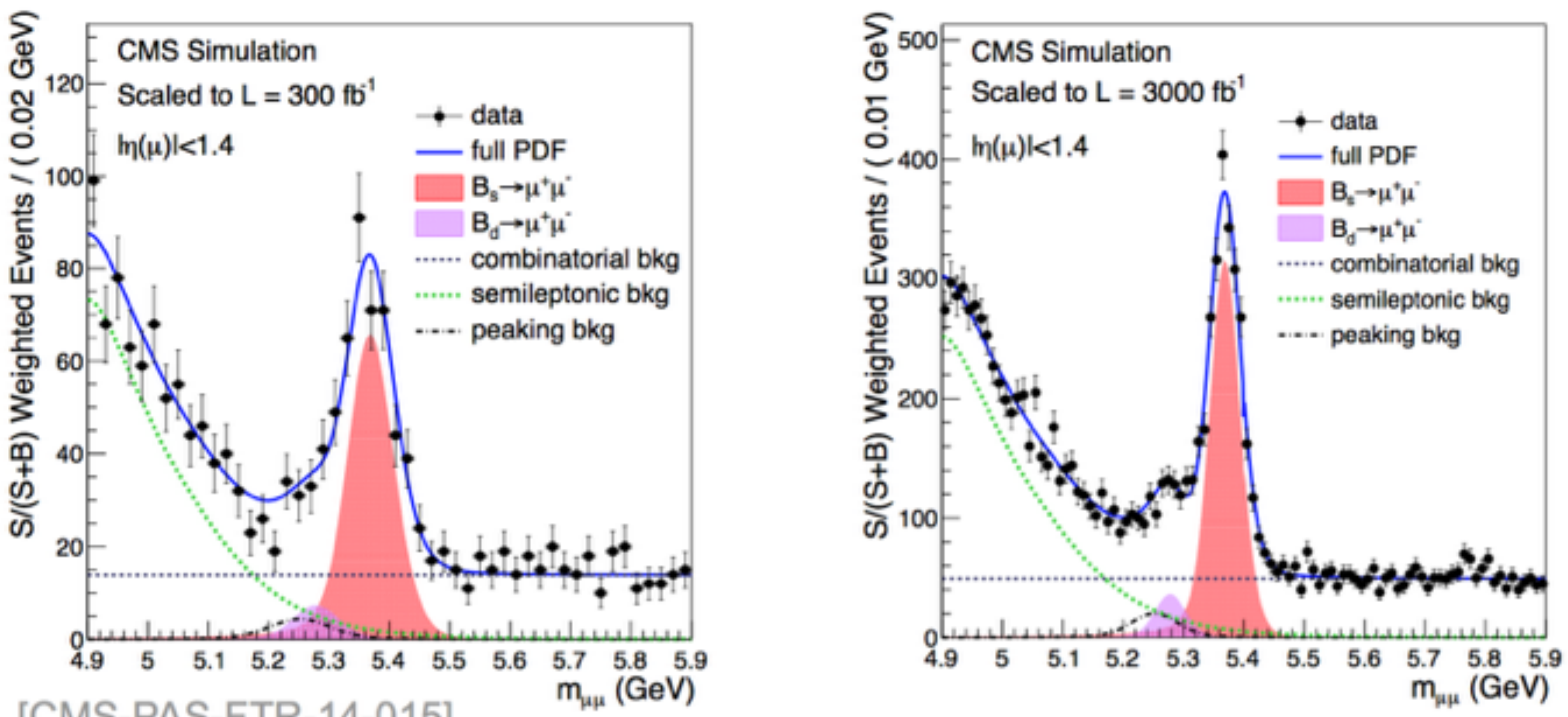
- $\mathcal{B}(B^0 \to \mu^+\mu^-)$ will remain stat. dominated with Upgrade II sample
- Projected statistical uncertainty for $\mathcal{B}(B^0_s \to \mu^+\mu^-)$ is 1.8%
- Total exp. systematic uncertainty expected to reduce to $\sim 4\%$
- Expected total experimental uncertainties

	now	23 fb^{-1}	300 fb^{-1}
absolute uncertainty $B^0_s \to \mu^+\mu^-$ [10^{-9}]	0.67	0.30	0.16
rel. uncertainty $B^0 \to \mu^+\mu^- / B^0_s \to \mu^+\mu^-$ [%]	90%	34%	10%

- Dominant theory uncertainties (B^0_s decay constant, CKM elements) also expected to reduce

Naively : probes C10. But additional observables become available with HL-LHC stats!

$B_s \to \mu\mu$ at CMS



[CMS-PAS-FTR-14-015]

$\mathscr{L}$ (fb^{-1})	$\delta BR(B_s)$	$\delta BR(B_d)$	$BR(B_d)$ sign.	$\delta[BR(B_s) / BR(B_d)]$
100	14%	63%	0.6-2.5σ	66%
300	12%	41%	1.5-3.5σ	43%
300 (barrel)	13%	48%	1.2-3.3σ	50%
3000 (barrel)	11%	18%	5.6-8.0σ	21%

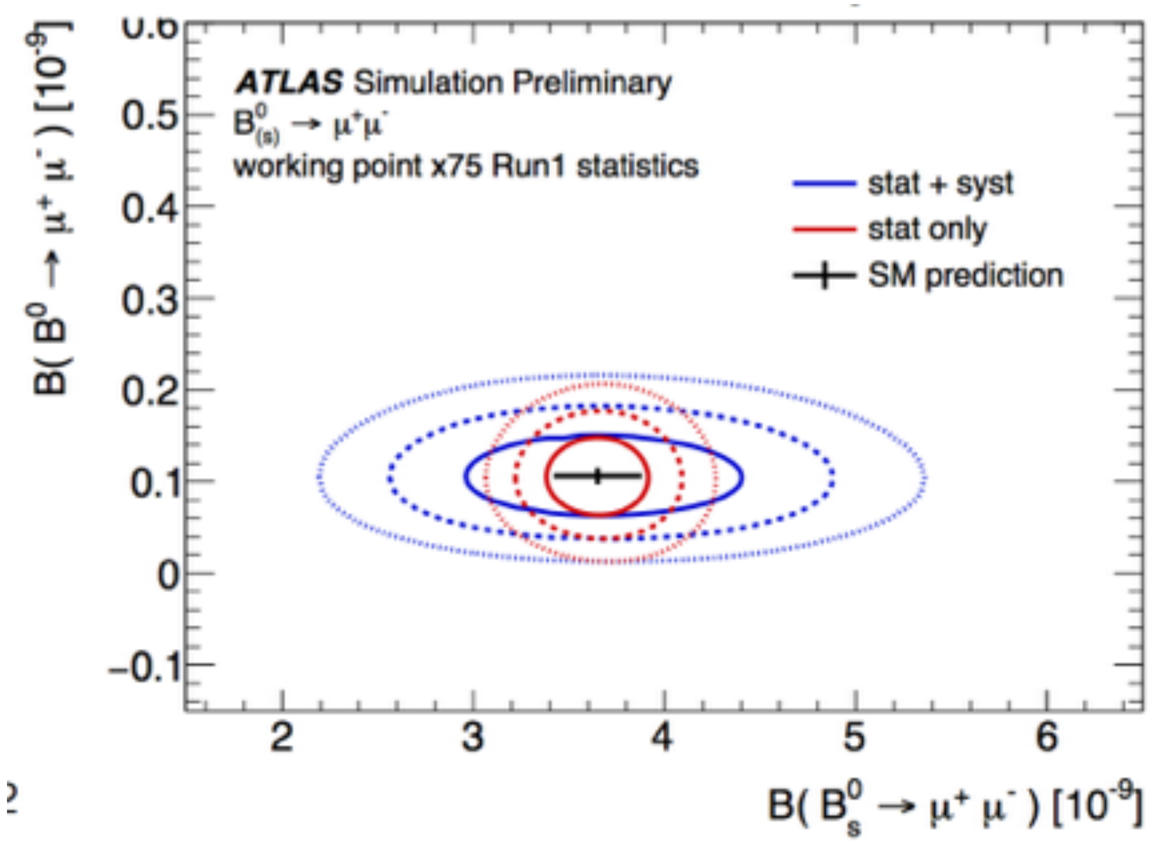
Probably can't harmonize systematics but should discuss combination qualitatively

$B_s \to \mu\mu$ at ATLAS & combination

- 3 trigger scenarios:
  - 2mu10
    - conservative: ~x15 Run1 stat
  - mu6_mu10
    - intermediate: ~x60 Run1 stat
  - 2mu6
    - high yield: ~x75 Run1 stat

