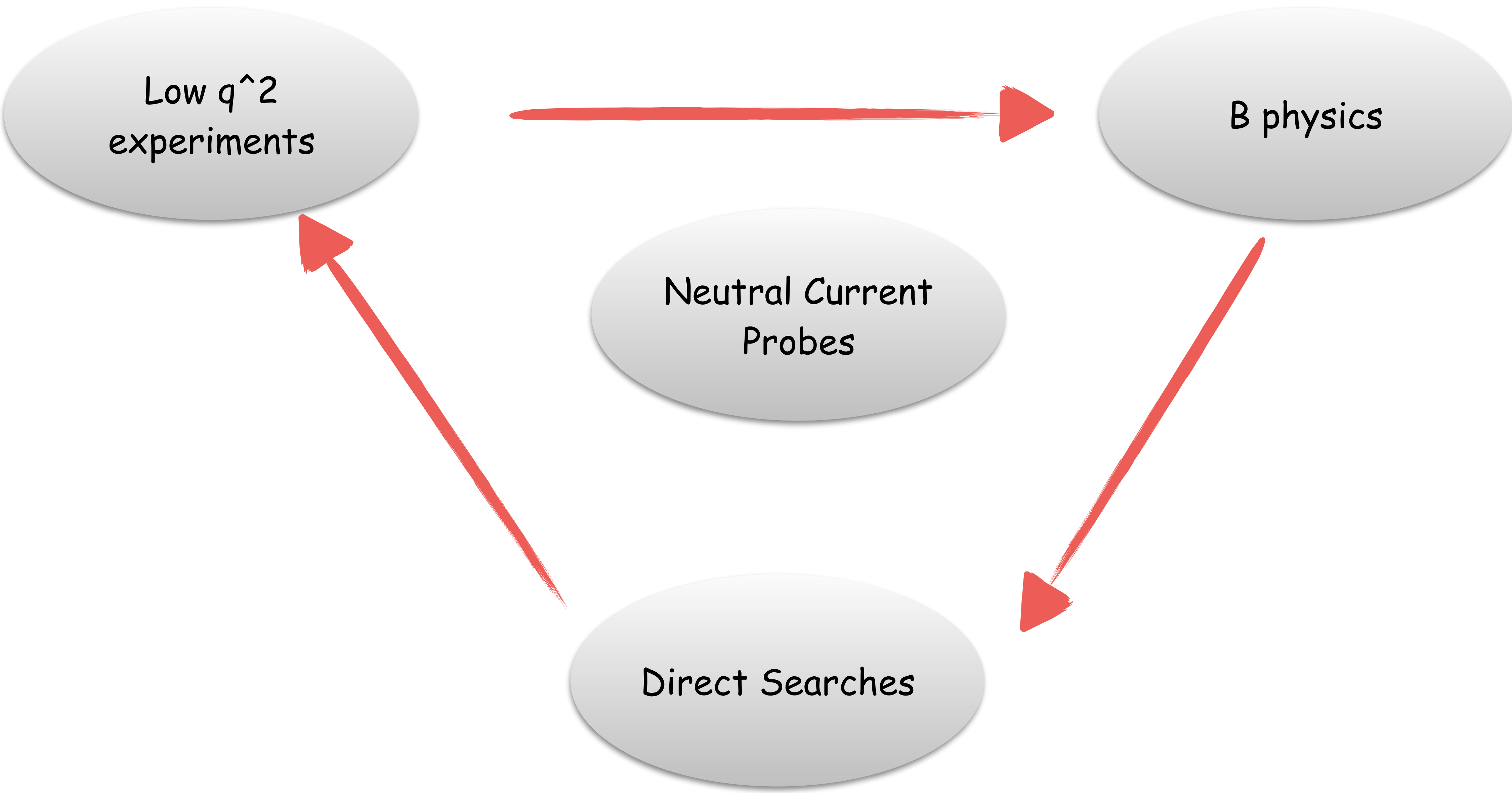
GDR-InF annual workshop
Sommieres
04-06 November

Flavour physics: From correlations to new probes

Fabrice Desse, Abhishek M. Iyer, Jacopo Cerasoli

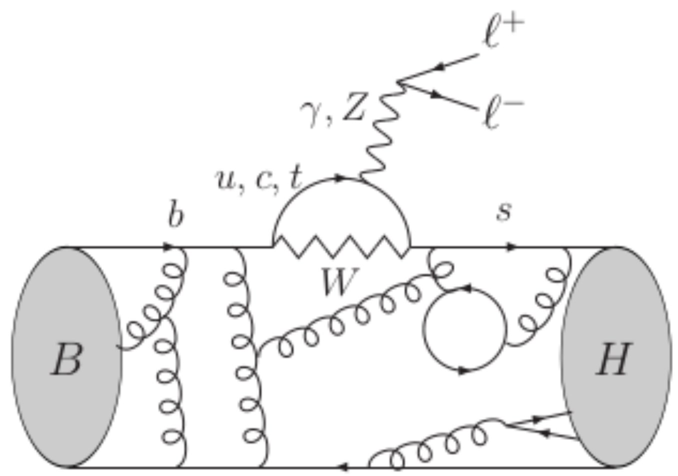
What is the goal of the talk?

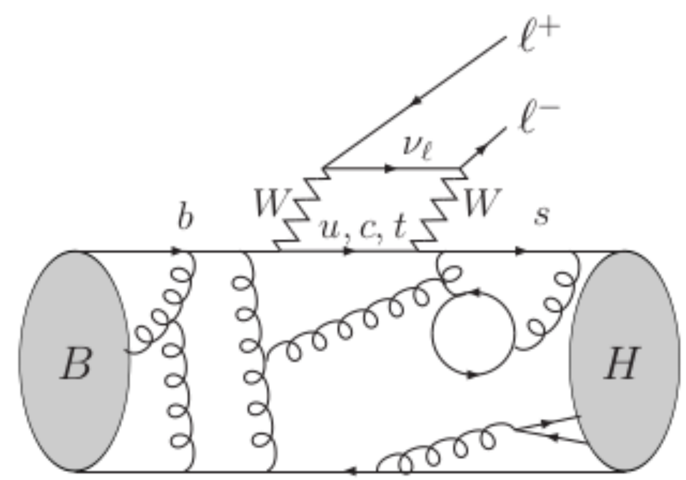


Motivations to Study *b-sll* physics

$b \to sll$ transitions are Flavour Changing Neutral Currents (FCNC) forbidden at tree-level in the Standard Model (SM):

- Sensitive to NP at loop level
- Can probe NP at much larger scales than direct searches

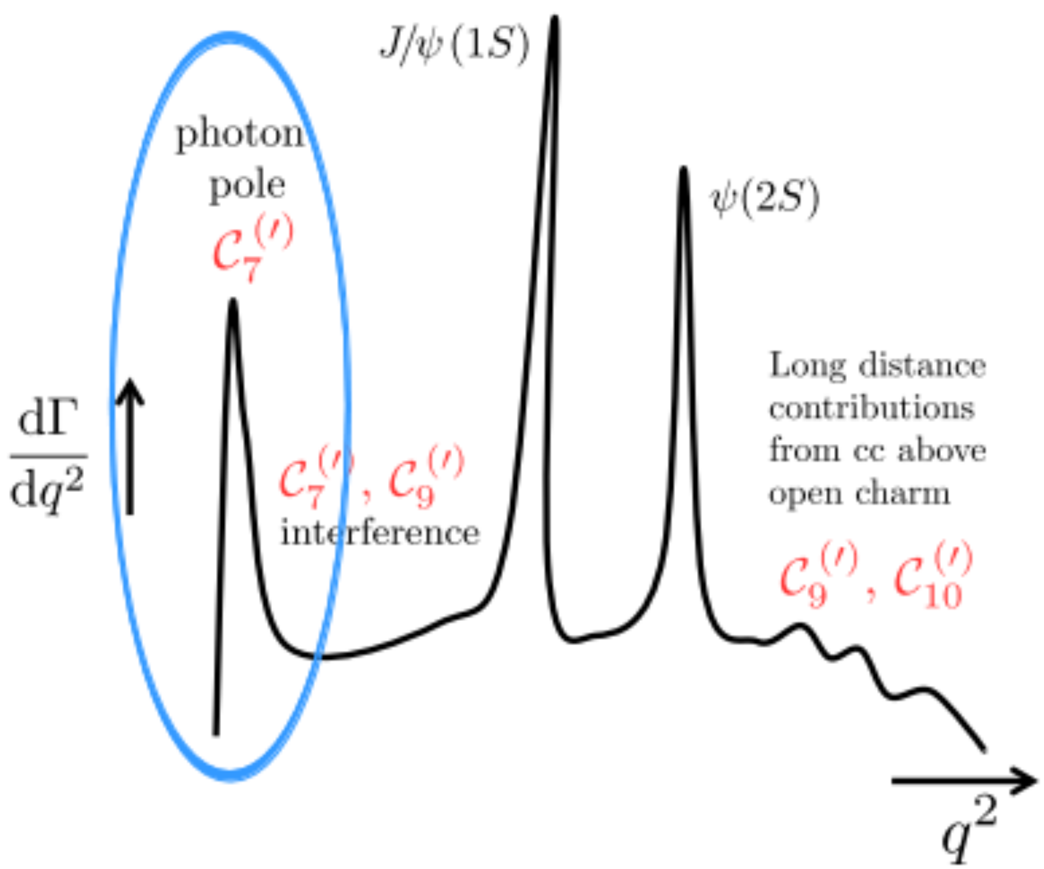




Parametrize NP contributions in a model independant way using effective field theory:

$$\mathcal{H}_{eff} \propto V_{tb} V_{ts}^* \sum_i \left(\mathcal{C}_i \mathcal{O}_i + \mathcal{C}_i' \mathcal{O}_i' \right)$$

Low q^2 angular analysis at LHCb



- With $e^{\pm}$ can go much lower in q^2 than with $\mu^{\pm}$
- Sensitive $\sim$ only to $\mathcal{C}_7^{(\prime)}$

Tensor operators in combination with other operators have been shown to explain the data for the anomalies

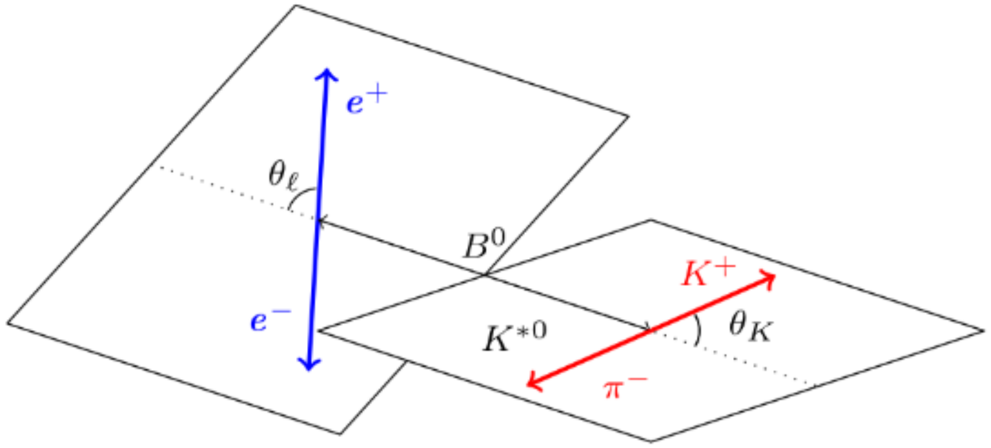
Bardhan, Byakti, Ghosh

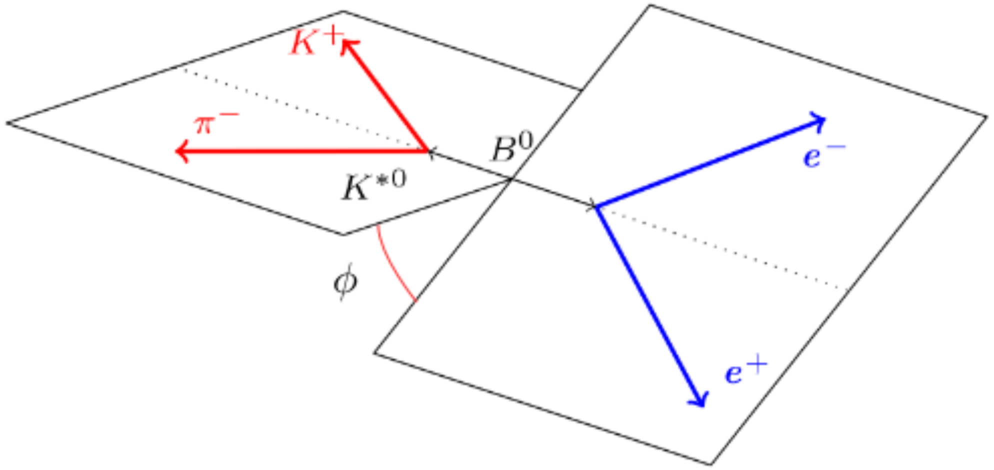
Putting constraints on $\mathcal{C}_7^{(\prime)}$

by measuring the angular distribution of $B^0 \to K^{*0} e^+ e^-$ at very low q^2 at LHCb

$$d^4\Gamma\left(B^0 \to K^{*0} e^+ e^-\right) = [\text{Probability density}] \times [d\text{Volume}] \quad ,$$

$$d\text{Volume} = dq^2 \times d\Omega = dq^2 \times d(\cos\theta_l)d(\cos\theta_k)d\phi$$





$$\left\langle \frac{[\text{Probability density}]}{[d\text{Volume}]} \right\rangle_{CP,q^2} = f\left(F_L(\mathcal{C}_i^{(\prime)}), A_T^{(2)}(\mathcal{C}_i^{(\prime)}), A_T^{Im}(\mathcal{C}_i^{(\prime)}), A_T^{Re}(\mathcal{C}_i^{(\prime)}), \cos\theta_l, \cos\theta_k, \tilde{\phi}\right)$$

$$\tilde{\phi} = \phi + \pi \text{ if } \phi < 0 \text{ else } \phi$$

Strategy of the analysis

$$\left\langle \frac{[\text{Probability density}]}{[d\text{Volume}]} \right\rangle_{CP,q^2} = f\left(F_L(\mathcal{C}_i^{(\prime)}), A_T^{(2)}(\mathcal{C}_i^{(\prime)}), A_T^{Im}(\mathcal{C}_i^{(\prime)}), A_T^{Re}(\mathcal{C}_i^{(\prime)}), \cos\theta_l, \cos\theta_k, \tilde{\phi} \right)$$

