Flavour anomalies in B decays at LHCb in modes involving leptons

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On behalf of the LHCb collaboration
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Outline

- Representation of anomalies in EFT
- Tree-level (semi-leptonic) decays
- Loop $b \rightarrow s, d$ decays
- Leptonic
- Glimpse at LFV searches
- Summary

Note: most results shown are based on full Run 1 (3 fb$^{-1}$) + 2015+2016 (2 fb$^{-1}$) Run 2 data
Effective Hamiltonians

Derived using Operator Product Expansion + renormalization group to sum up the radiative corrections*

\[ H_{\text{eff}} = \sum_i V_{CKM}^i C_i(\mu) O_i(\mu) \]

- Quark flavour couplings (CKM for the SM)
- Wilson coefficients, integrate physics from EW scale to \( \mu \) (~ 1 GeV)
- 6-dim operators (higher orders negligible)

Matrix elements of operators \( O_i \): non perturbative calculations: source of hadronic uncertainties (decay constants, form factors, etc...)

\( C_i/O_i \) mix under RG equations: in practice, use effective \( C_i^{\text{eff}} \)

For right-handed current, use of primed coefficients, \( C_i' \)

Type of operators

Historically, numbered according to the type of decay they intervene in:
- \(i = 1,2\) : tree diagrams. E.g., semileptonic tree
- \(i = 3-6\) : gluonic penguin
- \(i = 7-10\) : electroweak penguin (7\(\gamma\), 8G : magnetic-penguin)
- leptonic operators
- Box operators : to describe oscillations

Represented by effective vertices:

\[
O_1 = (b_i c_j)_{V-A} (\bar{u}_j d_i)_{V-A}
\]

Here color indices are crossed due to gluon exchange

\[
O_2 = (\bar{b} c)_{V-A} (\bar{u} d)_{V-A}
\]
Loop operators and new physics

Loop operators → massive (electroweak) virtual particles: New Physics might intervene. Wilson coefficients affected by NP.

\[ C_i(\text{')}) \rightarrow C_i(\text{')}) + C_i^{\text{NP}} \]

Electromagnetic penguin

\[ O_7 = (\bar{s} \sigma_{\mu\nu} (m_b R + m_s L) b) F_{\mu\nu} \]

\[ O_9(\text{')} = (\bar{s} b)_{V+A} (\bar{\ell} \ell)_V \]

\[ O_{10}(\text{')} = (\bar{s} b)_{V+A} (\bar{\ell} \ell)_A \]
LHCb detector

Forward single-arm spectrometer with warm magnet (possibility to inverse polarity)
Optimized for b and c hadron studies

Vertexing
Tracking stations

Particle ID Ring Imaging Cherenkov
Calorimeters and Muon Chambers

Acceptance $2 < \eta < 5$
Momentum resolution 0.5% to 1%
IP resolution ~ 20 $\mu$m
Time resolution ~ 45 fs

[INT.J.MOD.PHYS.A 30 (2015) 1530022]
[JINST 3 (2008) S08005]
LHCb data (2011+2012) – Run I

$10^{11}$ protons per bunch colliding at 7 (2011) and 8 (2012) TeV

Luminosity at IP8 (LHCb): $2-4 \times 10^{32}$ cm$^{-2}$ s$^{-1}$

About 1500 charged particles produced at each pp collision

$\sigma(b\bar{b}) \sim 75$ $\mu$b @ 7 TeV* in LHCb acceptance


Dominated by $B^+$ ($f_u$) and $B^0$ ($f_d$) species but also $B_s$, $f_s/(f_u + f_d) \sim 0.134$, $b$-baryons ($f(\Lambda_b)/(f_u + f_d) \sim 0.240$)


Output rate 3 kHz in 2011
4.5 kHz in 2012
LHCb data (2015-2018) – Run II

Bunch colliding at 13 TeV

$\sigma(bb) \sim 165 \, \mu\text{b} @ 13 \, \text{TeV}$* in LHCb acceptance
About 2.3 times the value @ 7-8 TeV


