LHCb: Status Report

Some Physics Results and Plans for the Future

Michael D. Sokoloff

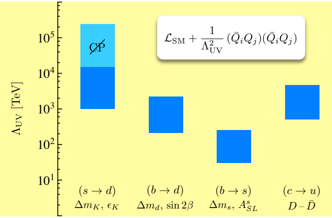
University of Cincinnati
on behalf of US-LHCb

November 13, 2014

Flavor Constrains BSM Physics

Operator	Bounds on Λ in TeV ($c_{\rm NP}=1$)		Bounds on $c_{\rm NP}$ ($\Lambda = 1$ TeV)		Observables
	Re	Im	Re	Im	
$(\bar{s}_L\gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4	9.0×10^{-7}	3.4×10^{-9}	Δm_K; ϵ_K
$(\bar{s}_R\, d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5	6.9×10^{-9}	2.6×10^{-11}	
$(\bar{c}_L\gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3	5.6×10^{-7}	1.0×10^{-7}	Δm_D; $\lvert q/p\rvert_D$, ϕ_D
$(\bar{c}_R\, u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	
$(\bar{b}_L\gamma^\mu d_L)^2$	6.6×10^2	9.3×10^2	2.3×10^{-6}	1.1×10^{-6}	Δm_{B_d}; $\sin(2\beta)$ from $B_d\to\psi K$
$(\bar{b}_R\, d_L)(\bar{b}_L d_R)$	2.5×10^3	3.6×10^3	3.9×10^{-7}	1.9×10^{-7}	
$(\bar{b}_L\gamma^\mu s_L)^2$	1.4×10^2	2.5×10^2	5.0×10^{-5}	1.7×10^{-5}	Δm_{B_s}; $\sin(\phi_s)$ from $B_s\to\psi\phi$
$(\bar{b}_R\, s_L)(\bar{b}_L s_R)$	4.8×10^2	8.3×10^2	8.8×10^{-6}	2.9×10^{-6}	

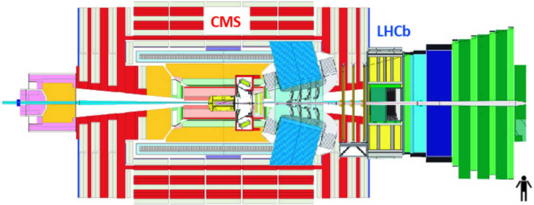
Flavor Structure in the SM and Beyond

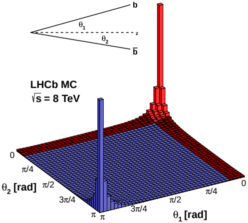


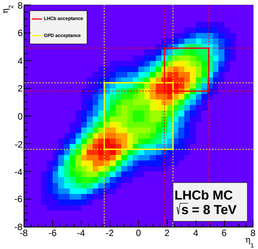
Generic bounds without a flavor symmetry

- Table above from Isidori and Teubert, Eur.Phys.J.Plus **129**, 40 (2014). Bounds on representative dimension-six $\Delta F = 2$ operators.
- Image to the left from M. Neubert, EPS-HEP-2011.

LHC Detector Acceptances for $b\bar{b}$ Production

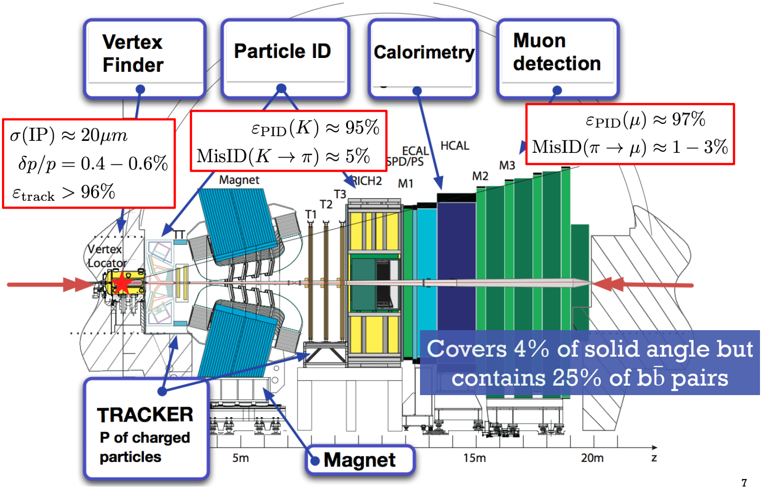






- LHCb is a forward spectrometer, optimized for accepting both B and $\overline{B}$ hadrons in an event;
- accepts about 10× as many triggers as ATLAS or CMS;
- $\sigma(c\,\bar{c}) \sim 20 \times \sigma(b\,\bar{b})$;
- acceptance in η complements ATLAS and CMS for many electro-weak studies.