Do a simultaneous 4D fit:

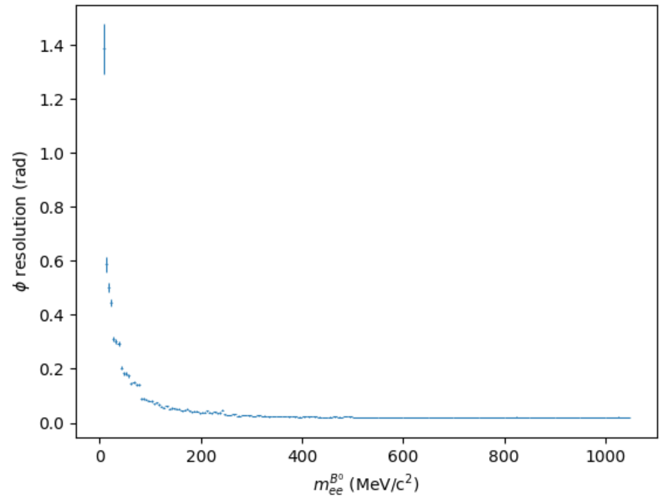
- $m(K^+\pi^-e^+e^-)$ to separate signal from background
- $\cos\theta_K$, $\cos\theta_\ell$, $\tilde{\phi}$ to dtermine F_L, $A_T^{(2)}$, A_T^{Im} and A_T^{Re}

The free parameters of the fit, Our physical observables that we fit

Choice of the q^2 bin

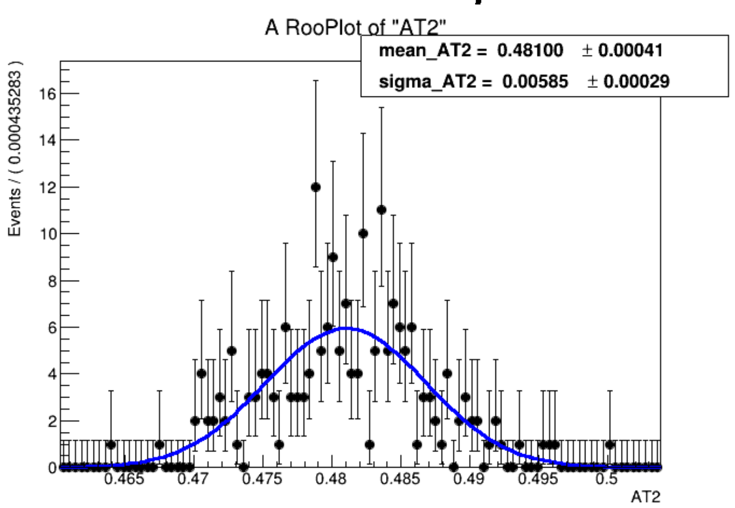
Lower boundary

Lower m_{ee} $\Rightarrow$ lower ee angle $\Rightarrow$ lower $\tilde{\phi}$ resolution



Chose $m_{ee} > 10\ \mathrm{MeV}/c^2$

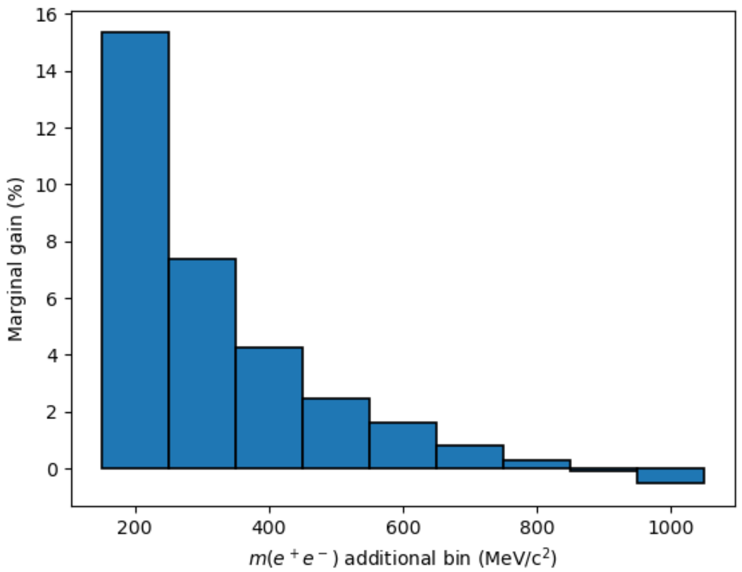
Estimated bias on $A_T^{(2)} \sim 4\%$



Upper boundary

$d\Gamma \propto (1 - F_L) A_T^{(2)}$

$\Rightarrow N_{eff} = N(1 - < F_L >)^2$



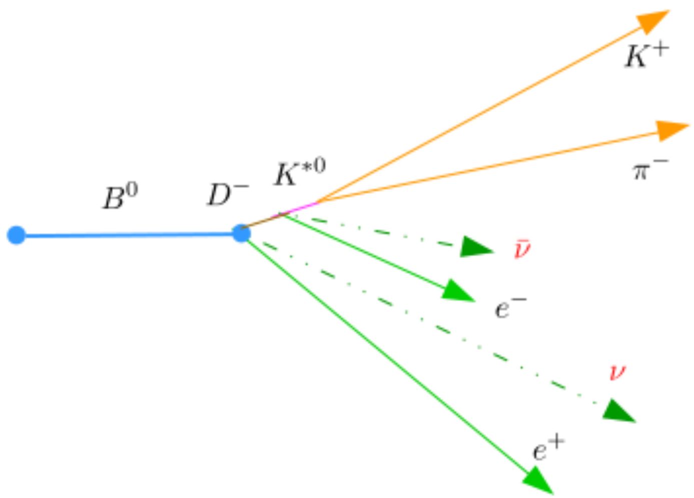
Avoid ρ^0

$(m_{\rho^0} = 770\ \mathrm{MeV}/c^2,\ \Gamma_{\rho^0} = 149\ \mathrm{MeV}/c^2)$

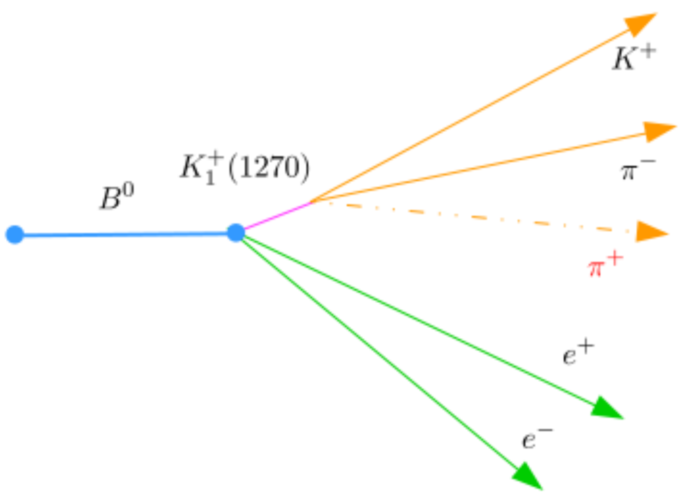
$m_{ee} < 500\ \mathrm{MeV}/c^2$

$$\boxed{m_{ee} \in [10, 500]\ \mathrm{MeV}/c^2 \Leftrightarrow q^2 \in [.0001, .25]}$$

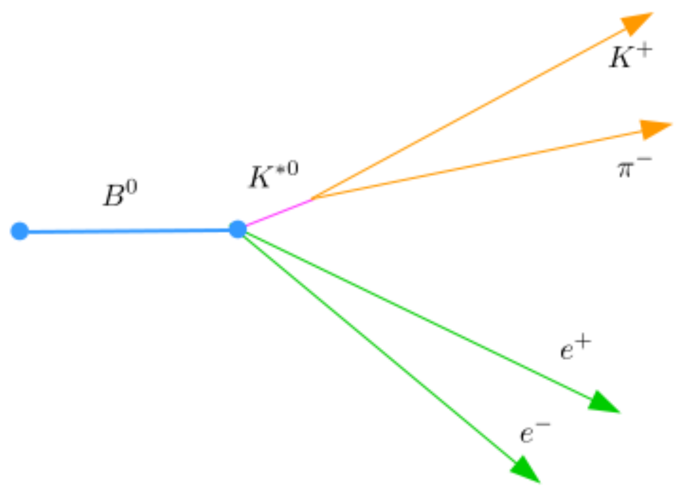
Main backgrounds



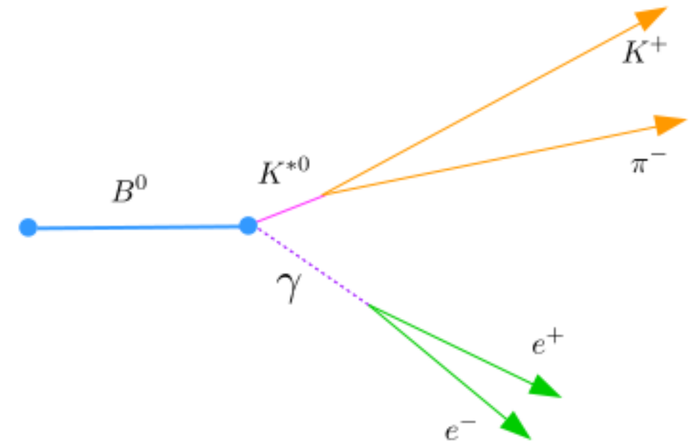
Semi-leptonic



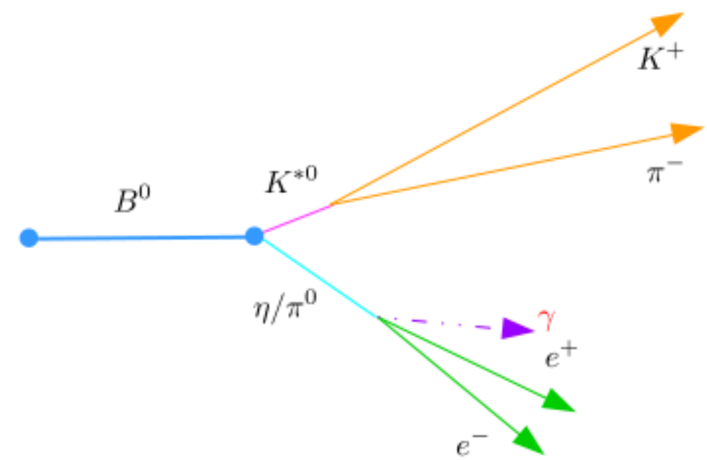
Partially reconstructed



Signal $B^0 \to K^{*0} e^+ e^-$



Photon conversion



Dalitz η or π^0 decays

Mass fit (full Run1 + Run2)

$B^0 \to K^{*0} e^+ e^-$

Converted photons

$B^0 \to K^{*0} \pi^0 (\to \gamma e^+ e^-)$

$B^0 \to K^{*0} \eta (\to \gamma e^+ e^-)$

Partially reconstructed

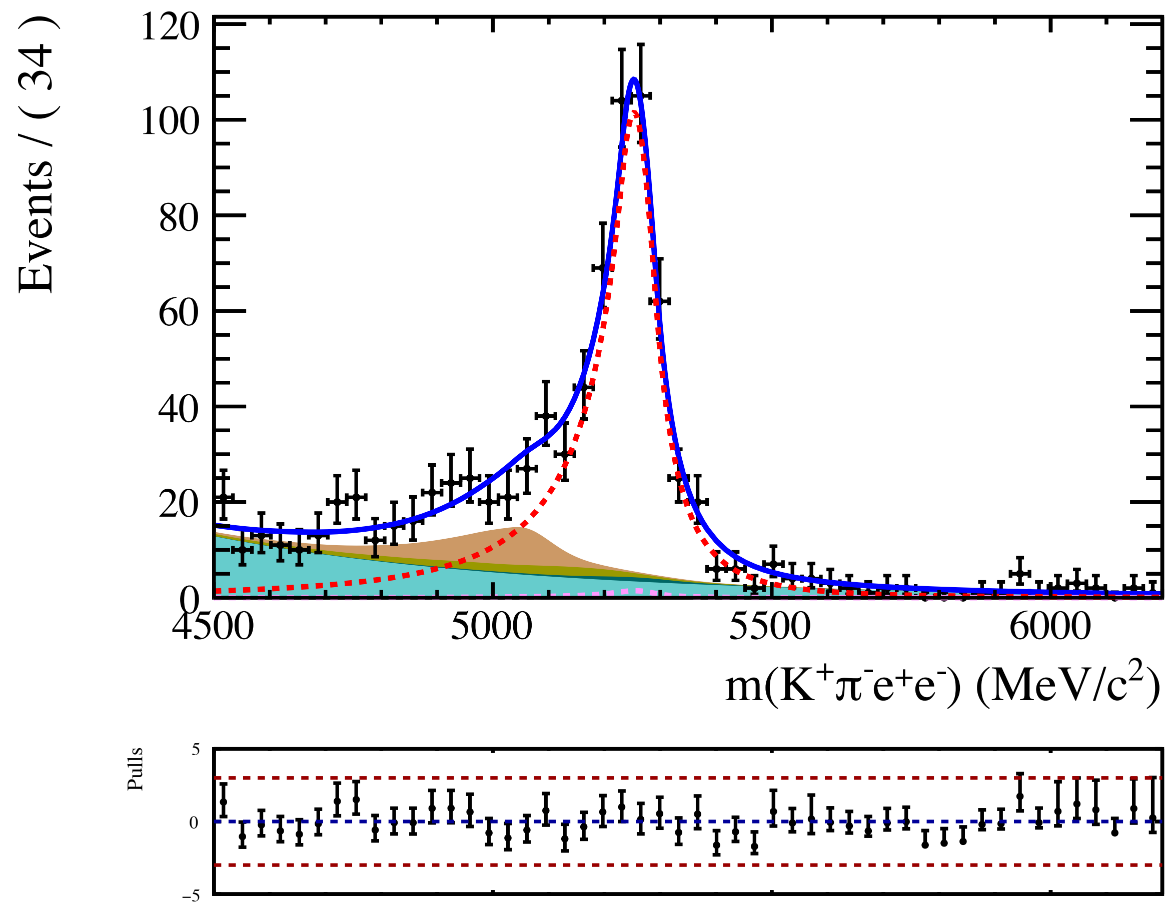
Combinatorial + semi leptonic

In angular fit window

$[5000, 5400]\ \mathrm{MeV}/c^2$

Signal yield = 454 events

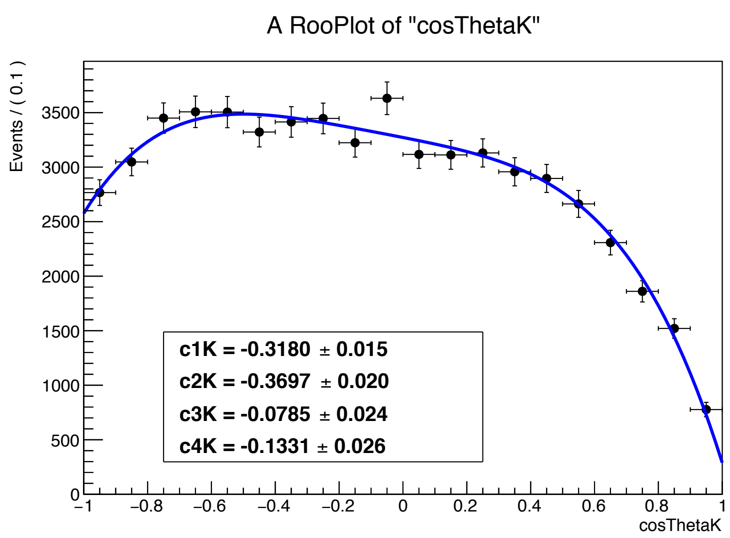
Total bkg = 103 events (23%)