- profiled likelihood contours
  - **red**: stat only
  - **blue**: stat + syst

- dominant systematic on BR(Bs): f_s/f_d

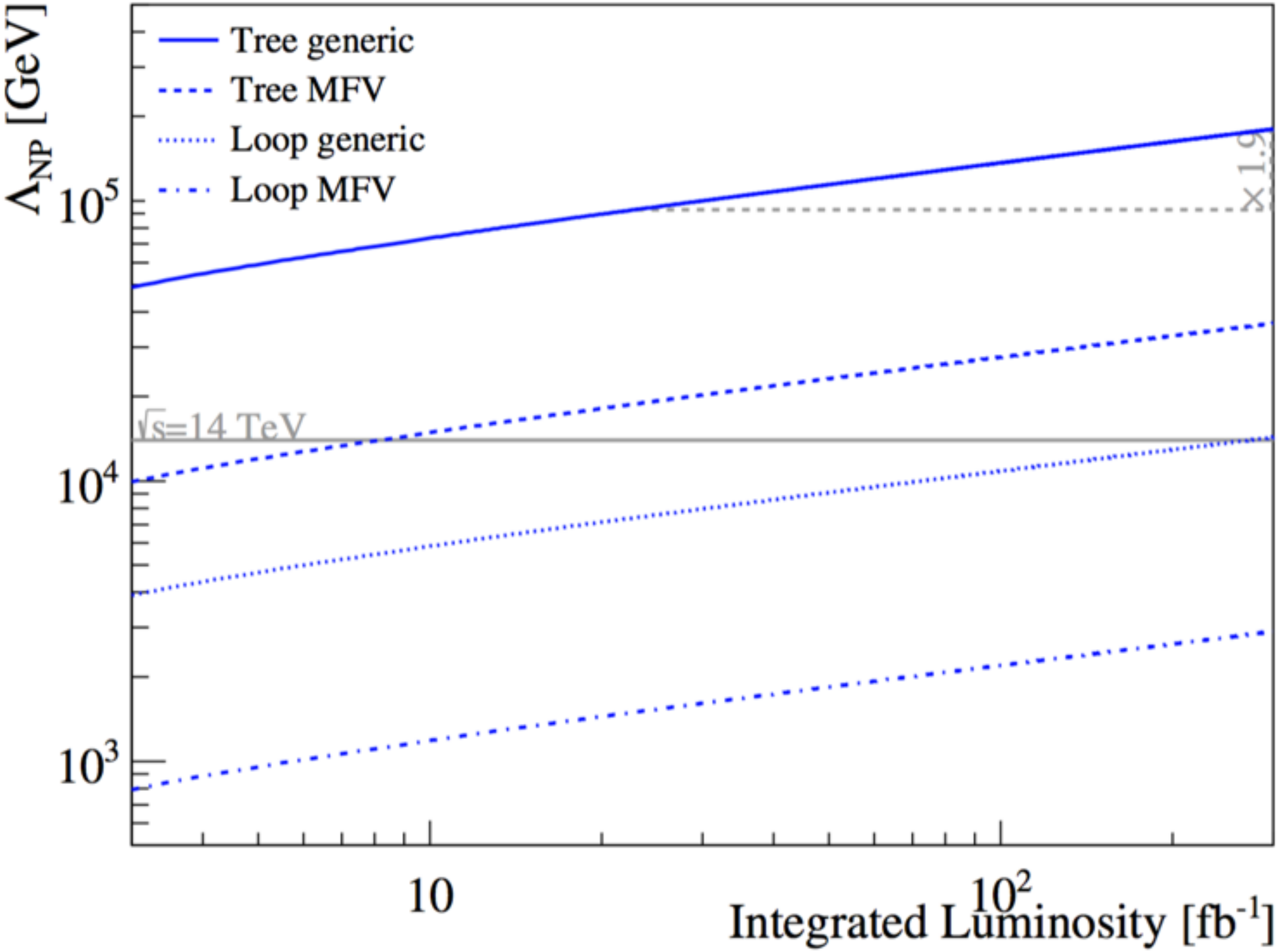


	σ(BR(B_s)) [10^{-9}]	σ(BR(B_d)) [10^{-9}]
CMS	0.40	0.019
ATLAS high-yield	0.46	0.028
ATLAS intermediate	0.47	0.031
ATLAS conservative	0.55	0.054

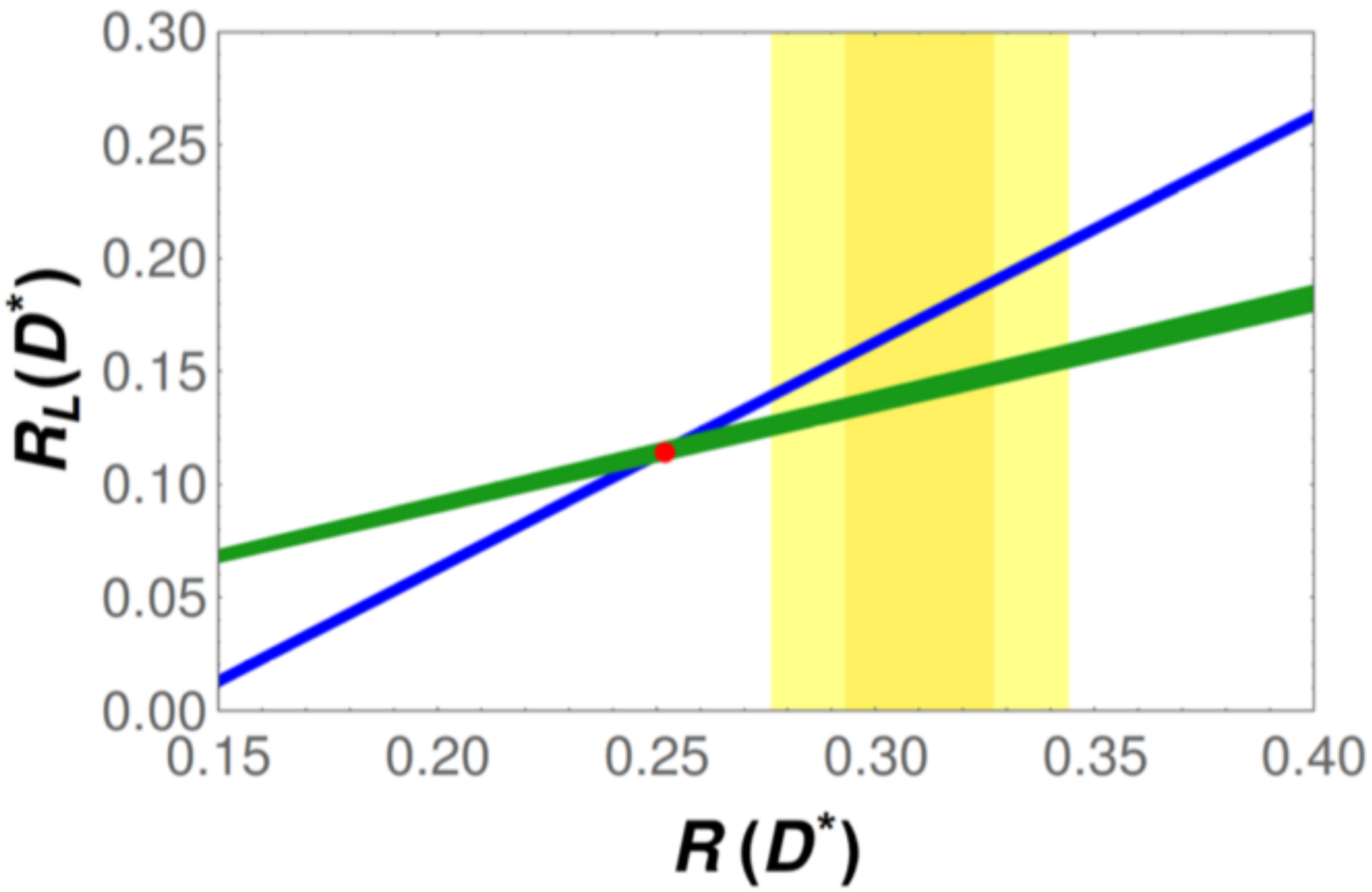
SM predictions: BR(B_s) = (3.65 ± 0.23) x 10^{-9}, BR(B_d) = (1.06 ± 0.09) x 10^{-10}

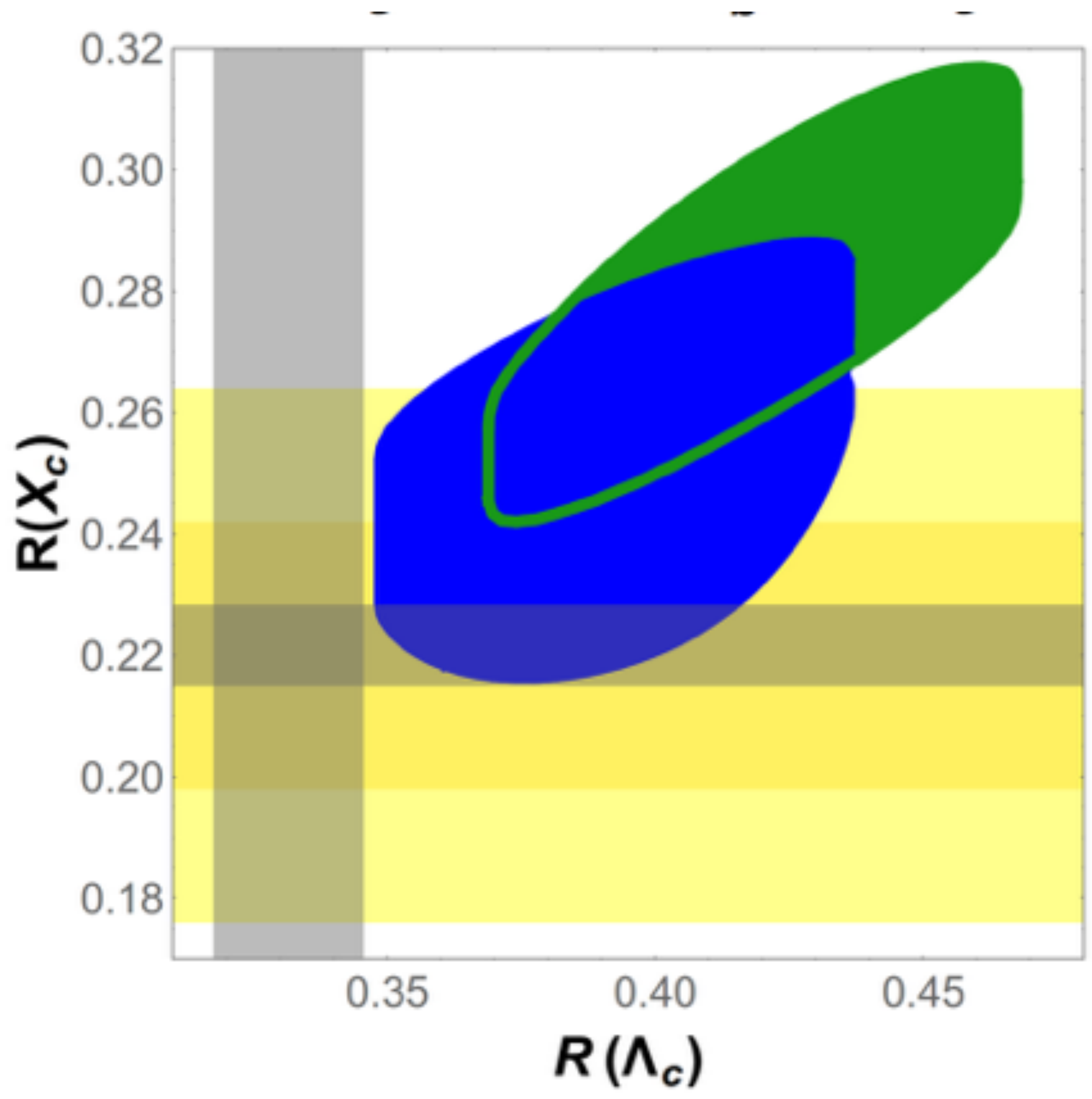
Big job done in last months to concretize alternative trigger strategies!