LHCb Detector [2008 JINST 3 S08005]



Vertex Finder

Particle ID

Calorimetry

Muon detection

$\sigma(\mathrm{IP}) \approx 20\mu m$
$\delta p/p = 0.4 - 0.6\%$
$\varepsilon_{\mathrm{track}} > 96\%$

$\varepsilon_{\mathrm{PID}}(K) \approx 95\%$
$\mathrm{MisID}(K \to \pi) \approx 5\%$

$\varepsilon_{\mathrm{PID}}(\mu) \approx 97\%$
$\mathrm{MisID}(\pi \to \mu) \approx 1 - 3\%$

Covers 4% of solid angle but contains 25% of $b\bar{b}$ pairs

TRACKER
P of charged particles

Magnet

Status and Future Plans

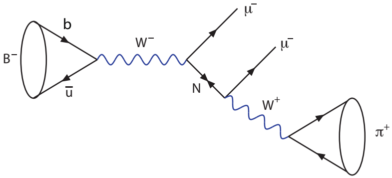
- **Some Selected Results:**
  - Search for Majorana Neutrinos [Syracuse]
  - Charge Asymmetry in $b\bar{b}$ Pair Production [MIT]
  - $D^0 \rightarrow K\pi$ Mixing and CPV Measurements [Cincinnati]
  - $B \rightarrow Z^- K^+; \quad Z \rightarrow \psi' \pi^-$ [Syracuse]
- **Not Discussed**
  - Joint CMS/LHCb **Observation of $\mathrm{B_s} \rightarrow \mu^+\mu^-$ and Evidence for $\mathrm{B_d} \rightarrow \mu^+\mu^-$**, about to be submitted to Nature.
- **Preparing for Run 2**

  Emphasis on the split High Level Trigger (HLT)
- **LHCb in the upgrade era**

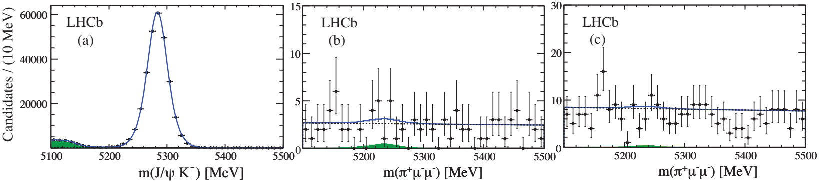
  Emphasis on the Upstream Tracker

also see talks by Nathan Jurik (Th. 3:41 PM) and Matt Kelsey (Fr. 9:56 AM)

Searches for Virtual and Real Majorana Neutrinos - I



- Virtual Majorana neutrinos constrained by upper limit on $\mathcal{B}(B^- \to \pi^+\mu^-\mu^-)$.
- Real Majorana neutrinos constrained as functions of $m(\pi^+\mu^-)$ for short decay times ($\mathcal{S}$, $\tau < 1$ ps) and long decay times ($\mathcal{L}$, $\tau > 1$ ps).

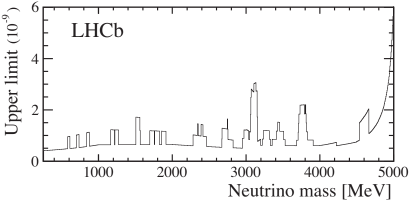


Invariant mass distributions for (a) the normalization channel $J/\psi K^-$, (b) $\pi^+\mu^-\mu^-$ ($\mathcal{S}$), and (c) $\pi^+\mu^-\mu^-$ ($\mathcal{L}$).

Searches for Virtual and Real Majorana Neutrinos - II

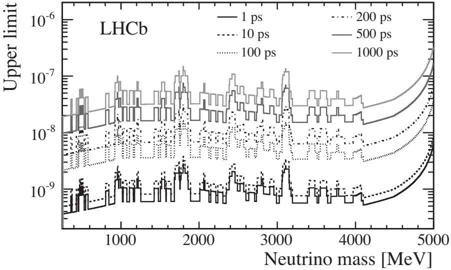
$\mathcal{B}(\mathbf{B^- \to \pi^+\mu^-\mu^-}) < \mathbf{4.0 \times 10^{-9}}$
valid for $\tau_N \lesssim 1$ ps, independent of m_N

PRL **112** (2014) 131802



Upper limits on $\mathcal{B}(B^- \to \pi^+\mu^-\mu^-)$ at 95% C.L. as a function of m_N in 5 MeV intervals for $\mathcal{S}$ selected events.