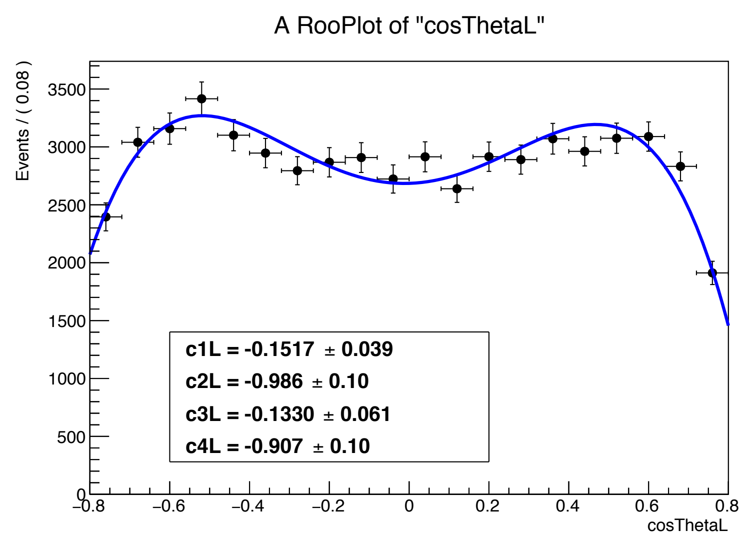
Angular acceptance

The reconstruction and the selection distorts the angular shapes.

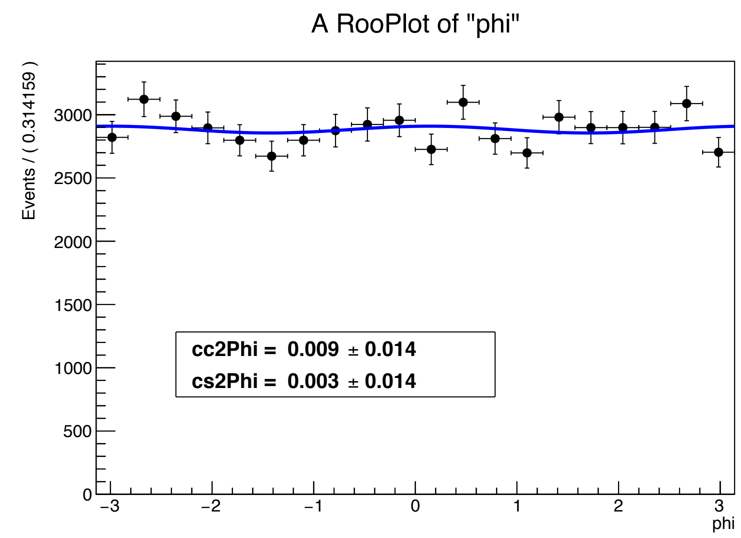
1. Generate (unphysical) signal MC with flat angles distributions
2. Apply reconstruction + full selection
3. Fit to obtain the angular acceptance



Order 4 Legendre polynomial



Order 4 Legendre polynomial

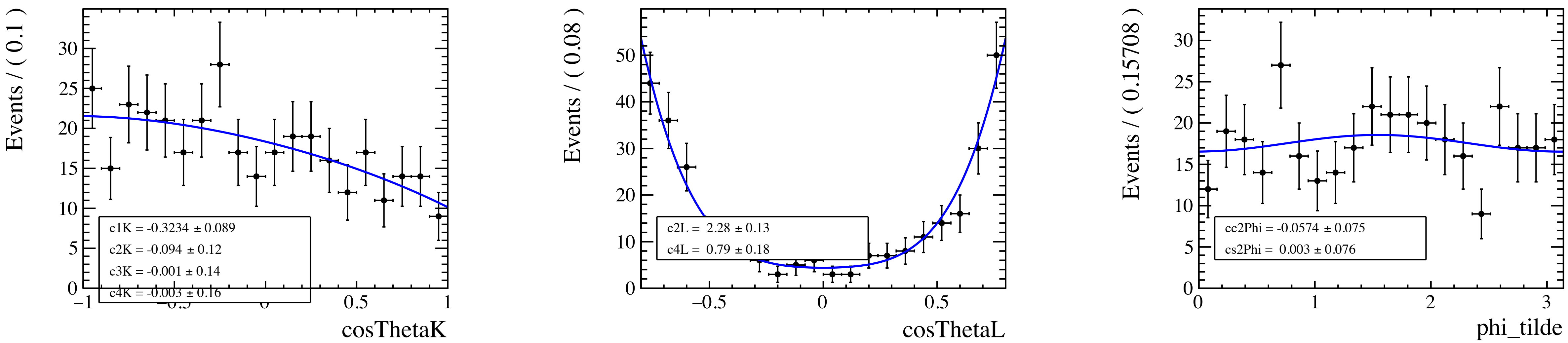


$1 + c_c \cos 2\phi + c_s \sin 2\phi$

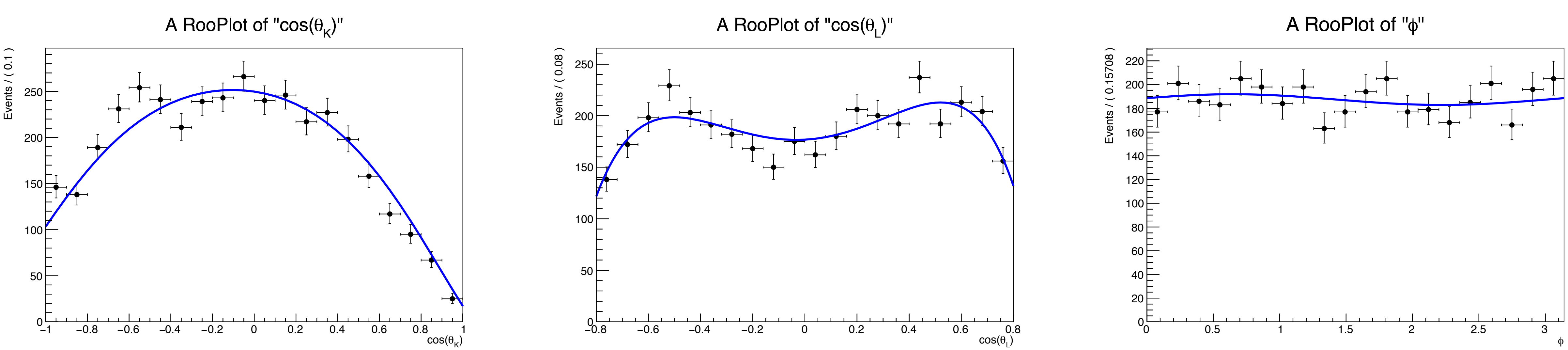
Angular modelling of the brackgrounds

Preliminary plots, still validating and doing crosschecks

1. Combinatorial and semi leptonic backgrounds: fit Legendre polynomial to $B^0 \to K^{*0} e^+ \mu^-$ data

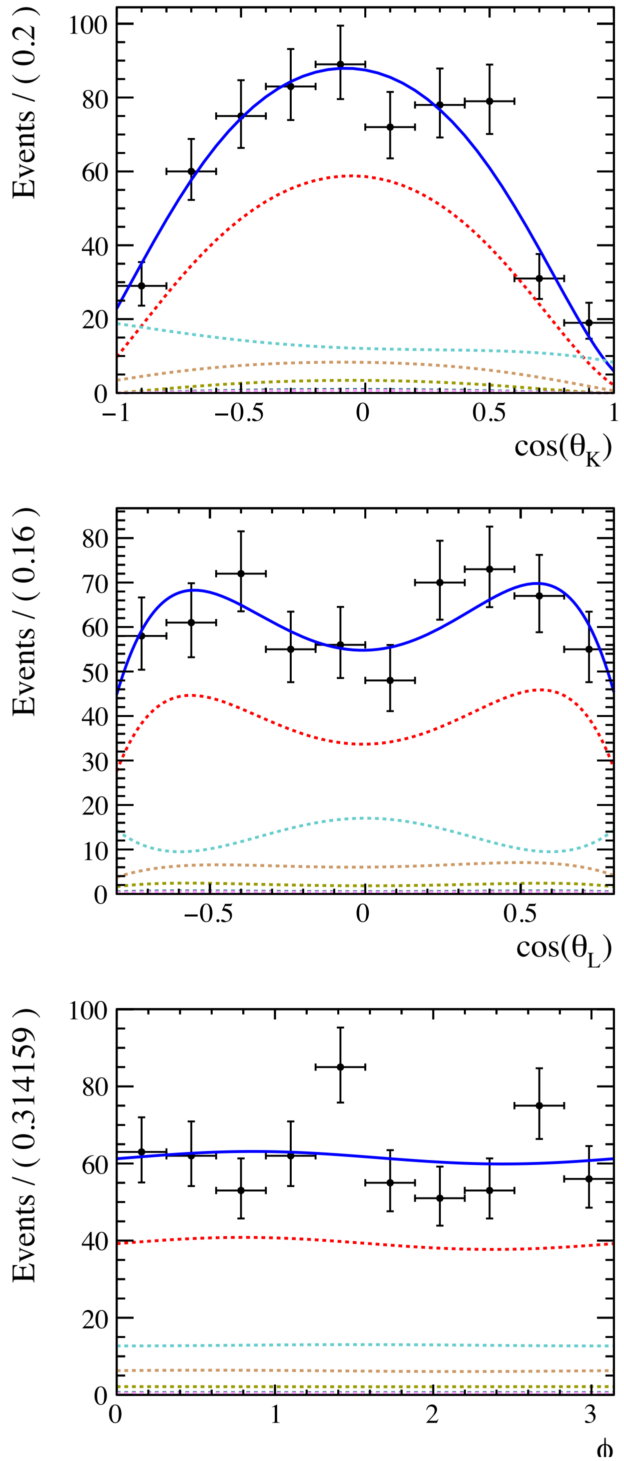


2. Partially reconstructed, converted photon and Dalitz backgrounds: fit signal PDF or Legendre polynomials to MC (here some example plots with partially reconstructed)

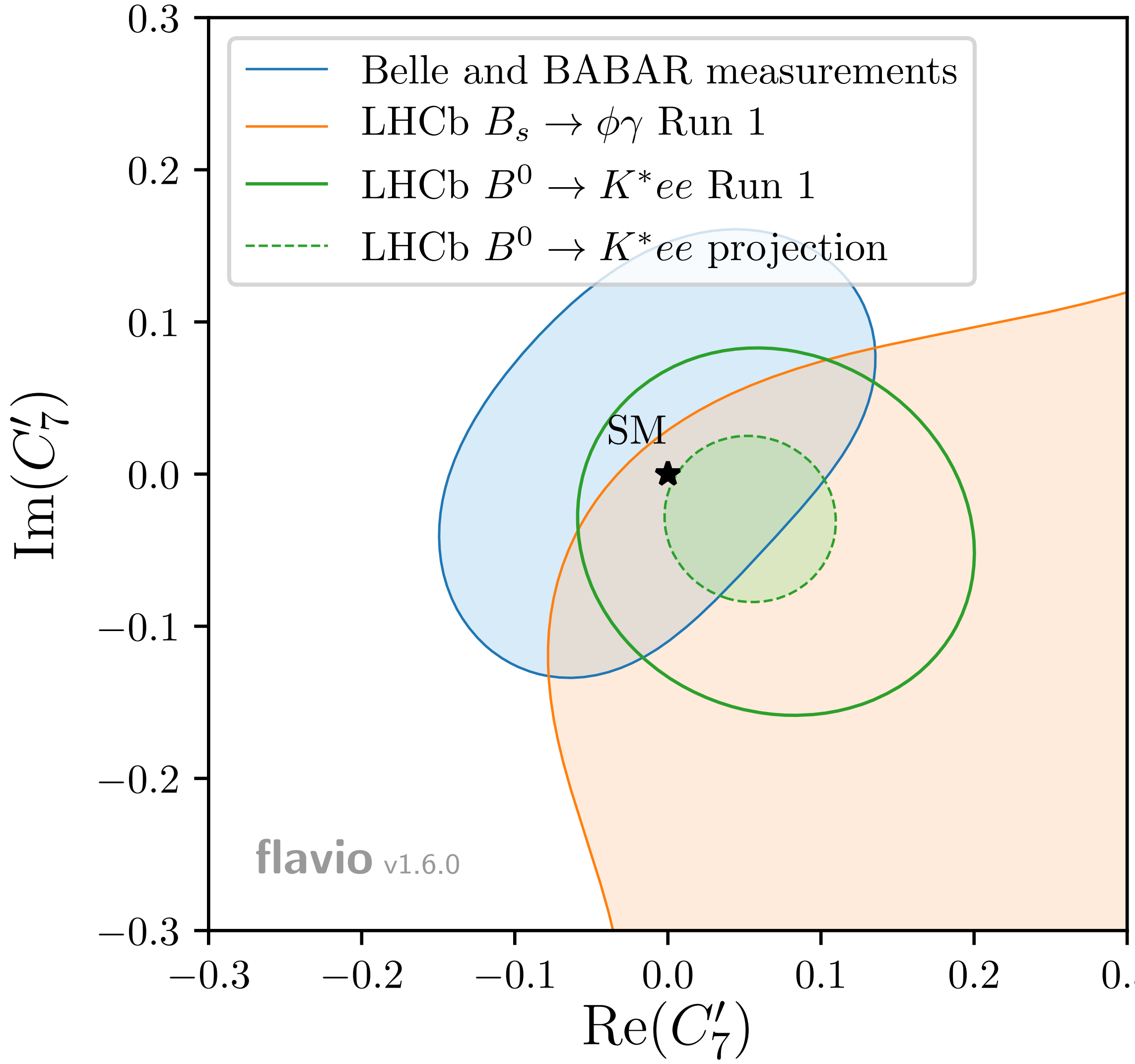


Angular fit

Toy generated with SM values



Estimated sensitivity on $A_T^{(2)} \sim 0.10$ (stat)