LHCb recorded luminosity in pp collisions / year

LHCb 2015 Trigger Diagram

- 40 MHz bunch crossing rate
- L0 Hardware Trigger: 1 MHz readout, high $E_T/P_T$ signatures
  - 450 kHz $h^\pm$
  - 400 kHz $\mu/\mu$
  - 150 kHz $e/\gamma$

Software High Level Trigger

- Partial event reconstruction, select displaced tracks/vertices and dimuons
- Buffer events to disk, perform online detector calibration and alignment
- Full offline-like event selection, mixture of inclusive and exclusive triggers

12.5 kHz (0.6 GB/s) to storage
Semileptonic tree $b \rightarrow c \ell \nu$
\[ H_b \rightarrow H_c^{(*)} \tau \bar{\nu} \text{ vs } H_b \rightarrow H_c^{(*)} \mu \bar{\nu} \]

Test of Lepton Flavour Universality in SM. NP might prefer heavy lepton (\(\tau\))

Measure:

\[ R(\ H_c^{(*)}) = \frac{BR(\ H_b \rightarrow H_c^{(*)} \tau \bar{\nu})}{BR(\ H_b \rightarrow H_c^{(*)} \mu \bar{\nu})} \]

Precise SM-based predictions:

\[ R(D) = 0.299 \pm 0.003 \quad H. \ Na \ et \ al., \ PRD \ 92(2015) \ 054510 \]
\[ R(D^*) = 0.252 \pm 0.003 \quad Fajfer, \ Kamenic, \ Nišandižić, \ PRD85 \ (2012) \ 094025 \]
\[ D.Bigi, \ Gambino, \ PRD \ 94 \ (2016) \ 094008 \]
Very specific topologies for different $\tau$ decays (leptonic vs hadronic)

Use of missing mass, muon energy, momentum transfer $q$, and $\tau$ decay time (hadronic mode)

**LEPTONIC** $\tau^- \rightarrow \mu^- \bar{\nu}_\mu$


**HADRONIC** $\tau^- \rightarrow \pi^- \pi^+ \pi^- (\pi^0)$

PRL 120 (2018) 171802, 2017-017
\[
\overline{B}^0 \rightarrow D^{*+} \tau^- \bar{\nu}_\tau \text{ vs } \overline{B}^0 \rightarrow D^{*+} \mu^- \bar{\nu}_\mu
\]

Specific variables and neutrino reconstruction

\[
m_{\text{miss}}^2 = \left( P_B - P_{D^*} - P_\mu \right)^2 \quad q^2 = \left( P_B - P_{D^*} \right)^2
\]

Use approximation of \( P_B \), infer the neutrino 4-momentum from geometrical considerations.

Two folds ambiguity for the determination of \( p_{\perp} \), resolved with a regression method.

\( p_{\perp} \quad \text{J. High Energ. Phys. (2017) 2017: 21} \)
$B^0 \rightarrow D^{*+} \tau^- \bar{\nu}_\tau$ vs $B^0 \rightarrow D^{*+} \mu^- \bar{\nu}_\mu$

$\tau^- \rightarrow \mu^- \bar{\nu}_\mu$

PRL 115 (2015) 111803

2D missing mass – muon energy fit

$\tau^- \rightarrow \pi^- \pi^+ \pi^-(\pi^0)$

PRL 120 (2018) 171802

$B^0 \rightarrow D^{*+} \pi^- \pi^+ \pi^-$ as normalization

2D fit $q^2$ – tau decay time from $3\pi$

Highest purity BDT bin

$R(D^*) = 0.291 \pm 0.021\text{(stat)} \pm 0.026\text{(syst)} \pm 0.013\text{(BR)}$

$R(D^*) = 0.336 \pm 0.027\text{(stat)} \pm 0.030\text{(syst)}$

$LHCb$
After recent (Belle) result, discrepancy went from $3.8\sigma$ to $3.1\sigma$ wrt SM.
\( B_c \rightarrow J/\psi \, \tau^- \, \bar{\nu}_\tau \) vs \( B_c \rightarrow J/\psi \, \mu^- \, \bar{\nu}_\mu \)

\( \tau^- \rightarrow \mu^- \, \bar{\nu}_\mu \, \nu_\tau \)