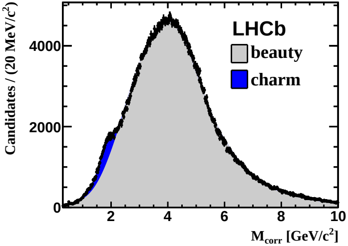
New trigger lines in 2015 will enhance sensitivity for high τ_N



Upper limits on $\mathcal{B}(B^- \to \pi^+\mu^-\mu^-)$ at 95% C.L. as a function of m_N, in 5 MeV intervals, for specific values of τ_N.

Charge Asymmetry in $b\,\bar{b}$ Pair Production - I

- Measurements in $p\bar{p}$ collisions at the Tevatron suggest that top (anti-) quarks are produced along the (anti-) proton beam direction more often than predicted by the SM. BSM physics can explain this.
- The LHC is a pp machine, effectively **an asymmetric q$\bar{\text{q}}$ collider**. Some theories proposed to explain the Tevatron results also predict a large charge assymetry in $b\bar{b}$ production.
- B and $\bar{B}$ decays are identified using topological and mass criteria (TOPO), the $b\bar{b}$ reconstructed jets using the anti-k_T algorithm, and B flavor tagged using muons from semileptonic decay.



After B candidates are identified as TOPO objects, the **background contamination** is studied using corrected mass:

$$M_{\mathrm{corr}} = (M^2 + p^2 \sin^2\theta)^{1/2} + p \sin\theta$$

where M and p are the mass and momentum of B-decay tracks in a jet.

Charge Asymmetry in $b\,\bar{b}$ Pair Production - II

$$A_C^{b\bar{b}} \equiv \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$$

where $\Delta y \equiv |y_b| - |y_{\bar{b}}|$.

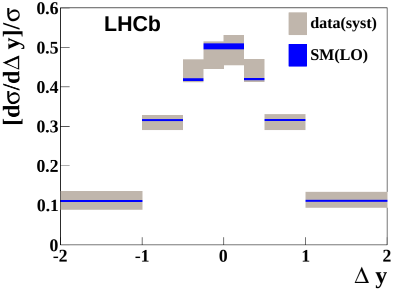
$A_C^{b\bar{b}}$ is measured in three regions of jet-jet mass, $M_{b\bar{b}}$

$(40 - 75)\ \mathrm{GeV} \qquad A_C^{b\bar{b}} = (0.4 \pm 0.4 \pm 0.3)\%$

$(75 - 105)\ \mathrm{GeV} \qquad A_C^{b\bar{b}} = (2.0 \pm 0.9 \pm 0.6)\%$

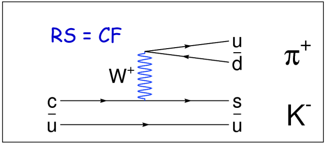
$> 105\ \mathrm{GeV} \qquad A_C^{b\bar{b}} = (1.6 \pm 1.7 \pm 0.6)\%$

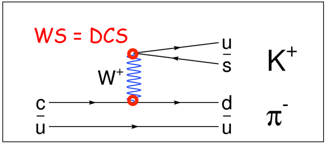
The data are consistent with Standard Model predictions.



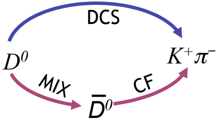
[PRL 113 (2014) 082003]

Time Evolution of $D^0 \to K\pi$





DCS and mixing amplitudes interfere to give a "quadratic" WS decay rate (x, y << 1):



$$\frac{\Gamma_{WS}(t)}{e^{-t/\tau}} \propto R_D + \sqrt{R_D}\,y' \left(\frac{t}{\tau}\right) + \left(\frac{x'^2 + y'^2}{4}\right) \left(\frac{t}{\tau}\right)^2$$

where $x' = x\cos\delta + y\sin\delta \qquad y' = y\cos\delta - x\sin\delta$

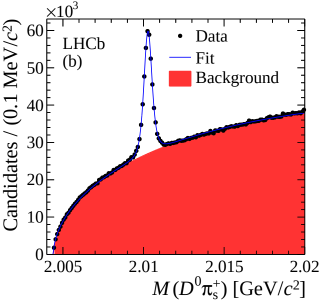
and δ is the phase difference between DCS and CF decays.