Summary of Part I

- $b \to sll$ decays sensitive to $\mathcal{C}_7^{(\prime)}$ at very low q^2
- Electrons in the final state allow to go down to $0.0001\,\mathrm{GeV}^2/c^4$
- Put constraints on $\mathcal{C}_7^{(\prime)}$: expected sensitivity $\mathcal{O}(5\%)$
- In the context of the anomalies: strong constraint on $\mathcal{C}_7^{(\prime)}$ very useful for the determination of $\mathcal{C}_{9,10}$ in global fits

Low q^2 experiments relevant for anomalies

These experiments can be classified into:

Atomic parity violation experiments in Cs

CS Wood et, al

Weak neutral current

Parity violation due to electron scattering of liquid hydrogen target

Jefferson Lab Collab

Both these experiments measure the weak charge of the Cs Nucleus and proton respectively

In SM model parametrization

$$\mathcal{L}_{Q_W,Q_P} = \frac{\bar{e}\gamma_\mu\gamma_5 e}{2v^2}\sum_{q=u,d} C_{1q}\bar{q}\gamma^\mu q$$

where

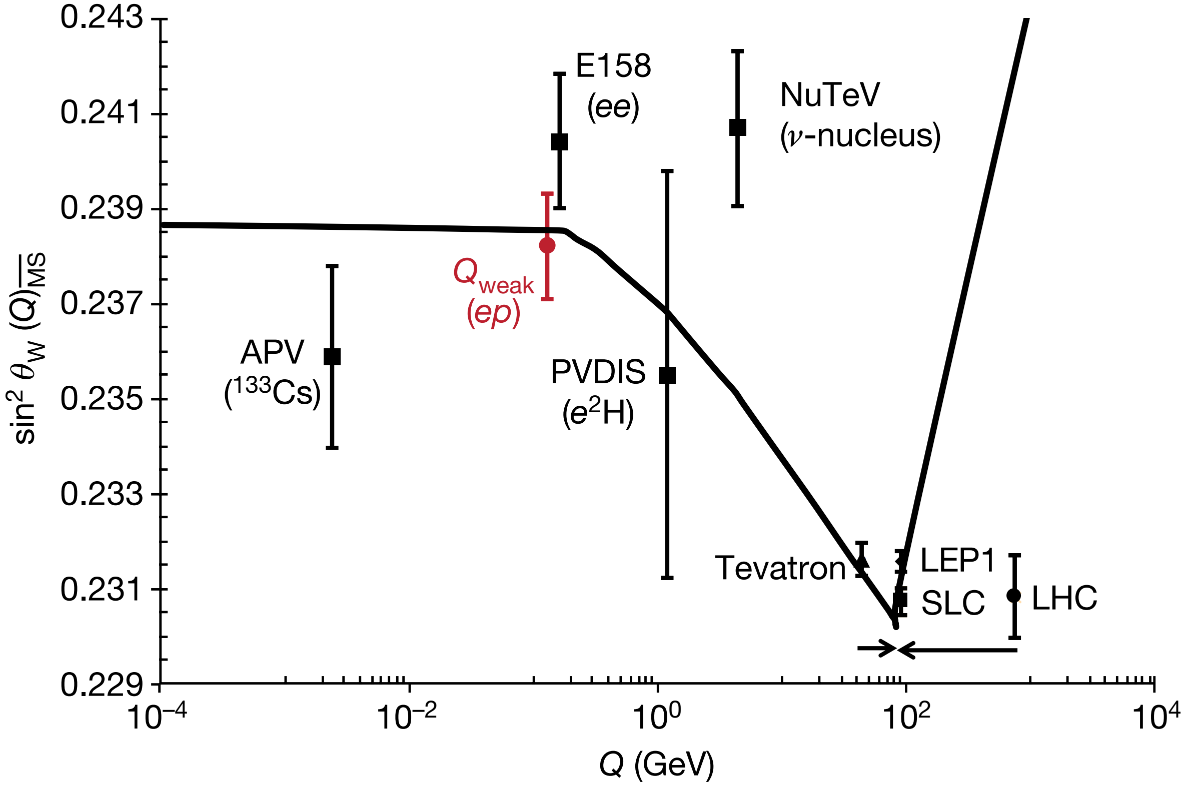
$$C_{1u} = -\frac{1}{2} + \frac{4}{3}\sin^2_{\theta_W}$$
$$C_{1d} = \frac{1}{2} - \frac{2}{3}\sin^2_{\theta_W}$$

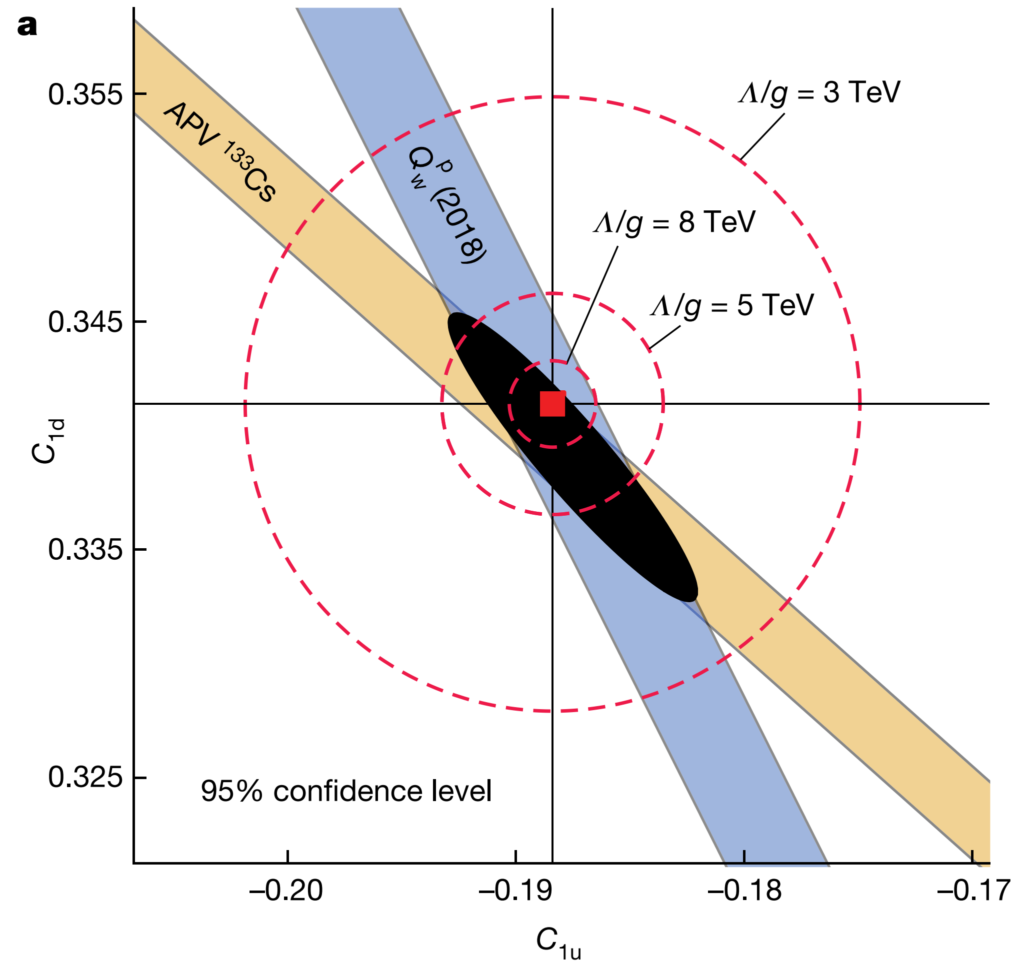
$$Q_W^p = -2\left[2C_{1u} + C_{1d}\right]$$
$$Q_W^{Cs} = -2\left[55(2C_{1u} + C_{1d}) + 78(C_{1u} + 2C_{1d})\right]$$

$$C_{1u}^{SM} = -0.1887 \pm 0.0022$$
$$C_{1d}^{SM} = 0.3419 \pm 0.0025$$

Jefferson Lab Qweak Collab
Nature

Lets combine the experiments (Parity Violating ones)





extraction of the weinberg angle from these measurements

So far:

How are these low energy experiments relevant for B anomalies

We also discussed the two parity violation experiments which measure the axiol vector electron and vector quark coupling to the Z boson

How are these connected?

Lets go back to the effective lagrangian description of both

Anomalies

$$\mathcal{H}_{eff} = -\frac{G_f \alpha}{\sqrt{2}\pi} V_{tb} V_{ts}^* \sum_i \mathcal{O}_{XY} C_{XY}$$

$$\mathcal{O}_{b_X \ell_Y} = (\bar{s}\gamma_\mu P_X b)(\bar{\ell}\gamma_\mu P_Y \ell).$$

$$C_{XY} = C_{XY}^{SM} + C_{XY}^{NP}.$$

Heavy quarks and chiral lepton current

A priori there is be no relation bet light and heavy quark coupling to NP

PV experiments

$$\mathcal{L} = \frac{\bar{e}\gamma_\mu\gamma_5 e}{2v^2} \sum_{q=u,d} C_{1q}^{eff} \bar{q}\gamma^\mu q$$

$$C_{1q}^{eff} = C_{1q}^{SM} + C_{1q}^{NP}$$

Light quarks and chiral lepton current

The effective Lagrangian with Z′

$$\mathcal{L} = \frac{Z'^{\mu}}{2\cos\theta_w}\,\Big[g_e(g'_e)\bar{e}\gamma_\mu P_{L(R)}e + g_\mu(g'_\mu)\bar{\mu}\gamma_\mu P_{L(R)}\mu$$
$$+ \sum_q (g_q\bar{q}\gamma_\mu P_L q + g'_q\bar{q}\gamma_\mu P_R q)$$
$$+ (g_t - g_q)V^*_{ts}V_{tb}\bar{s}\gamma_\mu P_{L,R}b + \ldots\Big]$$

From this lagrangian we can identify the additional contribution to the WC contributing to B anomalies as well as PV experiments

Since the fits for anomalies involve only on WC at a time, we consider the following three cases

	WC	operator	Best fit	2 σ
Case A	C_{LL}	$(\bar{s}_L\gamma^\mu b_L)(\bar{e}_L\gamma_\mu e_L)$	0.99	[0.37,1.61]
Case B	C_{LR}	$(\bar{s}_L\gamma^\mu b_L)(\bar{e}_R\gamma_\mu e_R)$	-3.46	[-4.76,-2.16]
Case C	C_{RR}	$(\bar{s}_R\gamma^\mu b_R)(\bar{e}_R\gamma_\mu e_R)$	-3.63	[-5.5,-2.67]

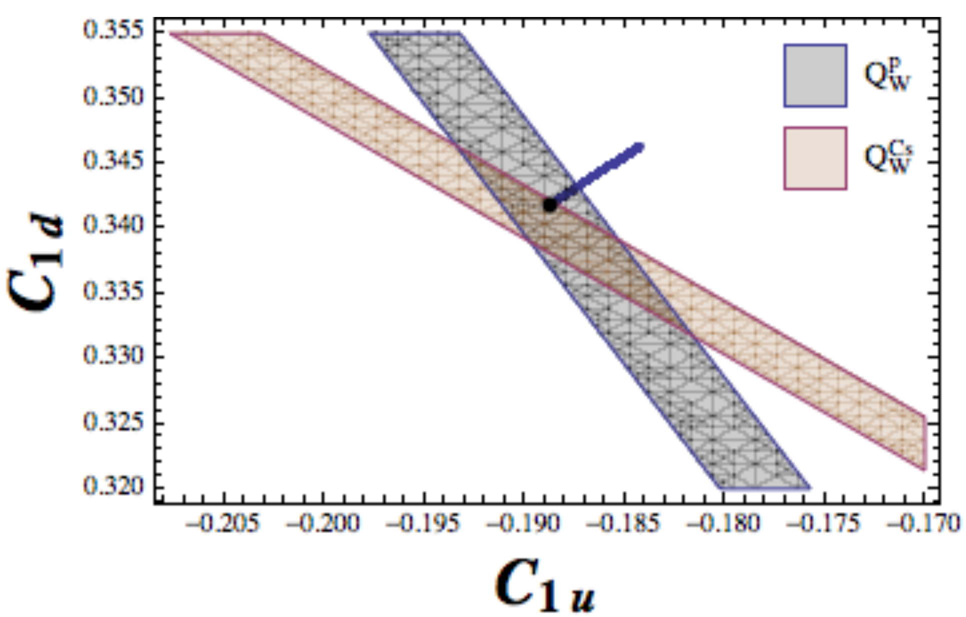
TABLE I. 2σ ranges used for the fits to Wilson coefficients in the case where only electron couples to New Physics.