NP scale probed @ HL-LHC



From discovery to interpretation

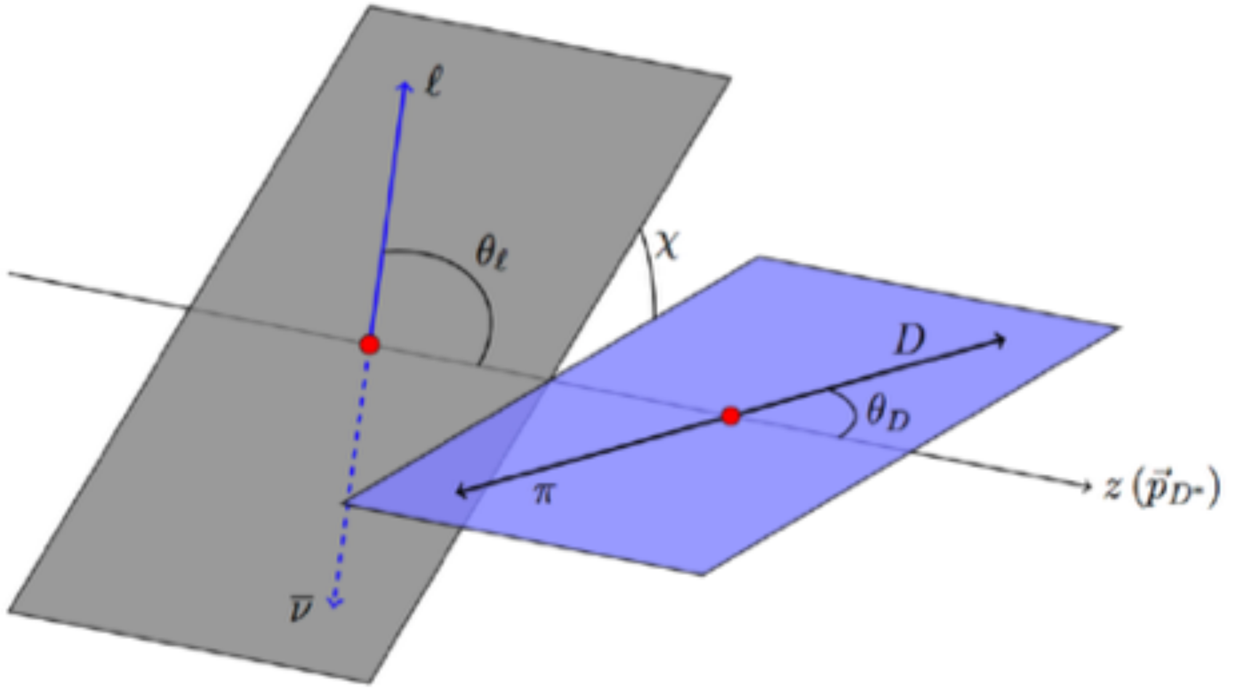


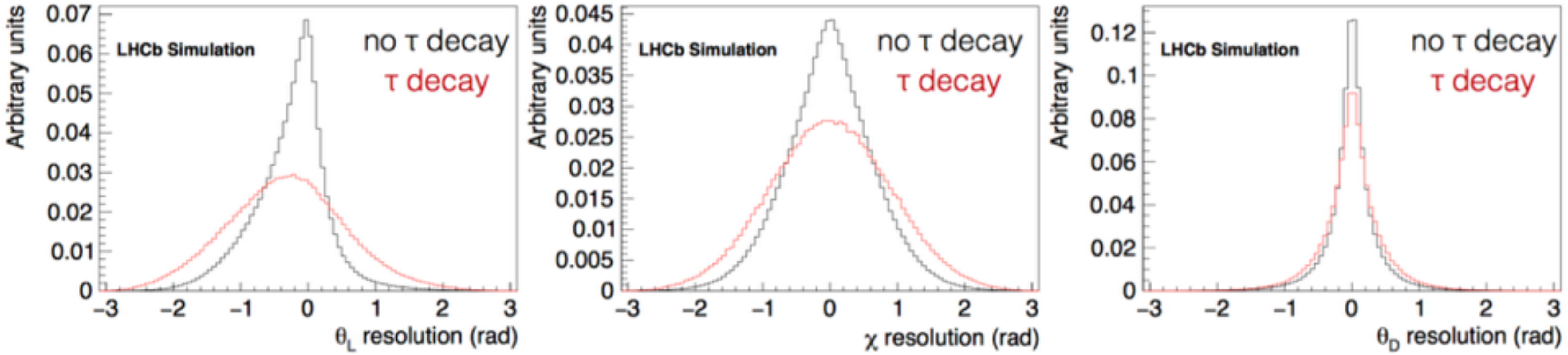


Angular observables and interplay between different R measurements very important

Angular observables in upgrade II

- Expect $\mathcal{O}(10\,\mathrm{M})$ $B \to D^* \tau \nu$ candidates in Upgrade II
- Sensitivity with Upgrade II: $\sigma(R_{D^*})/R_{D^*} \sim 1\%$
- Angular analysis would allow to determine spin structure of potential NP contribution

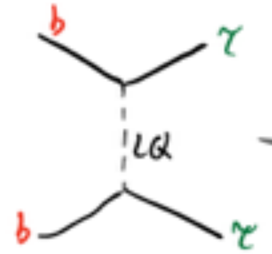


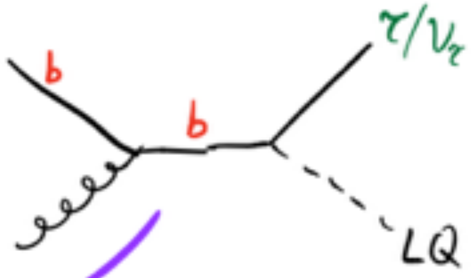


Connection to high-P_T searches

Best candidates to address both anomalies
1706.07808

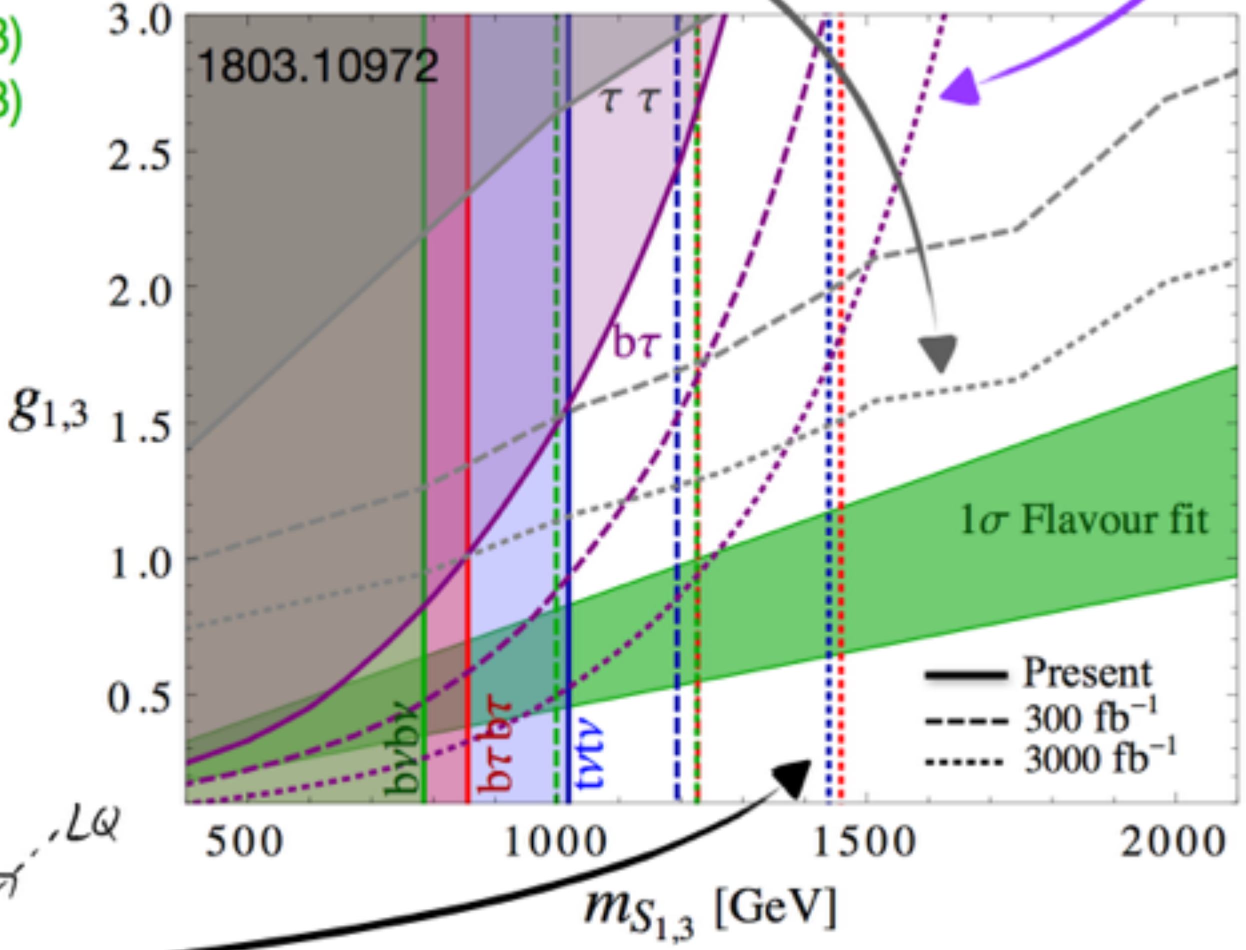
Working assumption: largest couplings to third generation fermions, couplings to lighter ones are CKM (flavour) suppressed.