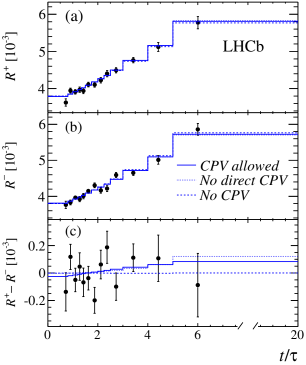
$m_i,\ \Gamma_i \Leftrightarrow$ weak eigenstates ; $\quad x \equiv \dfrac{\Delta m}{\langle\Gamma\rangle}\,; \quad y \equiv \dfrac{\Delta m}{2\,\langle\Gamma\rangle}\,; \quad \tau \equiv \dfrac{1}{\langle\Gamma\rangle}$

$D^0 \to K\pi$ Mixing and CPV Measurements

$$R^{\pm}(t) = \frac{\mathrm{WS}(t)}{\mathrm{RS}(t)} = R_D^{\pm} + \sqrt{R_D^{\pm}}\,y'\left(\frac{t}{\tau}\right) + \left(\frac{x'^{\pm 2} + y'^{\pm 2}}{4}\right)\left(\frac{t}{\tau}\right)^2$$

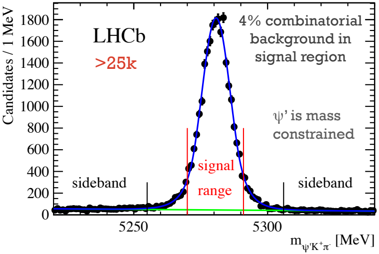
PRL **111** (2013) 251801

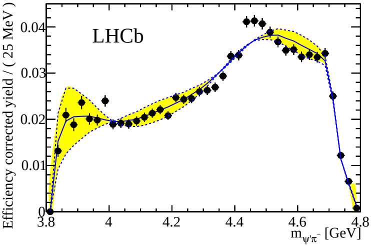




- ∼ 54 M RS signal;
- ∼ 230 K WS signal;
- **D^0, $\overline{D}^0$ mixing rates are equal, ±5%.**

$B \to Z(4430)K^+$; $Z(4330) \to \psi'\pi^-$; $|dc\,\bar{c}\bar{u}\rangle$

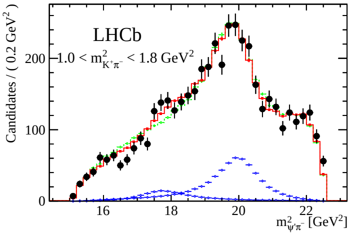




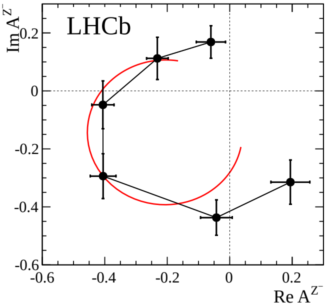
- $B \to \psi' K^+ \pi^-$; $\psi' \to \mu^- \mu^+$
- Amplitude fits plus model-independent analysis
- $Z(4430)^- \to \psi'\pi^-$ first observed by Belle [PRL 100 (2008) 142001]

- Background-subtracted, efficiency-corrected $m(\psi'\pi^-)$ distribution.
- Model projections of $\cos\theta_{K^*}$ moments up to order 4, allows for $J(K^*) \leq 2$, including correlated uncertainties.

Resonant Character of the $Z(4430)^-$ State, and More



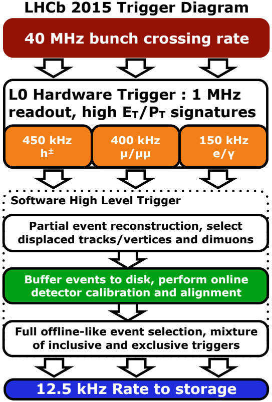
- Amplitude fit including $J^P = 1^+$ $Z(4430) \to \psi'\pi^-$ improves overall χ^2 corresponding to $18.7\,\sigma$. [PRL **112** (2014) 222002]
- Relative to $J^P = 1^+$, the 0^-, 1^-, 2^+, and 2^- hypotheses are rejected by at least $9.7\,\sigma$, $15.8\,\sigma$, $16.1\,\sigma$, and $14.6\,\sigma$.
- $\Rightarrow$ **4-quark resonant state**