**PRL 120 (2018) 121801**

**LHCb-PAPER-2017-035**

2 variables (missing mass, Bc decay time) + 1 category fit.
Category variable Z = bins in \( q^2 \) and muon energy.

\[ R(J/\psi) = 0.71 \pm 0.17 \text{(stat)} \pm 0.18 \text{(syst)} \]

Available SM-based predictions in the range 0.25 - 0.28 e.g. PLB452 (1999) 129, PRD73 (2006) 054024, PRD74 (2006) 074008

2\sigma above the range of predictions
New physics can intervene in the loops/boxes
Can be probed through the analysis of the dynamics of the decays
Or testing, e.g., lepton universality $b \to s \ell^+ \ell^- / b \to s \mu^+ \mu^-$
Dominated by $O_7, O_9, O_{10}$ operators
$b \to s(d) \ell^+ \ell^-$: contribution of operators vs $q^2$

$O_7$ dominated
Photon pole (e.g., for $K^*$ mode) below 0.045 GeV$^2$
$B \to X \mu^+\mu^- \frac{d\Gamma}{dq^2}$ spectra

$q^2 = (P_B - P_X)^2$

$B_s \to \phi \mu^+\mu^-$

JHEP 02 (2016) 104

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

LHCb

JHEP 06 (2014) 133

Data tends to be systematically below the SM-based predictions, up to $3.\times \sigma$
Dynamics for $B^0 \to K^{*0} \mu^+ \mu^-$, $B_s \to \phi \mu^+ \mu^-$

\[
\frac{1}{d(\Gamma + \Gamma)/dq^2} \frac{d^4(\Gamma + \Gamma)}{dq^2 d\Omega} = \frac{9}{32\pi} \left[ \frac{3}{4}(1 - F_L) \sin^2 \theta_K + F_L \cos^2 \theta_K \right.
\]

\[
+ \frac{1}{4}(1 - F_L) \sin^2 \theta_K \cos 2\theta_l 
- F_L \cos^2 \theta_K \cos 2\theta_l + S_3 \sin^2 \theta_K \sin^2 \theta_l \cos 2\phi 
+ S_4 \sin 2\theta_K \sin 2\theta_l \cos \phi + S_5 \sin 2\theta_K \sin \theta_l \cos \phi 
+ \frac{3}{2} A_{FB} \sin^2 \theta_K \cos \theta_l + S_7 \sin 2\theta_K \sin \theta_l \sin \phi 
+ S_8 \sin 2\theta_K \sin 2\theta_l \sin \phi + S_9 \sin^2 \theta_K \sin^2 \theta_l \sin 2\phi \left. \right]
\]

$q^2 = \mu^+ \mu^-$ invariant mass squared

Formula slightly different between $K^*$ (self-tagging) and $\phi$

$F_L$ : fraction of longitudinal polarization of $K^*/\phi$

$A_{FB} =$ forward-backward asymmetry of the dimuon system

$S_5 = A_5$ in the case of $\phi$

They depend on $B \to K^*/\phi$ form factors and Wilson Coefficients of the OPE
$B^0 \rightarrow K^{*0}_μ^+μ^-$ angular analysis

Form-factor independent (LO):

\[
P_{4,5,8}' = \frac{S_{4,5,8}}{\sqrt{F_L(1 - F_L)}} \quad P_{6}' = \frac{S_7}{\sqrt{F_L(1 - F_L)}}
\]

Descotes-Genon et al, JHEP 05 (2013) 137

Local discrepancies

PRL 118 (2017) 111801

3σ local discrepancies
\[ \Lambda_b \rightarrow \Lambda \mu^+ \mu^- : q^2 \text{ and angular spectra} \]

\[ \frac{d^5 \Gamma}{d \Omega} = \frac{3}{32 \pi^2} \sum_{i}^{34} K_i(q^2) f_i(\Omega) \]

**Performed with Run 1 + Run 2 data**

** Compatibility with SM-based predictions**
Boër et al, JHEP01 (2015) 155
Detmold et al., PRD93 (2016) 074501
R_K ratios