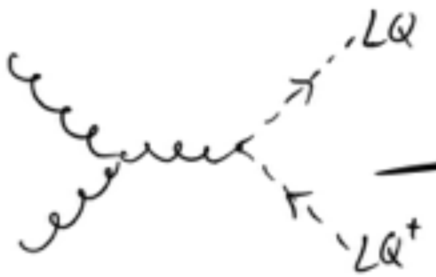




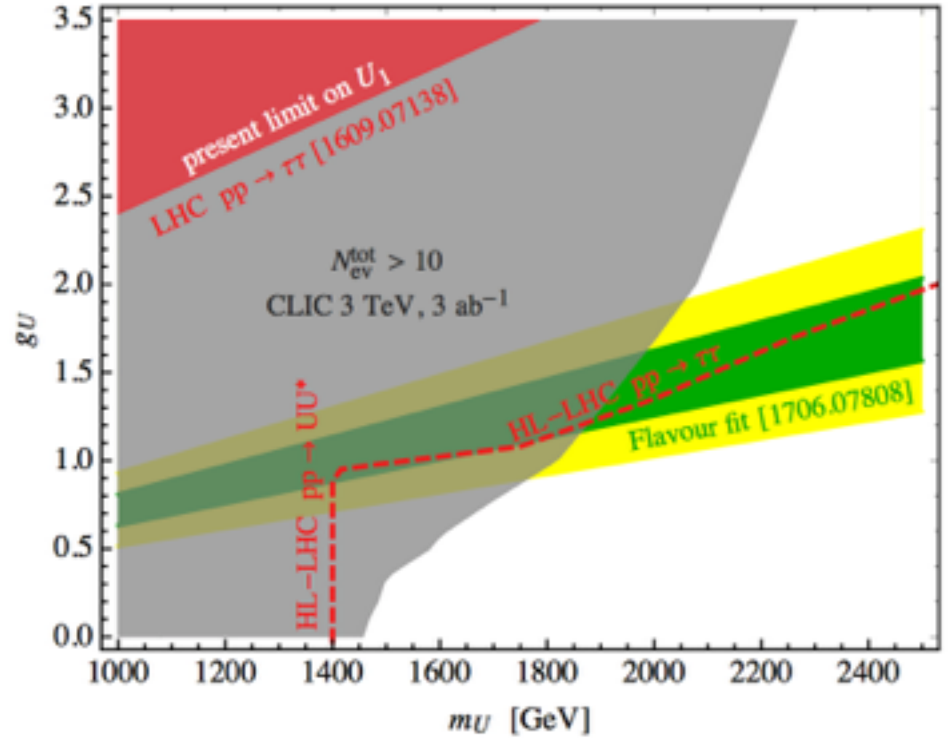
Scalar LQs

$S_1=(\bar{3},1,1/3)$
$S_3=(\bar{3},3,1/3)$

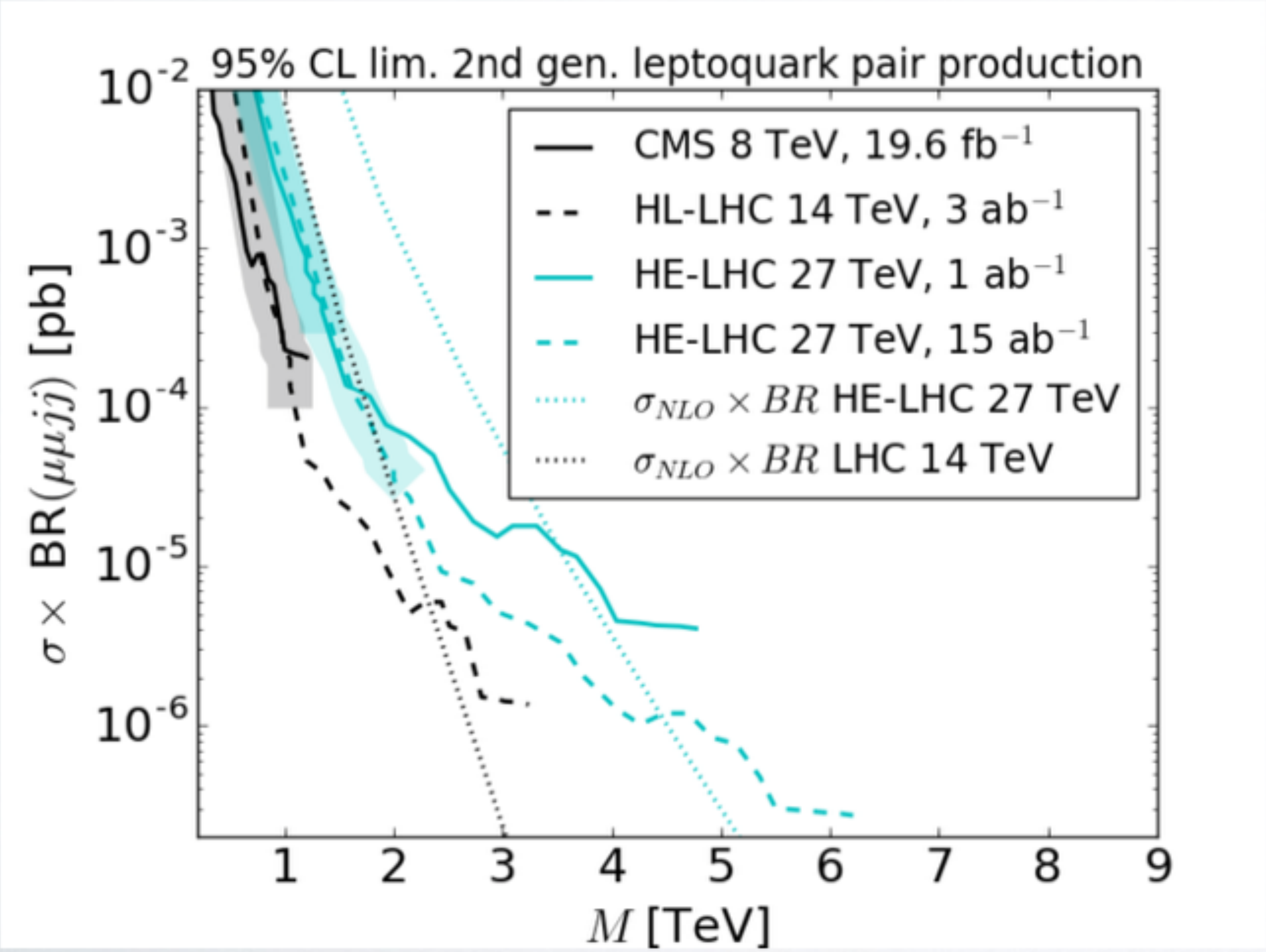




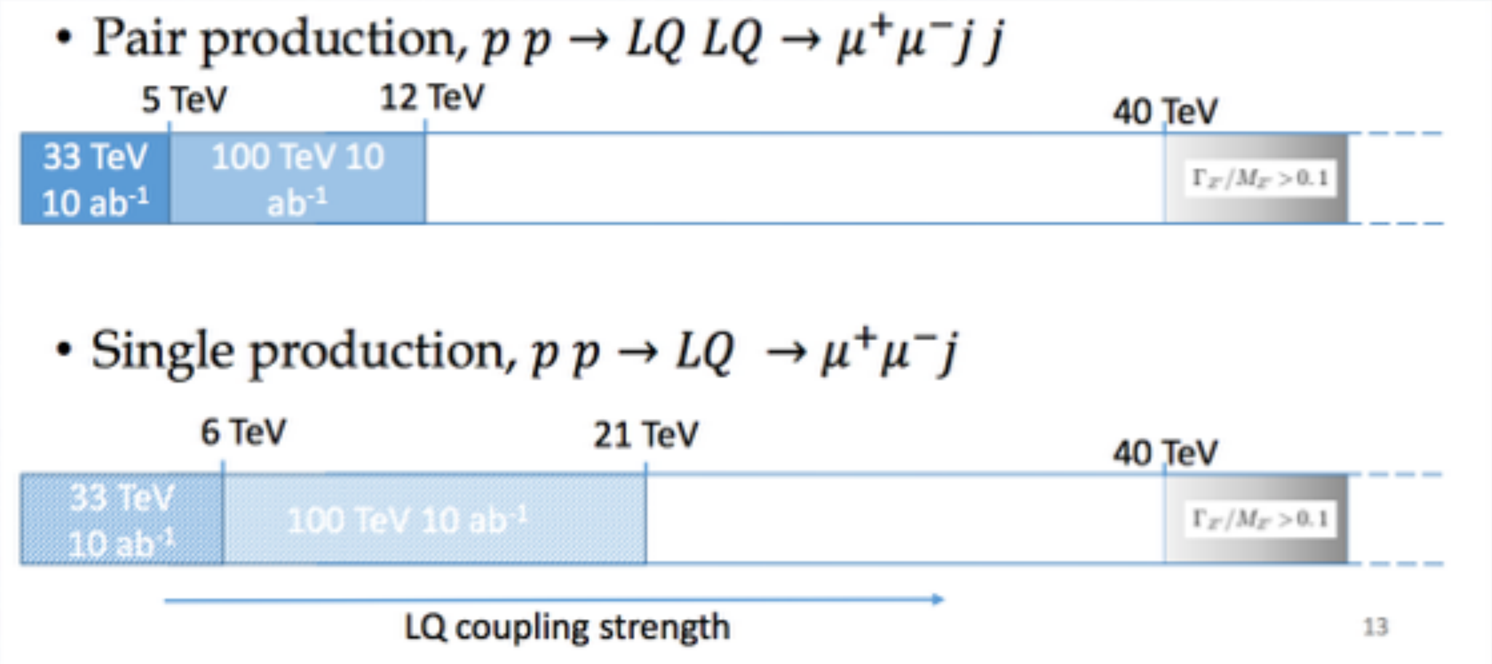
[CLIC, Yellow report, preliminary
Buttazzo, Greljo, Marzocca, Nardecchia]