- **A fit including an additional $J^P = 0^-$ $\psi'\pi^-$ amplitude with $m = (4239 \pm 18^{+45}_{-10})$ MeV and $\Gamma = (220 \pm 47^{+108}_{-74})$ MeV improves overall χ^2 corresponding to $6\,\sigma$.**

Preparing for Run 2

- **8 TeV → 13 TeV**
    - $\sigma(b\bar{b})$ and $\sigma(c\bar{c})$ increase $\approx 60\%$.
- **50 ns bunch length → 25 ns**
    - maintain $\mathcal{L}$, reduce pile-up.
- **increase output bandwidth, 5 kHz → 12 kHz**
    - record more data.
- L0 trigger maintained; **improve the HLT**
    - increase S:B and divide output into “regular data”, “parked data”, and a “turbo stream”.



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 $\mu/\mu\mu$

150 kHz e/γ

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 Rate to storage

The Split HLT – Working Harder and Smarter

- **The models considered assume**
  - **twice the 2012 computing power (53240 processors, 2012 units) and ~4 PB of disk for deferral**
  - **An Hlt1 process which will run in real time and an Hlt2 process which will run after calibration constants are available, nominally an hour later.**
- **Four tunable knobs:**

Hlt1 time/evt
18 ms in 2012

Hlt2 time/evt
200 ms in 2012

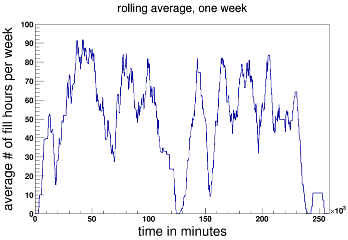
Fraction of events
sent to Hlt2
8% in 2012

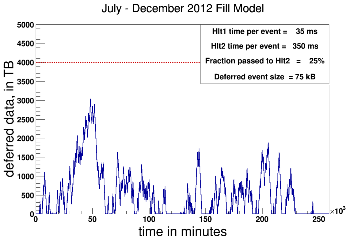
Size of events
sent to Hlt2
(55 kB in 2012)

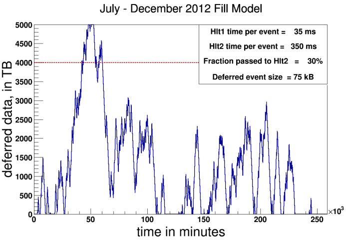
Most Weeks Have 168 Hours

- Clock week = 168 hours;
- Machine in fill ~ 50 hours/week;
- Best week, ~ 90 hours in fill;
- Deferral allows us to use all 168 hours in a week if disk available

- Split Hlt increases effective CPU power by more than a factor of 2

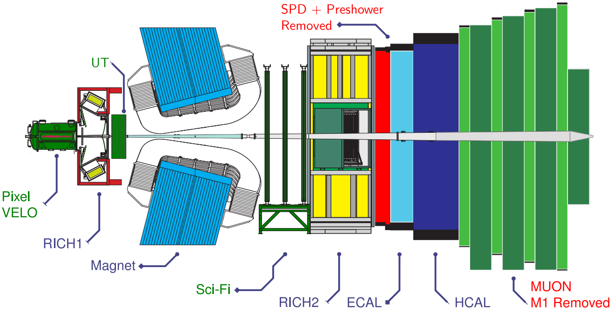

rolling average, one week


July - December 2012 Fill Model


July - December 2012 Fill Model

The Upgrade

- From 2018, LHCb will run at $\mathcal{L} = 2 \times 10^{33}\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}$

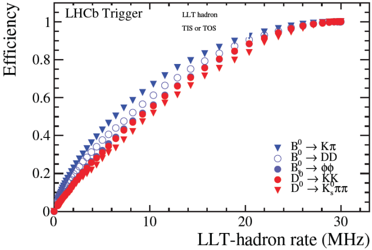


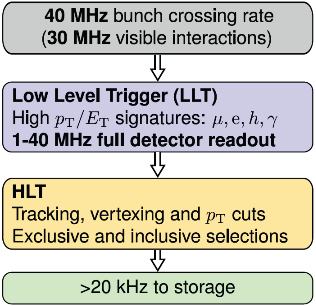
- VELO moves from r, ϕ strips to pixels: LHCb-TDR-013
- RICH replaces photon detectors, SPD, PRS, M1 removed: LHCb-TDR-014
- Trackers replaced: scintillating fibers + silicon microstrips: LHCb-TDR-015

The Upgrade Trigger – Fully Executed in Software

LHCb-TDR-016

- At $\mathcal{L} = 2 \times 10^{33}$ cm^{-2} s^{-1}, 1 MHz readout becomes a bottleneck:
  - Saturation problem: at increased lumi signal less well separated in L0.