Test of Lepton Flavour Universality: \( R_K (\text{SM}) = 1 \) (+corrections order < 10^{-3}) (excluding the γ pole for K* mode)

\[
R_K = \frac{BR(B^+ \to K^+ \mu^+ \mu^-)}{BR(B^+ \to K^+ e^+ e^-)} \quad \quad R_{K^*0} = \frac{BR(B^0 \to K^{*0} \mu^+ \mu^-)}{BR(B^0 \to K^{*0} e^+ e^-)}
\]

\( PRL \ 122 \ (2019) \ 191801 \)

New (Spring 2019)

Experimentally:

\[
R_K = \frac{BR(B \to K \mu^+ \mu^-)}{BR(B \to K J/\Psi (\mu^+ \mu^-))} / \frac{BR(B \to K e^+ e^-)}{BR(B \to K J/\Psi (e^+ e^-))}
\]

Minimize systematic uncertainties

\( q^2 \) range: above γ pole and background of type \( B \to \phi(\to \ell\ell) \) K
and below J/Ψ radiative tail
R_K ratios - fits

$B^+ \rightarrow K^+ \ell^+ \ell^-$

$1.1 \text{ GeV}^2 < q^2 < 6 \text{ GeV}^2$

$B^0 \rightarrow K^{*0} \ell^+ \ell^-$

$0.045 \text{ GeV}^2 < q^2 < 1.1 \text{ GeV}^2$

$1.1 \text{ GeV}^2 < q^2 < 6 \text{ GeV}^2$

Radiative Bremsstrahlung tail for electron modes
$R_K$ ratios, results

**B$^+$ → K$^+\ell^+\ell^-$**

$LHCb$

$$R_K = 0.846^{+0.060}_{-0.054} \left( \text{stat.} \right) + 0.016 \left( \text{syst.} \right)$$

2.5σ below SM-based predictions

**B$^0 → K^{*0}\ell^+\ell^-$**

$LHCb$

$$R_{K^0} = 0.66^{+0.11}_{-0.07} \left( \text{stat.} \right) \pm 0.03 \left( \text{syst.} \right)$$

2.1-2.3σ below SM

0.045 GeV$^2 < q^2 < 1.1$ GeV$^2$

1.1 GeV$^2 < q^2 < 6$ GeV$^2$

$$R_{K^0} = 0.69^{+0.11}_{-0.07} \left( \text{stat.} \right) \pm 0.05 \left( \text{syst.} \right)$$

2.4-2.5σ below SM
**B → ℓ⁺ℓ⁻ decays**

\[
\begin{align*}
\text{Contributions from } & O_{10}(') \\
& O_s(') = (\bar{s}b)_{V^{\pm A}} (\ell \ell) \\
& O_p(') = (\bar{s}b)_{V^{\pm A}} (\ell \ell)_p
\end{align*}
\]

**SM-based predictions:**

\[
\begin{align*}
\text{BR}(B^0 \rightarrow \mu^+\mu^-) &= (1.06 \pm 0.09) \times 10^{-10} \\
\text{BR}(B_s^0 \rightarrow \mu^+\mu^-) &= (3.66 \pm 0.23) \times 10^{-9}
\end{align*}
\]

C. Bobeth et al., PRL 112 (2014) 101801
\[ B \to \mu^+ \mu^- \text{ status} \]

**LHCb (PRL 118 (2017) 191801)**

\[ BR(B^0 \to \mu^+ \mu^-) < 3.4 \times 10^{-10} @ 95 \% CL \]

\[ BR(B_s^0 \to \mu^+ \mu^-) = (3.0 \pm 0.5 \text{ (stat)} ^{+0.3}_{-0.2} \text{ (syst)}) \times 10^{-9} \]

**ATLAS (JHEP 04 (2019) 098)**

\[ BR(B^0 \to \mu^+ \mu^-) < 2.1 \times 10^{-10} @ 95 \% CL \]

\[ BR(B_s^0 \to \mu^+ \mu^-) = (3.2^{+1.1}_{-1.0}) \times 10^{-9} \]

**CMS (PRL 111, 101804 (2013))**

\[ BR(B^0 \to \mu^+ \mu^-) = (4.4^{+2.2}_{-1.9}) \times 10^{-10} \]

\[ BR(B_s^0 \to \mu^+ \mu^-) = (2.8^{+1.1}_{-0.9}) \times 10^{-9} \]