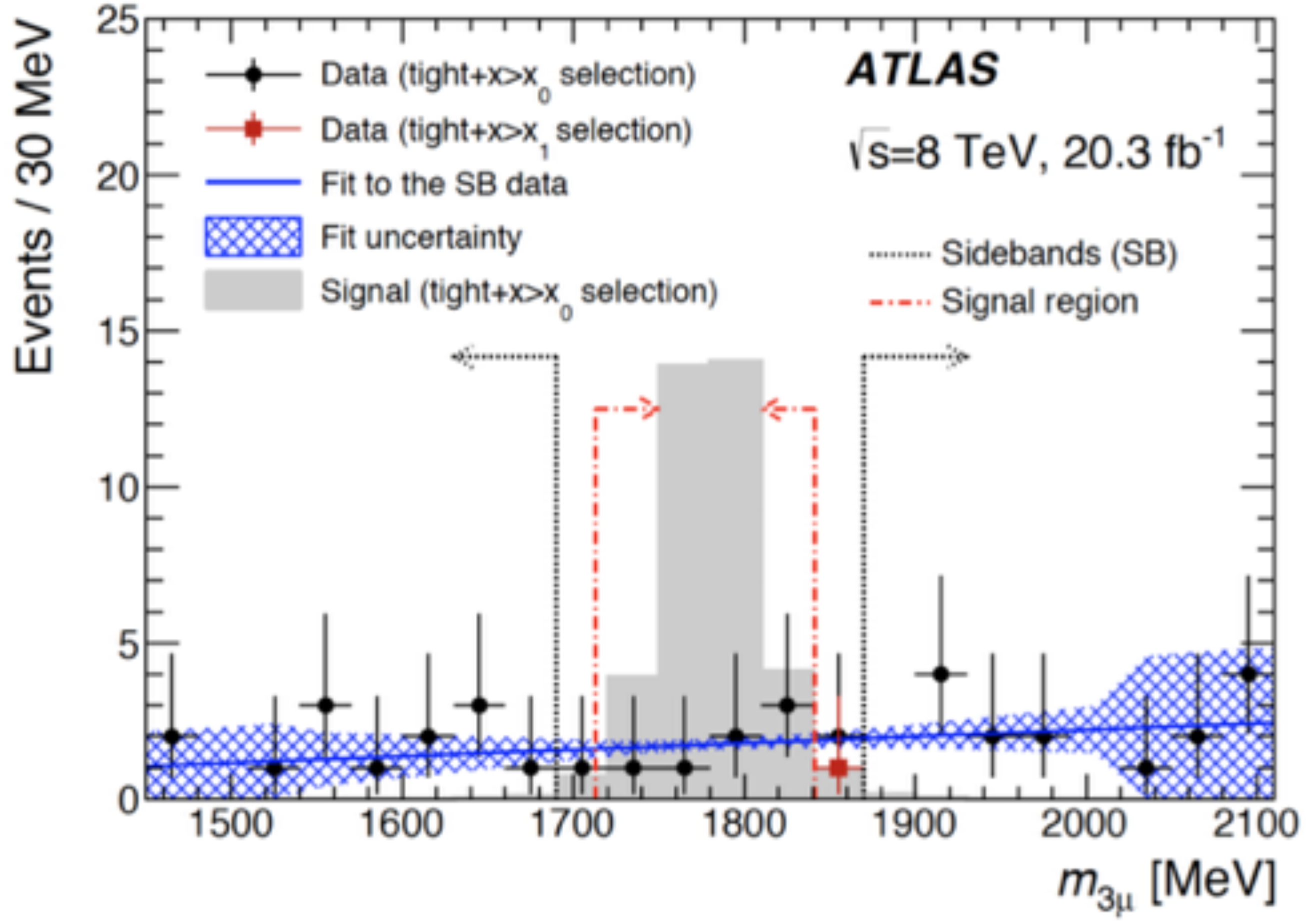
Connection to high−P_T searches



- Extrapolation from [CMS-PAS-EXO-12-041]
- Same hypothesis as before
- Take home message:



Connection to LFV (i.e. τ→3μ) searches



Expected $W \to \tau\nu$ events: 2.4×10^8

Signal region:

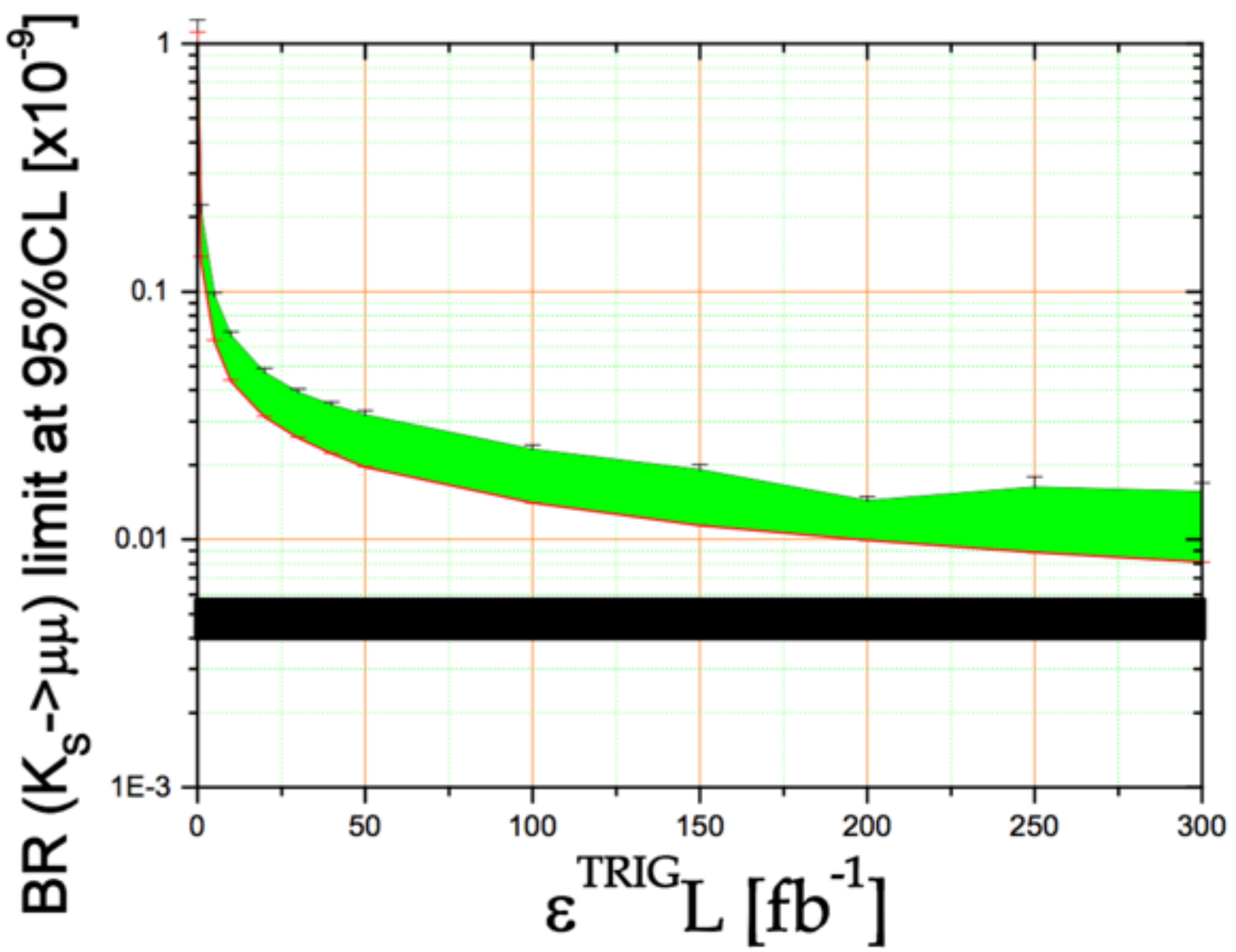
- Signal A x eff = **0.023**
- Background (how?) = **0.19 events**
- Observed: **0 events**

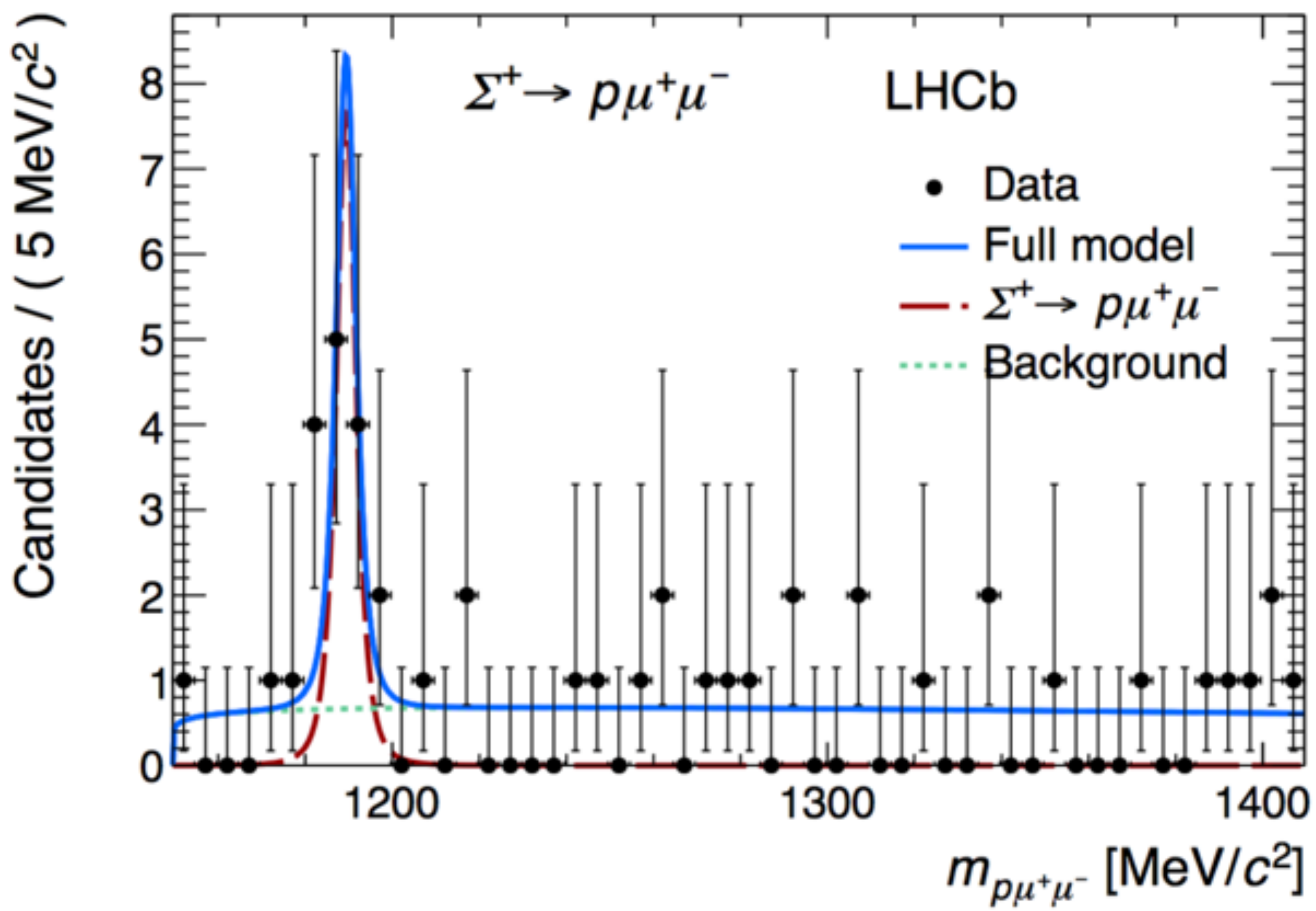
Exclusion limits on B at 90% CL

- Expected: **3.9×10^{-7}**
- Observed: **3.8×10^{-7}**

	Luminosity	Tau source	Source of projection	Limit
ATLAS	3000 fb^{-1}	$W \to \tau\nu$	**My naïve extrapolation** from the Run 1 (8 TeV, 20.3 fb^{-1}) results (slide 8)	**9×10^{-9}**
CMS	3000 fb^{-1}	Hadronic	**Simulated analysis** for the Upgraded CMS at HL-LHC	**4×10^{-9}**
LHCb	300 fb^{-1}	Hadronic	**My naïve $1/\sqrt{N}$ extrapolation** from the Run 1 (8 TeV, 3 fb^{-1}) results	$O(10^{-9})$