40 MHz bunch crossing rate
(**30 MHz** visible interactions)

Low Level Trigger (LLT)
High $p_\mathrm{T}/E_\mathrm{T}$ signatures: $\mu, \mathrm{e}, h, \gamma$
1-40 MHz full detector readout

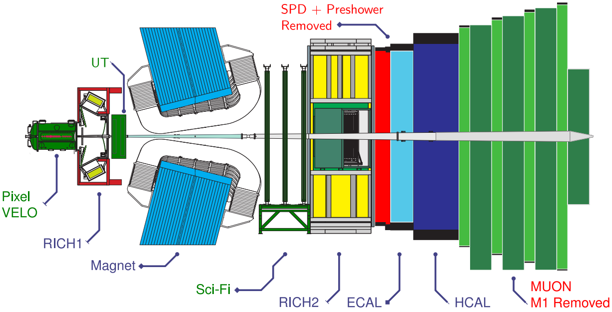
HLT
Tracking, vertexing and p_T cuts
Exclusive and inclusive selections

>20 kHz to storage

- Readout upgraded to 40 MHz: Full readout of 30 MHz Visible pp interactions
  - L0-hardware trigger removed, software Low-Level Trigger (LLT) as replacement
  - Acts as 'handbrake' during commissioning, $1 - 40$ MHz scaleable output rate

Focus on the Upstream Tracker (UT)

- From 2018, LHCb will run at $\mathcal{L} = 2 \times 10^{33}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$



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Motivations and Requirements for the Upstream Tracker

- improve HLT tracking
  - provide fast momentum estimate, will speed up tracking × 3; **critical for fully executing trigger in software**.
  - increase acceptance at low angle and overlap sensors to eliminate gaps;
- Higher luminosity
  - finer granularity to cope with increased particle density as $\nu \rightarrow 7.6$
- From 1 to 40 MHz readout
  - new front-end electronics
- Aim to collect 50 fb^{-1}
  - improve radiation hardness of sensors and electronics

The Upstream Tracker Team

Massachusetts Institute of Technology

CERN

INFN
Istituto Nazionale
di Fisica Nucleare

University of
Zurich UZH

University of
Cincinnati

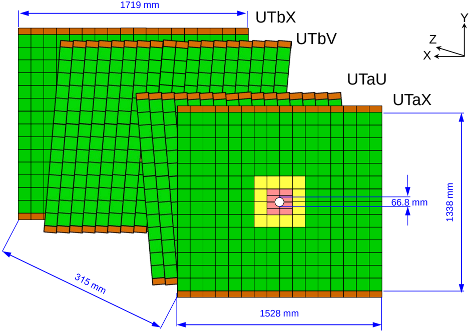
Syracuse University
Suos Cultores Scientia Coronat
Founded AD 1870

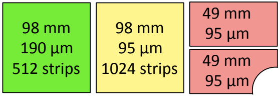
University of Maryland
1856

AGH

Upstream Tracker Geometry

- 4 planes inside light tight box flushed with N_2 or dry air
- Single-sided silicon microstrip sensors (strip pitch and length depending on position)
- Strips vertical on X, $\pm5^\circ$ on U/V planes
- Circular cut out around the beampipe
- 68 **staves**, staggered 10 mm in z to provide overlap in x





Upstream Tracker Geometry

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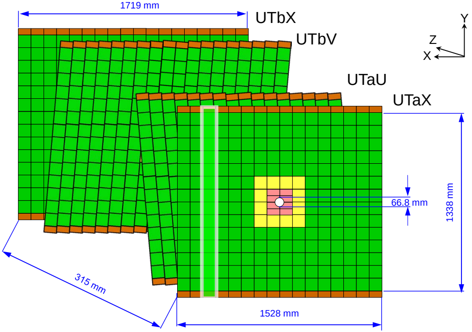
- Single-sided silicon microstrip sensors (strip pitch and length depending on position)
- Strips vertical on X, ±5° on U/V planes
- Circular cut out around the beampipe
- 68 **staves**, staggered 10 mm in z to provide overlap in x