G. D'Ambrosio, A.I, F.Piccinini, A Polosa
1902.00893

Case A

$$C_{LL} = \frac{\sqrt{2}\pi g_e (g_t - g_q)}{4\cos^2\theta_W m_{Z'}^2 G_F \alpha}$$

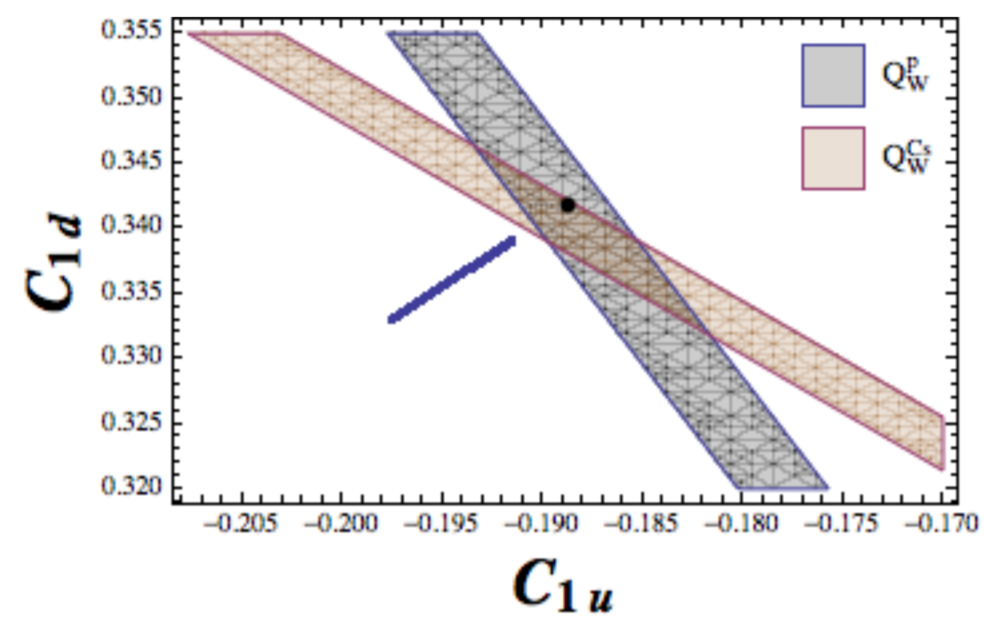
$$C_{1q}^{eff} = C_{1q}^{SM} + \frac{2v^2 g_e g_q}{8\cos^2\theta_W m_{Z'}^2}$$



Case B

$$C_{LR} = \frac{\sqrt{2}\pi g'_e (g_t - g_q)}{4\cos^2\theta_W m_{Z'}^2 G_F \alpha}$$

$$C_{1q} = C_{1q}^{SM} - \frac{2v^2 g'_e g_q}{8\cos^2\theta_W m_{Z'}^2}$$



For light quark we assume

$$g_q = g'_q$$

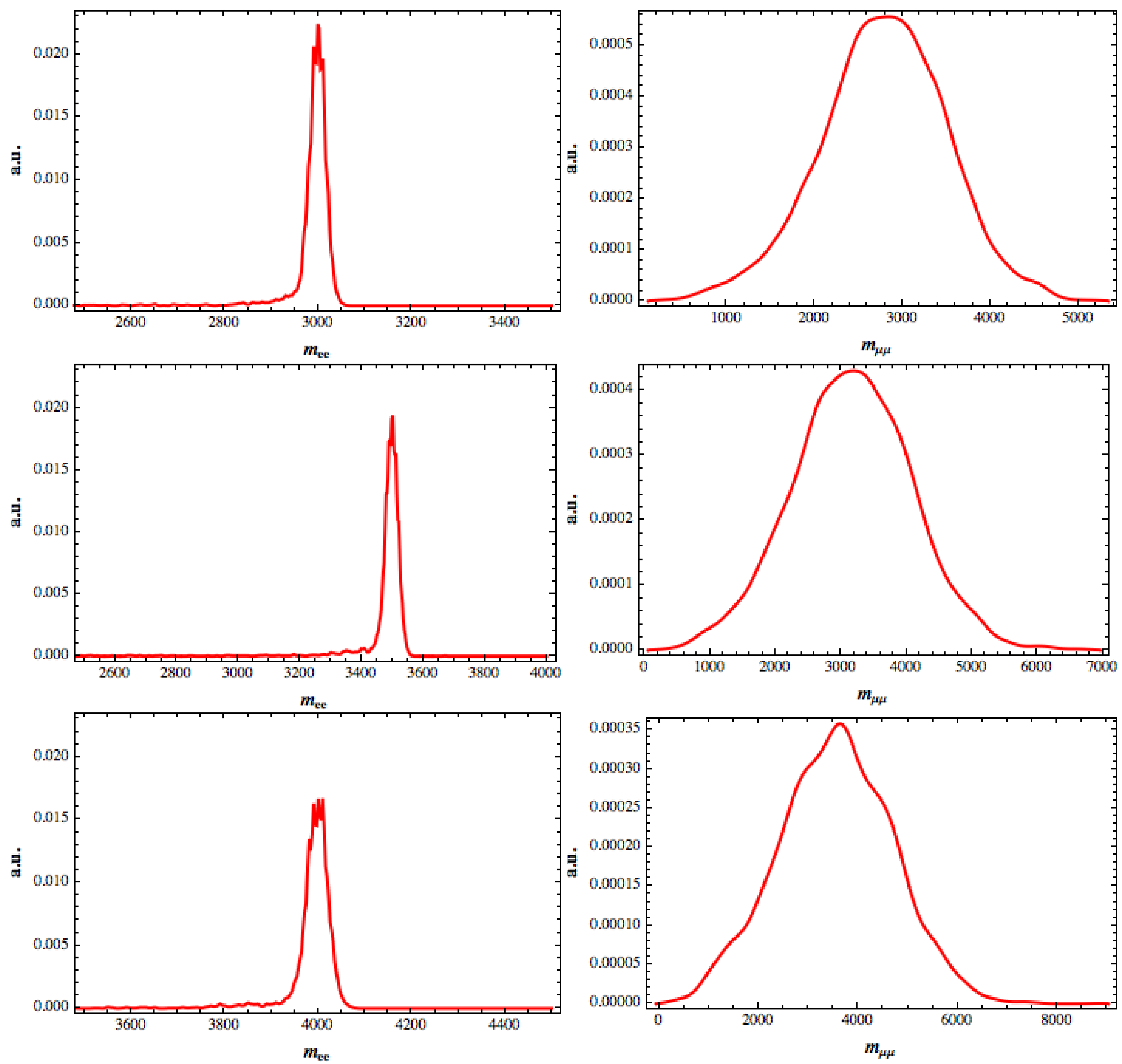
Has implications for direct searches!!

D’Ambrosio, F. Conventi, Iyer, Rossi, Mangano
To appear

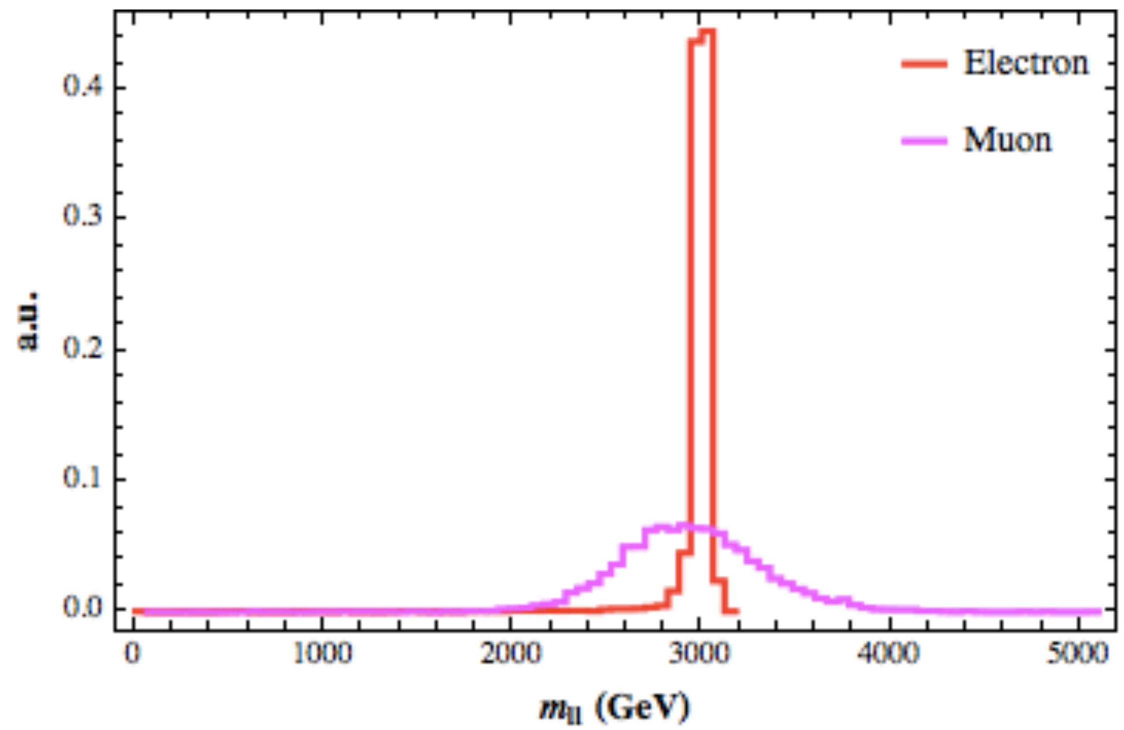
From indirect searches to colliders

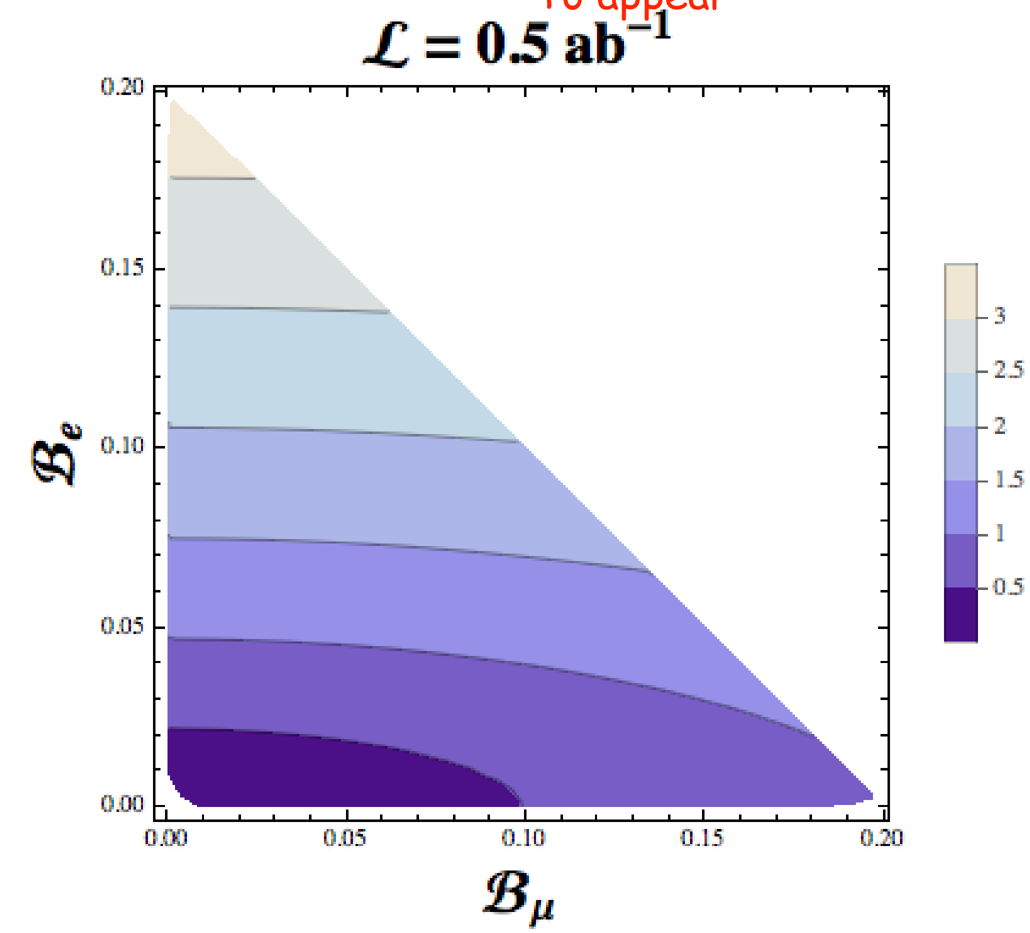
What are the prospects of an electron only solution in comparison to a muon only solution?

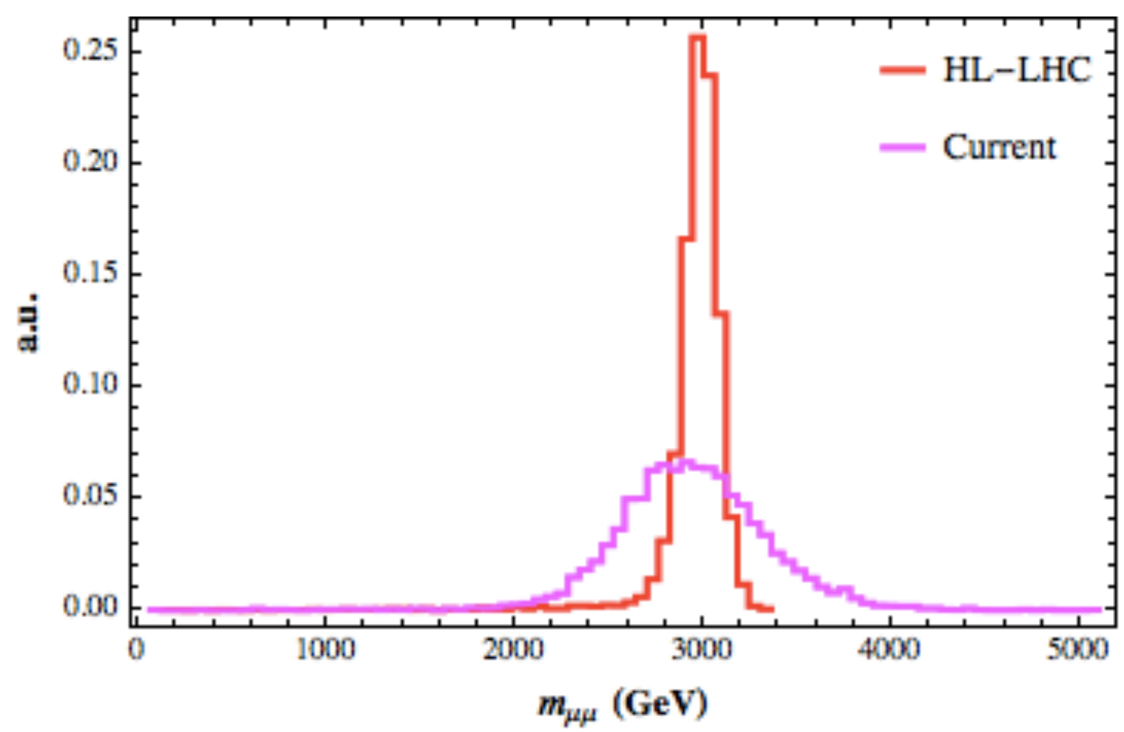
Current Lepton mass reconstruction efficiencies