Strange rare decays



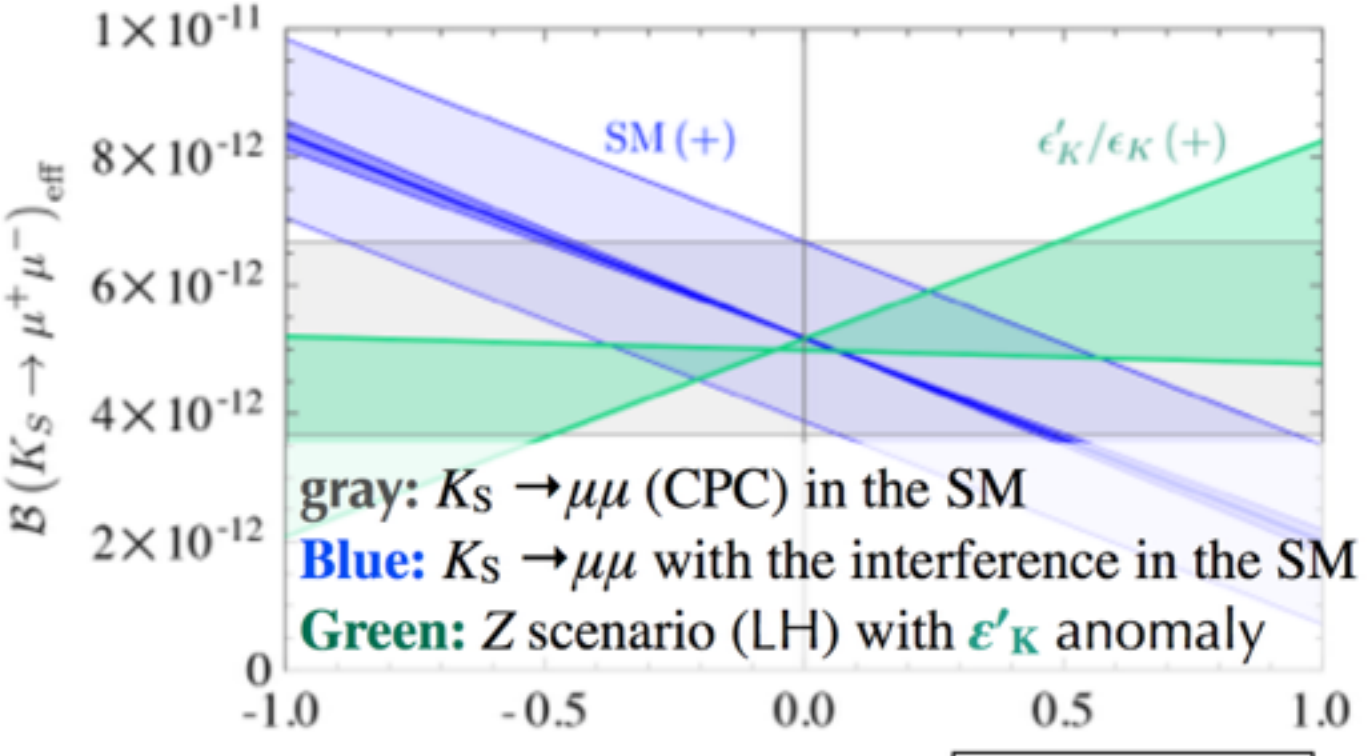


LHC production & LHCb geometry give great reach for strange physics if trigger works!

Strange observables unique to HL-LHC

- Interference contribution is comparable size to CPC of $K_S \to \mu\mu$ thanks to the large absorptive part of long-distance contributions to $K_L \to \mu\mu$
- The unknown sign of $\mathcal{A}(K_L \to \gamma\gamma)$ can be probed
- Nonzero dilution factor (D) can be achieved by an accompanying charged kaon tagging and a charged pion tagging

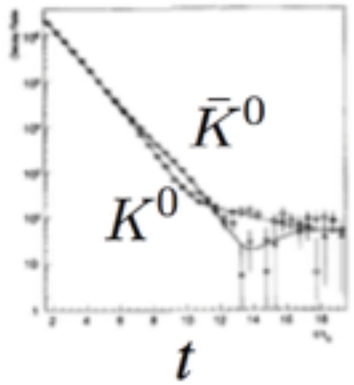
$$pp \to K^0 K^- X$$
$$pp \to K^{*+} X \to K^0 \pi^+ X$$
with $K^0 \to \{K_S, K_L\} \to \mu^+\mu^-$



$$D = \frac{K^0 - \overline{K}^0}{K^0 + \overline{K}^0}$$

cf. CPLEAR experiment (1990-99@CERN)

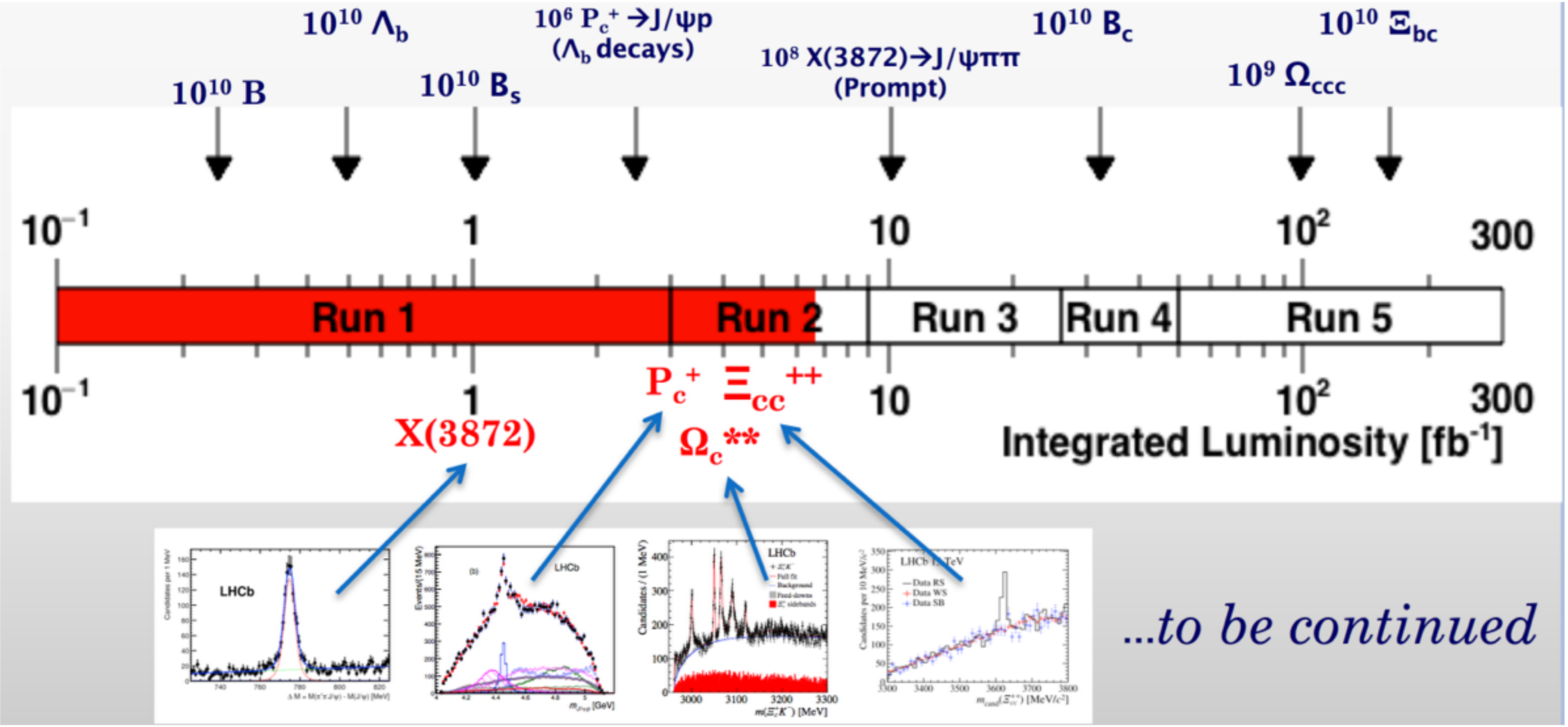
$$p\bar{p} \to \left[\begin{array}{l} K^0 K^- \pi^+ \\ \bar{K}^0 K^+ \pi^- \end{array} \right.$$



$\{K_S, K_L\} \to \pi^+\pi^-$
measured the interference between K_S and K_L
[CPLEAR collaboration '95]