Very recent CMS update (08/2019), CMS-PAS-BPH-16-004

Combination gives Bs mode 2\(\sigma\) below SM

\[ BR(B^0 \to \mu^+ \mu^-) < 3.6 \times 10^{-10} @ 95 \% CL \]

\[ BR(B_s^0 \to \mu^+ \mu^-) = (2.9^{+0.7}_{-0.6} \pm (0.2) (f_s/f_u)) \times 10^{-9} \]

ON GOING UPDATE OF COMBINATION

arXiv:1903.10434
Global fits to Wilson coefficients

A huge number of observables included

Example of arXiv:1903.10434, D.Straub et al.

Some configurations lead to significant enhancement of right-handed currents wrt SM-based predictions: triggers intense activity related to NP scenarios (New vector Z’, Leptoquarks, ...)
A word on LFV

If LFUV confirmed, what about LFV?, e.g.:

\( B \rightarrow \ell\ell', \ b \rightarrow (s,d)\ell\ell' \)

e.g. recent LHCb searches

\( B^0_s \rightarrow \tau^+\mu^- \)  \( \text{arXiv:1905.06614} \)

\[ \text{BR} \left( B^0 \rightarrow \tau^+\mu^- \right) < 1.4 \times 10^{-5} @ 95 \% CL \]

\[ \text{BR} \left( B^0_s \rightarrow \tau^+\mu^- \right) < 4.2 \times 10^{-5} @ 95 \% CL \]

\( B^+ \rightarrow K^+ \mu^\pm e^\mp \)  \( \text{LHCb-PAPER-2019-022} \)

\[ \text{BR} \left( B^+ \rightarrow K^+ \mu^- e^+ \right) < 9.5 \times 10^{-9} @ 95 \% CL \]

\[ \text{BR} \left( B^+ \rightarrow K^+ \mu^+ e^- \right) < 9.1 \times 10^{-9} @ 95 \% CL \]

→ NEW, preliminary, on its way to submission
Some theoretical papers (non-exhaustive) on LFUV/LFV


See also R. Volkas on Thursday; WG5; *Radiative neutrino mass models and the flavour anomalies*
Conclusion

- Persisting anomalies for several observables of leptonic and semi-leptonic modes
  - Some bridges with neutrino physics through LFV searches
- EFT analyses are becoming more and more accurate
  - Significance of NP contributions to Wilson coefficients becoming intriguing, e.g. for $C_9$
- More results and combinations are coming with analysis of full Run 2
- Excellent prospects for Run 3 and after, fundamental role of Flavour Physics, either ways:
  - Confirmation of anomalies or
  - Indirect constraint on high energy scales
Back up
$B_s \rightarrow \mu^+ \mu^-$ effective lifetime

LHCb (PRL 118 (2017) 191801)

$$\tau_{\mu^+ \mu^-} \equiv \frac{\int_0^\infty t \Gamma(B_s(t) \rightarrow \mu^+ \mu^-) dt}{\int_0^\infty \Gamma(B_s(t) \rightarrow \mu^+ \mu^-) dt}$$

![Graph showing the weighted $B_s^0 \rightarrow \mu^+ \mu^-$ candidates per (1 ps) vs. decay time in ps.]

$\tau(B_s \rightarrow \mu^+ \mu^-) = 2.04 \pm 0.44 \pm 0.05$ ps
News on radiative $b \to s \gamma$

Let handed $\gamma$ favoured, right handed suppressed by $m_s/m_b$

Mixing induced CP asymmetry suppressed similarly

Any substantial value of the parameters of time-dependent CP asymmetry would be an indication of NP

$$\frac{\Gamma_B(t)}{\Gamma_{\bar{B}}(t)} \propto \left[ \cosh (\Delta \Gamma t / 2) - A^{\Delta \Gamma} \sinh (\Delta \Gamma t / 2) \pm C \cos (\Delta m t / 2) \mp S \sin (\Delta m t / 2) \right]$$