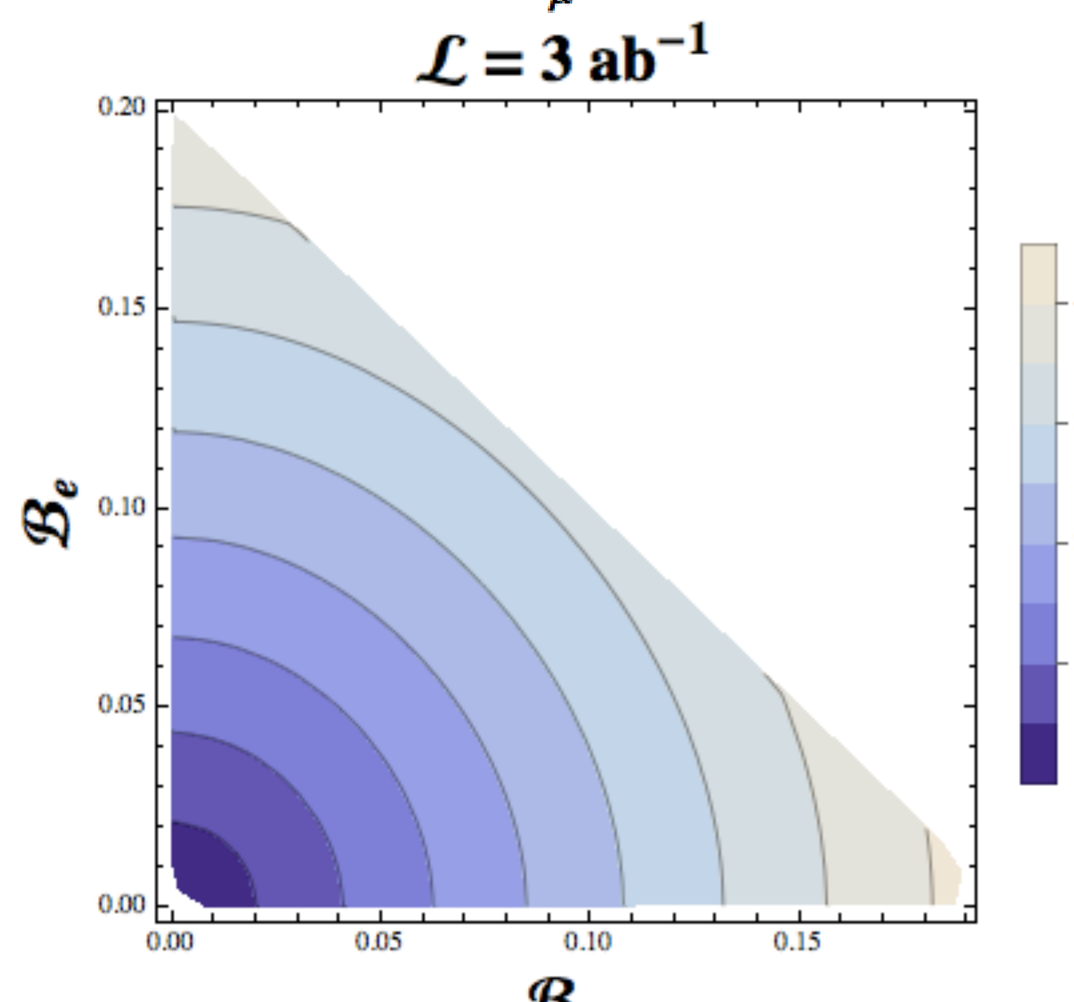


D'Ambrosio, F. Conventi, Iyer, Rossi, Mangano
To appear









Test of universality

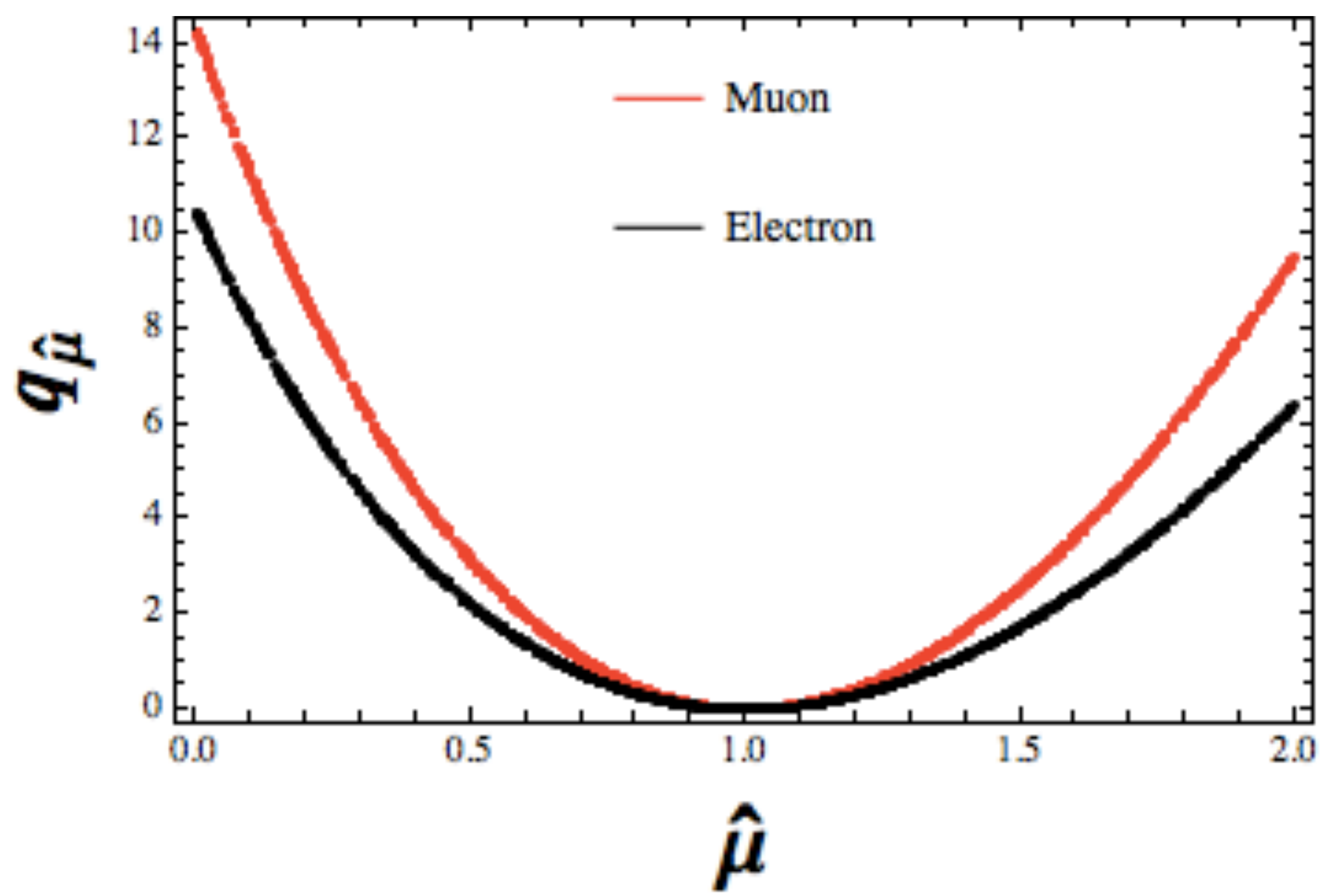
D'Ambrosio, F. Conventi, Iyer, Rossi, Mangano
To appear

Consider a general test statistic

$$q_{\hat{\mu}} = -2 \log \left[\frac{\hat{\mu} s + b}{s + b} \right]$$

Its defined separately for both the electrons and muons such that

$$\hat{\mu}_e + \hat{\mu}_\mu = 2$$



$$0 \leq \hat{\mu} \leq 2.$$

Summary of Part II

A note on di-tau modes

This test statistic can also be applied to explore non-universality in di-tau modes

This is relatively more involved owing to the tagging techniques used in identifying the tau

Substructure variables are known to work well especially for the hadronic tau

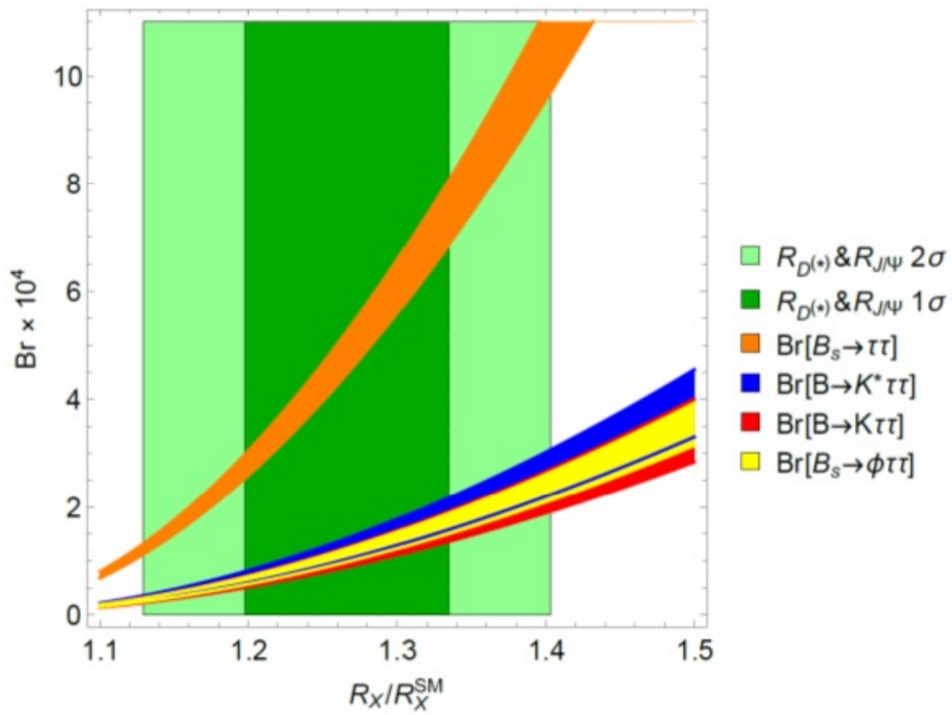
Chakraborty, Roy, Iyer

This analysis can be correlated with B-K* tau tau analysis at LHCb

Talk by Jacopo

Introduction

- b → s $l^+ l^-$ quark level transition at second order, **expected BR(B^0 -> K* $\tau^+ \tau^-$) ~ 10^{-7}** *
- Standard Model prediction based on LFU assumption, but…
- …due to new physics particles entering the loop, branching ratios could be enhanced up to hundreds times the SM predictions
- Tau lepton modes still largely unexplored
- Still lots of room for beyond the SM effects
- More complex experimentally



Capdevila, Crivellin, Descotes-Genon, Matias
arXiv 1712.01919

- Goal: perform study on **two final states** (and charged conjugates) using Run1 + Run2 data:

$$B \to K^*(\to K^-\pi^+)\tau^+(\to \pi^+\pi^+\pi^-\bar{\nu}_\tau)\tau^-(\to \pi^+\pi^-\pi^-\nu_\tau) \ \to$$ **3π3π final state**

$$B \to K^*(\to K^-\pi^+)\tau^+(\to \pi^+\pi^+\pi^-\bar{\nu}_\tau)\tau^-(\to \mu^-\nu_\tau\bar{\nu}_\mu) \ \to$$ **3πμ final state**

*https://arxiv.org/abs/1712.01919v1

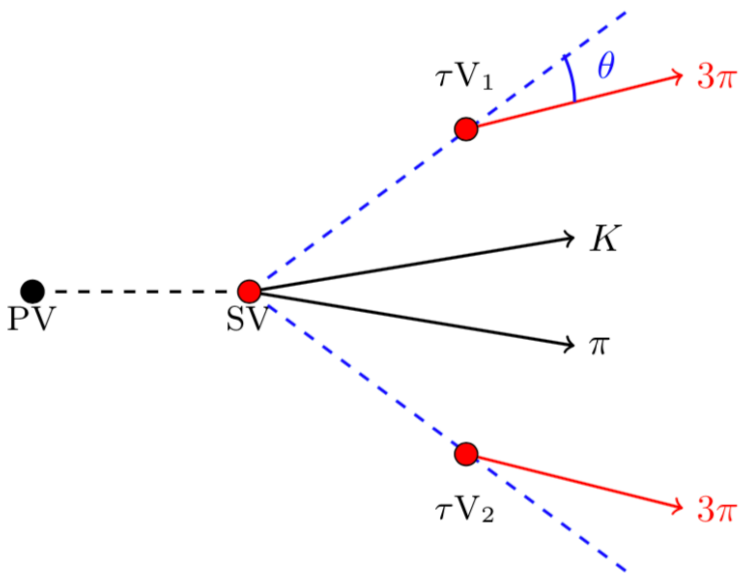
3π3π final state

Neutrinos and mass reconstruction

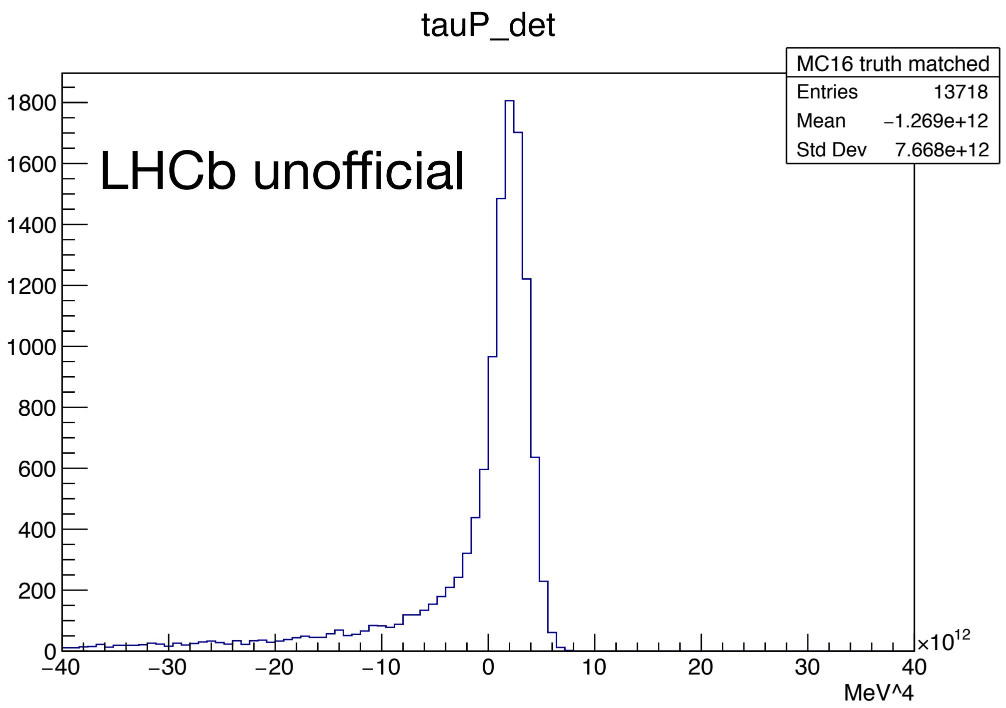
- Two neutrinos in final state, LHCb has not 4π coverage: missing energy!
- **Tau momentum can be reconstructed analytically** imposing its true mass:

$$|\vec{p_\tau}| = \frac{(m_\tau^2 + m_{3\pi}^2)|\vec{p}_{3\pi}|\cos\theta \pm E_{3\pi}\sqrt{(m_\tau^2 - m_{3\pi}^2)^2 - 4m_\tau^2|\vec{p}_{3\pi}|^2\sin^2\theta}}{2(E_{3\pi}^2 - |\vec{p_{3\pi}}|^2\cos^2\theta)}$$

$$\vec{p}_\tau = |\vec{p}_\tau|\,\vec{u}_\tau\ ,\ \vec{u}_\tau = \frac{\vec{p}_{\tau V} - \vec{r}_{SV}}{|\vec{p}_{\tau V} - \vec{r}_{SV}|}$$