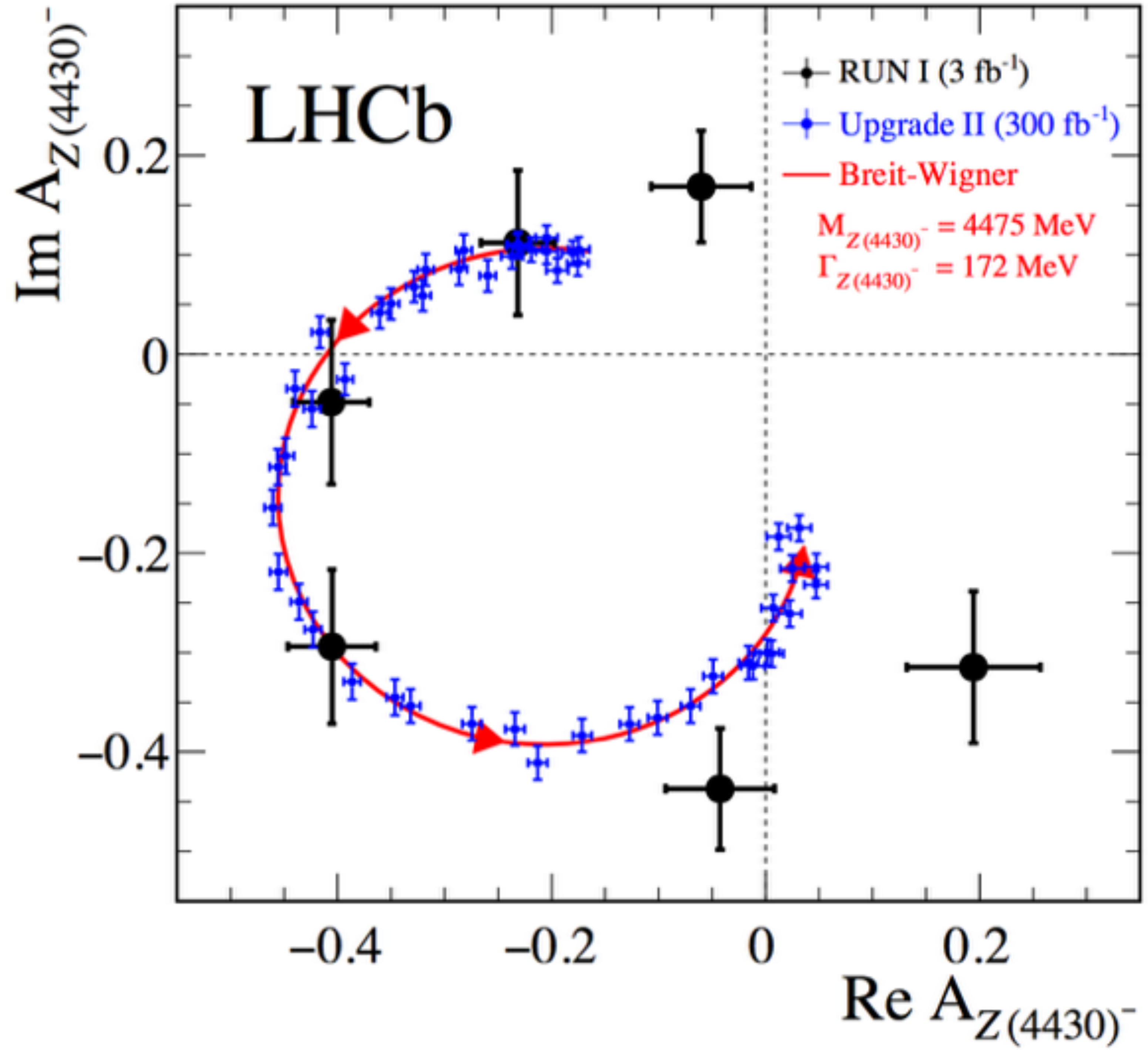
Spectroscopy & QCD

LHC is a unique tool for spectroscopy



...to be continued

Illustration of the power of HL-LHC



From discovery to precise characterization of exotic hadrons!

How heavy can HL-LHC let us probe?

and using also the heavy antiquark-diquark symmetry $\Rightarrow$ triply heavy pentaquarks

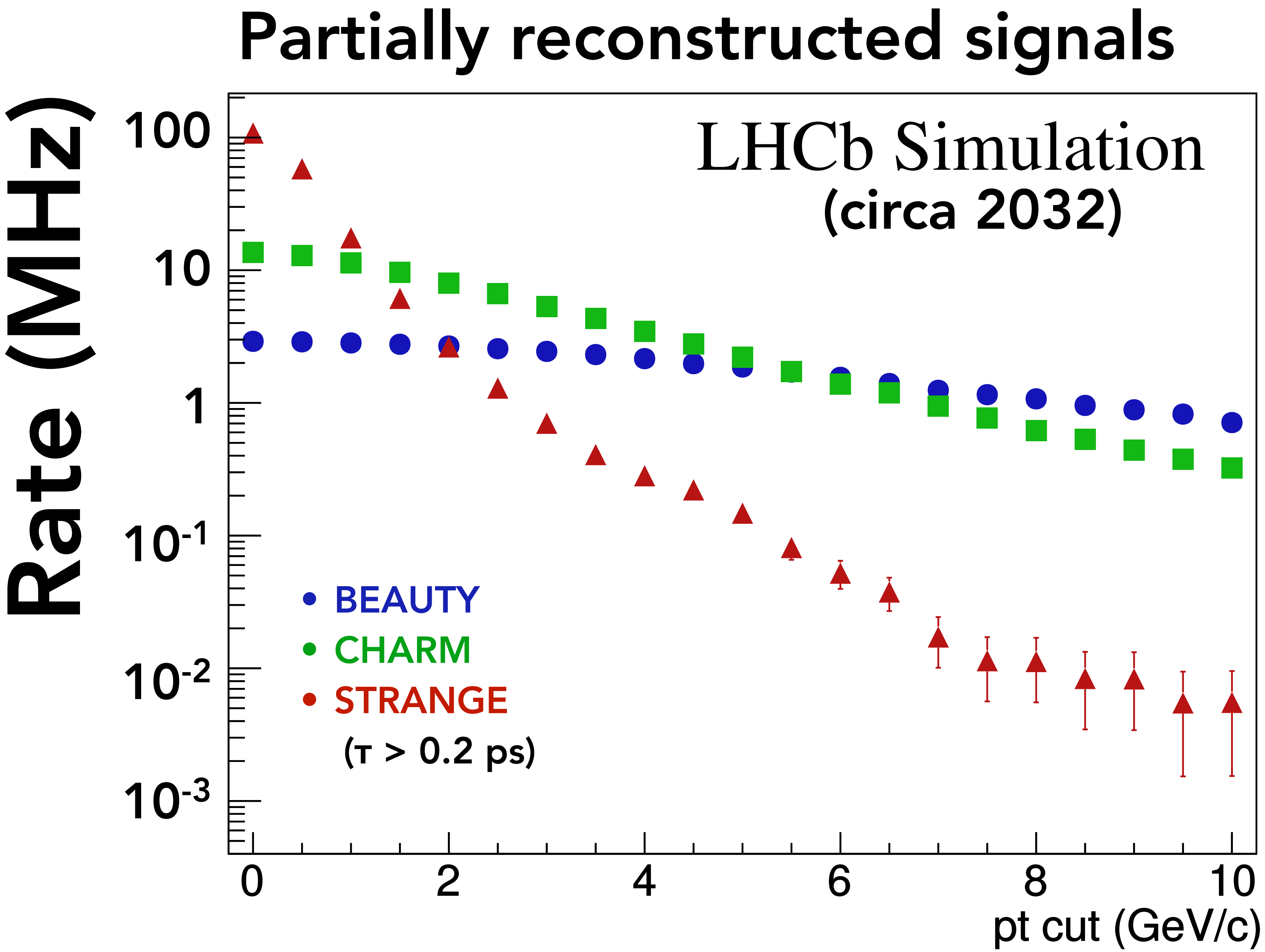
$$(QQl)Q\bar{l}' \sim (\text{“}\bar{Q}\text{”}l)Q\bar{l}' \qquad (QQQl\bar{l}') \qquad \mathcal{O}(1/m_Q \cdot v)$$

The QQ diquark appears as a point-like color antitriplet source, similar to a heavy antiquark, and this leads to an approximate heavy antiquarkdiquark symmetry (HADS)

State	$I(J^P)$	$V^{\rm LO}$	Thresholds	Mass ($\Lambda = 0.5$ GeV)	Mass ($\Lambda = 1$ GeV)
$\Xi^*_{cc}D^*$	$0(\frac{5}{2}^-)$	$C_{0a}+C_{0b}$	5715	$(M_{\rm th}-10)^{+10}_{-15}$	$(M_{\rm th}-19)^{\dagger}_{-44}$
$\Xi^*_{cc}\bar{B}^*$	$0(\frac{5}{2}^-)$	$C_{0a}+C_{0b}$	9031	$(M_{\rm th}-21)^{+16}_{-19}$	$(M_{\rm th}-53)^{+45}_{-59}$
$\Xi^*_{bb}D^*$	$0(\frac{5}{2}^-)$	$C_{0a}+C_{0b}$	12160	$(M_{\rm th}-15)^{+9}_{-11}$	$(M_{\rm th}-35)^{+25}_{-31}$
$\Xi^*_{bb}\bar{B}^*$	$0(\frac{5}{2}^-)$	$C_{0a}+C_{0b}$	15476	$(M_{\rm th}-29)^{+12}_{-13}$	$(M_{\rm th}-83)^{+38}_{-40}$
$\Xi'_{bc}D^*$	$0(\frac{3}{2}^-)$	$C_{0a}+C_{0b}$	8967	$(M_{\rm th}-14)^{+11}_{-13}$	$(M_{\rm th}-30)^{+27}_{-40}$
$\Xi'_{bc}\bar{B}^*$	$0(\frac{3}{2}^-)$	$C_{0a}+C_{0b}$	12283	$(M_{\rm th}-27)^{+15}_{-16}$	$(M_{\rm th}-74)^{+45}_{-51}$
$\Xi^*_{bc}D^*$	$0(\frac{5}{2}^-)$	$C_{0a}+C_{0b}$	9005	$(M_{\rm th}-14)^{+11}_{-13}$	$(M_{\rm th}-30)^{+27}_{-40}$
$\Xi^*_{bc}\bar{B}^*$	$0(\frac{5}{2}^-)$	$C_{0a}+C_{0b}$	12321	$(M_{\rm th}-27)^{+15}_{-16}$	$(M_{\rm th}-74)^{+46}_{-51}$
$\Xi_{bb}\bar{B}$	$1(\frac{1}{2}^-)$	C_{1a}	15406	$(M_{\rm th}-0.3)^{\dagger}_{-2.5}$	$(M_{\rm th}-12)^{+11}_{-15}$
$\Xi_{bb}\bar{B}^*$	$1(\frac{1}{2}^-)$	$C_{1a}+\frac{2}{3}C_{1b}$	15452	$(M_{\rm th}-0.9)[\text{V}]^{\text{N/A}}_{\dagger\dagger}$	$(M_{\rm th}-16)^{+14}_{-17}$
$\Xi_{bb}\bar{B}^*$	$1(\frac{3}{2}^-)$	$C_{1a}-\frac{1}{3}C_{1b}$	15452	$(M_{\rm th}-1.2)^{\dagger}_{-2.9}$	$(M_{\rm th}-10)^{+9}_{-13}$
$\Xi^*_{bb}\bar{B}$	$1(\frac{3}{2}^-)$	C_{1a}	15430	$(M_{\rm th}-0.3)^{\dagger}_{-2.4}$	$(M_{\rm th}-12)^{+11}_{-13}$
$\Xi^*_{bb}\bar{B}^*$	$1(\frac{1}{2}^-)$	$C_{1a}-\frac{5}{3}C_{1b}$	15476	$(M_{\rm th}-8)^{+8}_{-7}$	$(M_{\rm th}-5)^{\dagger}_{-8}$
$\Xi^*_{bb}\bar{B}^*$	$1(\frac{3}{2}^-)$	$C_{1a}-\frac{2}{3}C_{1b}$	15476	$(M_{\rm th}-2.5)^{\dagger}_{-3.6}$	$(M_{\rm th}-9)^{+9}_{-11}$
$\Xi^*_{bb}\bar{B}^*$	$1(\frac{5}{2}^-)$	$C_{1a}+C_{1b}$	15476	$(M_{\rm th}-4.3)[\text{V}]^{\text{N/A}}_{+3.3}$	$(M_{\rm th}-18)^{+17}_{-19}$

Juan M Nieves (IFIC)

DAQ is the critical experimental point



Every bunch crossing contains signal relevant to spectroscopy : real-time analysis only way

Theory & models & conclusions

NP @ HL-LHC : discovery→understanding

HL-LHC datasets give numerous complementary observables which are not theoretically limited. This is true in both CKM metrology and in the study of rare decays and processes.