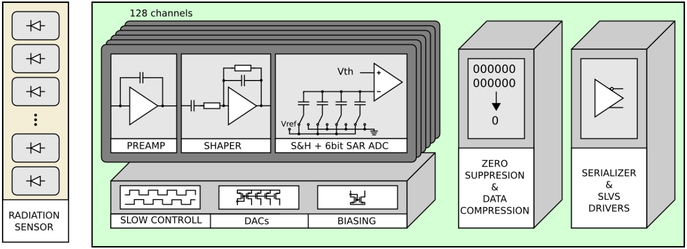
🟩	🟨	🟥	🟥
98 mm 190 µm 512 strips	98 mm 95 µm 1024 strips	49 mm 95 µm	49 mm 95 µm



SALT ASIC

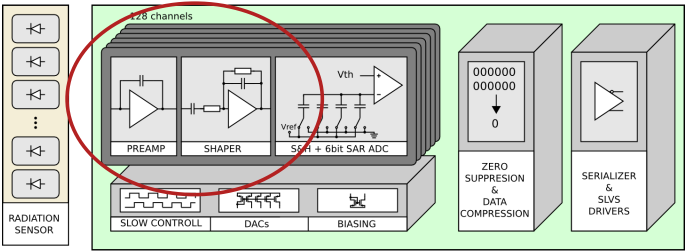
SALT = Silicon ASIC for LHCb Tracker

- 40 MHz readout
- 128 channels
- TSMC CMOS 130 nm technology
- 73 μm pitch on input pads



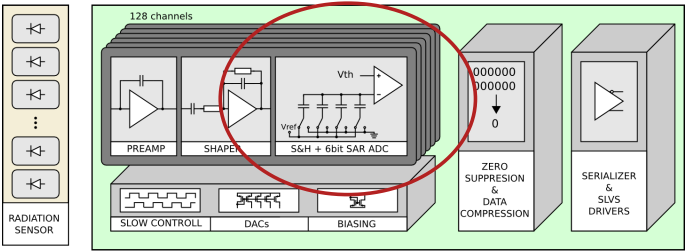
SALT ASIC - analog block

- Peaking time ~ 25 ns
- Remainder after $2\times$peaking time $\sim 5\%$ $\Longrightarrow$ minimise pile up, spill over
- Sensor capacitance $5-15$ pF
- Power consumption $1-2$ mW/channel
- Both polarities $\Longrightarrow$ n^+-in-p and p^+-in-n



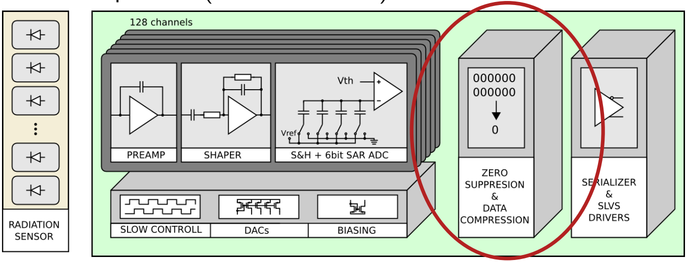
SALT ASIC - ADC

- SAR, 6 bit resolution
- power consumption < 0.5 mW at 40 MS/s



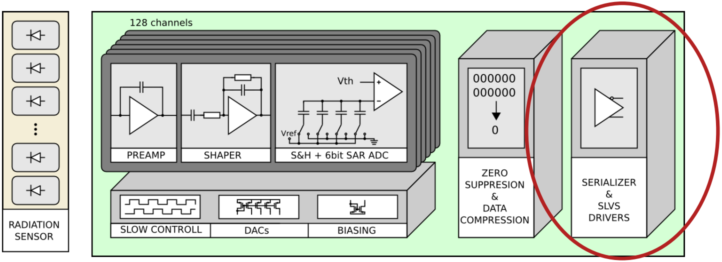
SALT ASIC - digital signal processing block

- Bad/noisy channel masking
- Pedestal subtraction
- Mean common mode subtraction
- Zero suppression
- Data compression (header and data)