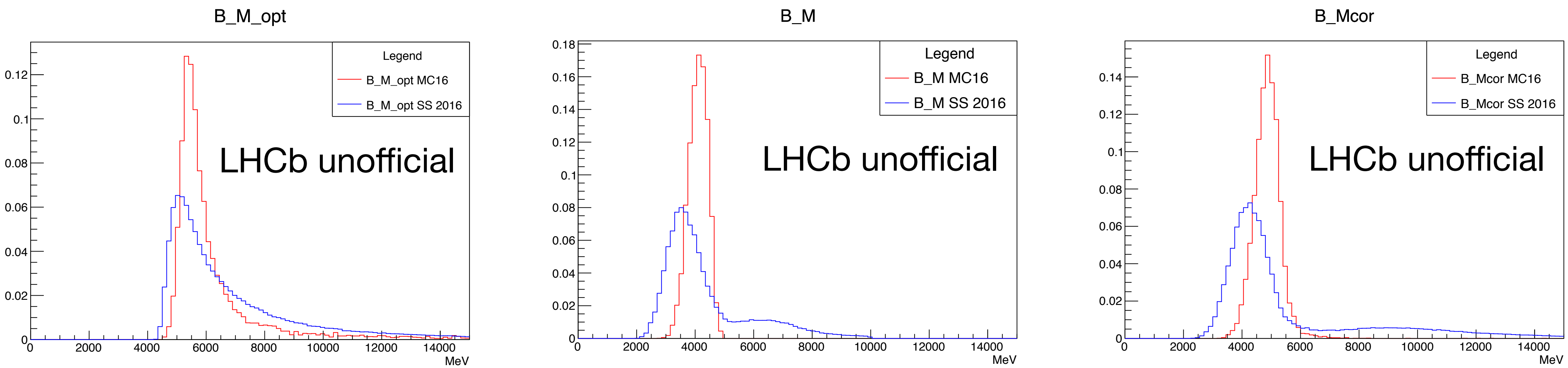


- Due to vertex resolution the discriminant can be negative
- In signal sample only 33% candidates have positive discriminant for both taus, discriminant set to 0 if negative
- **Four-fold ambiguity on B mass.** "Optimal" solution is chosen as the one with minimum angle between reconstructed momentum and B direction (from primary and secondary vertices)



Mass discriminating power & analysis strategy

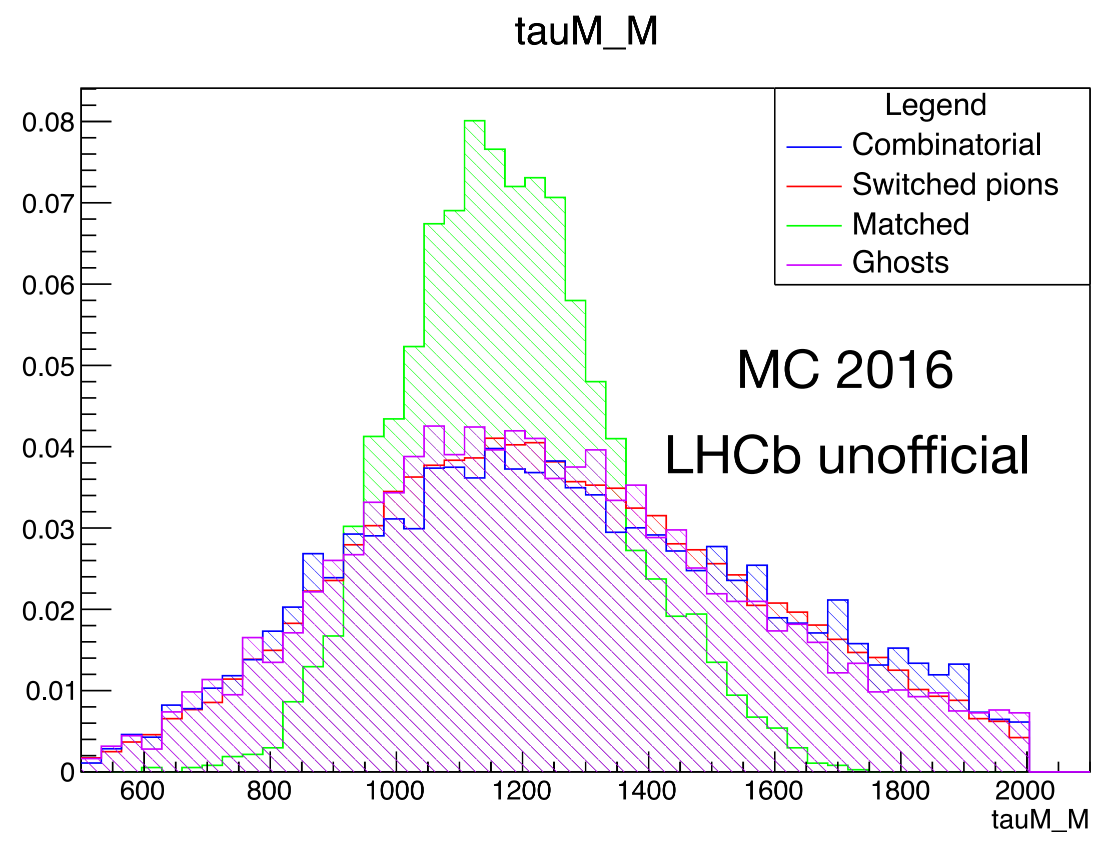
- Different masses can be defined:
  - Analytically reconstructed
  - Visible mass
  - “Corrected” mass $M_{cor} = \sqrt{P_T^2 + M_{vis}} + P_T^2$
- **None of them very discriminating** compared to background from same sign data (selected requiring both taus to have the same charge) but still work in progress:

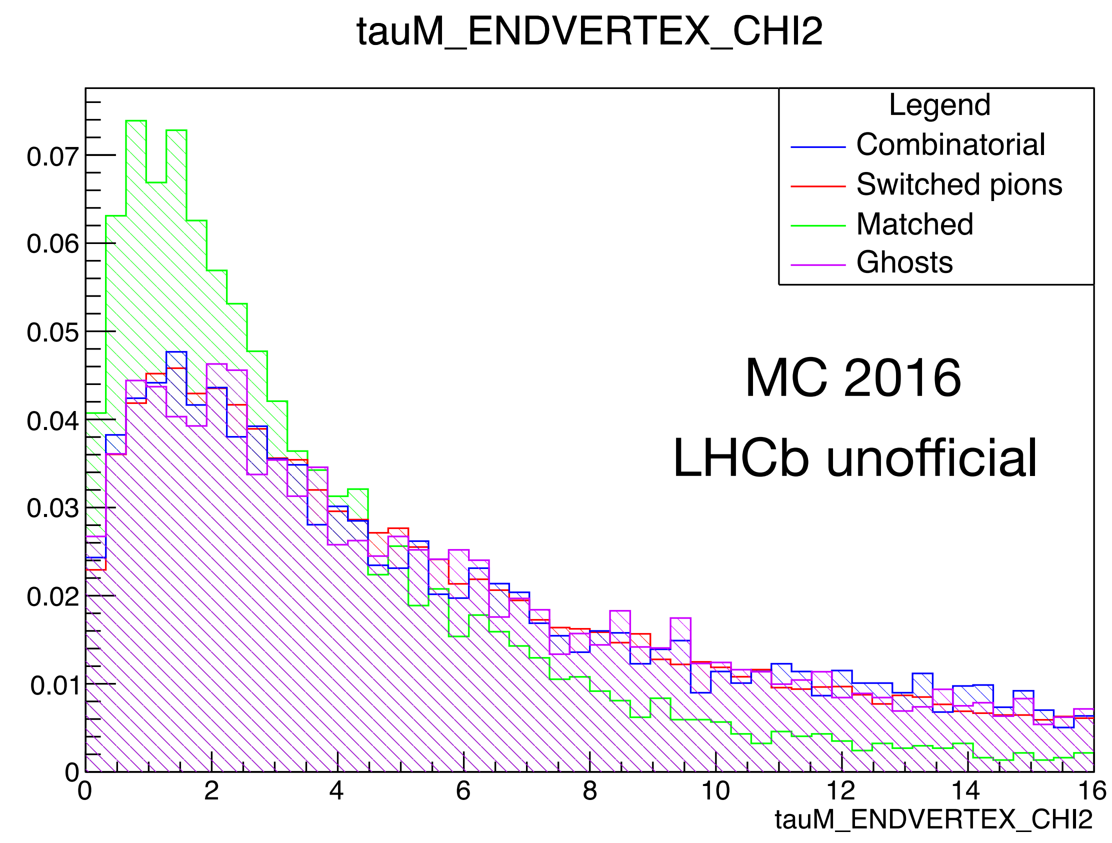


- Not enough mass discriminating power to fit, need to modify analysis strategy:
  - Loose cut-based preselection
  - MVA-based selection, 2 BDTs in sequence
  - **Fit on third BDT**
  - $B^0 \to D^+ \, (\to \pi^+\pi^+K^-) \, D_s^- \, (\to K^+K^-\pi^+)$ used as (preliminary) normalization channel to avoid introduction of uncertainty on luminosity and cross-section measurements

Event multiplicity issue

- On signal sample, **truth matching requires tracks to be matched to true MC particles**
- Only half of the events contain a fully matched and correctly reconstructed B -> K* tau+ tau- decay, currently investigating why
- Observed events in which **the decay is reconstructed swapping pions** between different taus or between taus and K*, investigating why the correctly reconstructed candidate is not selected
- Considerable amount of non-signal candidates in MC sample, ~10 candidates per event:

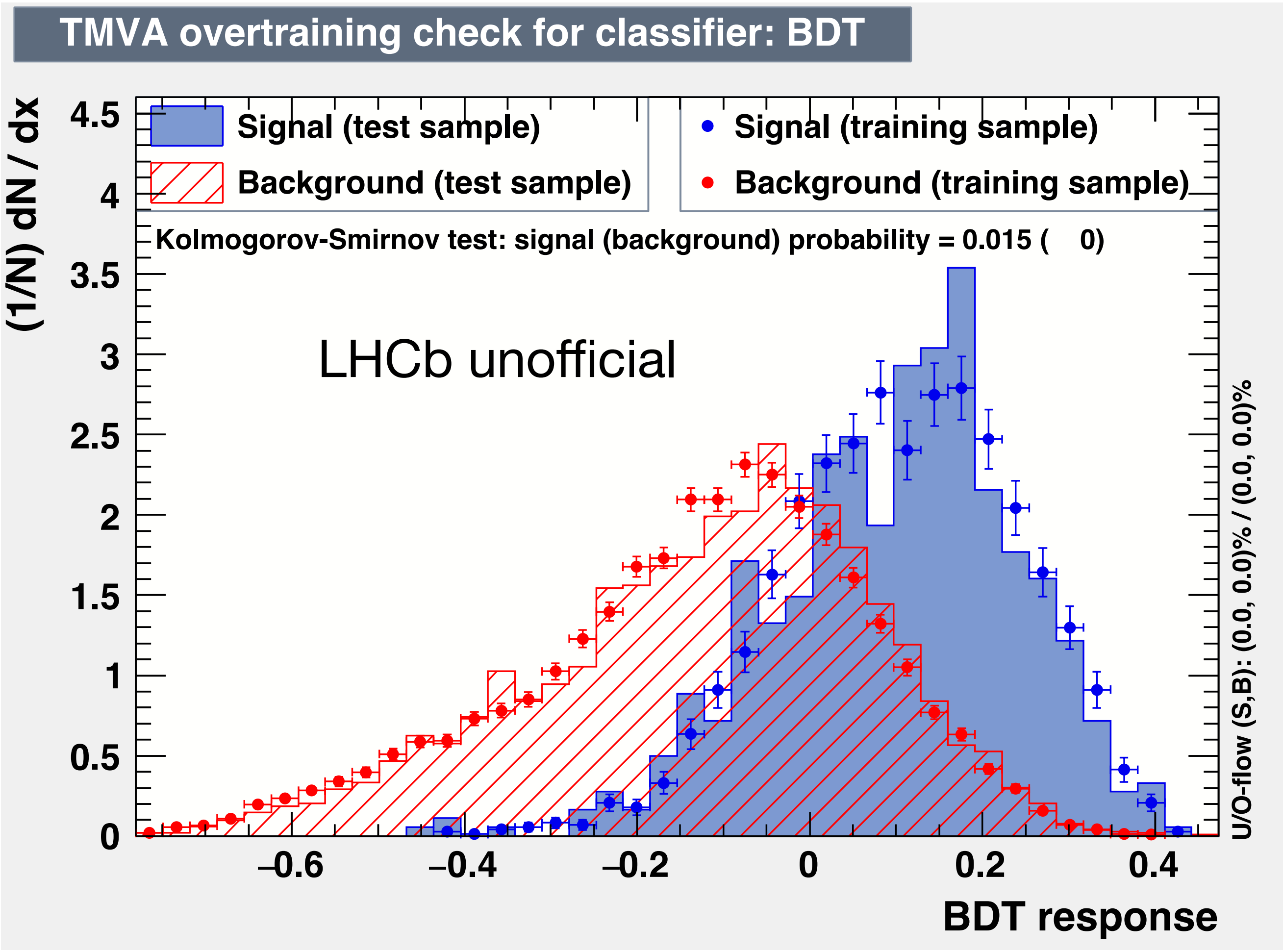




- Currently trying to understand why a significant fraction of signal is lost

Selection

- **Loose cut-based preselection** on isolation variables: quantify the probability of a track in proximity of the signal candidate to be part of the candidate itself
- **BDT-based selection**, trained against:
  - Fully matched and reconstructed **signal MC events**
  - **Same sign data** as background sample
- First BDT trained using isolation variables
- Second BDT trained after the first BDT cut, using flight distances and vertex information