Photon helicity and weak phases

CP violation in the decay

Expected to be close to zero within SM (e.g., PLB664 (2008) 174)

\[ B_s \rightarrow \phi(KK) \gamma \]

\[ B^0 \rightarrow K^*(0) (K^+\pi^-) \gamma \] selected with similar requirements to control the time-dependent efficiency

\[ A_{\Delta\Gamma_{\phi\gamma}} = -0.67^{+0.37}_{-0.41} \pm 0.17, \quad C_{\phi\gamma} = 0.11 \pm 0.29 \pm 0.11, \quad S_{\phi\gamma} = 0.43 \pm 0.30 \pm 0.11 \]

First measurements of those parameters for Bs meson radiative decay
Compatible with SM within current accuracy
$$\Lambda_b \rightarrow \Lambda \gamma$$

$B^0 \rightarrow K^0(K^+\pi^-)\gamma$ used as normalization channel

No proper vertex reconstructible (flying $\Lambda$ and $\gamma$): require small DOCA between $\Lambda_b$ and $\Lambda$, assuming $\Lambda_b$ originates from closest PV to $\Lambda$ trajectory

Analysis with reduced Run 2 sample (1.7 fb$^{-1}$)

First observation of a b-baryon radiative decay

$$BR(\Lambda_b \rightarrow \Lambda \gamma) = 7.1 \pm 1.5 \, (\text{stat}) \pm 0.6 \, (\text{syst}) \pm 0.7 \, (\text{ext})$$

Compatible with SM
Projections for the future


<table>
<thead>
<tr>
<th>Yield</th>
<th>Run 1 result</th>
<th>9 fb⁻¹</th>
<th>23 fb⁻¹</th>
<th>50 fb⁻¹</th>
<th>300 fb⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^+ \to K^+e^+e^-$</td>
<td>254 ± 29 [274]</td>
<td>1120</td>
<td>3300</td>
<td>7500</td>
<td>46000</td>
</tr>
<tr>
<td>$B^0 \to K^{*0}e^+e^-$</td>
<td>111 ± 14 [275]</td>
<td>490</td>
<td>1400</td>
<td>3300</td>
<td>20000</td>
</tr>
<tr>
<td>$B^0_\gamma \to \phi e^+e^-$</td>
<td>-</td>
<td>80</td>
<td>230</td>
<td>530</td>
<td>3300</td>
</tr>
<tr>
<td>$\Lambda_b \to pK^+e^+$</td>
<td>-</td>
<td>120</td>
<td>360</td>
<td>820</td>
<td>5000</td>
</tr>
<tr>
<td>$B^+ \to \pi^+e^+e^-$</td>
<td>-</td>
<td>20</td>
<td>70</td>
<td>150</td>
<td>900</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$R_X$ precision</th>
<th>Run 1 result</th>
<th>9 fb⁻¹</th>
<th>23 fb⁻¹</th>
<th>50 fb⁻¹</th>
<th>300 fb⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_K$</td>
<td>0.745 ± 0.090 ± 0.036 [274]</td>
<td>0.043</td>
<td>0.025</td>
<td>0.017</td>
<td>0.007</td>
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<tr>
<td>$R_{K^{*0}}$</td>
<td>0.69 ± 0.11 ± 0.05 [275]</td>
<td>0.052</td>
<td>0.031</td>
<td>0.020</td>
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<td>$R_\phi$</td>
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<td>0.076</td>
<td>0.050</td>
<td>0.020</td>
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<tr>
<td>$R_{pK}$</td>
<td>-</td>
<td>0.105</td>
<td>0.061</td>
<td>0.041</td>
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<td>$R_{\pi}$</td>
<td>-</td>
<td>0.302</td>
<td>0.176</td>
<td>0.117</td>
<td>0.047</td>
</tr>
</tbody>
</table>
Prospects for R(X)

Upgrade DAQ scheme

LHCb Upgrade Trigger Diagram

30 MHz inelastic event rate (full rate event building)

Software High Level Trigger

- Full event reconstruction, inclusive and exclusive kinematic/geometric selections

Buffer events to disk, perform online detector calibration and alignment

Add offline precision particle identification and track quality information to selections
Output full event information for inclusive triggers, trigger candidates and related primary vertices for exclusive triggers

2-5 GB/s to storage