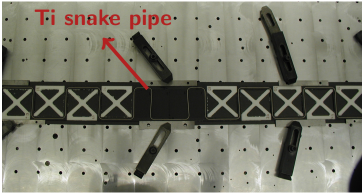
SALT ASIC - serialisation

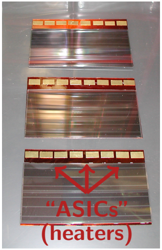
- Create and transmit data frames to peripheral electronics
- Serial links $\Longrightarrow$ e-links
  - ☐ 5 e-links per ASIC but $2-5$ active depending on sensor position
- SLVS I/O standard
- 320 MBit/s data rate

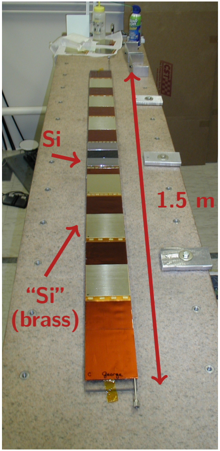


Stave Protoyping at Syracuse

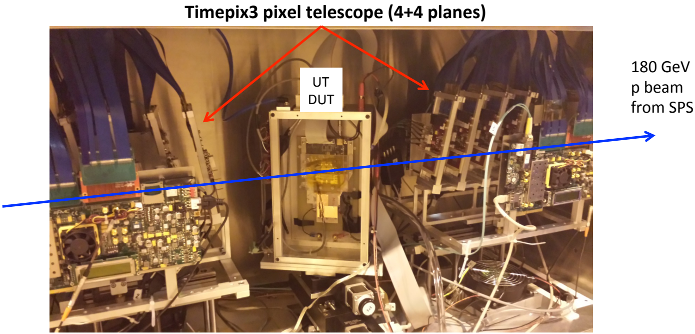
- First mechanical/thermal prototype completed
  - ☐ realistic stave materials (CFRP, foam core)
  - ☐ snake pipe design
  - ☐ Ti tube bent and epoxied into the stave
  - ☐ maximum heat load mimicked by heaters
  - ☐ successfully cooled down, well below −5°C on sensors
  - ☐ measurements ongoing, including deflection and thermal contraction





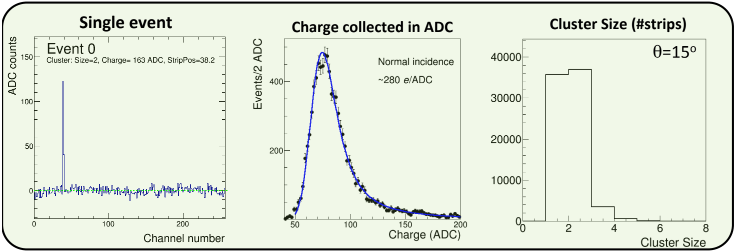


UT Testbeam: October 20-26, 2014



- ☐ **Primary goal**: to validate the performance of the n-in-p and p-in-n sensors up to the maximum expected radiation dose of ~40 MRad (n-in-p) and 1 Mrad (p-in-n)
- ☐ **Secondary goals:**
  - ☐ Signal, noise and S/N characterization
  - ☐ Resolution –vs- angle, cluster sizes, etc
  - ☐ Efficiency across detector
- ☐ **Only a couple weeks old, so analysis is ongoing…**

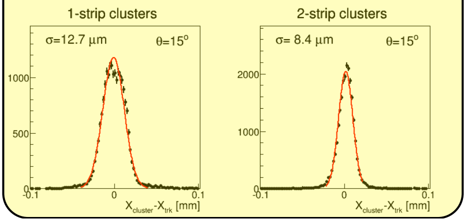
UT Prototype Sensor Performance


Single event

Charge collected in ADC

Cluster Size (#strips)

Resolution (strip pitch = 80 μm)


1-strip clusters

2-strip clusters

- ☐ **Full depletion of n-in-p sensors up to 24 MRad**
- ☐ **Landau distributions look roughly as expected.**
- ☐ **2-strip resolution: σ_{Gauss} ~8.4 um**
- ☐ **Many studies in progress.**

Bon appetit

Summary

- Flavor physics probes Standard Model and Beyond the Standard Model physics. It complements the high p_T physics program of ATLAS and CMS.
- LHCb ran very well during Run 1. We have published over 200 journal papers.
- Run 2 promises about twice as much $b\bar{b}$ and $c\bar{c}$ per fb^{-1}, and $\mathcal{L} \sim 5$ fb^{-1} compared to 3 fb^{-1} in Run 1.
- The upgrade era promises another order of magnitude greater data.
- US-LHCb is leading the Upstream Tracker construction project. This is critical to the upgrade. We are making excellent progress.