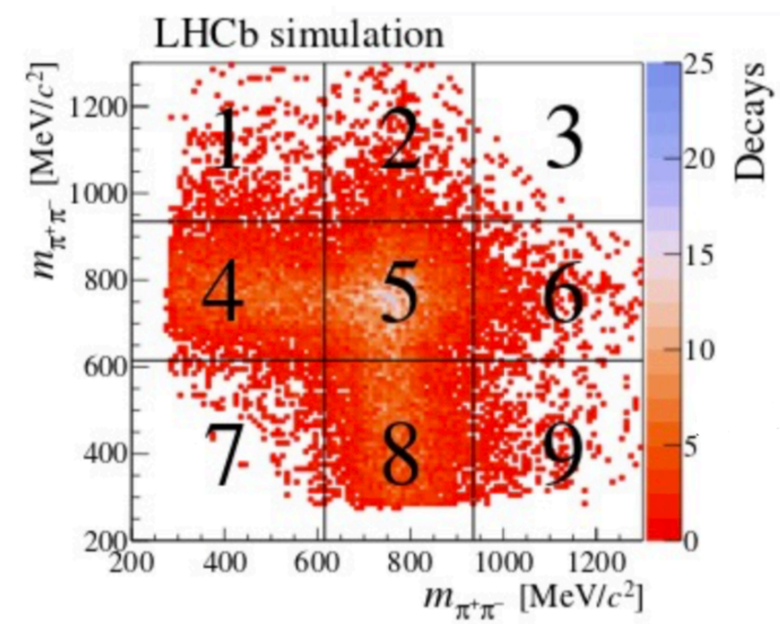


Background categorization

- **Same Sign data** used for BDT training
- **Simulated inclusive B sample**
  - Used to identify background from exclusive decays after selection
  - Expected backgrounds from B decaying into D mesons:

$$B^- \to D^*(2007)^0\ \pi^+\ \pi^+\ \pi^-\ \pi^-\ \pi^-$$
$$B^0 \to D^*(2010)^-\ D_s^{*+}$$
$$B^+ \to \bar{D}^0\ D_s^+\ \pi^+\ \pi^-$$
$$\ldots$$

  - Investigating vertex topology
  - Veto on D mass?
- Plan to consider other possibilities for background characterization:
  - Combinatorial background from K* mass sidebands
  - Background regions in "dalitz" plane (as done in $B_s \to \tau^+\ \tau^-$)
  - Exclusive MC samples

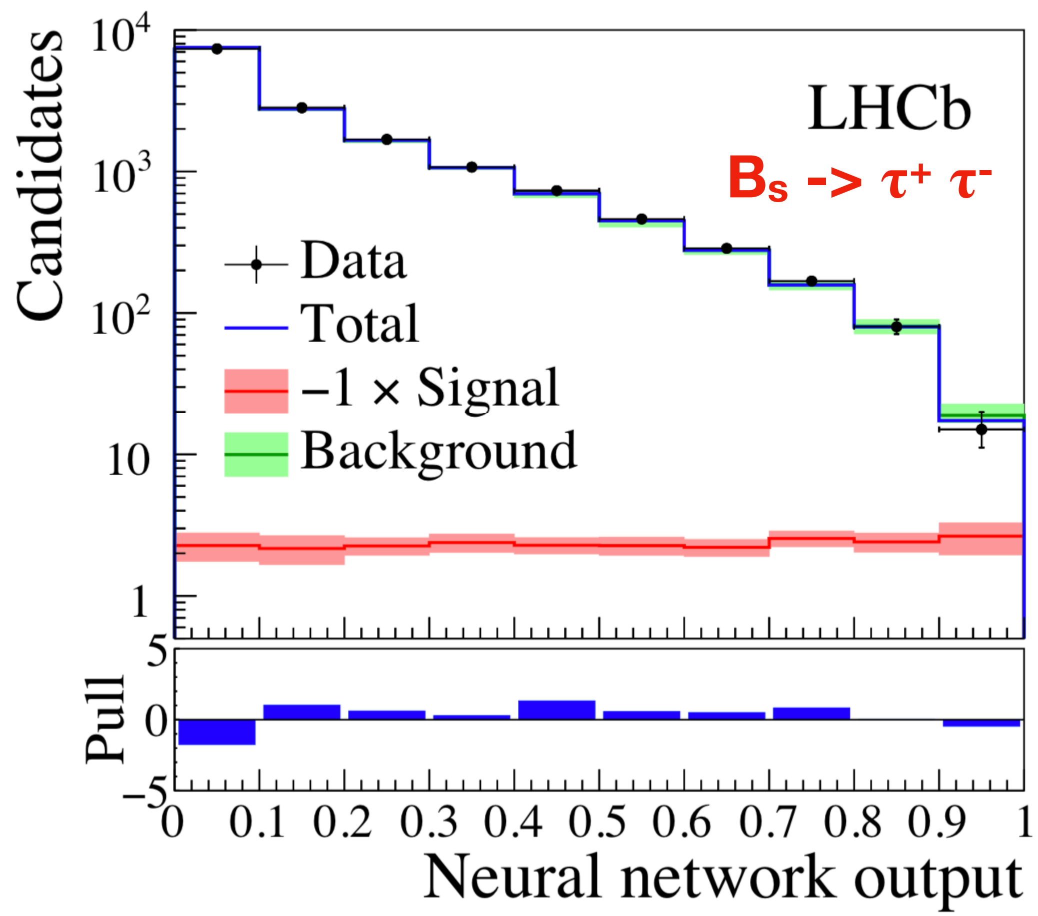


$B_s \to \tau^+\ \tau^-$

https://arxiv.org/pdf/1703.02508.pdf

Fit BDT

- Mass discriminant power not enough to perform a fit: **trained a third BDT** with masses and momenta
- Same samples used, after the first and second BDT cuts
- Fit strategy similar to the $B_s \to \tau^+ \tau^-$ case:



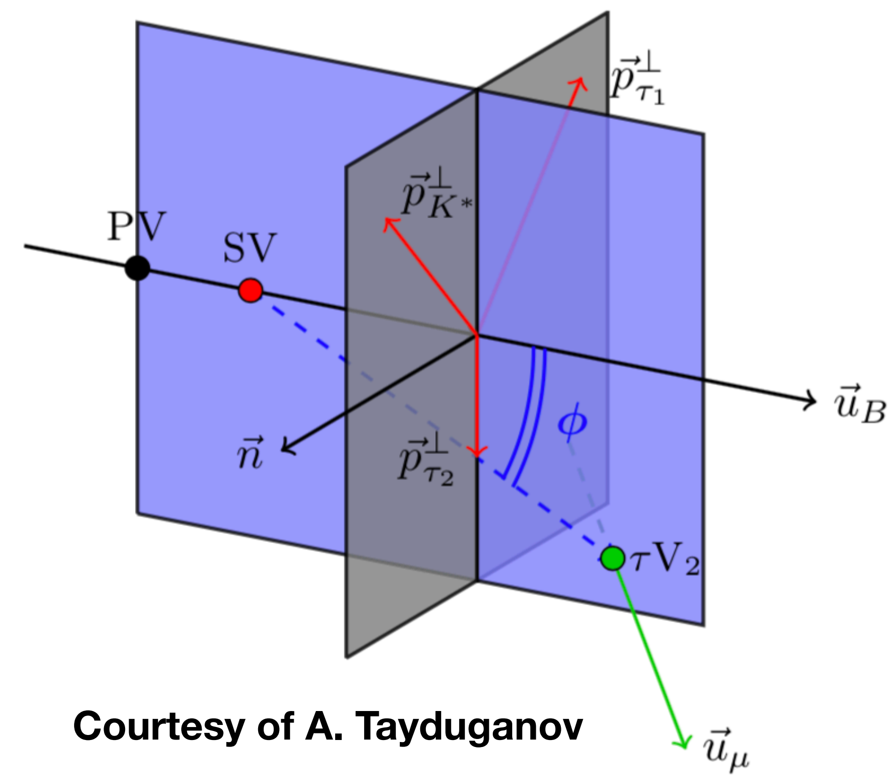
https://arxiv.org/pdf/1703.02508.pdf

- Comparison data-MC for the BDT variables ongoing using normalization channel

3πμ final state

Neutrinos and mass reconstruction

- Tau decaying into three pions (tau1) reconstructed analytically with two-fold ambiguity
- Information on decay vertex position for tau decaying into muon (tau2):
  1. tau2 transverse momentum wrt B flight direction: $\overrightarrow{p_T^{\tau_2}} = -\overrightarrow{p_T^{\tau_1}} - \overrightarrow{p_T^{K^*}}$
  2. Plane containing tau2 transverse momentum and B flight direction
  3. Intersection between plane and muon track: **tau2 vertex**!

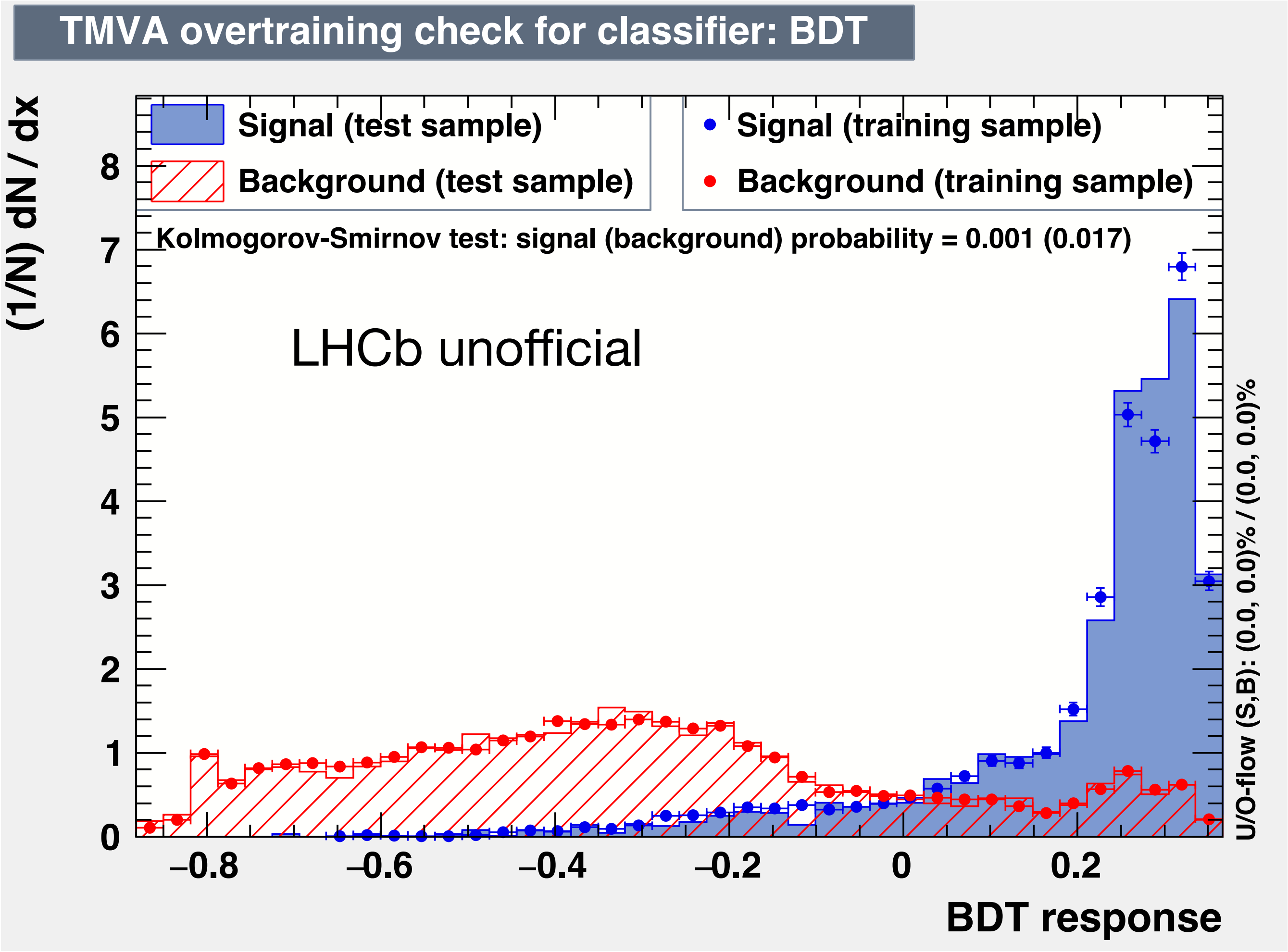


Courtesy of A. Tayduganov

- Using transverse momentum and angle between B flight direction and tau2 flight direction one gets tau2 momentum
- 54% taus have positive discriminant, set to 0 if negative
- **Two-fold ambiguity on B mass**, constrain on B flight direction already used
- Higher fractions of true events in MC sample, less background
- Masses still not discriminating, strategy similar to the 3π3π case

Selection

- **Loose cut-based preselection** on isolation variables
- **BDT-based selection**, trained against MC signal sample and SS data
- First BDT trained using isolation variable
- Second BDT trained using isolation, flight distances and vertex information



Summary of Part III

- B physics with taus in the final state very promising field
- Work in progress in two different final states
- Challenging analysis: multiple candidates, lots of background, poor mass discriminating power
- Selection almost completed, still not optimized
- Fit will be probably performed on BDT
- Background characterization ongoing
- Next steps: Data-MC comparison and define a fit strategy

Joint Conclusions

There is a lot of interesting physics to be explored in the electron and tau mode

While providing a new perspective to the anomalies, they serve to be independent portals for NP searches previously unexplored

The indirect modes coupled with the direct searches could serve to complement each other.