Global interpretation allows characterization of any observed NP! Connects to and can guide direct high-P_T searches.

Crucial to continue exploring not only beauty but also baryonic, charm, and strange sectors, complementary information and unique opportunities.

Complementarity @ LHC

Ex. of systematics @ HL-LHC

	LHCb	ATLAS	CMS
φ_s	Statistically dom.	Tagging scales with size, rest (modelling, $B^0 \to J/\psi K^{*0}$, trigger eff., alignment) stays the same. 40 mrad very conserv. (~Run I).	Run 1: 31 mrad, prospects for YR. Dominant: $\|\lambda\|$ free, kaon pt weighting, fit model, angular efficiency.
$B_s^0 \to \mu^+\mu^-$	4%. Current dominated by knowledge of f_s/f_d, BR of normaliz. modes, 2% PID and 2% track reconstruction	Main syst: (f_s/f_d) ~ 8.3% "conservative" as same for Run I	Main syst. from knowledge of semileptonic decays (20%) and peaking backgrounds (10%)

Take home messages:

- **Flavour WG should define a similar strategy for main and common systematics (being optimistic or not, how to scale them)**
- **importance to list the main syst. expected in any future document to pin down complementarity between the experiments!**

Backups

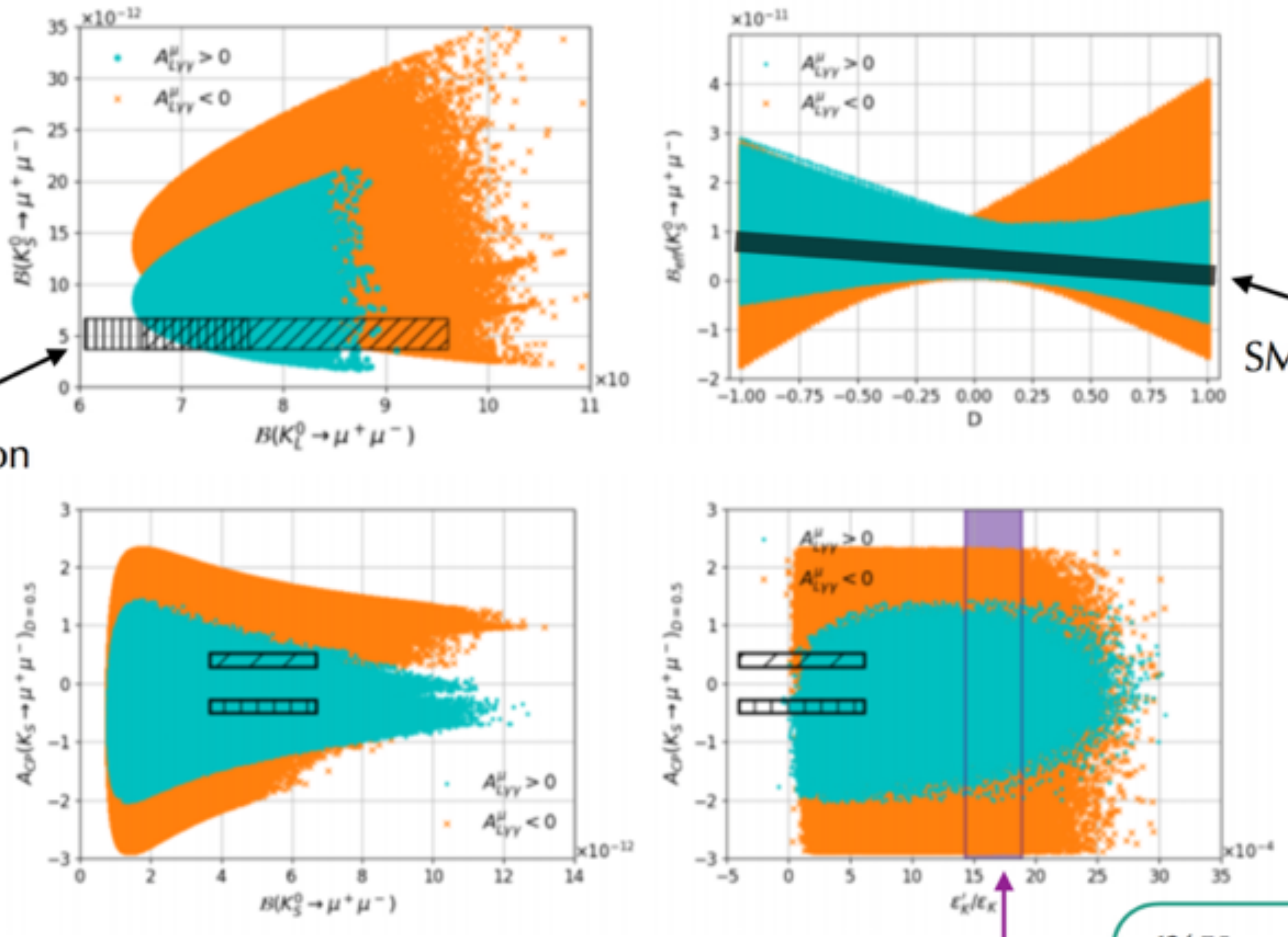
NP model predictions in Kaon physics

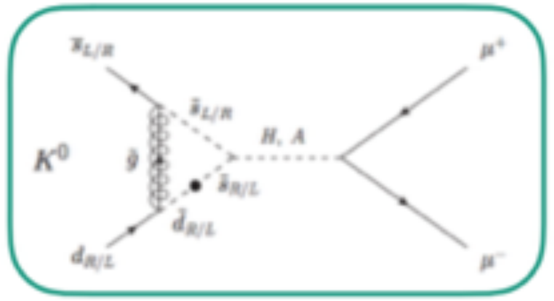
One of the MSSM scenario from Chobanova, D'Ambrosio, TK, Martinez, Santos, Fernandez, Yamamoto '18

mass difference between right-handed squarks, large tanβ, light M_A~TeV

No inter-ference plot (D=0)

D=0.5





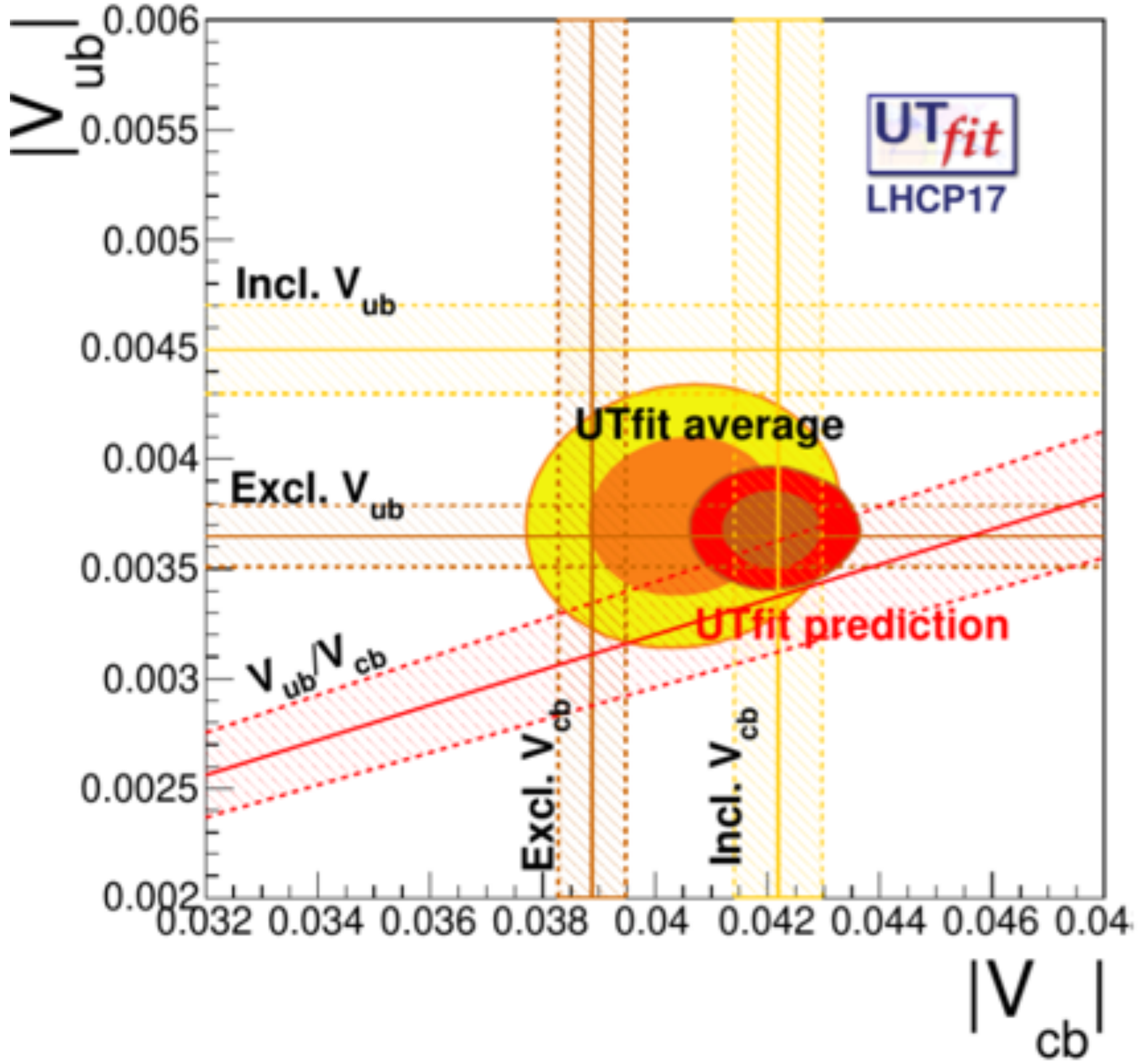
Large deviations from SM predictions are possible in the MSSM

$$\mathcal{B}(K_S \to \mu^+\mu^-)|_{\mathrm{MSSM}} \sim \mathcal{O}(1) \times 10^{-11}$$

As in other areas, complementary observables very important

From measurement to interpetation

The other tree-level constraints from semileptonic B decays are in less good shape: the long-standing disagreement between incl. and excl. measurements is still there, but there are promising new developments



CLN parametrization of the $B \to D^*$ FF's uses HQ relations which may be responsible for the $|V_{cb}|$ discrepancy. Still inconclusive, but…

Grinstein, Kobach, arXiv:1703.08170
Bigi, Gambino, Schacht, arXiv:1703.0612

New attempts at computing FF's on the lattice at small q^2

Martinelli et al., in progress